MERENTUTKIMUSLAITOKSEN JULKAISU
HAVSFORSKNINGSINSTITUTETS SKRIFT N:o 96

A STUDY
OF THE
SEDIMENTS OF THE NORTH BALTIC
AND
ADJOINING SEAS

BY
STINA GRIPENBERG

HELSINKI — HELSINGFORS
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PREFACE.

In 1924 Professor ROLF WITTING, Director of the Thalassological Institute of Helsingfors, suggested that I should undertake the examination of a number of bottom samples which were to be collected from the Gulf of Finland, the Gulf of Bothnia and the North Baltic during the yearly cruises of the s/s Nautilus. This suggestion was followed, and the results of the investigation are set forth in the present paper. About a hundred and thirty samples, collected during the years 1924—1930, were examined. The chief value of an investigation of this kind, apart from a mere knowledge of the character of the sediments, is its bearing on the early history of the Baltic Sea. In this respect, the results presented are only to be regarded as a contribution to the subject, since an examination allowing of more definite and detailed conclusions would have demanded not only chemical and mechanical, but also mineralogical and biological analyses of the samples.

The investigation was carried out at the Chemical Laboratory of the Thalassological Institute. The great number of samples to be analyzed made some assistance in the work necessary. Financial help from the SOHLBERGIAN FOUNDATION of the FINNISH SOCIETY OF SCIENCES enabled me to secure the assistance of Mr LENNART WASASTJERNA and Mr BJÖRN BJÖRKENHEIM. Mr WASASTJERNA analyzed about eighty five samples or parts of samples for organic matter and about fifty samples for carbonates, and also made all the nitrogen analyses. Furthermore, for about a year, he carried out part of my routine work at the laboratory, thus enabling me to devote more time to my work on the bottom samples. Mr BJÖRKENHEIM made about fifty analyses of organic matter. For my own part I made the first twenty five analyses of organic matter (stations F1 to F25A), about ninety analyses of carbonates and all the rest of the analytical and experimental work.

I feel very much indebted to Professor WITTING, Director of the Institute, to Mr GUNNAR GRANQVIST, Acting Director of the Institute, and to Professor KURT BUCH, Chief of the Chemical La-

boratory, for constant interest in my work and readiness to facilitate it in every way. I particularly wish to thank them, as well as all my colleagues on the staff of the Institute, for many suggestions received in discussing with them different problems connected with the work.

I further wish to express my thanks to the SOHLBERGIAN FOUNDATION for the valuable help received, to Dr ASTRID CLEVE-EULER of Guldsmedshyttan, Sweden, for kindly examining two samples (F64 and F78) as to their content of diatoms, to Dr GUSTAF TROEDSSON of Hälsingborg, Sweden, for examining the fragments of Silurian fossils collected at the Finngrundens Banks, to Mr G. GREENE, M. A., and Mr R. MORRELL, M. A., for kindly reading the English manuscript, and to Mr BJÖRKENHEIM for the care and interest with which he performed his task. I regret that the premature death of Mr WASASTJERNA has prevented me from showing him the final result of the work in the practical execution of which he gave me such valuable assistance.

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Helsingfors
September, 1934.

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Fig. 1. Hydrographical stations.

I. INTRODUCTION.

1. HISTORICAL NOTES.

The bottom samples described in this paper were collected on the yearly cruises of the s/s Nautilus, the research vessel of the Thalassological Institute of Helsingfors. Most samples were taken at the points regularly visited each year and internationally known as stations F1 to F81. The positions of these stations are indicated on Fig. 1. The most southerly is situated in latitude $57^{\circ}22'$, at about the height of the middle part of Gotland. From here northwards the samples, about 130 in number, are distributed almost evenly over the Baltic proper, the Gulf of Finland and the Gulf of Bothnia. A description of the bottom configuration of these parts of the Baltic will not be given here. The reader is referred to the survey by WITTING in the 'Text-Book of the Atlas of Finland' (32) 1910 or 1925, the work of ANDRÉE (5) or the survey by PRATJE (89).

Sediments from these regions have not previously been subjected to any extensive examination. The Swedish Hydrographical Expedition of 1877 (66) collected a number of bottom samples from the south and middle parts of the Baltic, only two of their stations lying within the territory now under examination. More recently HESSLE (47) investigated the bottom of the Baltic along the Swedish coast from the south point of Island Öland to the inmost part of the Bay of Bothnia, treating, however, the material exclusively from the point of view of the zoologist, giving in his list of bottom samples only their outward appearance, and no chemical data. In 1907 the German research vessel Poseidon repeated the Swedish investigations of 1877. The bottom samples then collected, of which 24 came from localities above lat. 57°N , were examined by SPETHMANN (101), who made mechanical analyses of the samples, and by APSTEIN (7), who described the different types of deposits and mapped their distribution. Later on SJÖSTEDT (100) investigated the sediments of the Danish Sound and adjoining waters from a biological point of view.

2. COLLECTION AND FIRST EXAMINATION OF SAMPLES.

Most of the samples treated here are more or less fine-grained. The reason for this is to be found in the character of the samplers

Fig. 2. Bottom samplers of SJÖSTEDT, GILSON and TRASK.

used. There were three different types. That most used was a glass tube sampler built on the principles of the EKMAN sampler (24), but considerably smaller (Fig. 2). It was manufactured in Helsingfors according to the description given by SJÖSTEDT (*loc. cit.*). It is fitted with a removable glass tube (length 50 cm, inner diameter 15mm) into which the sample enters and in which it is kept until examination. When this sampler was brought on board, after having been operated, a paraffined cork stopper was inserted at the lower end of the glass tube, the tube was then taken out, the water at the top of the tube cautiously poured out and another stopper inserted at top. In this way quite untouched profiles were obtained, showing the initial arrangement of layers. The length of the samples varied very much, perhaps due to the angle at which the sampler touched the bottom. It may be that loose samples have a tendency to slip out of the tube, as loose muds were sometimes found to be only a few centimetres long, whereas stiff clays often reached 30 cm and more. The whole length of the glass tube was never filled owing to resistance and perhaps compression within the narrow tube. With the SJÖSTEDT sampler only clays and fine sands can be obtained. Though the construction does not permit the water to pass through the tube while the sampler is being hauled in, yet coarse sediments are apt to fall out, unless the lowest part of the sample is fine-grained. No conclusion therefore can be drawn as to the character of the bottom if the sampler comes up empty. A greater amount of sediment was obtained with another modification of the EKMAN sampler, described by TRASK (112, 115). This sampler is considerably simpler in construction and lighter than the EKMAN sampler, weighing only about 15 kgr. The iron collecting tube is 1 meter long with an inner diameter of 4.5 cm. This iron

tube naturally has to be emptied at once. This was done into glass jars in which the sample was protected against oxidization and drying. On the other hand no information was obtained by this method as to the length of the sample, whether it consisted of different layers, their thickness etc. The sample had to be treated as homogeneous. Fortunately no serious error seems to have arisen from this fact, because at the localities where the TRASK sampler was used the deposits are apparently more or less uniform to the depth reached by the sampler. Both these samplers work equally well in deep and in shallow water. The sampler of GILSON is for shallow water only (34)¹; it is difficult to handle even at a depth of 20 metres; it was used only in studying the interesting deposits round the Finngrundens Banks in the Bothnian Sea. This sampler consists of a bowl, about 20 cm in diameter attached in the middle to an iron rod. The instrument is dragged for some time along the bottom; when hauled in, a lid falls down protecting the contents of the bowl from being washed out. But if a pebble is caught between the bowl and the lid, water will enter and complete or partial washing will follow. Nevertheless, some samples of clayey sands and pebbles were obtained with this instrument; its greatest achievement being a piece of limestone, 650 gr in weight.

When the samples were brought home they were subjected first to an external examination. The length of a glass tube sample was noted, its colour, consistency, whether it presented different layers etc. Then it was removed from the tube. A well-fitting piece of cork stopper, about half a centimeter thick, was inserted at the top and pushed towards the sample. The pressure of the cushion of air thus formed was generally enough to make the sample slide out of the tube. It was dried on filter paper for a few minutes, then divided into two halves vertically down the middle by means of pairs of microscopic slides. This revealed the interior of the sample. It was now examined under the microscope, especially as to the presence or absence of diatoms. When no diatoms were found in small samples from the top or the bottom of the profile, some of it was treated with strong hydrochloric acid, washed with water and burnt on a cover glass with spirit. If renewed examination revealed no diatoms the sample was considered not to contain any. It was not thought necessary to concentrate the diatoms,

¹) The sampler was supplied by Prof. GILSON. It is somewhat simpler in construction than the one described in Publ. d. Circonst. No. 35.

Fig. 3. Bottom samples F77, F32A ($\frac{1}{2}$ of natural size) and F33 1926 (about $\frac{2}{3}$ of natural size).

as the samples in which none were found generally showed other characteristics which distinguished them from the rest¹⁾. The sample was now left on the filter paper for some days until it was completely dry. If, when wet, it presented layers distinctly different in grain size or colour, these were separated and subsequently kept in separate glass jars. Some of the latter samples were stored on wooden blocks in which grooves of the diameter of the glass tube had been made. Both halves of the sample were thus kept in their initial order of layers, until further examination. Fig. 3 shows some of these samples. The samples taken with the TRASK sampler, were also air dried, lest some of the organic matter contained in them should evaporate if they were heated. That this fear was well-founded some experiments recorded later (page 22) will show. These sam-

¹⁾ In this connection it may be noted that the species of *Chaetoceras*, easily recognizable even to an unexperienced eye, was found in many samples from the Gulf of Finland and the Baltic, not only in the surface layers but also deep in the mud, in one case at the lower end of a sample 19 cm long (F53). According to APSTEIN, this diatom, though developing in great masses every spring in the Baltic, is never found in the bottom deposits. *Chaetoceras* sp. was found at the following stations: F40, F41, F44, F45, F50, F53, F56, F62.

ples were spread out on sheets of parchment paper, which were placed on thick layers of newspaper, frequently renewed. From the parchment paper the dry sediments were easily removable; they were then stored in glass jars.

In the following, when individual samples are referred to, the station of collection will be given and, in the case of several samples having been taken at the same station, the year of collection will be added.

II. CHEMICAL ANALYSIS.

3. INTRODUCTION.

The great number of samples rendered it impossible to subject them all to complete chemical analysis. It was moreover considered that the interest of the result would in no way repay the work and time such a scheme would require. The deposits of the Baltic derive their origin to a great extent from the primitive rocks of Fennoscandia, being the result of the mechanical disintegration of these rocks, which took place during the Ice-age. Though some chemical decomposition occurred simultaneously (TAMM 106) it did not play a very prominent part in the process. A complete analysis of any individual sample would therefore not contribute much to its characterization. Apart from mechanical analysis, it was considered that this characterization was best attained by analyses of carbonates and organic matter, the latter comprising determination of organic carbon and of nitrogen.

Great importance was attached to mechanical analysis. The silt and clay fractions, especially, were studied in detail by division into several subgroups. It was hoped in this way to get a basis for classification and an insight into the mode of formation of the sediments. It may be said that the results have largely justified expectations, although it was found that organic matter content offered a better basis for classification.

For calculating the mechanical analyses it was necessary also to determine the salt content of the dried samples. As the salinities of the bottom waters, at the localities where the samples were taken, are known, it is possible from the salt content of a sample to calculate the approximate amount of water it initially contained.

All the chemical analyses were calculated on air dry sample. The contents of a jar containing the whole or part of a sample was coarsely ground so that there was no danger of the particle size distribution being altered, then a small amount was finely powdered in a porcelain and finally in an agate mortar. The results thus represent average values for the sample, or part of sample, studied. The samples stored on wooden blocks were treated somewhat differently. Independently of whether in wet or dry condition the profile seemed uniform, it was divided into three to five parts, which were analyzed separately.

An insight in the distribution of carbonates and organic matter within the sample was thus obtained.

4. DETERMINATION OF CARBONATES.

For the determination of carbon dioxide bound as carbonates a method by VESTERBERG (125) was adopted. It constitutes an adap-

Fig. 4. VESTERBERG'S apparatus for determination of carbonates.

tation for soil analysis of the well-known method of CL. WINKLER ¹⁾ for determining alkali hydroxides in the presence of carbonates. The carbon dioxide, set free by hydrochloric acid, is caught in a known amount of barium hydroxide solution, containing barium chloride. Barium carbonate precipitates, and the excess of alkali is determined by titration with hydrochloric acid. The chief feature of the method of VESTERBERG is, however, that the operation takes place in vacuo, which considerably facilitates and shortens the process.

An analysis was made in the following manner. From 0.2—0.5 gr (or more if the CO_2 -content was small), of a finely powdered air dry sample was introduced in a fractionating flask A (Fig. 4), of 100—150 c. c. capacity. About 40 c. c. of CO_2 -free water were added

¹⁾ Treadwell, Quantitative Analyse, 9:te Auflage, p. 485, Leipzig und Wien 1921.

and, in order to bind any hydrogen sulphide present, 1 c. c. of a 4 % mercuric chloride solution. The flask could be connected with a thick-walled receiver B, of about 300 c. c., by means of a piece of vacuum rubber tubing. The stopper of A carried a small funnel C, provided with a tap, and that of B two glass tubes with taps, D and E. About 25 c. c. of N/10 barium hydroxide were introduced into B. In order to avoid any contamination with CO_2 from the air, the following procedure was adopted: About 4 gr of barium chloride and a few drops of phenolphthalein or cresolphthalein were introduced into B, the stopper put on and the receiver evacuated, then filled with CO_2 -free air. The alkali solution was now let in through the tube D, which was then rinsed with CO_2 -free water. The flask A was filled with CO_2 -free air in the same way, then connected with B. The whole apparatus was now evacuated to a pressure of about 10—20 millimetres. An oil-pump operated by hand produced the desired vacuum in less than a minute. Laboratory air was freed from CO_2 by being passed through a glass tube filled with soda lime a metre long and with a diameter of 2.5 cm. The tap E having been turned, some c. c. of 2N hydrochloric acid were cautiously introduced through the funnel C. The funnel was then rinsed with a few c. c. of CO_2 -free water. When the visible reaction, if any, had ceased, the flask was warmed with a very small flame and kept boiling for about 10 minutes. At the low pressure in the flask this was enough to drive out all the carbon dioxide. Through the funnel C, a slow stream of CO_2 -free air was now let in, automatically carrying the small amounts of CO_2 still in the flask and the tube into the receiver. When atmospheric pressure had been restored, the receiver was disconnected, shaken, and left standing until the solution had become clear, — generally overnight although this was not necessary. The precipitate of barium carbonate was now sufficiently insoluble to allow of a return titration with N/10 hydrochloric acid. The stopper of B was taken out, the tubes rinsed with CO_2 -free water and the titration effected while a stream of CO_2 -free air was being passed through the flask.

It is essential that CO_2 -free water should be used and the apparatus filled with CO_2 -free air before the analysis is begun, also, naturally, that no CO_2 should be allowed to enter from outside. Laboratory air contains about 1 c. c. CO_2 per litre, i. e. 2 mgr. The bulk of the apparatus is about half a litre. Consequently, if the carbon dioxide in the apparatus is not expelled, there is an error of 1 mgr in the CO_2 -amount. The CO_2 -content of distilled water may amount to $2.5 \cdot 10^{-4}$

moles ¹⁾ or 11 mgr per litre. If 60 c. c. are used for an analysis this means an error of 0.7 mgr. The total error may thus amount to almost 2 mgr. In the beginning, before CO₂-free water was used, blank tests often gave this amount, but afterwards, as a rule, not more than 0.1 mgr corresponding to 0.05 c. c. N/10 HCl and thus lying almost within the titration error.

The following tests show the accuracy of the method. Two portions of MERCK's pure calcium carbonate were analyzed:

Weight 91.8 mgr, found by analysis 91.6 mgr

» 74.2 » » » » 74.3 » .

A bottom sample which had been found to contain only 0.02 % CO₂ was carefully mixed with enough pure calcium carbonate to bring the calculated CO₂-content up to 6.09 %. Four portions of the mixture were analyzed giving the following results:

CO₂ found by analysis 6.07, 6.09, 6.06, 6.09, mean 6.08 %

CO₂ calculated 6.09 %.

The agreement was thus very good. Generally two analyses were considered satisfactory if they did not differ by more than 0.1 %. In the List of Analyses (Table 19) the mean of two or more analyses are given, except in the cases where the scarcity of the material did not allow of a second analysis.

The results were calculated as percentage CO₂ of the air dry sample. In the table the corresponding amount of calcium carbonate is also given, though part of the carbon dioxide may have been bound to magnesium. This part was only determined in four cases. According to a method by VESTERBERG (124) the samples were treated with 2 % acetic acid, which only attacks the carbonates. Calcium was then as usual precipitated as oxalate and titrated with potassium permanganate, while magnesium was precipitated as NH₄MgPO₄ and weighed as pyrophosphate. The experiments were only considered as preliminary, but show a fairly good agreement between the CO₂-content found by direct analysis and the quantity calculated from the calcium and magnesium analyses. Magnesium carbonate was only found to constitute about 1.5—3 % of the calcium carbonate content. The results may be given here, as they demonstrate the accuracy of the analyses:

¹⁾ KOLTHOFF, I. M., Die Massanalyse, Zweiter Teil, p. 78, Berlin 1928.

Table 1. *Analyses of magnesium content in carbonate containing samples.*

Sample	(1) % CaCO ₃ from Ca-anal.	(2) % MgCO ₃	(3) Sum of carbo- nates %	(4) MgCO ₃ in % of CaCO ₃	(5) % CO ₂ calc.	(6) % CO ₂ observed	(7) % CaCO ₃ calc. from CO ₂ obs.	(8) Diffe- rence betw. col. (7) and (3)
F31 1924	40.02	0.86	40.88	2.1	18.04	18.32	41.64	0.76
F31B 1925, fraction b)....	35.70	0.55	36.25	1.5	15.97	16.06	36.52	0.27
Fragments of limestone fr.								
F31B 1925	54.49	0.84	55.33	1.5	—	—	—	—
F33 1925, fraction c)	28.32	0.84	29.16	3.0	12.92	12.99	29.54	0.38

In the first case the agreement between carbon dioxide observed and that calculated is not very good, and the difference between the amount of calcium carbonate calculated from the CO₂-content and the sum of the carbonates is consequently high. In the other two cases this difference is only about 1 % of the total carbonates. It is true that the carbonates of all the samples examined probably had the same origin, viz. the submarine limestone at Finngrunden, and no conclusion therefore can be drawn as to the magnesium content of samples from other localities. The Swedish Hydrographical Expedition of 1877 found much higher contents in samples from the South Baltic. As high amounts of carbonates were only found in the vicinity of the Finngrunden, the error in the carbonate content, arising from the fact that the whole of the carbon dioxide was attributed to calcium carbonate, cannot in any case involve high values. — In Table 19 very low amounts of CO₂, below 0.1 %, are not given as CaCO₃, as the carbon dioxide of such samples may probably be attributed in part to the water they originally contained, and in part to decomposed organic matter.

5. DETERMINATION OF ORGANIC MATTER.

Organic matter was determined by combustion in vacuo, and collection of the carbon dioxide formed in a vacuum receiver of the same kind as that used for the carbonate determinations. The method was introduced by VESTERBERG and slightly modified by TAMM (105). The author introduced the same precautions against contamination with atmospheric carbon dioxide, as already described for carbonate analysis. The finely powdered sample is mixed with about four times its volume of fused and powdered lead chromate, containing 10 % potassium dichromate. It is then transferred into a copper combustion boat and introduced into an ordinary combustion tube, 70- 75

cm long, prepared in the following way. Beginning at the end which is to be connected with the receiver, there is first a reduced roll of copper wire gauze, 10 cm long, then a 20 cm layer of granulated copper oxide, held in place at both ends by short oxidized spirals of copper wire, then a 5—10 cm layer of granulated lead chromate and again a short oxidized spiral. Next comes the boat and lastly a 10 cm oxidized spiral. The layer of lead chromate was added to make sure that chlorides and sulphur dioxide, formed by combustion of iron sulphides present in most samples, were retained. The combustion is done in an ordinary combustion furnace, but if one is not available a simpler arrangement can be used. In the present case two iron rods were attached to ordinary supports, as shown in Fig. 5.

Fig. 5. Simple arrangement for combustion in vacuo.

The combustion tube was suspended between the rods in a groove of sheet iron, bent to form upstanding edges on which shields of asbestos board were hung (not shown in the figure). Pieces of asbestos board with catches covered the tube, which protruded 5 cm at each end of the groove. The latter had long openings on either side to allow the entrance of the combustion gases from five Teclu burners with flat burner attachments. The combustion is done in the ordinary manner, but care must be taken not to heat the lead chromate until fusion, as breakage of the tube will inevitably follow. When the sample has been introduced, the tube is evacuated and filled with CO_2 -free air, then evacuated again and connected with the evacuated receiver previously filled with a known amount of N/10 baryum hydroxide, 4 gr of baryum chloride and a few drops of cresolphthalein, all these operations being done exactly in the way already described for carbonate analysis. The lamps under the reduced spiral and the

copper oxide are now lit. The evacuation is continued for some time to make sure that all connections are air tight, after which the one with the pump is broken off and combustion begun. When after about half an hour no more gas bubbles enter the receiver, the combustion is ended, a slow stream of CO_2 -free air is let in, and the heat gradually lessened. Atmospheric pressure having been restored, the receiver is disconnected, shaken and left standing until the liquid has become clear, then titrated. With this method of combustion, the oxygen delivering materials are contained in the tube and no supply of gaseous oxygen is needed. Further the reduced pressure makes it possible to perform the combustion in a closed space, so that no loss of CO_2 through incomplete absorption need be feared. In opposition to EKSTRÖM (25) who rejected the method on account of its inaccuracy, I have obtained very satisfactory results, when proper care was taken to exclude all atmospheric carbon dioxide; naturally, a newly filled combustion tube had to be heated until at blank tests the baryum hydroxide solution remained absolutely clear. The accuracy of the method is best shown by comparing the results obtained on the same sample, by different workers at different times. In Table 2 below some instances of this kind are given, in which samples containing various amounts of organic matter were analyzed by different investigators. The amount of carbon dioxide multiplied by the factor 0.471 gives the organic content. (The validity of this factor for sea bottom sediments is discussed below.) The contents are given as percentage of air dry sample.

Table 2. *Analyses of organic matter performed by different workers.*

Sample		F55 1921 %	F50 1925 %	F37 1924 %	F66 1924 %	F37 1925 %
Worker G	{	0.72	1.26	—	—	—
		0.73	1.26	—	—	—
» B		0.70	—	2.21	3.80	7.74
» W	{	—	1.25	2.26	3.70	7.64
		—	—	—	3.75	—

The greatest deviation between two single analyses is 0.1 %. Two analyses were considered good if they did not differ by more than this amount. In some instances greater variations were found, apparently due to uneven distribution of the organic matter in the sample. Then two or three more analyses were made and their mean taken. In some instances a single analysis was accepted, when it was supported by values found in neighbouring parts of the same

sample or in another sample from the same locality. A deviation of 0.1 % in organic matter corresponds to about 0.2 in carbon dioxide. The tolerance was thus greater than in the carbonate analyses and this is due to the fact that the deviation becomes greater when CO_2 is converted into carbonate, but smaller when converted into organic matter.

In soil analysis it is usual to calculate the organic content either from the CO_2 -amount by applying the factor 0.471 to the latter, or from the organic carbon by means of the factor 1.724. This corresponds to an amount of 58 % carbon in soil organic matter. Though the formation of organic matter in the soil from fresh material depends on a great many factors, such as temperature, moisture, aeration and, above all, the activity of various micro-organisms, yet the final product is of fairly constant composition. WAKSMAN (119) has shown that the decomposition processes bring about an accumulation of resistant substances of plant origin, chiefly lignin and lignin-like complexes and of nitrogenous substances of microbial origin, chiefly proteins. As decomposition advances, the ratio of carbon to nitrogen in the product tends to become constant, its value ranging from 8 to 12, the mean being 10. There is thus a certain »decomposition equilibrium». When this is reached, the ratio between the carbon given off as CO_2 and the nitrogen changed into nitrate remains more or less constant with further decomposition, which shows that the relative composition of soil organic matter tends to remain constant (SIFVERS and HOLTZ 99).

TRASK and co-workers (115) subjected a number of marine muds to a detailed analysis according to the method of WAKSMAN. He found on the one hand, an unmistakable similarity to the composition of soil organic matter, but, on the other, certain differences probably due to differences in origin of the organic constituents. Decomposition products of plankton, — zoo- as well as phytoplankton — and of animal benthos and nekton, constitute ingredients in marine muds, not to be found in land humus. Marine sediments were found to be somewhat richer in nitrogen than soils are, and especially in resistant nitrogenous compounds. This fact, which was revealed by the analyses, is also expressed in the C:N ratio of marine muds. HAMMAR (42) examined 25 sediments from 18 representative environments of deposition adjacent to the coasts of North and South America and found the mean ratio to be 8.5. TRASK found a mean of 8.3 in 85 samples from the Channel Islands region in California, the ratio being approximately the same for deposits rich and poor in organic matter. The mean for all sediments analyzed was 8.4; lower than the mean for soils, which is 10, but still lying within

the values frequently occurring in soils. As the factor 0.471 is used for all kinds of soils it thus seems permissible to use it also for marine muds. For Baltic sediments it seems even specially appropriate as the mean C:N ratio for 81 such sediments was found to be 10.0 (see Section 28) or exactly the same as for soils and considerably higher than the ratio found by TRASK and his co-workers. The mean for arable soils in Southwest Finland is likewise 10, in the interior of the country somewhat higher¹⁾. The high C:N ratio in the Baltic indicates that the contribution of plant material — chiefly land humus — to the organic component of the bottom sediments, is greater than in the Ocean.

In the List of Analyses (p. 121) the amount of organic carbon and the approximate content of organic matter, calculated from the carbon dioxide by means of the factor 0.471, are given.

In analyzing organic matter in samples containing carbonates, these have first to be removed, even if their amount is determined separately and thus may be deducted from the result. Especially if the amount is high, the decomposition by combustion may not be complete. WAHNSCHAFTE and SCHUCHT (118), citing ALBERT and BOGS, propose the use of sulphurous acid for this purpose. We adopted their method and treated the weighed samples a few times on a water bath with small portions of saturated sulphur dioxide solution, after which they were transferred into the combustion boat. But, in thus treating some samples which had already been analyzed in the ordinary way, it was found that the sum of the carbon dioxide amounts from organic matter and from carbonates was smaller than the amount found by direct analysis, in other words, organic matter was lost during the treatment. A great many analyses were made in both ways and losses ranging from 0 to about 2 % of the sample, or up to 20 % of the organic matter therein, were observed. Samples containing no carbonates were also treated with the same result. Finally some samples were treated with water only and losses of the same order of magnitude observed. Of the 37 samples analyzed in both ways, 9 gave the same result within the experimental error; 3 gave a surplus from 0.4—0.9 % (unevenness of the material?), 5 losses from 0.2—0.3 %, 14 losses from 0.3—0.7 %, 6 losses from 0.9—1.9 %, losses from 0.7—0.9 were lacking. The mean loss (ignoring the anomalous cases showing a higher amount after treatment) was 0.48 % CO₂, and of the typical ones, having losses from 0.3—0.7 %, it was 0.56 %. On an average one may say that the result of organic matter analysis on samples, which have been subjected to preliminary

¹⁾ Private communication by Prof. B. AARNIO, Helsingfors.

treatment with SO_2 -solution, is about 0.5 % too low, when calculated as carbon dioxide, which corresponds to about 0.25 % in organic matter. If a certain fraction of the organic matter is volatile with water vapor or easily destructible, one would expect the loss to be fairly constant, expressed as percentage of the organic matter content. This does not seem to be the case. In one instance a loss of 0.4 % represents 15 % of the organic matter content, whereas in another a loss of 0.5 % represents only 3 %. However, in 23 cases out of 34, the loss was below 10 % of the organic matter, the mean of all being 7 %. It seems probable that the way the samples were treated — with many or only a few portions of SO_2 -solution, whether they were left on the water bath for a long or a short time etc. — was important for the result. In any case it is evidenced that bottom samples should not be heated when dried, as part of the organic matter may be decomposed. The treatment of sample F62 1924 gave an interesting result. This sample consisted of three layers, the uppermost was almost black and yielded 5.41 % organic carbon dioxide plus 1.12 % CO_2 from carbonates, then followed a dark grey layer containing 5.58 % and 1.35 % of these respectively, finally a brownish-grey layer, which in spite of the light colour was very rich in organic matter, giving 10.84 % organic CO_2 and 0.75 % CO_2 from carbonates. The treatment with SO_2 -solution effected losses of 0.93, 0.96 and 1.87 %, corresponding in all three cases to 17.2 % of the organic carbon dioxide! Thus except that the loss was unusually high, it was in this case constant throughout the sample.

In Table 19 the organic matter of samples containing carbonates was calculated by subtracting the CO_2 -amount of the latter from the amount found by direct combustion. In some cases combustion was only done after preliminary treatment with SO_2 ; I have, however, refrained from correcting the results in view of the very varying losses caused by the treatment.

6. DETERMINATION OF NITROGEN.

The nitrogen analyses were done by Mr WASASTJERNA alone, according to the micro-KJELDAHL method. For each analysis 50—100 mgr of substance was used. Copper sulphate was used as a catalyst and sodium sulphate added in order to raise the boiling point of the sulphuric acid. Heating was continued until discoloration, which required half an hour or more. All samples were analyzed in duplicate and considered good if they did not differ by more than 0.03 % from each other. They generally agreed within 0.02 %. Blank tests were made before and after each series of 8 analyses. As in the

case of the carbon analyses it was found that individual analyses differed more in samples with a high content of organic matter. This was found to be due to uneven distribution of nitrogen as seen from analyses recorded p. 160. In such cases the values given are the mean of several analyses. More representative analyses could have been obtained if greater amounts of substance had been treated by the ordinary KJELDAHL method. The scarcity of the material, however, forbade this, nitrogen being determined almost exclusively in glass tube samples.

7. DETERMINATION OF ELECTROLYTES.

In oceanography the salinity of a water sample is calculated from the chlorine content by means of the well-known equation of KNUDSEN:

$$S \text{ ‰} = 1.805 \text{ Cl ‰} + 0.03$$

where S and Cl are expressed as grams per kilogram of sea water. The same equation applies to the salt content of a bottom sample if, as seems natural, the relative composition of the salts in the water contained in it, is supposed to be the same as in sea water. Fine-grained bottom deposits however also contain absorbed bases¹⁾, clay particles in suspension mostly carrying a negative electric charge. In determining salinity by using KNUDSEN's formula the absorbed ions are naturally not included. The chlorine content of a bottom sample can easily be determined directly in the sample, as will be shown below, but the absorbed bases have to be removed before a determination is possible. Chlorine was determined in all samples which were subjected to mechanical analysis; preliminary determinations of absorbed bases were made in some twenty cases, the amounts thereof, however, were not taken into account in calculating the results of the mechanical analyses. Thus the salinities given in Table 19 represent the salt content of the water contained in the bottom samples before drying, not the entire content of electrolytes therein. The values recorded are the mean of two, not differing more than 0.1 ‰, except in the cases where, owing to scarcity of material, only one analysis could be made. Generally double analyses agreed very well as is seen from Table 19 below.

Combined with a knowledge of the salinity of the bottom water, the salt content affords a means of determining the lower limit for

¹⁾ There seems to be some uncertainty in literature, whether the exchangeable bases should be called *absorbed* or *adsorbed* ions. I have chosen the former expression which is supported by the definitions of *absorption* and *adsorption* given by WIEGNER (127).

the water content of a sample in its natural state. If S is the percentage salinity of the bottom water (gr salt per 100 gr of sea water) and s that of the dry sample, the weight of which is P , w the amount of sea water and x the percentage thereof in the sample in its natural state, then

$$\begin{cases} \frac{Sw}{100} = \frac{sP}{100} \\ w = \frac{x(P+w)}{100} \end{cases}$$

The elimination of P and w gives

$$x = \frac{100}{S+s} s$$

As in this investigation most samples were dried on filter paper, part of the water and salts therein were drawn off and thus escaped determination. Very fine-grained samples and such as contain a high amount of organic matter may show so-called negative absorption (WIEGNER 131, MARTSON 61), that is the salinity of the water contained in the sample may be less than that of the bottom water, even if the relative composition is the same, or, in other words, there may be a surplus of water molecules in the sample. The values calculated from the equation for x and recorded in Table 19 therefore represent minimum values of the initial water content of the sample. Unfortunately direct determinations were not made on the fresh samples.

All samples mechanically analyzed were freed from electrolytes by electrodialysis or ordinary dialysis. Determination of the chlorine content in the dialysate would, however, have involved concentration of large volumes of liquid, and therefore an attempt was made to determine chlorine directly in the sample by the ordinary titration method of MOHR after adding a few c. c. of distilled water. It was found that if N/10 solution of silver nitrate was used, the colour change with potassium chromate could be seen clearly. With N/20 solution it was no more distinct. To four portions of 0.5 à 1 gr of a bottom sample, from which all salts had been removed by dialysis, 3 c. c. of a sea water were added, the titration of which demanded 2.62 c. c. of N/10 silver nitrate solution. The mixtures were titrated and 2.62, 2.65, 2.62 and 2.58 c. c. of the silver solution used respectively, thus the whole of the chlorine was recovered. Three bottom samples F18 1928, F56 1928 and F65A 1928 were subjected to dialysis for about a fortnight, during which the water was changed four times. Table 3 gives the chlorine found from the dialysates and by direct titration.

Table 3. *Comparison of methods for chlorinity determination.*

	F65A	F18	F56
% Cl from dialysate	0.48	0.56	1.00
» » by direct titration	0.48	0.58	0.95

The agreement is good in the first two cases, but in the last there is a deficiency, which is perhaps not accidental, as seen from the following four experiments recorded in Table 4. Weighed portions of four bottom samples, which had been freed from salts through dialysis, were evaporated to dryness with known amounts of sea water. The chlorine content was partly calculated, and partly determined by direct titration of the finely powdered samples.

Table 4. *Chlorinity determination by direct titration.*

	0.66	0.73	0.78	0.73
% Cl found by titration ..	0.70	0.68	0.75	0.81
	0.67	0.76	0.78	0.79
		0.72	0.79	
% Cl calculated	0.71	0.77	0.82	0.82
% Cl recovered	96	96	96	89

The deficiency observed in the last case of Table 3 is confirmed by Table 4. The simplest explanation is perhaps that chlorine ions are mechanically occluded by clay particles through incomplete dispersion of the latter. This view is supported by the fact that when sea water was added to salt-free samples and titrated at once, without preliminary evaporation to dryness, the whole of the chlorine was recovered. As the deficiency did not exceed 0.1 % it was, however, considered that the agreement between calculated and observed values was good enough, and that for the purpose for which the chlorine analyses were made, direct titration gave sufficiently accurate results.

From the chlorine content the salinity was found by multiplication by the factor 1.805, the constant term of the KNUDSEN equation being insignificant, when concentrations are expressed as percentages.

In this connection the results of some preliminary determinations of absorbed bases may be recorded. The washing waters of the first series of twenty samples that were subjected to dialysis, were saved, and the bases, in 300 c. c. of each, titrated according to the method

used for determining excess base in sea water. (See e. g. WATTENBERG 122.) Five c. c. of N/50 hydrochloric acid were added, the carbon dioxide boiled off, the solutions cooled, precautions being taken to exclude atmospheric CO_2 , and the excess of acid titrated with N/50 baryum hydroxide solution, using methyl red as indicator. Both the absolute and the relative errors of the determinations are, however, high, as the values found were very small and only about a twentieth part of the amount of dialysate was analyzed. Nevertheless an idea of the order of magnitude of bases exchangeable by dialysis is obtained. The results, given in Table 5, are calculated as milliequivalents of bases in 10 gr of substance (column 1). For the sake of comparison the content (2) of organic matter and (3) of calcium carbonate, (4) the salinity, (5) the median of the size distribution (page 48), as well as (6) the general character of the sample (page 93) are also given.

Table 5. *Determination of exchangeable bases from dialysate.*

Station	(1) Milli- equiva- lents of bases in 10 gr of soil.	(2) Orga- nic mat- ter %	(3) CaCO_3 %	(4) S in sample %	(5) Median μ	(6) General character
F1 1924, fraction a)	1.2	1.0	—	0.18	27	Sandy mud
F1A 1925	0	1.3	—	0.19	21	Sandy mud
F7 1925	2.1	0.4	—	0.09	120	Fine sand
F8 1925	6.7	6.3	—	0.76	2.9	Silty mud
F12 1925	2.4	5.4	—	1.00	2.7	» »
F13 1924	1.9	2.3	—	0.27	17	Sandy mud
F18 1925	1.0	3.3	—	0.79	2.0	Clayey mud
F19 1925	1.7	3.8	—	0.99	1.4	Clayey mud
F21 1925, fraction b)	0.8	0.8	—	0.28	3.0	Varved silt
F24 1925	1.8	3.3	—	0.98	1.2	Clayey mud
F25A 1925	0.1	3.2	—	0.60	1.5	» »
F26 1925	2.3	3.8	—	0.57	0.9	» »
F28 1925, fraction a)	1.6	0.4	2.84	0.39	1.2	} Varved clay
» » » b)	2.1	1.1	1.60	0.41	0.9	
» » » c)	6.9	1.0	1.86	0.37	1.0	
F29 1925	0.5	3.9	—	0.63	1.2	Clayey mud
F30 1926	2.1	3.4	0.48	0.70	1.0	» »
F30 1925	1.0	1.3	0.43	0.69	0.8	Very stiff clay
F31 1924	5.4	0.5	41.6	0.11	25	Dusty sand
F31B 1925, fraction b)	2.5	0.4	36.5	0.12	16	Coarse silt

The table shows that the order of magnitude of the exchangeable bases is the same as in soils. Chiefly Na^+ , K^+ and Ca^{++} are exchanged against H^+ -ions by ordinary dialysis, whereas by electrodialysis Mg^{++} is also removed, the exchange of which demands a reaction below pH 5, as was shown by ODÉN AND WILKSTRÖM (80). Sea bottom sediments, however, are probably chiefly saturated with sodium, as so-

dium ions constitute 77 % of all the bases present in sea water, whereas magnesium ions only form 18 %¹⁾.

Table 6. *Determination of exchangeable bases from electro-dialysate.*

Milliequivalents in 10 gr of soil.

Station	(1) Total bases	(2) Carbonates	(3) Sea salts	(4) Absorbed bases	(5) Median μ
F18 1928	5.5	0.1	1.8	3.6	2
F42 »	4.4	0.5	1.1	2.8	0.6
F55 1924	8.8	1.5	1.2	6.1	0.6
F65A 1928	8.0	0.2	1.5	6.3	0.8
F78 1924	10.8	0.2	6.2	4.4	0.6
F79 1928	5.8	0.9	1.3	3.6	0.6

On an average higher amounts of bases were found by electro-dialysis, as is seen from Table 6 in which column (1) gives milliequivalents of bases in 10 gr of soil, found by titration of dialysate from kathode chamber, (2) milliequivalents of carbonates from CO_2 -analysis, (3) milliequivalents of sea salts from direct titration of chlorine and (4) »absorbed bases», their amount being the difference between column (1) and the sum of (2) and (3); column (5) finally gives the median of the size distribution.

¹⁾ Sea water of 35 ‰ S contains a total of 0.604 equivalents of salts per kilogram. A water of 1 ‰ contains following amounts of the most important ions (БУЧЕ etc. 18):

	Milliequ. per kgr	%		Milliequ. per kgr	%
Cl'	15.58	90.3	Na'	13.29	77.9
Br'	0.02	0.1	K'	0.28	1.6
SO ₄ ''	1.60	9.3	Mg''	3.08	17.9
HCO ₃ '	0.06	0.3	Ca''	0.60	3.5
	17.26	100.0		17.25	100.0

The mean equivalent weight of sea salts is 58 (35/0.604), very nearly that of sodium chloride. The mean weight of the kations is 21, that of the anions 37. According to weight the relative amounts of the different ions are the following (after LEGENDRE 55):

	%		%
Cl'	55.29	Na'	30.59
Br'	0.19	K'	1.11
SO ₄ ''	7.69	Ca''	1.20
CO ₃ ''	0.21	Mg''	3.73
	63.38		36.63

As will be shown in Section 19, electrodialysis is not without influence on particle size, particles having a diameter $< 2\mu$ apparently being attacked and split into smaller aggregates. For this reason electrodialysis was abandoned as a method of preliminary treatment for mechanical analysis. In an extensive study on electrodialysis, published when the mechanical analyses, connected with this work, were already finished, ODÉN AND WIKSTRÖM (80) have shown that side by side with kation exchange, weathering takes place during electrodialysis. The higher amount of bases found in the electrolysate is thus accounted for, not only by magnesium, but also by a chemical — and consequently from the standpoint of mechanical analysis, an undesirable — influence on the soil particles. This is in perfect accordance with the results of mechanical analysis of dialyzed and electrodialyzed samples arrived at by the author.

III. MECHANICAL ANALYSIS.

8. INTRODUCTION.

A natural sediment contains particles of a great many different sizes. As a rule, a group of grains of similar properties predominates, giving the sediment its characteristic appearance. The difference between a sand and a silt or clay is very pronounced. For the sake of better comparison the size limits for different grain classes have been fixed by convention. The international scale proposed by ATTERBERG distinguishes the following fractions:

I	Diameter	> 2	mm, gravel	гравел
II	»	2—0.2	» sand	песок
III	»	0.2—0.02	» mo (Swedish word, fine sand)	
IV	»	0.02—0.002	» silt	ил, илест
V	»	< 0.002	» clay.	

In the English and the American scales the size limits of the fractions are somewhat differently fixed. The greater the number of fractions the more detailed is the description of a soil. BÖGGILD (12) in his work on the bottom samples of the «Fram» expedition, introduced a continuous curve to characterize composition. The curves by which he presented the mechanical analyses of the samples, are identical with the distribution curves, the theory of which was later worked out in detail by ODÉN (73, 76). The abscissae of the distribution curve $F(r)$ are the radii or diameters of the soil particles in natural or logarithmic scale; any two ordinates enclose a surface, the area of which indicates the percentage of particles within the two corresponding radii.

Mathematically the total of grains in the soil is expressed by the equation

$$\sum_{r=0}^R K = \int_0^R F(r) dr,$$

K being an individual grain size and R the upper size limit of the particles. Some of the newer methods of mechanical analysis give continuous curves from which the distribution curve may be deduced by mathematical analysis, but any set of fractions obtained by any

Fig. 6. Distribution, summation and sedimentation curves of sample F55 1924.

method may serve as a basis for the construction of a diagram the upper limit of which more or less approximates to the ideal distribution curve.

Another curve convenient for illustrating size distribution regardless of method, is the summation curve. The amount of particles between two diameters is here given by the difference between the corresponding ordinates. Any single ordinate represents the sum of particles smaller than the corresponding abscissa. The

distribution curve illustrates successive fractions of a sample as surfaces, whereas the summation curve represents them as lines.

The continuous experimental curves referred to above are the sedimentation curves, which, though not directly illustrating composition, only need mathematical interpretation to do so. The ordinates of the sedimentation or accumulation curve record the successive amounts of particles accumulating with time on the bottom of, or passing a given height in a settling suspension. Thus time forms the abscissa. The sedimentation, summation and distribution curves are exemplified in Fig. 6 which presents the composition of a bottom sample F55 1924. Frequent use will be made of these curves for illustrating the results of mechanical analysis.

During the last decades a great many investigations have been published treating the theoretical and practical side of mechanical analysis. At the present moment I think we are entitled to say that conditions influencing the result are known and controllable, but the task is by no means a simple or easy one. As all methods, except dry sieving, deals with the material in suspension, mechanical analysis in reality comprises the solution of two different problems of equal importance: 1) the preparation of the suspension and 2) the analysis proper. Especially as regards the newer methods, the automatic balance of ODÉN (73, 79), the sedimentation tube of WIEGNER (126), the pipette method of ROBINSON (92), the »pelometer» of GOLDSCHMIDT-GRENNESS (35—37), the centrifuge of TRASK (113) and the numerous modifications of these described in literature, — especially as regards all these the preliminary treatment is of decisive importance. By the classical and universally known methods of ATTERBERG, SCHÖNE, KORECKÝ¹⁾, the influence of variations in the mode of preparation is not so obvious, because in a way preparation takes place alongside of the analysis. That is why the newer methods, when compared with the older, often do not appear to give such good results, if sufficient care is not given to preliminary treatment.

Though it would seem natural to treat the methods of preliminary treatment first and analysis afterwards, I have chosen the opposite order, because the value of different modes of preparation cannot be estimated without the methods of analysis being known. Therefore, after a short exposition of the theory of mechanical analysis, the

¹⁾ For description see, for instance, WAHNSCHAFTE UND SCHUCHT: Wissenschaftliche Bodenuntersuchung, Berlin 1924.

methods used in this investigation will first be described. Afterwards the preparation of the suspension will be treated from a theoretical and practical point of view. Finally some experiments on coagulation with sea water, an operation which in a way is the opposite of preliminary treatment, will be recorded.

9. OUTLINE OF THEORY.

Mechanical analysis of particles in suspension is based upon the formula, set forth in 1849 by STOKES, of the relation between velocity v and radius r of a spherical particle of specific gravity σ , falling through a medium of specific gravity σ_0 and viscosity η , under the influence of gravity:

$$v = \frac{2}{g} \frac{\sigma - \sigma_0}{\eta} r^2; \quad (1)$$

g is gravitational acceleration; if the particle is centrifuged, g has to be replaced by centrifugal acceleration. STOKES' formula is an expression of the general law which states that a body moving through a medium under the influence of a constant force, attains a constant velocity as soon as the resistance of the medium becomes equal to the moving force¹⁾. In the case of soil particles, moving through a column of water, a practically constant velocity is attained within so short a time that it may be considered as constant from the beginning of the movement. The formula stipulates that the particle should be spherical, which condition is obviously not fulfilled in the case of natural sediments. To meet this difficulty ODÉN (75) introduced the term «equivalent radius». The radius of a spherical particle, of the same specific gravity and velocity, is attributed to all particles having a common velocity, regardless of their size and form. The equivalent radius may be considered as the mean radius of all particles having the same velocity. The validity of STOKES' law for small particle sizes, has been established by many investigators, recently by ANDREASEN (4). But for particles having a diameter $> 50 \mu$ the more accurate equation of OSEEN should be used, which constitutes an extension of STOKES' law.

¹⁾ A detailed discussion of the theory underlying mechanical analysis is to be found in HERMANN GESSNER: Die Schlämmanalyse, Leipzig, 1931.

If the constants entering into equation (1) are joined into a new constant C , the equation may be written

$$v = C r^2. \quad (2)$$

The constant C varies with σ , σ_0 and η ; the two latter varying with temperature only, C depends on temperature and the specific gravity σ of the settling particles. In the case of soils, σ is almost constant, varying between 2.6 and 2.7; and during a single analysis it naturally remains constant, as the different fractions of a soil have approximately the same specific gravity¹). Temperature on the contrary may vary appreciably, if proper means are not taken to keep it constant. The value of C ($\sigma = 2.70$) is $3.237 \cdot 10^4$ at 15° and $3.674 \cdot 10^4$ at 20° (GESSNER p. 232). For a temperature rise of 5° , the constant C thus increases by 13 %, causing a corresponding increase in the velocity of the falling particles. That considerable analytical errors may be caused by variations of temperature is obvious.

The practical application of STOKES' law requires determination of the velocity of the settling particles or of some property of the suspension, which depends on the varying velocity. Mostly the simple relation

$$v = \frac{h}{t} \quad (3)$$

is used, where h is the height of the water column passed and t the time elapsed since the beginning of the movement. Some instances of application will be given below in connection with the description of the methods used.

A classification of grain classes, independent of the law of STOKES, could be founded on settling velocity only. This has been done e. g. by ROBINSON. Nevertheless, as was pointed out by ODÉN «it is easier and more familiar to the human mind to think in terms of size than in terms of velocity.»

The methods of mechanical analysis are of two essentially different kinds: 1) sedimentation methods, in which the particles are allowed to fall through a column of standing water (ATTERBERG, ODÉN, WIEGNER-GESSNER, GOLDSCHMIDT-GRENNESS) and 2) elutriation methods in which they are carried away by a current of constant

¹) For the possible variation of specific gravity in the smallest grain sizes on account of hydration, see Section 20 p. 79.

velocity (BOLLENBACH, SCHÖNE, KOPECKY). Every method has its optimum of accuracy within certain grain classes. Because of the great disparity of the particles in a soil sample (in this investigation particles from 2—0.0002 mm were determined) it is generally necessary to use more than one method for each sample. After a discussion of the possible errors of various methods, KÖHN (53), in a comprehensive study on the theory and practice of mechanical analysis, summarizes his views on the methods to be used in the following table:

Table 7.
Grain size and methods of mechanical analysis.

Diameter	>0.5 mm	Sieves.
»	2—0.02 »	Elutriation methods.
»	0.05—0.001 »	Sedimentation methods (pipette method).
»	<0.002 »	Centrifuge.

Amongst sedimentation methods KÖHN recommends the pipette method, which is widely used in England and the United States. When temperature is kept constant this method gives good results even for particles smaller than 1μ ; in this investigation it was used down to 0.2μ . At the time (1928) when KÖHN recommended centrifuging for the smallest grain classes, a method of this kind had not yet been worked out. TRASK's apparently very useful centrifuge method which applies to particles from 20μ downwards, was published two years later.

In the present work the pipette method, as worked out by KÖHN, was used for grain classes $< 20\mu$, sieves for sands > 0.5 mm and the elutriation method of BOLLENBACH (13) for intermediate particle sizes. In the preliminary work the method of WIEGNER was also used.

A number of recent investigations, amongst them the above mentioned study by KÖHN, deal with the general conditions, partly overlooked by earlier investigators, which should be fulfilled to ensure accurate and reproducible results. Preliminary treatment is of the greatest importance, but some other circumstances should also be taken into account. The importance of temperature control, pointed out above, has been especially emphasized lately, the viscosity of water being very sensitive to changes in temperature. Also the cylinder or tube in which analysis is effected, should not be too narrow or regular sedimentation will be disturbed in the vicinity of the walls.

10. THE PIPETTE METHOD.

The concentration of every single particle size is considered to be uniform all over a well-shaken suspension. If the latter is left standing, each particle size sinks to the bottom with its own particular velocity independently of all the others, the possibility of coagulation precluded. After a certain time every grain of, say, the biggest size will have reached the bottom, even those which at the beginning of the movement were at the surface. This disappearance of the biggest grain size from the suspension happens at the moment when

$$t = \frac{h}{v},$$

h being the height of the suspension and v the velocity of the particles. On the other hand at a *given* moment t_1 , and a *given* depth H below the surface, only those grain sizes are left whose velocities are $< \frac{H}{t_1}$. Consequently if we remove a thin horizontal layer of the suspension from the depth H at the moment t_1 , determine the amount of particles in it and express it in percentage of the original amount, we know the amount A_1 , of particles having velocities $< \frac{H}{t_1}$. If a new sample is taken at the moment t_2 , the particles in it determined and expressed in the same way, we get the amount A_2 of particles with velocities $< \frac{H}{t_2}$. The difference $A_1 - A_2$ is the amount of particles having velocities $> \frac{H}{t_2}$ but $< \frac{H}{t_1}$:

$$\frac{H}{t_1} > v > \frac{H}{t_2}$$

By repeating the procedure, as many fractions as desired may be determined. The law of STOKES gives us the radii r_1, r_2, r_3 corresponding to the successive velocities $\frac{H}{t_1}, \frac{H}{t_2}, \frac{H}{t_3} \dots$ taken as limits. The values $A_1, A_2, A_3 \dots$ may be used directly to construct a summation curve.

The above is the simple theory of the pipette method.

Its practical value depends on the possibility of removing a thin horizontal layer from a given depth by means of a pipette. For this purpose special pipettes have been constructed; KÖHN, however, in the study mentioned above, has shown that in any case a sphere rather than a horizontal layer is drawn off. But at the same time he

proves that the error arising from this is negligible, provided the sample is not taken too near the surface of the suspension. Still pipettes, closed at the end and provided with fine side holes are preferable; as no particles can then fall out while the pipette is being removed from the suspension.

KÖHN constructed a pipette, attached to a stand (Fig. 7), by means of which samples of 10 c. c. may be taken from varying depths of the suspension. It is essential that the introduction and withdrawal of the pipette causes as little disturbance of the suspension as possible. This is more easily attained if the pipette is attached to a stand along which it glides without shaking, than if operated in the ordinary way. An even better construction is the one by ANDREASEN (3, see also GESSNER p. 86) in which the pipette is never moved from the suspension during analysis, being attached either to the bottom or the lid of the cylinder in which sedimentation takes place. The only drawback of ANDREASEN's construction is that as many pipettes are needed as the number of analyses made at the same time, whereas one of KÖHN's pipettes is sufficient. In this investigation from 20 to 45 analyses were done simultaneously.

Fig. 7. The pipette of KÖHN.

KÖHN (*loc. cit.*) gives a very convenient table containing settling velocities and times needed for a 10 cm fall for particles of specific gravity 2.7, 2.5 and 2.3 at the temperatures 5°, 10°, 15°, 20°, 25° and 30°. For grain sizes from 20 μ upwards the equation of STOKES-OSEEN was used for the calculation. Table 8 below contains settling times extracted from KÖHN's table for particles of specific gravity 2.7 at a temperature of 20°:

Table 8. *Settling times for a 10 cm fall of various grain sizes at 20°.*

Diameter	Time	Diameter	Time	Diameter	Time	Diameter	Time
0.5 mm	2 ^s 24	0.05 mm	44 ^s 2	5 μ	1 ^h 13 ^m	0.5 μ	5 ^d 1 ^h
0.2 »	4 ^s 8	0.02 »	4 ^m 27 ^s	2 »	7 ^h 35 ^m	0.2 »	31 ^d 12 ^h
0.1 »	12 ^s 5	0.01 »	18 ^m 10 ^s	1 »	30 ^h 15 ^m		

Every diameter is here 2 or 2.5 times larger than the following one. In samples analyzed by the pipette method the following fractions were determined:

	IV	V	
$> 20 \mu$	$20-10 \mu$	$2-1 \mu$	$< 0.2 \mu$
	$10-5 \text{ »}$	$1-0.5 \text{ »}$	
	$5-2 \text{ »}$	$0.5-0.2 \text{ »}$	

The grain classes IV and V of the international scale were thus subdivided into 3 and 4 fractions respectively. The results were calculated on dry sample, free from electrolytes and organic matter.

An analysis by this method was made in the following way: From 5—10 gr ¹⁾ of a series of air dry bottom samples were weighed out in Petri dishes and the moisture determined by weighing again after drying at 100°—105° for 12—18 hours. The samples were then subjected to preliminary treatment and finally transferred into the cylinders in which analysis was effected and the volume of the suspensions brought up to one litre. The cylinders were kept in a small room without direct light or heating; temperature was almost constant here without any measures being taken to keep it so. During the three weeks of the first series, for instance, the temperature varied within $\pm 1^\circ$ from the mean which was 21°.

The initial concentration of the suspension was calculated after subtracting the loss on drying, the amount of organic matter and of sea salts from the original weight. After thorough shaking, samples of the suspension were taken after certain intervals of time, which were determined with the aid of KÖHN's table for the prevailing temperature. The specific gravity was always taken as 2.7. In two cases, for F42 1928 and F68 1928, the sp. gr. was determined directly by means of a pycnometer and found to be 2.74 and 2.72 respectively. The samples were washed out from the pipette into weighing glasses and dried first on a water bath and then for four hours at about 105° in a drying oven, then weighed. The weights found were expressed in percentage of the original amount contained in 10 c. c.

It is important that the fractions are determined in order of decreasing coarseness. If, as may sometimes be found convenient in connection with other work, the fine grain classes are determined first, too high values will be found for coarser grains, because each time a sample of 10 c. c. is removed (the total being 1 litre), the concentration of particles, having already passed the depth from

¹⁾ When material was scarce, down to only 2.5 gr were used.

which the sample is taken, rises by 1 %. This circumstance, which is of no importance if the coarser grains are already determined, may cause considerable errors. In the extreme case of the coarsest fraction being determined last, the error amounts to as many percentages of this fraction as the number of fractions already determined. The error may be corrected by calculation, but it is simpler to avoid it. In the first series of 20 analyses in this investigation a correction of this kind had to be made, but in the other series the error was avoided.

The accuracy attained with the pipette method is seen from Table 9, which records double analyses of a few samples.

Table 9. *Double analyses performed with the pipette method.*

Station	$>20 \mu$ %	$20-10 \mu$ %	$10-5 \mu$ %	$5-2 \mu$ %	$2-1 \mu$ %	$1-0.5 \mu$ %	$0.5-0.2 \mu$ %	$<0.2 \mu$ %
	d	d	d	d	d	d	d	d
F42 1928, electro-	4.7	3.5	4.9	13.9	18.4	21.6	24.0	9.0
dialyzed	0.8	0.3	1.2	0.5	0.3	0.7	1.3	3.5
	5.5	3.2	3.7	13.4	18.1	20.9	22.7	12.5
F61 1928, electro-	13.9	9.9	8.4	15.8	13.3	13.1	17.2	8.5
dialyzed	0.6	0.4	1.4	0.7	0.2	0.1	1.5	0.7
	13.3	10.3	9.8	16.5	13.5	13.2	15.7	7.8
F65A 1928, dialyzed	4.8	5.3	5.8	16.2	13.8	14.0	21.5	18.7
	1.6	0.0	0.6	0.4	1.5	1.6	0.4	1.6
.....	6.4	5.3	6.4	15.8	12.3	15.6	21.1	17.1

It should be born in mind that the samples were weighed before the preliminary treatment, so that errors (possibly losses) caused thereby, are included in the result. If 10 gr had been taken for the analysis, the initial amount in 10 c. c. of the suspension was about 95 mgr; consequently the weight in milligrams of any fraction approximately equalled the percentage thereof, and a difference of 1 % between similar fractions of two parallel analyses corresponds to a difference of 1 mgr in the actual weights observed. In this connection a fraction may be taken either as the sum of particles smaller than a certain size or as the amount between two size limits. In Table 9 the mean difference between fractions of the latter kind is 0.8 %, being the same for percentages above and below 10 %. GLESSNER states that a mean deviation of 2 % may be considered as a fairly good agreement; in that case 0.8 % is a good result. The relative differences are of course higher. For percentages below 10 % the mean relative deviation is 13 %, for fractions above 10 %, however, only 5 %. The high deviation between the last fractions

of F42 is not included in the mean values, as, obviously, it is not due to the method.

When all circumstances are taken into account, the accuracy may be considered satisfactory. From Fig. 8 showing the analyses recorded in Table 9 as summation curves it is evident that the character of each sample can be judged equally well from either of the two corresponding curves. A greater accuracy would not permit more far-reaching conclusions.

Fig. 8. Comparison of analyses by the pipette method.

11. THE METHOD OF WIEGNER AND INTERPRETATION OF THE SEDIMENTATION CURVE.

If two communicating tubes contain liquids of different specific gravities the heights of the liquids will be inversely proportional to the specific gravities. This principle WIEGNER (126) made use of

in constructing the sedimentation tube (Fig. 9). It consists of a large tube A for the suspension and a narrow measuring tube B to be filled with water, separated by a stopcock. A is about 100—120 cm long and 4—5 cm wide. Both tubes carry centimetre scales, in the top part subdivided into millimetres. When the suspension has been introduced into A, the tube is thoroughly shaken, then suspended in a strictly vertical position. The stopcock is opened and the heights in both tubes above the entrance of the side tube are recorded.

If H_0 is the height in tube A and h_0 that in B, further s_0 the specific gravity of the suspension and s_p that of the soil, the initial concentration of which is P_0 (gr soil/litre), then

$$s_0 = \frac{h_0}{H_0} \quad (1)$$

the specific gravity of water being unity. On the other hand

$$s_0 = \frac{1000 - \frac{P_0}{s_p} + P_0}{1000} = 1 + P_0 k, \quad (2)$$

k being a constant.

At the time t , when all grains having velocities $> \frac{H_t}{t}$, have settled into the bottom part of A, we find in the same way

$$s_t = \frac{h_t}{H_t} = 1 + P_t k. \quad (3)$$

As A is very much wider than B, H_0 and H_t are practically equal. Therefore

$$\frac{P_t}{P_0} = \frac{h_t - H_0}{h_0 - H_0} \quad \text{and} \quad \frac{P_0 - P_t}{P_0} = \frac{h_0 - h_t}{h_0 - H_0}$$

This means that the decrease in height of the water in the tube B is a direct measure of the amount of particles settling out of the suspension.

Expressed in percentage of the initial height difference, $h_0 - H_0$, the decrease $h_0 - h_t$ at the moment t is identical with the corresponding ordinate of the sedimentation curve of the soil (see page 31).

The initial height difference depends on the concentration of the suspension, which should generally not be above 20 gr per litre.

Fig. 9.
Sedimentation tube of
WIEGNER.

For a soil this corresponds to an initial difference of about 13 mm. It is evident that accurate measurements by this method are possible only with special devices for accurate readings. With this in view, all the numerous modifications of the WIEGNER method, described in literature, were constructed. The method of GESSNER (33) which records the decrease photographically, permits accurate determination of grain sizes from 4 to 200 μ . It thus has a wider scope in respect of coarse grains than the pipette method, but cannot compete with the latter as regards the smallest sizes. In the present work, the original construction of WIEGNER was used for comparing different methods of preliminary treatment.

The theory of the sedimentation curve has been worked out by ODÉN (73—76), originally with a view to interpreting the curves obtained with the automatic balance he constructed, a short description of which would perhaps be of interest, as by this method ODÉN (27, 74) made what were probably the first attempts to determine accurately the size distribution in sea bottom sediments. On the one pan of a sensitive balance, which pan is immersed in the suspension, the soil accumulates, while on the other the increased weight is counterbalanced by automatically added weights. The successive ordinates of the sedimentation curve are thus directly recorded. The apparatus which on account of certain theoretical objections raised against it and especially because of its expensive construction, has not come into general use, has recently undergone a modification by CORRENS and SCHOTT (19), who use it for the analysis of the bottom samples collected by the German «Meteor» Expedition. An improvement is that analysis is possible even if only small amounts of soil (1 gr) are available.

If $F(r)$ is the ordinate of the distribution curve then $F(r)dr$ is the amount of particles, having radii between r and $r + dr$. The relation between the distribution curve $F(r)$ and the sedimentation or accumulation curve $P(t)$, as given by ODÉN, is expressed in the following equations:

$$\begin{cases} F(r) = -2 \sqrt{\frac{C}{h}} \cdot t^{1/2} \cdot \frac{d^2 P(t)}{dt^2} & (1) \\ r = \sqrt{\frac{h}{Ct}} & (2) \end{cases}$$

The latter equation is derived from STOKES' equation

$$v = C r^2,$$

C being the constant of that equation, h the height and t the time of sedimentation.

Fig. 10. Graphical interpretation of sedimentation curve.

Equations (1) and (2) can be interpreted either graphically or numerically. ODÉN's graphical solution is shown in Fig 10. Two tangents of the accumulation curve corresponding to the abscissae t_n and t_{n+v} mark off on the axis of ordinates a part AD equal to the amount of particles, whose sedimentation times (for the particular height h of the experiment) lie between t_n and t_{n+v} . Consequently by drawing tangents to the curve through points corresponding to any radii (equation (2)) taken as size limits, the sample analyzed may be subdivided into as many fractions as desired, which fractions may serve for the construction of a distribution curve.

The following mathematical interpretation was given by the author (38, 39). The amount of a single particle size K_n , which covers the height h in the time t_n may be expressed by the following equation, the simple deduction of which will not be given here:

$$K_n = t_n \left[\frac{P_n - P_{n-1}}{t_n - t_{n-1}} - \frac{P_{n+1} - P_n}{t_{n+1} - t_n} \right]. \quad (3)$$

P_n is the ordinate of the accumulation curve corresponding to t_n , P_{n-1} and P_{n+1} two neighbouring ordinates lying so near P_n that the intermediate parts of the accumulation curve may be considered practically rectilinear, t_{n-1} and t_{n+1} the sedimentation times of the latter (Fig. 10). This equation is transformed into the following of general validity:

$$K = t \frac{d^2 P(t)}{dt^2} dt, \quad (4)$$

when the points P_{n-1} , P_n and P_{n+1} , taken nearer and nearer to each other, finally coincide. Equation (4), being independent of the formula of STOKES, expresses in the simplest way the relation between

grain fraction and accumulation curve. The total amount of particles expressed in terms of the accumulation curve is then

$$\sum K = \int_0^{\infty} t \frac{d^2 P(t)}{dt^2} dt. \quad (5)$$

On the other hand, according to the definition of the distribution curve

$$\sum K = \int_0^R F(r) dr, \quad (6)$$

R being the upper limit of grain sizes. In accordance herewith, except from equation (3), equation (4) may also be found from (1) and (2). Through derivation of (2) we find

$$dr = -\frac{1}{2} \sqrt{\frac{h}{C}} \cdot t^{-3/2} \cdot dt \quad (7)$$

which expression combined with (1) gives

$$F(r) dr = t \frac{d^2 P(t)}{dt^2} dt \quad (8)$$

The amount of a single grain size K , theoretically expressed by (4) and numerically by (3) is equal to a surface element defined by (8).

The application of equation (3) to a succession of grain sizes within two limits, t_n and t_{n+v} , leads to the following expression of the total of grains within the limits:

$$\sum_n^{n+v} K = t_n \frac{P_n - P_{n-1}}{t_n - t_{n-1}} + P_{n+v} - P_n - t_{n+v} \frac{P_{n+v+1} - P_{n+v}}{t_{n+v+1} - t_{n+v}} \quad (9)$$

The position of the points, P_{n-1} , P_n , P_{n+v} , P_{n+v+1} , is seen from Fig. 10. Equation (9) is the numerical expression of the graphical method of ODÉN. A consideration of Fig. 10 shows that

$$\begin{aligned} AB & \text{ is equal to } t_n \frac{P_n - P_{n-1}}{t_n - t_{n-1}} \\ BC & \text{ » » » } P_{n+v} - P_n \\ CD & \text{ » » » } t_{n+v} \frac{P_{n+v+1} - P_{n+v}}{t_{n+v+1} - t_{n+v}} \end{aligned}$$

and

$$AD = AB + BC - CD.$$

If only a few fractions are desired the graphical method is convenient, but if a detailed analysis is aimed at, the application of equation (3), being independent of the accidental errors involved in the drawing of the tangents, probably gives the most accurate results.

The following two analyses afford a comparison of the methods of WIEGNER and KÖHN:

	Method	Grain sizes				
		$>20\mu$	$20-10\mu$	$10-5\mu$	$5-2\mu$	$<2\mu$
F55 electrolyzed, not boiled	Wiegner	2.9	5.7	1.3	13.7	76.4
F55 dialyzed, boiled	Köhn	4.0	3.7	2.6	10.0	79.7

The results are essentially the same. The somewhat dissimilar preliminary treatments, probably account in the same degree as the different methods of analysis, for the deviations observed.

12. THE ELUTRIATION METHOD OF BOLLENBACH.

Unlike the methods described hitherto, the elutriation method effects an actual separation of particles of different sizes. If a settling particle meets an upward moving current, the velocity of which is greater than its own, it will be carried away by the current. If on the contrary, the velocity of the particle is superior to that of the current, it continues its way downwards, and if the two velocities are equal the particle remains suspended. In this way particles having velocities lower and higher than that of the current are separated from each other. It is essential that the velocity of the current be constant. If in different parts of the apparatus the current has different constant velocities, then the soil may be divided in many fractions simultaneously. On this principle many methods of mechanical analysis, especially older ones, are founded.

In oceanography washing out methods have long been used. BÖGGILD (11, 12) in examining the bottom samples of the Danish »Ingolf» Expedition (1895—1896) and those of the »Fram» Expedition (1893—96) was the first to apply the method of SCHÖNE, by which he separated the samples into four groups. THOULET (110, 111), in analyzing the samples collected during the scientific campaigns of the PRINCE OF MONACO (1901) on board the »Princesse Alice», besides dry and wet sifting, used a modified method similar to that of BOLLENBACH, described below. Finally E. PHILIPPI (87) adopted the method of SCHÖNE for the bottom samples of the German »Gauss» Expedition (1901—1903).

The elutriation methods are subjected to a critical review by KÖHN in the paper already cited repeatedly. KÖHN especially recom-

mends the method of KOPECKY¹⁾, as best fulfilling the demand for a constant current without disturbing eddies. The apparatus of KOPECKY modified by KÖHN (53) consists of two glass tubes, about 60 cm long and with such diameters (3.0 cm and 5.6 cm resp.) that the velocity of the current, varying inversely with the square of the diameter, is equal to that of grain size 100μ in the first and 50μ in the second. The apparatus of SCHÖNE²⁾ differs from that of

Fig. 11. Elutriation method of BOLLENBACH.

KOPECKY in the shape and size of the tubes. The method of KOPECKY was tested by the author, but it was found that the dimensions of the tubes were too large for the small amounts of soil available for analysis. It was especially difficult, after analysis was made, to wash out the residue completely. Most samples were analyzed first by the pipette method and subjected to further treatment only if the fraction $> 20\mu$ exceeded 10 %. Thus at best only a few grams were available for the washing out analysis. For such small amounts the simple apparatus of BOLLENBACH of much smaller dimensions proved useful (13, see also Grenness 36).

In BOLLENBACH's apparatus the tubes are replaced by a glass A of the shape shown in Fig. 11, holding about half a litre. In the top part, which is cylindrical, separation is effected. The water enters through a tube reaching down to the bottom. Distilled water is preferable, but in the present case Helsingfors tap water, which is rather poor in salts, especially in lime, was used. The water could not, however, be taken directly from a tap as it has to fulfil certain special requirements: 1) it must be of a constant temperature, 2) the gases in the water should be in equilibrium with the atmosphere, so that no bubbles are deposited on the walls of the glass and tube, 3) to prevent coagulation, caused even by small concentrations of salts, some ammonia should be added (see Section 15). In the present case the water was drawn into a tinned copper container holding 100

¹⁾ See GESSNER p. 126 OR WAHNSCHAFTE UND SCHUCHT p. 48.

²⁾ " " p. 122 " " " " p. 34.

litres and left standing overnight to give off superfluous gases. In the morning the temperature was adjusted to 20° and enough ammonia added to give a normality of 0.002. To produce a constant current the water should enter the glass under constant pressure. This was achieved by means of an overflow flask B, into which the water was siphoned from the container. The latter was placed about 1.5 m above the laboratory table, the overflow about half a metre below. Velocity was regulated by means of a screw (D). Two different velocities were used, corresponding to the grain sizes 50μ and 100μ . It proved difficult with these arrangements to attain the velocity necessary for separating particles of 200μ from the rest. This would have required a velocity of 2.08 cm/sec or an outflow of 2.9 litres per minute, the horizontal section of the cylindrical part of the glass being 23.26 sq. cm. Grain size 50μ corresponded to an outflow of 0.315 litre, 100μ to 1.115 litres per minute.

The piezometer tube E carrying a millimetre scale served to regulate and control the outflow. Calibration was done by observing the outflow per minute for different heights of the water column in the piezometer tube. The heights corresponding to the desired outflows were then interpolated from a curve having the outflows as abscissae and the heights in the tube as ordinates. When there were no air bubbles in the connection between the overflow flask and the glass A the height of the water column in the piezometer tube remained constant within a few millimetres. The difference in height between the velocities of 50μ and 100μ , on the other hand, was about 30 cm. The maintaining of practically constant velocities thus presented no difficulties.

A double analysis by this method may be recorded. It is that of fraction < 0.5 mm, separated by sieve from sample F15 1926. The result was:

Fraction	$>100\mu$		$100-50\mu$		$<50\mu$	
	63.5 %	diff.	24.5 %	diff.	12.0 %	diff.
		0.1		1.0		0.9
	63.4 %		25.5 %		11.1 %	

An analysis by this method lasted about three-quarters of an hour. The sample was introduced into A, the flow of water started and very slowly brought up to the velocity corresponding to 50μ . After about half an hour, depending on the amount of grains not much smaller than 50μ , the cylindrical top part of the glass was free of particles; the receiver was now changed, — basins with outlets

holding 5 litres were used — and the velocity increased until the height in the piezometer tube reached the 100μ level. Generally after about a quarter of an hour the top part of the glass was clear again and the analysis complete. The water was now decanted from the basins, the fine sand at the bottom collected in a small porcelain dish, dried on a water bath and weighed; the residue in the glass was treated likewise, whereas the first fraction was rejected and the amount thereof ($< 50\mu$) calculated.

An analysis by the washing-out method is very convenient for coarse grains. For smaller sizes, below 50μ , the time necessary for complete separation is considerably longer.

13. SIEVES.

The fraction $> 100\mu$ left in the glass, after an analysis by the BOLLENBACH method, was first dried and weighed, then subdivided into the following fractions by sifting:

$> 2\text{ mm}, 2 - 1\text{ mm}, 1 - 0.5\text{ mm}, < 0.5\text{ mm}.$

The sifting was performed with a set of MÜLLER brass sieves with round holes of guaranteed size, forming with bottom part and lid, a cylinder 13 cm high and 5 cm in diameter. Sifting was the only treatment to which certain purely sandy samples were subjected.

14. PRESENTATION OF RESULTS.

The three important curves illustrating size distribution, the accumulation or sedimentation curve, the summation curve and the distribution curve, have already been described (p. 31). The analysis of the accumulation curve was given, theoretically and practically, in connection with the method of WIEGNER (p. 42). There remain a few words to be said about the way in which the summation and distribution curves, given in this paper, were constructed. For both curves the abscissae are given in logarithmic scale. Because of the great disparity of the particles in a soil (the diameter of a small sand grain, 200μ , being a thousand times that of the smallest particles determined or 0.2μ) it would be impracticable to present the diameters of a complete analysis in a natural scale. Whether in natural or logarithmic scale the construction of a summation curve is simple. Over the points on the abscissa, corresponding to the size limits of the analysis, the

percentage of grains smaller (or larger) than these limits are erected as ordinates. The points thus determined are united by straight lines or a smooth curve (Fig. 6 and 8). The amount of particles between any two diameters is then equal to the difference between the corresponding ordinates.

The distribution curve is the upper limit of a diagram which presents composition as a surface. Theoretically, the ordinate of the distribution curve $F(r)$ is the first derivate of the summation

curve S : $F(r) = \frac{dS}{dr}$. Given a summation curve, the construction of the distribution curve may be founded on this relationship.

The following consideration, however, leads to a distribution diagram founded on direct analytical data only. If a series of particle sizes in a soil form a geometrical progression, their logarithms will form an arithmetical progression. Thus, if a number of fractions are given, the limits of which differ by a certain factor, for instance 2, as in the fractions $20-10\mu$, $10-5\mu$, $5-2.5\mu$, then, on a logarithmic scale, these limits will be represented by a sequence of equidistant points. A theoretically correct distribution diagram is obtained, if, with the distance between two points as basis, a series of columns are erected, the heights of which correspond to the percentages of particles within the respective size limit. The uneven upper limit of the columns may be replaced by a smooth curve which then, depending on the number of fractions determined, more or less approximates to the ideal distribution curve (Fig. 6.) A diagram of this kind has the advantage that the ordinate (= the height of a column) has an immediate significance, recording how many percent of the sample lie between two successive size limits. Generally the ordinate of the distribution curve, given as $F(r)$, has no obvious meaning and it is only by counting the number of units of surface between two diameters, that the percentage of particles between these limits are found.

As previously described, the following fractions were determined in this investigation, by the methods of KÖHN, BOLLENBACH and by sifting:

I gravel	II sand	III very fine sand	IV silt	clay	V colloidal clay
>2 mm	2—1 mm		20—10 μ	2—1 μ	<0.2 μ
	1—0.5 »	100—50 μ	10—5 μ	1—0.5 μ	
	0.5—0.1 » ¹⁾	50—20 μ	5—2 μ	0.5—0.2 μ	

¹⁾ The sand fraction was carried down to 100 μ , because with the means available it proved impracticable in the BOLLENBACH analysis to produce the velocity necessary for the 200 μ limit (see page 47).

The size limits of these subgroups differ by the factor 2, except those of the last row, in which the diameter of the upper limit is 5 and 2.5 times that of lower. A subgroup, the limits of which differ by the factor 2, will be called a primary subgroup. The logarithm of 2 to the base 10 is 0.3 and that of 2.5 is 0.4, therefore the values found for the size groups 50—20 μ , 5—2 μ and 0.5—0.2 μ have to be multiplied by $3/4$ in order to give the correct height of the columns to be erected over the corresponding parts of the abscissa. If the columns were given heights equal to the values actually found by analysis, then their surfaces would be too large, the distance between the limiting diameters in these groups being 0.4 against 0.3 in the others. Similarly the value for the size group 0.5—0.1 mm has to be multiplied by $3/7$. If such a reduction were not made, a false idea would be obtained of the degree of sorting in the sediment.

The two extreme groups, characterized by only one size limit, are generally given as squares added at the ends of the distribution diagram. The area of these squares corresponds to the percentage of particles in the groups concerned. Considering that the distribution curve at both ends must somehow come down to the abscissa again, and that it must comprise the wider range of particle sizes the higher the percentage of these extreme fractions, another manner of representing the coarsest and the finest fraction was adopted. These groups are given as triangles, the heights of which are equal to the heights of the neighbouring columns, and stretching so far to the sides that the areas become equal to the percentages of particles within these groups. In this way an idea is obtained of the extreme particle sizes in the distribution diagram. One assumption must however be made: that the distribution curve has no secondary maxima in these extreme groups.

TRASK (115, 116) in analyzing the bottom samples of the «Marion» Expedition, and in his survey for the American Petroleum Institute of bottom deposits from all parts of the world, refrained altogether from graphical presentation of mechanical analysis, introducing the following notions and constants lent from statistical analysis: the median, M , the first and third quartiles, Q_1 and Q_3 , the coefficients of sorting So and of skewness Sk .

The median is the midpoint of the frequency distribution. Fifty percent of the weight of the sediment is composed of particles larger in diameter than the median, and fifty percent of smaller particles. Similarly, the two quartile diameters separate each half of the sample in equal parts. Twenty five percent of the sample is

larger than the first quartile and seventy five percent larger than the third quartile.

The coefficient of sorting is a numerical measure of the degree of sorting in a sediment. It is defined as

$$So = \sqrt{\frac{Q_1}{Q_3}}.$$

The coefficient of skewness is a measure of the dissymmetry of the size distribution, defined as

$$Sk = \frac{Q_1 \cdot Q_3}{M^2}.$$

The significance of the two coefficients is seen from Fig. 6. When the diameters are given in logarithmic scale, then $\log So$ is half the distance between Q_1 and Q_3 and $\log Sk$ the difference between the distances Q_1M and Q_3M .

TRASK found that So is less than 2.5 in well sorted sediments, greater than 4.5 in poorly sorted and about 3 in normally sorted. The coefficient of skewness is a ratio varying about unity. If Sk is greater than 1, the maximum sorting lies on the fine side of the median, if it is less than 1, the maximum lies on the coarse side, and if Sk is about 1, the maximum coincides approximately with the median. In the latter case the size distribution is symmetrical. For further details the reader is referred to the works of TRASK.

As pointed out by TRASK these constants »are not substitutes for a complete analysis». In interpreting them a more or less regular size distribution has to be assumed. Thus they cannot indicate secondary maxima in the distribution which, as seen from Fig. 31—41, often occur in Baltic deposits, post-Glacial as well as late-Glacial. Nevertheless, the coefficient of sorting, being independent of the position of the mode of the distribution is always useful, when taken as a measure of the range of the principal particle sizes in a sample. A good measure of the sorting, which is readily accessible without calculations, is the maximum height of a primary subgroup. A low coefficient of sorting is always accompanied by a high distribution diagram and vice versa (provided the sediment is not stratified). In interpreting the coefficient of skewness prudence should be observed. It is true that a coefficient of skewness which greatly differs from unity always indicates a strongly asymmetrical size distribution, but on the other hand a sample may have a decidedly

asymmetrical distribution and yet the coefficient may indicate symmetry. This is evident for instance from diagram 2, Fig. 31, and diagram 85 Fig. 41. If used with discrimination the two coefficients are valuable for comparison purposes especially if detailed analysis has revealed that the frequency distributions of the samples compared have only one maximum, not situated far from the median, or if there is reason to believe that this is the case. — The median alone is a very good single characteristic of a sediment. For distributions which are symmetrical or nearly so, whether well or poorly sorted, it coincides with the mode or at least falls into the mode group. And even if this is not the case it indicates in a general way, the character of the sediment.

In this work the terminology adopted in the List of Samples and in Table 19 for describing the minerogen component of a sample, will be the following: The sediment will be given the character of the size group containing the median of the frequency distribution, but when two maxima are at hand, which both influence the outward properties of the sample, the character of these maxima will be indicated. The mode group cannot be used for classification purposes as in cases when its position is asymmetrical and particularly when the sorting is poor and it hardly exceeds the neighbouring groups, it cannot be considered to specially characterize a sample. The different groups will be referred to in the following way:

Table 10. *Designation of grain classes.*

	Size group	Designation
I	>2 mm	gravel, pebbles
	2—1 »	coarse sand
II	1—0.5 »	medium »
	0.5—0.1 »	fine »
III	100—50 μ	very fine »
	50—20 »	dusty »
	20—10 »	coarse silt
IV	10—5 »	fine »
	5—2 »	very fine »
	2—1 »	stiff clay
	1—0.5 »	very stiff »
V	0.5—0.2 »	» »
	<0.2 »	colloidal »

The author is aware that these names are not exactly the same as those generally used for the subgroups of the international scale. The greater number of subgroups in this case made some alterations necessary. It may seem strange that there is no transitional group between very fine silt and stiff clay. It would have been preferable to refer the very fine silt fraction to the clay group; as then samples, the median of which lie between 2 and 5μ , might have been called clays, as would seem most natural, but this would have implied a deviation from the international scale. Nevertheless these names seem to give a fairly good idea of the kinds of deposit characterized by each of these groups.

It must be emphasized that the above terminology applies only to the minerogen component of a sediment and that consequently a sediment which is morphologically a loose black mud may be described as a stiff clay from the standpoint of mechanical composition. The terminology adopted for the general description of the samples will be given in Section 21 after a discussion of the conditions of settling, and the general features of Baltic deposits.

IV. PRELIMINARY TREATMENT.

15. OUTLINE OF THEORY.

The first question which presents itself in connection with preliminary treatment of a sea bottom sample for mechanical analysis is the following: should a suspension be prepared with sea water or with distilled water? As is well-known, sea water, in common with solutions of electrolytes in general, has coagulating properties. In sea water clay particles do not exist as single particles, they form aggregates. What then is particle size in a sea bottom deposit? It is obvious what is meant by the size, say, of a sand grain. Also the behaviour of a sand grain in distilled water and in solutions of electrolytes is simple: it sinks to the bottom with a constant velocity regardless of all other grains present. But if a sand grain is subdivided into smaller parts by mechanical disintegration or weathering these parts with decreasing size assume new and gradually changing properties, displayed especially in solutions of electrolytes. The behaviour of fine-grained suspensions in many ways resembles that of colloidal solutions. One of the most important properties of such solutions is that the particles in suspension carry an electric charge, in clay suspensions a negative charge. This is evidenced during electrodialysis, when clay particles are deposited on the anode membrane¹). According to modern views on the structure of colloidal particles, (WIEGNER 128, 131—133) each clay particle is surrounded by a double layer of ions: an inner layer of absorbed negative ions firmly attached to the surface by the action of residual valence and lattice forces, and a corresponding outer layer of electrostatically attracted, but freely movable, positive ions, forming a diffuse swarm around the particle. A particle including the inner and outer layer of ions forms a micelle.

¹) As a matter of fact it was repeatedly noticed that clay particles during electrodialysis were also deposited on the kathode membrane, leaving when removed a patch of ferric hydroxide on the latter. MARRSON (61) has shown that colloidal clay in which the ratio $\text{SiO}_2/\text{sesquioxides}$ is low, in other words, which are rich in sesquioxides, carry a positive charge in acid solutions. During electrodialysis, as is well-known, the reaction of the clay becomes acid-- In the formation of both positively and negatively charged clay particles *in situ*, lie perhaps the preliminary conditions for the development of concretions on the sea bottom.

In a settling suspension the micelles, as such, move downwards. The outer layer of positive ions forms in a soil the exchangeable bases. In an electromagnetic field the micelle is split up, the positive ions moving to the negative pole, while the negative inner ions carry the particle to the positive pole. The stability of a suspension depends on the height of the potential between inner and outer layer. The higher the potential the more repulsion exceeds attraction, when particles are brought into contact with each other by Brownian movement or by sedimentation. A high potential prevails in a suspension containing no or almost no electrolytes except the absorbed ions. Then every single particle behaves like a sand grain moving through the suspension independently of the others. In the presence of electrolytes, on the other hand, the potential decreases and if it sinks below a certain critical value the adhesive forces get the upper hand and coagulation follows. A somewhat different view on the cause of stability and the mechanism of coagulation, lately developed by MATTSON (61—63), will be referred to in Section 20 in connection with the coagulation experiments.

A particle in a coagulated suspension is formed of a varying number of micelles and contains a varying amount of electrolytes and of water molecules. The size of such a particle is not well defined, especially because of the unknown amount of water in it and it can hardly be found by application of STOKES' law, as the settling velocity of strongly hydrated aggregates ¹⁾ is most probably different from that of single particles following that law. It should also be borne in mind that the water content of the secondary aggregates in the final sediment on the sea bottom is not the same as that of the initial aggregates from which it was formed. (Sediment coagulation BRENNER 16 and TRASK 115). The result of coagulation is influenced in general by the concentration of the suspension and of the electrolytes, by the nature and hydration of the latter as well as by the initial distribution of particle sizes in the suspension, as has been shown by WIEGNER (128, 132), GALLAY (30) and TUORILA (117).

It is thus evident that the use of sea water in the preliminary treatment of sea bottom sediments for mechanical analysis cannot effect dispersion into single particles, nor into any definite particle sizes, corresponding to a definite set of conditions. (See Table 17 giving analysis of F65A after treatment with sea water, and composition of suspension coagulated with same). Especially if a sample has been dried, it seems impossible to devise a preliminary treatment by which the particular state of coagulation prevailing in the natural

¹⁾ See section 20, p. 79—80.

sediment could be reproduced. For the purpose of studying the formation of deposits and especially the velocity of sedimentation in the sea, a knowledge of the size of the secondary aggregates is desirable. At the present moment the only way by which this might be achieved with some success is to treat with sea water such samples as have been preserved in a state of natural moisture. In this respect the results attained by PRATJE (88) on board the «Meteor» will be of great interest. PRATJE analyzed with sea water, according to the method of ATTERBERG, bottom samples freshly brought on board; subjecting them, as a mere preliminary treatment, to trituration with the fingers in a porcelain basin.

But except for this special purpose, the object of preliminary treatment of bottom samples, as of soils in general, can only be dispersion into single particles. In this way the sediment is brought into a definite and reproducible state and an insight is gained of its ultimate composition.

The notion of single particle size is here used in the sense implied in the expression itself, namely that there exists in every soil ultimate particles of definite sizes, no matter their actual dimensions, and that analysis of a suspension dispersed into these ultimate sizes leads to one and only one distribution curve.

It follows from the discussion above that single particles or micelles can exist only in suspensions which contain no or almost no electrolytes other than the absorbed ions. Such suspensions should of course be prepared with distilled water. In the case of sea bottom deposits the result will nevertheless not be satisfactory unless the sea salts contained in the samples are removed too. Though greater dispersion is attained with distilled water than with sea water there is still no clue for estimating to what extent the initial state of coagulation has been suppressed as long as sea salts are still present in the sample. Even for comparison purposes the salts should be removed, as two bottom samples treated in the same way, but containing different amounts of salts, will not necessarily be in the same state of dispersion. Only complete removal of all free electrolytes can ensure dispersion into single particles and bring the samples into comparable conditions.

It is however, necessary to point out that the notion of «single particle size» has undergone some modification in later years. It even seems possible that in future the statement that a suspension contains single particles will have to be accompanied by a statement of the nature of the exchangeable ions present. GEDROIZ (31) found that the size distribution of a soil varied with the exchangeable kations,

the highest dispersion being attained when the soil was saturated with sodium. The influence extended to particles up to $10\ \mu$ in diameter, but most notable was the variation in particle sizes below $1\ \mu$. If GEDROIZ's results are confirmed it not only means that an excess of electrolytes brings about formation of aggregates, but also that the absorbed bases, i. e. the outer layer of kations in the micelles, have a similar effect. MATTSON, who shares the views of GEDROIZ considers the latter effect to be an actual variation in the size of the micelles and consequently makes a distinction between aggregation and flocculation or coagulation; aggregation being an increase in the size of the micelles, flocculation a linking together of a number of micelles. MATTSON studied soil colloids, the varying particle sizes of which did not exceed $0.1\ \mu$. From the standpoint of ordinary mechanical analysis such a variation is of no consequence. But the variations observed by GEDROIZ cannot be left out of consideration. It is, however, to be hoped that they may be attributed to flocculation, as the experimental method of GEDROIZ does not seem to preclude the presence of some electrolyte in excess of the absorbed bases. In that case the experiment would be another instance of the differing susceptibility to electrolytes displayed by soil suspensions saturated with various kations, in which respect Na-soils are known to be the most stable. Some cases of extremely slow coagulation, observed by the author (see p. 84), are perhaps to be attributed to the same cause as the variations established by GEDROIZ.

For the time being we may probably still consider the notion of single particle size to have a definite meaning for all sizes determinable by ordinary mechanical analysis¹⁾. But care must be taken to free the grains of a definite size from the coating of particles of colloidal dimensions, which may or may not vary in size. The colloidal particles, being the chief seat of the exchange capacity, the best way to ensure this is perhaps the method recommended by GEDROIZ, which consists in saturating the soil with sodium or lithium ions. Such ions are known to be strongly hydrated and soils saturated with them show considerable swelling. The dispersing effect of saturation with Na⁺-ions might therefore be described as a mechanical disintegration of the aggregates brought about by the bulk of the water molecules accompanying the sodium ions. For the purpose of preliminary treatment the method of Na⁺-saturation was worked out by AMAR NATH PURI (91), who states that besides Na⁺-saturation, a pH of 8.5 is also necessary for complete dispersion. The method was not tested in connection with the present investigation as it

¹⁾ For the possible influence of hydration see section 20 p. 79—80.

had not yet been published when the analytical work was being undertaken.

In the present work the sea salts were removed by ordinary dialysis or electrodialysis, at which process part or all of the absorbed ions are likewise removed and replaced by hydrogen ions. It is true that hydrogen saturated soils are less stable than Na⁺-saturated (WIEGNER 128) i. e. more susceptible to coagulating influences, but on the other hand, except in the case of carbonate containing soils, they proved perfectly stable under the conditions of mechanical analysis. An advantage of dialysis is that no new electrolytes are introduced and that consequently there is no danger of other electrolytes than the absorbed ions being present in the final suspension.

The coagulating power of electrolytes is not the only factor to be considered in preliminary treatment. The coagulating, or more generally speaking, cementing effect of humus stuffs is another and that of calcium carbonate a third. There is further the mechanical cohesion between the soil particles to overcome. Various methods of preparation have been devised to meet the requirements of different kinds of analyses. The methods common in soil science may be said to comprise one or more of the following five kinds of treatment:

- 1) Mechanical treatment, such as boiling, shaking, trituration with a pestle or a hard brush,
- 2) chemical treatment with oxidizing agents in order to destroy organic compounds cementing the grains,
- 3) chemical treatment with acids for the solution of carbonates,
- 4) addition of so-called peptisators or stabilisators, which further dispersion and prevent coagulation, and — recommended especially in later years —
- 5) removal of electrolytes by washing or dialysis.

WIEGNER (129, 130) has shown that mechanical treatments which increase the number of collisions between the particles have a dispersing effect only if there are no or almost no electrolytes present. If these have been removed, boiling is more effective than any other mechanical treatment.

Instead of the earlier, rather aggressive nitric acid and sodium hypobromite methods, ROBINSON (92) introduced a 6 % solution of hydrogen peroxide as oxidizing agent; and this is now widely in use and has lately been recommended by the Bureau of Soils of the United States¹⁾. Some workers refrain from using chemical methods

¹⁾ The publication of the Bureau of Soils (GESSNER p. 176), which recommends removal of electrolytes as general method of preliminary treatment, hydrogen peroxide as oxidizing agent and the pipette method for mechanical analysis, was published when most of the analyses connected with this work were already made.

altogether, as this involves a change in the initial character of the soil. In the case of Baltic bottom samples, the mechanical analysis of which presents an interest especially from a geological point of view, removal of organic matter, formed independently of the mineral part of the sediment, seems natural; whereas the carbonates which derive their origin from mechanically disintegrated bedrock, should not be touched.

The peptisator which is most frequently used is ammonia. The favourable effect of hydroxyle ions is probably connected with the so-called «total absorption» of hydroxydes in soils, which is regarded as an absorption of hydroxyle ions into the inner layer of anions surrounding the clay particles, causing an increase in the negative charge of the latter. According to another interpretation hydroxyle ions simply neutralize hydrogen ions present in soils not fully saturated with bases. Alkali, moreover, has a dissolving influence upon humus stuffs. However, ammonia may have unfavourable effects if added in too high a concentration. The result depends on the other electrolytes present. A normality of 0.01 is recommended by ODÉN (77), while WIEGNER suggests N/10 ammonia for non washed soils. WIEGNER, however, regards washing as the most effective method of preparation for lime free soils. For bottom samples washing in most cases proved favourable even if the sample had a moderate carbonate content. This is seen, for example from the analyses of the three parts of sample F28 1925, given on page 103.

All circumstances taken into consideration, the following method of preliminary treatment was regarded as best suited to ensure dispersion of sea bottom samples into single particle size: 1) destruction of organic matter with H_2O_2 , 2) removal of electrolytes by electro-dialysis or ordinary dialysis, 3) boiling for 1—2 hours, 4) addition of some ammonia to the strongly acid electro-dialyzed samples (20 c. c. N/10 NH_3 to 1 litre) until a normality of from 0.001 to 0.002 was attained. Likewise ammonia was added to samples suspected of coagulation.

16. HYDROGEN PEROXIDE TREATMENT.

The samples are placed in large beakers, covered with water and treated on a water bath with three portions of 6 % H_2O_2 -solution. If the amount of organic matter is high the first portion causes considerable frothing. Then more water is added and the suspensions boiled for a quarter of an hour for decomposition of excess H_2O_2 . Besides oxidization of organic matter, the hydrogen peroxide also

effects a general dispersion of the sample. It is not necessary to crush or grind the sample beforehand. The dry lumps may be placed directly in the beaker. This favourable effect may be interpreted as a purely mechanical one. The hydrogen peroxide solution permeates the dry lumps, gaseous oxygen is formed within from decomposing H_2O_2 -molecules, and this necessarily causes complete breaking up of the lumps.

The efficacy of the method was tested in one case when the organic carbon of »Lumparen IVA 1926« was determined before and after treatment with hydrogen peroxide, and found to be 2.70 % and 0.32 % respectively. Thus 88 % of the organic matter had disappeared entirely, the rest may have been present in soluble form.

In the case of bottom samples the method has an additional effect, which is not altogether favourable. Samples having a high content of organic matter generally also contain a considerable amount of ferrous sulphide, which is partly, if not wholly, oxidized by the hydrogen peroxide. That this is so is seen at once from the colour of the over-lying solution when a suspension treated with hydrogen peroxide has settled. This causes a change in the initial composition of the suspension and a decrease in weight of the solid matter therein, which cannot be corrected. From samples originally containing iron oxides part of the iron will pass into soluble form. At subsequent dialysis the soluble iron readily diffuses through the membrane, but part of it probably remains in a colloidal form causing slow coagulation during mechanical analysis. In samples rich in iron especially in those from the Bothnian Bay the formation of many thin layers was often observed after a few days standing. The same applies probably to samples containing manganese oxides, though of those subjected to mechanical analysis only one, F30A 1928, had a content of manganese oxides high enough to attract notice during analysis. The question of how samples rich in iron or manganese oxides should be prepared for analysis demands further attention.

17. ELECTRODIALYSIS.

Removal of electrolytes was effected first by electrodialysis, later by dialysis through collodion membranes only, comparison of the two methods having shown that particles smaller than 2μ were apt to be attacked by electrodialysis and split into smaller particles. Electrodialysis as preliminary treatment for mechanical analysis has been recommended by BRADFIELD (14) but apparently without a

close comparison of the result with other methods of preparation. As the method is very convenient and bigger particles are apparently not attacked, it is valuable, when a subdivision of the clay fraction is not aimed at. The simple arrangement for electrodialysis adopted by the author, and useful for laboratories not especially equipped for electrochemical work, will therefore be described here. Instead of using a vessel divided in three parts by membrane partitions, ordinary one-litre beakers were used, in which the electrodes, enclosed in diffusion shells, were introduced. The arrangement is shown in Fig. 12. At first, extraction shells dipped in collodion solution were used, but later parchment diffusion shells (Schleicher & Schüll, No. 579), 10 cm high and holding about 100 c. c., were adopted. They were attached to short glass tubes of the same diameter, by means of tight fitting pieces of rubber tubing and immersed to a depth of 8 cm in the suspension. The half cylindrical electrodes, 3.5×7 cm, of gold plate for the anode and nickel plate for the kathode, were held in place

Fig. 12. Simple arrangement for electrodialysis.

by being passed through rubber stoppers, their smallest distance being about 5 cm. The gold was somewhat attacked by the chlorine, but not so much as to interfere with the normal course of electrodialysis. The rubber stoppers were provided with holes for a siphon and a tube for refilling with distilled water (not shown in the figure). A continuous flow of water through the electrode chambers was not arranged, but there were frequent refillings, especially in the beginning of the experiment (every ten minutes). The electric current was taken directly from the plant of the town (120 volt D. C.). A lamp resistance and a current meter were introduced, and in the beginning the current was adjusted to less than 1 ampère by coupling in series the four cells operated simultaneously. After a few hours, when most of the sea salts had been removed and the resistance in the cells had increased, these were coupled in parallel series. In this way undue heating was avoided. When the current was on, air was blown through the suspension to keep it in constant movement.

As mentioned above, four bottom samples were electrodialyzed at the same time. When the hydrogen peroxide treatment was ready, more distilled water was added to the beakers, the electrodes with surrounding membranes introduced and electrodialysis begun.

Because of considerable endosmotic water flow to the kathode chamber, more water had to be added to the suspension from time to time. The endpoint of electrodialysis is reached, when all sea salts ¹⁾ have been removed and all the absorbed bases replaced by hydrogen ions. A strong acid reaction, however, appears in the suspension much before this, in fact quite in the beginning of the experiment. This is due to the presence of the membranes, which, themselves carrying a negative charge, exert a retarding influence on the passage of anions. The temporary excess of the latter in the suspension is compensated by hydrogen ions (PAULI and VALKÓ 82 p. 370).

ODÉN and WILKSTRÖM in the study on electrodialysis already referred to (page 27), recommends the use of a positive membrane, cellophane, on the anode side; not, however, expressly as a means of lowering the acidity in the suspension, but in order to create endosmotic water flow to the anode chamber too and thereby to increase the rate of kation exchange. But judging from the slowly decreasing pH values recorded, the cellophane membrane in fact prevents formation of superfluous hydrogen ions. That this is so is confirmed by LÖDDESÖL (58) who also recommends cellophane as anode membrane. An observation often made during electrodialysis was that suspensions, which after the treatment with hydrogen peroxide were well dispersed, coagulated completely some time after electrodialysis had begun. Subsequently they were gradually dispersed again. This phenomenon was probably caused by the excess acidity in the beginning.

Electrodialysis was generally continued about 20 hours, then the chlorine and sulphate reaction in the anode chamber had completely disappeared; neutrality in the kathode chamber, however, had usually not been attained, because of slowly progressing hydrolysis in the suspension. As already pointed out, ODÉN has shown that electrodialysis is always accompanied by weathering, even when a positive membrane is used on the anode side. — Relatively coarse-grained lime and limonite free soils are the most suitable for electrodialysis.

18. DIALYSIS.

The object of dialysis, as of electrodialysis, is to remove all free electrolytes from the suspension and thereby to increase the potential of the suspended particles above the critical value. At the same time absorbed Na^+ - K^+ - and Ca^{++} -ions, are exchanged for hydro-

¹⁾ For composition of sea salts see note p. 28.

gen ions. Mg^{++} -ions are not exchangeable by dialysis, the removal thereof demanding a pH below 5.0, as was shown by ODÉN. For dialysis, collodion bags in the shape of Erlenmeyer flasks holding 150 c. c. were used. The bags were attached with rubber strings to short pieces of glass tube and suspended in large beakers (800 c. c.). Samples which were to be dialyzed were evaporated to a small volume on a water bath, after the treatment with hydrogen peroxide, then transferred into the collodion bags. Because of the high osmotic pressure within, the level of the suspension rose considerably and, if attention was not given to this, overflowing sometimes occurred. Dialysis was continued for about two months during which the water in the beakers was changed 6—8 times, the first time within 2 days, then with gradually longer intervals. In the beginning, as long as and if the samples were still coagulated, the liquid within the bags was changed also. The dialysates were stirred every day and the cakes of soil settling in the bags cautiously crushed with the fingers from the outside. In comparison with the long time that dialysis was continued, the number of changes of the outer water may seem few. A consideration of the following facts gives the explanation. The volume of the dialysate was about 4 times that of the suspension. If equal concentration of the ions inside and outside the membrane was reached, then every time the water was changed the concentration of each ion within the bag had sunk to $\frac{1}{5}$ of its initial value. Now the presence of the membranes influences the equilibrium, in accordance with the theory of DONNAN, but in a manner which leads to further decrease of the concentration within the suspension (PAULI and VALKÓ p. 366). If six changes (seven outer waters) are effected, then the concentration of electrolytes within the suspension will sink to at least $(\frac{1}{5})^7$ or $\frac{1}{78\,000}$ of the initial value. Dialysis was fast in the beginning, as could be seen from the iron containing suspensions, the outer waters of which, assumed a yellow colour within a few minutes. With decreasing concentration, equilibrium is reached much more slowly and there is no proof that in the present case it was always reached, but it is probably more effective to extend dialysis over a longer period of time than to shorten time and change the water more often.

When dialysis was ready the samples were washed out of the collodion bags into beakers, boiled for one to two hours covered with clock glasses, then allowed to cool and transferred into the cylinders for mechanical analysis. In carbonate containing soils boiling sometimes caused slow coagulation of the smallest grain classes, as was seen partly from the appearance of layers after a few

days of standing, partly from the analytical result, — the grain class 1—2 μ being sometimes abnormally high and the distribution curve displaying a typically »coagulated» appearance. Some instances of this kind will be given in Section 20.

19. COMPARISON OF METHODS.

The analyses in Table 11 made by WIEGNER's method on a bottom sample »Lumparen IVB», (organic matter 4.7 %, salinity 0.5 %) show the increasing dispersion effected by 1), 2) continued electrodialysis, 3) hydrogen peroxide treatment, and 4) by boiling.

Table 11. *Effect of various methods of preparation on sample »Lumparen IVB».*

	(1)	(2)	(3)	(4)
	Electrodialyzed			
	10 ^h	26 ^h	16 ^h Treated H ₂ O ₂	16 ^h Treated H ₂ O ₂ boiled
> 100 μ	2.8 %	5.0 %	0 %	0 %
100—50 »	3.5 »	1.8 »	0 »	0 »
50—20 »	18.7 »	7.9 »	(> 20 μ) 4 »	0 »
20—10 »	54.0 »	19.8 »	4 »	(> 10 μ) 1 »
10—5 »	4.5 »	46.0 »	7 »	8 »
5—2 »	2.8 »	(5—3.5 μ) 6.5 »	23 »	20 »
< 2 »	13.8 »	(< 3.5 μ) 13.0 »	62 »	71 »

Experiments (1), (2), and (3) were made on different portions of the same sample, (4) was portion (3) boiled for 1 $\frac{1}{2}$ hours. Sample (1) electrodialyzed 10 hours, but not otherwise treated, shows the typical composition of a coagulated soil. A single grain class 20—10 μ is absolutely dominating. Experiment (2) shows that continued dialysis displaces the maximum towards finer grain classes. In this case, however, not electrolytes, but organic matter influences dispersion most. After hydrogen peroxide treatment, 16 hours' electrodialysis is enough to displace the maximum into the clay group, and the boiling of the same sample effects further dispersion, as foreseen by WIEGNER. The distribution diagrams of Fig. 13 show the result graphically.

The effect of small amounts of ammonia on electrodialyzed samples is seen from Table 12 and Fig. 14, which contains triple analyses of two bottom samples F18 1928 and F56 1928, the organic matter, salinity and carbonate content of which were the following:

	% organic matter	% salinity	% carbonates
F18 1928	3.5	1.05	0
F56 1928	3.2	1.71	3.09

Table 12. *Effect of ammonia on electrodialed samples.*

Sample	>20 μ	20—10 μ	10—5 μ	5—2 μ	2—1 μ	1—0.5 μ	0.5—0.2 μ	<0.2 μ
F18 1928, electrodialed,								
not dispersed with NH ₃ ..	8.8	8.9	13.1	18.1	15.8	15.6	11.7	7.7
dispersed with NH ₃ ..	7.7	10.1	13.0	18.8	14.1	12.5	6.7	17.1
dialyzed, boiled	8.0	8.5	12.9	19.9	14.9	12.6	13.4	9.9
F56 1928, electrodialed,								
not dispersed with NH ₃ ..	33.0	11.3	8.0	9.5	7.5	8.7	17.5	4.4
dispersed with NH ₃ ..	33.0	11.5	7.6	8.9	6.5	6.5	13.5	12.5
dialyzed, boiled	32.5	10.6	8.5	10.5	6.1	9.6	13.9	8.3

Three portions of 10 gr of each sample were treated with hydrogen peroxide; then two portions electrodialed, one of them being treated with ammonia; the third dialyzed and subsequently boiled. The electrodialed samples were not boiled, the long continued stirring during electrodiales representing in itself an increase in the number of collisions between the particles. The summation curves of Fig. 14 show that down to 2 μ , in fact almost down to 1 μ , the results are practically identical. Below 2 μ , the sample admixed with a small amount of ammonia lies above those not so treated. In both cases the dialyzed sample lies between the two electrodialed ones, showing a higher dispersion than the sample not treated with ammonia but a lower dispersion than the one treated. The fact that a higher amount of «absorbed bases» was found in electrodialed samples (Tables 5 and 6, p. 27) combined with the higher dispersion of these in comparison to dialyzed ones, leads one to the conclusion that electrodiales has a chemical influence on dispersion. It seems as if the smallest grains were transformed into aggregates of still smaller particles, the final dispersion of the aggregates, however, occurring only after addition of ammonia. In the case of F56 1928 containing 3 % carbonates, the influence of elec-

Fig. 13. Effect of different methods of preliminary treatment on sample «Lumiparen IVB».

Fig. 14. Triple analysis of F18 1928 and F56 1928.

trodialysis is more marked. Otherwise the presence of the carbonates, in this case, did not in any way disturb the course of preliminary treatment.

The effect of electro dialysis compared to dialysis is further seen from Table 13 and Fig. 15. The organic matter, salinity and carbonate contents of the samples are also given.

Table 13. Comparison of electrolyzed and dialyzed samples.

Sample	Organic matter %	Carbonates %	Salinity %	>20 μ	20-10 μ	10-5 μ	5-2 μ	2-1 μ	1-0.5 μ	0.5-0.2 μ	<0.2 μ
F29A 1928	0.8	3.16	0.32								
1. Electrolyzed				42.2	6.4	10.6	15.8	10.3	4.1	4.8	5.8
2. Dialyzed				39.9	6.2	11.0	19.4	11.1	9.6	2.8	
F30A 1928	3.5	0.23	1.26								
1.				2.4	5.7	5.8	15.2	15.0	16.9	17.6	21.4
2.				4.9	4.9	7.4	18.0	16.8	17.9	19.1	11.0
F55 1924	0.7	0.72	0.69								
1.				3.9	4.8	4.8	8.5	11.6	13.7	22.1	30.6
2.				4.0	3.7	2.6	10.0	13.1	19.4	29.2	18.0
F65A 1928	1.6	0	0.87								
1.				3.8	5.7	7.4	14.7	13.5	14.3	15.6	25.0
2.				5.6	5.3	6.1	16.0	13.0	14.8	21.3	17.9
F78 1924	3.6	0	3.6 ¹⁾								
1.				4.8	2.8	2.9	9.4	16.7	16.6	19.5	27.3
2.				0.8	2.5	2.9	13.6	15.5	20.7	25.9	18.2

The two portions of each of the samples F29A, F55 and F65A are identical within the analytical errors down to 1μ, but differ considerably below that grain size. The same is true of F78 as regards the clay group. As in Table 12, the influence of electro dialysis is thus

¹⁾ This sample was taken from the water sampler and brought to the laboratory in a glass cylinder, covered with water, which evaporated during storage, causing the high salinity.

confined to the smallest grain classes, which *a priori* are the ones most susceptible to dissolution. The result is especially convincing as regards sample F55 1924, which belongs to a type of clays of almost constant mechanical composition (Fig. 34). These clays (see Table 25 p. 207) generally contain 19–21 % in subgroup 1–0.5 μ , 28–29 % in subgroup 0.5–0.2 μ and not above 25 % in subgroup $< 0.2 \mu$. The analysis of the electrodialyzed portion gave 14 %, 22 % and 31 % in these groups respectively, which result is thus quite inconsistent with the general composition of the type and shows that subdivision of the smallest grain sizes must have occurred. In F30A the dissolving influence of electrodialysis seems to extend over all grain sizes. An observation made during electrodialysis affords an explanation. Some of the dry lumps of this sample were light brown in colour and seemed to be concretions in the making. They were supposed to contain limonite and were avoided when the portions for mechanical analysis were weighed out.

Fig. 15. Comparison of analyses of electrodialyzed and dialyzed samples.

Disseminated throughout the sample were also small dark brown dusty lumps which could not be avoided. During electrodialysis a dark brown precipitate appeared in the cathode chamber, which was found to be not ferric but manganic hydroxide. Manganous ion was also present in the dialysate, whereas the iron reaction was weak. Higher manganese oxides were consequently distributed throughout the sample, and apparently concentrated in the brown lumps. Hydrogen peroxide must have caused some reduction, but it is doubtful to what extent the cementing effect on the particles was suppressed¹⁾. Also

¹⁾ The U. S. Bureau of soils recommends addition of acetic acid before hydrogen peroxide treatment to samples containing manganese oxides. (Gessner p. 177).

the summation curve of the dialyzed sample is therefore not quite correct. »Grain size» is, in fact, not well defined in such a sample and it may be queried whether, when higher oxides of manganese and iron are present, these should be dissolved or not. The answer depends on the purpose of the analysis. In any case the two analyses of F30A show that the sample is a fine-grained clay, 50 % being smaller than about $1\ \mu$. The almost parallel course of the two curves above $5\ \mu$ indicates that there is perhaps an analytical error in the group $> 20\ \mu$ or an actual difference in the amount of coarser particles. The same applies to the upper portion of F78. —

The effect of different methods of preliminary treatment may finally be illustrated by comparison of three analyses made by Dr PARKER D. TRASK of the American Petroleum Institute on samples from the Baltic, collected for him by the Thalassological Institute of Helsingfors, and analyses made by the author on the same sample or on one from the same locality. In Table 14 the data given by Dr TRASK (115, tables G and H p. 294, 298) and the corresponding data found by the author are given. Dr TRASK gives the following description of his method of preliminary treatment: »the sample, after being weighed, is broken into small parts, placed in a beaker, covered with N/24 sodium carbonate, allowed to stand over night, transferred to a mortar, rubbed gently with a rubber pestle, and placed in a mechanical shaker for 24 hours.» This method is quite different in character from the one used by the author. Sea salts are not removed and organic matter not destroyed, though it may

Table 14.¹⁾ *Comparison of mechanical analyses made by Dr TRASK and the author.*

Sample	Q ₁	M	Q ₂	So	Sk	Sand	Silt			Clay		Colloid		
							50—20 μ	20—10 μ	10—5 μ	5—2 μ	2—1 μ	1—0.5 μ	0.5—0.2 μ	< 0.2 μ
						1 000—50% %	%	%	%	%	%	%	%	%
F3 1928 TRASK	19	7.9	2.8	2.60	0.85	11			54		29		6	
F3 1928 electrodyalized	25	7	1.9	3.63	0.97	29.8	12.4	14.5	17.1	8.7		17.4		
F40 1928 TRASK	13	6.4	2.2	2.43	0.70	1			62		27		10	
F40 1924 dialyzed	6	2	0.5	3.65	0.67		3.9	9.1	16.4	20.5	12.2	11.4	13.8	12.8
F40 1925 »	6	2	0.5	3.45	0.80		1.9	10.0	19.2	19.4	13.7	11.8	13.2	10.9
F80 1928 TRASK	30	8.8	3.2	3.06	1.24	14			53		20		13	
F80 1930 dialyzed	5	1.1	0.4	3.51	1.42	0.4	10.6	8.7	4.8	15.4	12.5	17.2	19.3	11.2

¹⁾ The classification in sand, silt, clay and colloid in this table is the one used by Dr TRASK.

be, to some extent, dissolved in the alkaline solution. As is seen from Table 14, the resulting suspensions are considerably coarser than those achieved by removal of electrolytes and destruction of organic matter. In the case of F3, Dr TRASK and the author actually analyzed the same sample, but the analyses of F40 and F80 were made on similar samples from the same locality, but collected at different periods. The two analyses on F40 made here, agree very well and as F41, the nearest station, also has a median of about $2\ \mu$, there is no reason to suppose that F40 1928 was comparatively much more coarse-grained. Similarly all analyses on samples from the Baltic from F74 to F81 give medians from $0.5\text{--}1\ \mu$ and third quartiles from $0.2\text{--}0.5\ \mu$, from which it follows that F80 1928 and F80 1930 must have had essentially the same composition. From the data in Table 14 the two Figures 16 a and 16 b were drawn. Fig. 16 a gives the distribution curves constructed on all available data and Fig. 16 b the summation curves from $1\ \mu$ upwards. In the case of F3 1928, the electrodyalyzed sample is somewhat coarser above $10\ \mu$ than the other, but otherwise the dialyzed samples show a considerably finer dispersion than the ones treated with sodium carbonate. A comparison of the coefficients of sorting shows that samples F3, F40 and F80, if incompletely dispersed, seem better

Fig. 16. Comparison of analyses made by Dr TRASK and the author.

sorted than complete dispersion reveals them to be. It has already been pointed out and will further be emphasized in the next section treating the coagulation experiments, that one of the characteristics of more or less coagulated suspensions is a high degree of sorting.

20. COAGULATION.

A few experiments were made in order to study the process of coagulation in sea water. The variety of electrolytes in sea water, consisting of mono- and divalent kations as well as anions, necessarily renders coagulation a very complex phenomenon¹). The relative composition being, however, more or less the same everywhere, the coagulating power of sea water may be regarded as a function of salinity. The result of coagulation, on the other hand, greatly depends on the concentration of the suspension and the initial distribution of particle sizes in it. In nature the coagulating power of sea water effects its influence chiefly on the muds brought down by the rivers. Coagulation of river muds has been the subject of many investigations, resulting in a variety of observations and interpretations. However, only the recent development of colloid chemistry in general has made possible a real understanding of the essential features of the problem. Coagulation in soil suspensions has lately been studied systematically, amongst others by MATTSON, GEDROIZ and by WIEGNER and co-workers, especially by GALLAY and TUORILA. WIEGNER has emphasized the important part of kation exchange in the process. Many of the results attained also apply to coagulation in sea water.

Coagulation is either slow or rapid. When to a stabile colloidal system a small amount of electrolyte is added, slow coagulation sets in. With increasing concentration of the electrolyte it becomes more and more rapid until, at a certain concentration, a highest value is attained not exceeded by further addition of the electrolyte. Coagulation then has passed from slow to rapid. TUORILA (117) summarizes the result of rapid coagulation of soil suspensions in the following way: In suspensions composed of particles of all sizes (TUORILA used suspensions with particle sizes up to about 100 μ) aggregates with diameters from 20—40 μ are formed, particles smaller than 20 μ disappearing almost completely.

For the processes in nature the greater or lesser rapidity of a phenomenon is of minor importance compared to the final result. The rapidity does not solely depend on the concentration of the electrolytes, but also on that of the suspension. The lower the con-

¹) For composition of sea water see note p. 28.

centration, the slower the coagulation. The nature of the coagulating ion has an influence on the product. Coagulated clays are the stronger hydrated the stronger the hydration of the flocculating ion. The most important kations in sea water are sodium and magnesium. Both are strongly hydrated and cause formation of »voluminous, slimy, viscous» aggregates (WIEGNER). A clay coagulated with sea water has exactly those properties, it is of a decidedly liquid appearance. The same applies to the more watery kinds of bottom samples in their natural state, but not necessarily to marine sediments as a rule, the appearance of which depends on many factors such as the organic matter content and the slow changes (dehydration, sediment coagulation) taking place in the sediment after its deposition.

As a contribution to the knowledge of the coagulating properties of sea water, a series of experiments were carried out with water of varying salinity. It was of interest to ascertain whether the size of the aggregates finally formed depended on the salinity of the suspension and whether, as in the experiments of TUORILA, there was a certain maximum size for the aggregates.

A fine-grained suspension, free from electrolytes was prepared by mixing together a number of suspensions left over from KÖHN-analysis. Contrary to the suspensions used by TUORILA it was given only a small amount of particles $> 20 \mu$ in order to be comparable, if possible, to fine-grained river muds. The concentration of this suspension was determined by the evaporation to dryness of two samples of about 300 and 500 c. c. Portions of about half a litre were poured into a series of cylinders, the initial suspension being well stirred each time a portion was taken out. The actual volume filled into each cylinder was noted. Then distilled water and varying amounts of a 34 ‰ sea water were added, so that the salinities in the cylinders marked 1—12 amounted to:

	1	2	3	4	5	6	7	8	9	10	11	12
S ‰	0	0.25	0.50	0.75	1.0	1.5	2	4	8	15	23	34
S equivalent- ents/litre	0	0.004	0.009	0.013	0.017	0.026	0.035	0.069	0.14	0.26	0.40	0.59

The suspensions in cylinders 11 and 12 were prepared by treating dry portions of the initial suspension directly with sea water. The total volume in each cylinder was 1 litre, the starting concentration essentially the same, varying from 94 to 106 mgr per 10 c. c. As soon as the sea water had been added, the cylinders were thoroughly shaken, then left standing overnight. All the cylinders from 5 (1 ‰) onwards, coagulated completely within less than 1 hour, Nos 3 and

Fig. 17. Mechanical analyses of coagulated suspensions.

4 within a couple of hours; in cylinder 2, of 0.25 ‰ salinity, signs of coagulation were to be seen only the following day, when analysis was begun. A greater number of fractions than usually were taken in order to follow the phenomenon more closely. The analysis of cylinder 1 containing the uncoagulated suspension gave the following result:

$>20\mu$	$20-15\mu$	$15-10\mu$	$10-7.5\mu$	$7.5-5\mu$	$5-3\mu$	$3-2\mu$	$2-1\mu$	$1-0.5\mu$	$0.5-0.2\mu$	$<0.2\mu$
2.8	2.2	4.2	5.6	4.7	10.4	10.7	14.6	17.3	22.2	5.4 ‰

The initial suspension was consequently rather fine-grained, the median being 1.3μ . The analyses are recorded in Table 15 and graphically in Fig. 17, distribution diagrams in this case showing the result most clearly. The unit of surface was chosen in such a way that the height of the columns directly report the percentage of particles between any two diameters differing by the factor $\frac{4}{3}$ ($20-15\mu$, $10-7.5\mu$).¹⁾ The analysis offered a source of error otherwise not encountered. Each portion of 10 c. c. taken with the KÖHN pipette, contained a varying amount of sea salts the weight of which in the case of the higher salinities by far exceeded that of the soil to be determined. The salt content was determined in a special sample taken from the (almost) clear supernatant liquid in the coagulated suspensions. All pipette samples were carefully dried. Nevertheless this circumstance may account for small anomalies in the result.

Before any interpretation of the result is undertaken a question poses itself: is it correct to express the result in terms of grain sizes rather than in terms of settling velocities, or in other words, is the formula of STOKES valid for coagulated particles? TUORILA discusses the question and answers it in the affirmative. If this is so, then from the present experiment it seems to follow that the notion of radius and specific gravity of coagulated particles must be modified, or else the result will be in contradiction with the general results arrived at by WIEGNER (128) and GALLAY (30) by means of viscosimetric measurements on coagulated suspensions. When, nevertheless, in Fig. 17, the diameter as found from the formula of STOKES is still kept as abscissa it is not in the sense of equivalent radius but in that of equivalent velocity. It is easier to visualize a certain velocity by saying that it is equal to that of a certain grain size, than by stating the velocity itself.

¹⁾ Because of the greater number of subgroups, the diagrams of Fig. 17 are thus not directly comparable to those on Fig. 31—41. Drawn in the same way as these, diagram 2 on Fig. 17 would have clearly shown the coagulated state of the suspension, as the max. height of the diagram (in subgroup $5-2\mu$) would then have been 41 %.

Table 15. *Mechanical analysis of suspensions coagulated with sea water.*

No.	Salinity ‰	>20 μ %	20—15 μ %	15—10 μ %	10—7.5 μ %	7.5—5 μ %	5—3 μ %	3—2 μ %	2—1 μ %	1—0.5 μ %	<0.5 μ %
1	0	2.8	2.2	4.2	5.6	4.7	10.4	10.7	14.6	17.3	27.6
2	0.25	7.0	0.9	5.3	3.9	5.3	34.2	21.0	18.8	3.5	
3	0.50	5.7	1.7	1.7	10.0	72.1	5.1	1.5	2.1	0.2	
4	0.75	7.2	0	7.6	64.1	17.0	1.0	2.0	1.1		
5	1.0	4.0	1.4	13.5	76.1	2.3	1.6	1.2			
6	1.5	3.1	2.8	18.3	72.9	0.8	2.1				
7	2.0	6.0	1.6	23.8	65.5	0.6	2.4				
8	4.0	4.9	0.5	66.4	25.6	2.4	0.2				
9	8.0	8.0	1.4	71.7	15.8	1.1	2.0				
10	15.0	4.3	4.0	76.7	5.7	5.3	3.9				
11	23.0	8.1	9.2	78.4	3.0	1.4					
12	34.0	13.6	3.3	69.2	13.9						

A consideration of Fig. 17 shows that sea water diluted to a salinity of 0.25 ‰, corresponding to a normality of 0.004 causes slow coagulation, which after a night's standing has completely changed the distribution of the suspension. Initially there were 45 % of particles smaller than 1 μ ; in 0.25 ‰ sea water only 3.5 % are left, whereas the groups with settling velocities corresponding to 1—2 μ , 2—3 μ and 3—5 μ , especially the last, have considerably increased. Of particles > 5 μ there is about the same amount as before. In cylinder 3, with 0.5 ‰ salt, the change is still more radical, the distribution diagram already presenting a typically coagulated appearance. The dominating groups in cylinder 2 have almost disappeared, but the next group 5—7.5 μ has increased enormously: from 5 to 72 %. There is also an indication of increase in the group 7.5—10 μ , which subsequently becomes dominant in cylinders 4, 5, 6 and 7. In cylinder 5 this size-group attains its maximum with 76 %. Particles with settling velocities smaller than that of 7.5 μ have practically disappeared. Already in cylinder 5, but more pronounced in 6 and 7, the fraction 10—15 μ begins to increase, gaining dominance in 8 and all the following cylinders, while fraction 7.5—10 μ slowly falls back. In cylinders 10 and 11 the maximum is reached with 77 and 78 % respectively. In 12, the last cylinder with 34 ‰ salt, there is a slight decrease, but whether it is real or an analytical error due to the high amount of salts, is difficult to decide.

The first conclusion which presents itself after a consideration of this series of distribution diagrams is that coagulation begins with the smallest grains, gradually progressing to the bigger. If the essential difference between slow and rapid coagulation is the velocity of the phenomenon, then cylinders 2, 3 and 4 may be considered as stages rapidly passed by 5 and all the others coagulating completely within a short time. This is contradictory to statements by ODÉN

(75) and by GALLAY, who point out that coarser particles react more rapidly to the influence of electrolytes than small ones. The very fine-grained character of the initial suspension may account for the observed difference in this respect.

Another reflection, which poses itself, is that with progressing coagulation the suspensions become more and more sorted. The observation often made in the course of mechanical analysis that more or less coagulated suspensions are characterized by one dominating size group, is thus confirmed. The highest degree of sorting is seen in 5; a fact which is noteworthy as this was the first cylinder coagulating rapidly. An attempt was made to determine the velocity by which in the different cylinders the top of the column of coagulated particles moved downwards, in order to get an idea of the approximate smallest velocity and the rate of increase in velocity with increasing concentration of the flocculating ions. In cylinder 2 no sharp limit between the coagulum and the solution could be seen, in 3 too the limit was not quite distinct, but in the others it was easily observable. Cylinders 11 and 12 were not included as the experiments with 23 ‰ and 34 ‰ water were made later than the others.

In cylinders 3—10 the following lowest settling velocities (mean of two) were observed:

Table 16. *Settling velocities of aggregates in coagulated suspensions.*

Cylinder	3	4	5	6	7	8	9	10
salinity ‰	0.50	0.75	1.0	1.5	2.0	4.0	8.0	15.0
settling velocity cm/min.	0.24	0.35	0.42	0.47	0.51	0.57	0.61	0.65
diameter from formula of STOKES	6.6 μ	8.0 μ	8.7 μ	9.2 μ	9.6 μ	10.2 μ	10.5 μ	10.9 μ
relative diameter of aggregates ..	—	—	1.55	1.38	1.27	1.11	1.07	1

If these results are compared with the distribution curves in Fig. 17, it is seen that the dominating groups in cylinders 3—7 comprise in fact very narrow ranges of particle sizes. The degree of sorting in the coagulated suspensions is thus still considerably higher than is revealed by the arbitrarily chosen size limits of the mechanical analysis. In cylinders 5, 6 and 7 the particles in the dominating groups are of nearly uniform size, their settling velocities lying chiefly in the range 9—10 μ .

Table 16 is shown graphically in Fig. 18, in which the observed velocities in centimetres per minute are checked against the corresponding salinities in logarithmic scale.

The first steep slope of the curve marks the advancing process of coagulation, which in this case was complicated by kation exchange, being the effect both of the added sea water and of the free hydrogen ions ¹⁾ liberated by exchange with the kations of the sea salts. (Part of the hydrogen ions were neutralized by the excess base of the sea water). Suspensions of hydrogen saturated soils are perfectly stable under the conditions of mechanical analysis; hydrogen ions may thus be said to be quite harmless when forming part of a micelle as exchange kations, yet they act as strong coagulators even in small quantities when free. The nature of the effect is not quite clear; MATTSON (62, p. 377) describes the phenomenon by saying that «the exchange acidity mobilizes the trivalent kations Al and Fe».

Fig. 18. Settling velocities of aggregates in coagulated suspensions.

The joint effect of the sea salts and the exchange acidity is expressed in the first rapid increase in settling velocity. At about 1.0 or 1.5 ‰ there is a bend in the curve and the increase in velocity becomes more slow. Settling velocity, high degree of sorting and direct observation of the coagulation process thus indicate that 1 ‰ is a critical salinity which marks complete coagulation under the conditions at hand (hydrogen saturation of fine-grained soil, 10 gr soil per litre). The changes taking place at higher salinities are most probably a result of secondary effects. Investigations by WIEGNER and GALLAY and by MATTSON afford an explanation.

MATTSON (61—63) has lately developed new ideas as to the cause of stability and the mechanism of coagulation in soil suspensions. According to MATTSON part of the ions in the outer layer, i. e. part of the exchangeable ions, exist in a dissociated condition. A colloidal particle including the exchangeable ions, i. e. a micelle, behaves

¹⁾ It should be remembered that the original suspensions used for the experiment had undergone prolonged dialysis and were thus chiefly hydrogen-saturated.

like a weak electrolyte. Because of dissociation a high osmotic pressure prevails in the immediate neighbourhood of the particle, supporting the tendency of the ions to move away from the surface, until this osmotic tendency is counterbalanced by the backward electrostatic pull. The different ability of the ions to diffuse into the outside medium against the electrostatic attraction depends upon the specific nature of the ions, such as hydration and valence. Strongly hydrated ions, especially Li^+ and Na^+ , are strongly dissociated. The phenomenon of dissociation can also be described by saying that various amounts of water are fixed or imbibed around particles saturated with various kations. The imbibed water forms part of the micelle, together with the dissociated ions forming the micellar solution (to be sharply distinguished from the outside or intermicellar solution). The strong swelling of dry soils saturated with Na^+ - or Li^+ -ions when brought into contact with pure water is due to the formation of the micellar solution. The varying ability of the ions to dissociate is expressed in the *HOFMEISTER* series:

The more dissociated the absorbed ions, the stronger is the swelling, the higher the potential and the more stable the suspension. A high potential is a phenomenon generally accompanying stability, not causing it. Having frequently noted a higher potential in a coagulated suspension than in the original stable one *MATTSON* denies the existence of a critical potential for soil suspensions and rejects the idea that electrostatic repulsion between the particles accounts for stability.

The stability of a suspension and the swelling of a soil is greatest in the absence of free electrolytes. A neutral salt added to a colloidal system, will be distributed between the micellar and the intermicellar solution according to the laws of the *DONNAN* or membrane equilibrium, which demand that the product of the ions of the salt inside and outside the membrane (in this case inside and outside the micellar solution) should be the same¹⁾. *MATTSON* shows that the formation of the *DONNAN* equilibrium must cause suppression of the swelling and of the osmotic hydration, consequently a decrease of the «effective radius» of the micelles. At the same time, as is well-known, stability decreases. At a certain concentration of the electrolyte the adhesive forces between the particles come into play and coagulation follows. Not agreeing with the view that electrostatic repulsion accounts for stability, *MATTSON* also rejects the

¹⁾ See *PAULI UND VALKÓ* 82 p. 238.

consequence thereof, viz. that flocculation depends on neutralization of the free charges on the surface of the particles, or what comes to the same thing, on suppression of the potential between the inner and outer layer of ions; he founds this opinion on the fact that not only kations but anions too may cause flocculation in soil suspensions. As both kations and anions enter in the DONNAN equilibrium and have a similar effect he regards the decrease of the average effective radius of the micelles as the chief cause of flocculation and suggests the possible existence of a «radius of adhesion» within which the attracting force alone is effective. Micelles would then remain dispersed as long as their «radius of hydration» is greater than the «radius of adhesion». Under such circumstances Brownian movement is sufficient to account for dispersion. Rapid flocculation begins when the two radii are equal. As the phenomenon is very complex the «radius of adhesion» may be considered as a variable factor like the «radius of hydration». Flocculation does not effect molecular union of particles, but the linking together of micelles. This explains the high water content of coagulated flocks and foresees its variability with the concentration of the free electrolyte.

The effect of increasing amounts of electrolyte, is not limited to final coagulation of the suspension; the influence continues to exert itself on the coagulated flocks. Viscosimetric measurements by WIEGNER and GALLAY on flocculated soil suspensions showed that the viscosity after having attained a maximum value, decreases on further addition of the flocculating ion. The effect was notable at concentrations far below those of the sea water used in the present coagulation experiments. According to theory, viscosity is a function of the relative volume occupied by the colloid. WIEGNER therefore interpreted the phenomenon as a dehydration of the micelles forming the coagulated flocks. MATTSON's viscosimetric measurements on colloidal suspensions are in perfect accordance herewith; moreover WIEGNER's interpretation follows directly from the views MATTSON developed later on dissociation and the effect of the DONNAN equilibrium.

In the case of the coagulation experiments recorded in Table 15 a similar explanation seems appropriate: the change in the size distribution from cylinder 6 onwards may be considered as an expression of increased falling velocity caused by dehydration of the coagulated flocks. It would thus constitute a decrease of the particle size, not an increase as the distribution diagrams seem to imply.

However, if dehydration is accepted as explanation of the increased settling velocity at higher salinities, then the question of

the validity of the law of STOKES for coagulated aggregates poses itself. TUORILA found that the six primary conditions for its validity ¹⁾ are fulfilled for coagulated as well as for not coagulated suspensions, with the exception of the first condition which demands that the particles should be spherical. But nor is this condition fulfilled for soil particles in general, and it was overcome with the introduction of the notion of equivalent radius. There is, however, one feature of the question which did not influence TUORILA's results, but which must be considered in this connection. One of the quantities influencing the settling velocity as expressed in the formula of STOKES,

$$v = \frac{2}{9} g \frac{\sigma - \sigma_0}{\eta} r^2,$$

is the specific gravity σ of the settling particles, and this may be variable in a coagulating suspension. The specific gravity of a strongly hydrated aggregate cannot be the same as that of the dry soil. Theoretically the question also touches particles dispersed into »single particle size» when saturated with various kations, the settling bodies in a soil suspension being the micelles, i. e. the particles with their envelope of water and exchange kations, not the solid nuclei thereof. MATTSON (63 p. 307) calculates the thickness of the water layer in a Na⁺-saturated and a Ca⁺⁺-saturated natural soil colloid at about 1.6 r and 0.6 r respectively, r being the radius of the solid nucleus of the micelle. If the specific gravity of the dry colloid is 2.65 then the specific gravities of the two micelles will be 1.1 and 1.4! The average particle radius of the Na⁺-saturated colloid was 34 $\mu\mu$ (62, p. 400). For particle sizes determinable by ordinary mechanical analysis, the influence of varying hydration is naturally much less, but the possibility thereof cannot altogether be left out of consideration. If the thickness of the imbibed water layer becomes even $\frac{1}{10}$ of that of the solid particle the specific gravity decreases from 2.65 to 2.24, as simple calculation shows, which means a 25 % decrease of the settling velocity. Particle sizes in the clay fraction (below 2 μ) have probably to be interpreted both in the sense of equivalent velocity (same velocity as corresponding dehydrated particle having specific gravity of dry soil) and in that of equivalent radius. The question is connected with that of the exchange capacity. Particles with an appreciable exchange capacity may also be noticeably hydrated. GEDROIZ states that clay particles below 1 μ constitute the chief bearers of the exchange capacity, but that

¹⁾ For the conditions of the validity of the law of STOKES, see discussion GESSNER p. 10.

naturally the highest capacity belongs to particles of colloidal dimensions.

For coagulated flocks the influence of hydration is more obvious, the changes in the micelles becoming clearly noticeable when magnified by formation of clusters with greatly increased settling velocities. From the formula of STOKES it is easy to deduce that the radii of micelles or aggregates, differing in size by the thickness of the imbibed water envelope only, will be inversely proportional to the settling velocities.

The formula of STOKES may be written

$$6 \pi r \frac{\eta}{g} v = \frac{4}{3} \pi r^3 (\sigma - \sigma_0)$$

where the right side represents the weight of the particle when in suspension. This weight is the same for two particles with radii r_1 and r_2 and settling velocities v_1 and v_2 , if the solid nucleus is the same in both, the possible difference in specific gravity between the micellar and the intermicellar solution not being considered. Consequently

$$6 \pi r_1 \frac{\eta}{g} v_1 = 6 \pi r_2 \frac{\eta}{g} v_2$$

and

$$\frac{r_1}{r_2} = \frac{v_2}{v_1}$$

According to this formula minimum diameters were calculated for the aggregates in the completely coagulated cylinders (from 5 onwards), expressed in terms of that of the last cylinder 10. The values found are given in the last row of Table 18. It is seen that the radii of the aggregates decrease by more than one third, as the salinity increases from 1 to 15 ‰. In order to be able to calculate the approximate size of the aggregates we must make some assumption as to the hydration of the aggregates in cylinder 10. A minimum value for the latter may be found in the following way. We may assume the aggregates not to contain less water than the natural sediment. In the List of Analyses we find the minimum initial water content of the samples, as calculated from the salinity of the samples and that of the bottom water (see p. 25). The salt contents found in some very fine-grained (median about 0.5μ) late-Glacial sediments of the North Baltic (salinity of bottom water 10–12 ‰) with a low content of organic matter are seen to correspond to about 40 % of water. This is a minimum value calculated on the assumption that

the salinity of the water in the sample is the same as that of the bottom water. If the whole of this water is ascribed to the micellar solution and all particles are supposed to be equally hydrated, then the ratio between the radii of the innermost solid particle and that of the micelle will be 1 : 1.4¹⁾. The specific gravity of such a particle will be 1.6. From the equation of STOKES we find that the diameter of a particle having sp. gr. 1.6 and settling velocity 0.65 cm per minute is 183 μ . This would be the minimum size of the aggregates in cylinder 10. In cylinder 5 the radii are 1.55 times larger, the diameters therefore nearly 300 μ . We arrive in this way to »settling units» of macroscopic dimensions, in better agreement with the characteristic outward appearance of coagulated suspensions than the sizes of 8–10 μ calculated in the ordinary way from the formula of STOKES.

A way of calculating the size of the aggregates in coagulated suspensions has been outlined above. It constitutes an attempt to take into account the hydration of the micelles. The calculations cannot claim at any exactitude, as the assumption that the aggregates in cylinder 10 contained 40 % of water is too uncertain. When some information is gained as to the relative volume of the micellar solution under various conditions, the method may prove useful.

In this connection an experiment made in order to compare the sizes of the aggregates in a natural sediment to those of a coagulated suspension may be recorded. For this purpose two suspensions of a sample F65A (median 0.8 μ) were prepared. A portion of 10 gr was first dialyzed, then transferred into a cylinder; the suspension was made up to one litre with distilled water and just enough sea water to make the resulting salinity equal to that of the bottom water at the station (6 ‰). To another portion of 10 gr as much distilled water was added as was required to make the salinity in the sample

¹⁾ If the radius of the solid nucleus is r_1 , its specific gravity 2.7 and the radius of the micelle r_2 , then the relative weight of the micellar solution will be

$$\frac{r_2^3 - r_1^3}{2.7 r_1^3 + r_2^3 - r_1^3} = \frac{40}{100},$$

the specific gravity of the micellar solution taken as equal to unity. From this equation follows

$$\frac{r_2}{r_1} = 1.4$$

The specific gravity of such a particle will be

$$\frac{2.7 r_1^3 + (1.4^3 - 1) r_1^3}{1.4^3 r_1^3} = 1.6.$$

equal to that of the bottom water, then a suspension thereof prepared with sea water of the same salinity. The dispersion was effected solely by treating the clay with a hard brush. It was surprising how easily the clayey mass was dispersed, but the resulting suspension had a typically coagulated appearance. The two suspensions were then analyzed as to their mechanical composition. The result is given in Table 17.

Table 17. *Coagulation and dispersion of sample F65A with sea water.*

	$>20\mu$ %	$20-10\mu$ %	$10-5\mu$ %	$5-2\mu$ %	$2-1\mu$ %	$1-0.5\mu$ %	$0.5-0.2\mu$ %	$<0.2\mu$ %
F65A dialyzed	5.6	5.3	6.1	16.0	13.0	14.8	21.3	17.9
» dispersed with 6‰ sea water	4.5	83.9	10.5	1.1				
» coagulated with 6‰ sea water	6.9	1.8	91.0	0.2				

The table shows that 84 % of the sediment, when dispersed with sea water, has settling velocities corresponding to size group 20—10 μ , but coagulated with the same water 91 % of the sample lies between 10 and 5 μ . Even if there was a real difference in the size of the aggregates, most of the difference in settling velocity is probably due to the greater hydration of the newly formed aggregates.

As to conditions in the sea, only vague conclusions can be drawn from the various coagulation experiments recorded above. As pointed out in the beginning, conditions in nature will differ from these laboratory experiments especially as regards the concentration of the suspensions. It is not likely, however, that aggregates formed in dilute suspensions will be larger than those formed in more concentrated ones. We may therefore look upon a settling velocity corresponding to a particle diameter of 20 μ as a probable upper limit for aggregates of fine-grained material formed in the sea. The limit is lower than that found by TUORILA in suspensions also containing coarse grains (up to 100 μ). At a temperature of 5° the settling velocity of such particles is $2.55 \cdot 10^{-2}$ cm/sec. or approximately 1 metre per hour. The actual settling velocity will naturally depend on the motion of the water at the place of deposition. In discussing the mechanical composition of the samples in Section 32, it will be shown that coagulation in the sea of the finest grain sizes possibly leads to quite small aggregates only (below 2 μ), judging from the fact that some very fine-grained late-Glacial clays, presumably deposited in saline water, were found to be sorted even within the clay group.

Some cases of extremely slow coagulation leading to settling velocities not above that of 5 μ may finally be described. A series

of mechanical analyses had to be interrupted because of intervening work when grain class 10—5 μ had been determined and the cylinders

Fig. 19. Slow coagulation in carbonate containing suspensions.

were left standing for three months. Signs of coagulation in the form of many fine layers had been noticed in a few of the cylinders quite in the beginning, but these were left untouched and the analysis

thereof continued to the end¹⁾. The results are shown in Table 18 and Fig. 19. For comparison, analyses of non-coagulated similar samples from the same localities are given in two cases. All the coagulated samples contained carbonates. Other carbonate containing samples belonging to the same series of analyses and treated in exactly the same way did not coagulate, but behaved quite normally.

From the table, it is not clear at once which of the samples had coagulated, but a glance at the diagrams in Fig. 19 shows it most clearly: as in the earlier experiments, the coagulated samples are highly sorted, with one size group absolutely predominant.

Table 18. *Slow coagulation in carbonate containing suspensions.*

	Carbo- nates %	>20 μ %	20—10 μ %	10—5 μ %	5—2 μ %	2—1 μ %	1—0.5 μ %	0.5—0.2 μ %	<0.2 μ %
F32A 1926 coagulated	about 7	5.4	6.7	6.8	34.0	35.7	9.4	2.1	
F33 1926 »	» 20	6.9	6.3	8.0	54.3	20.7	2.7	1.1	
F33 1925 non »	29.5	2.5	5.4	2.8	17.1	22.8	22.1	23.0	4.3
F74 1930 »	2.60	1.3	3.8	7.4	24.1	42.5	17.7	3.2	
F76A 1924 »	2.45	4.2	7.7	5.7	17.0	49.6	13.1	2.7	
F76A 1930 non »	0	0	1.2	7.8		11.1	22.8	32.4	24.8

In three of the four cases the predominant group still lies within the clay group. In F32A 35.7 % lie within 2—1 μ , in F74 42.5 % and in F76A as much as 49.6 % within that group. In F33 54.3 % lie within 5—2 μ (height of the distribution diagram 40.7 %); a tendency in the same direction is seen in F32A of which 34.0 % lie in the 5—2 μ group. In natural soils the height of a »primary subgroup» rarely exceeds 25 % in the clay and silt groups (in fact a higher value was met with only once). We may therefore conclude that if in analyzing a natural soil a higher value than 25 % appears in any primary subgroup below 20 μ and especially if the neighbouring groups are low, coagulation has almost certainly taken place. On the other hand, if many fine layers appear at the top of a cylinder during the course of an analysis, but the latter nevertheless leads to a normal distribution curve it is evident that only the smallest grain classes were in the process of coagulating in these layers and the analysis is unreliable only for these grain sizes. In a few similar

¹⁾ It is probable that redetermination of the size groups > 5 μ would not have given absolutely the same result as before, but as all size groups below 5 μ were directly determined this could not have changed the general character of the distribution diagram.

cases occurring in connection with the present work the grain classes below 1μ were not determined.

The analyses given in Table 18 confirm the conclusion already drawn from the experiments recorded in Table 15 and Fig. 17: the smallest grains coagulate first. Formation of many fine layers had been observed in the top part of the cylinders after about 40 hours standing, which shows that the smallest grains were already in the process of aggregation, but after three months the coagulation in two cases had hardly advanced further than to particles of 2μ diameter and in the two other cases to 5μ . In the terminology introduced by WIEGNER these coagulation processes are probably to be considered as instances of *slow perikinetic coagulation*, that is, effected by collisions brought about by Brownian movement. The cause of such collisions leading to coagulation in the cases recorded, must be sought in the slight solution of calcium carbonate in combination with the exchange of hydrogen ions (absorbed in the dialyzed soil) for Ca^{++} -ions. That part of preliminary treatment which favoured solution of CaCO_3 , was the boiling of the dialyzed samples; prolonged shaking would have been better in the case of carbonate containing samples. It is, however, noteworthy that sample F33 1925 which contained almost 30 % of carbonates, did not coagulate, though treated in the same way, but formed a suspension, 72 % of which was smaller than 2μ .

Above, the grain sizes have been calculated in the ordinary way regardless of the possible influence of hydration on the settling velocity of the aggregates. This is necessary, as there is no clue for estimating the effect of hydration, and also justifiable, as both H^- and Ca^{++} -ions give rise to poorly hydrated aggregates.

The extremely slow coagulation processes, revealed by these analyses and probably caused by minute quantities of electrolytes in the suspensions, are perhaps phenomena of the same kind as the varying dispersion observed by GEDROIZ (see p. 56) in soils saturated with various kations. GEDROIZ saw the cause of the differences solely in the nature of the saturating ions. But as after saturation he removed the surplus of saturating ion by washing and decantation it is probable that small quantities of free electrolyte were left, influencing the final dispersion.

V. THE SAMPLES.

21. GENERAL CHARACTER.

In the well-known classification of marine deposits given by MURRAY and RENARD the sediments of the Baltic naturally occupy a place among the terrigenous deposits. They are essentially shallow-water deposits, of deep-sea deposits only Blue mud may be considered to have analogons among Baltic sediments. The only common characteristic of shallow-water deposits is the fact that they were deposited in more or less shallow water, therefore a detailed classification of such deposits can only be given regionally and by taking prevailing conditions into account. The formation of sediments similar to Blue mud is also due to favourable local conditions. The sediments of the Baltic must consequently be classified from a purely local point of view.

The origin of the Baltic is to be sought in a vast depression formed by geological agencies in pre-Glacial times, but the Baltic of to-day is essentially the result of the late-Quaternary events which accompanied the final disappearance of the ice cover from northern Europe: transgressions and regressions caused by the interaction of subsidence and upheaval of land, melting of ice, drainage of lakes and eustatic rise of the sea level. The chief stages in the development of the Baltic, designated by special names, will be stated here in accordance with the views set forth by SAURAMO (94, 95) in his works on the Quaternary geology of Finland and the Baltic.

The Baltic Ice Lake was an ice-dammed lake formed during the Gothi-Glacial period by accumulated glacial waters from the waning ice sheet. It existed until about 8 000 B. C.; then a considerable fall of the water level occurred, several fluctuations of the level having taken place before. The final drainage of the Baltic Ice Lake, which marks the beginning of the Fini-Glacial period, occurred in the year —1073 of the Swedish late-Quaternary chronology (DE GEER). The surface of the Yoldia Sea, now formed, was on a level with that of the ocean, 28 metres below the last stage of the Baltic Ice Lake. The water of the Yoldia Sea was brackish, there being a broad connection with the ocean over the central part of Southern Sweden. Through the rise of the land, the connection was again several times cut off and new falls followed. The stage that has hitherto been coupled with the Yoldia name lasted some 500 or 700 years, and it was up till

now considered that the long soft water period of the Ancylus Lake succeeded it immediately. SAURAMO (95), however, has shown recently that the marine facies probably lasted about 1800 years i. e. until the end of the Fini-Glacial period and some 600 years of the beginning of the post-Glacial period. Then the connection with the ocean had definitely been cut off and the Baltic had once more been changed into a lake, the Ancylus Lake. At the beginning of the Yoldia Stage the margin of the melting ice sheet crossed the Baltic south of the Åland Islands and some 1000 years later it had reached the North Kvarf, crossing it in a west-easterly direction. When the Ancylus Lake was at its maximum extent, about 6 000 B. C., the whole of the Bothnian Gulf was free from ice.

The first stage of the Ancylus Lake was a period of transgression, but during the later stage a great regression set in. According to modern views, the level of the ocean was also in the course of rising during the Ancylus period. About 5 000 B. C. the Ocean attained the level of the Ancylus Lake in the region of the Danish Sound and the Belts. A connection was formed which subsequently broadened. Salt water once more entered the Baltic and together with it marine animals and plants. The Ancylus stage was thus brought to an end and the Litorina period had begun. The rise of the sea level continued for some time and the water of the Litorina Sea was finally more saline than that of the present Baltic. The transgression of the Litorina Sea had two or perhaps three culmination points with small regressions in between. The upheaval of land, however, which all the while continued unabated, gained the upper hand over the sea and a more continuous regression set in. The connection with the ocean therefore grew narrower, salinity decreased, the shore line advanced, and present conditions in the Baltic developed.

The fine-grained deposits forming along the margin of the retreating ice sheet during the Baltic Ice Lake and Yoldia periods were the characteristic varved sediments which have been the subject of such intense study by Scandinavian geologists during the last decades. They constitute a yearly record of geological events from late-Quaternary onwards. DE GEER in Sweden was the first to point out that a study of these sediments afforded a means of establishing an exact geological chronology. In Finland the corresponding investigations have been carried out by SAURAMO. A yearly varve, from a few millimetres to some centimetres thick consists of two layers, a coarse lower layer and a fine-grained upper layer, the formation of which depends on the different transporting capacity of the glacial waters along the ice margin during summer and winter. In

localities where a great number of varves have developed, the difference in grain size between the two layers decreases upwards, finally disappearing altogether. The upper part consists of a uniformly very fine-grained clay, deposited when the ice margin had already retreated far beyond the place of deposition. This very fine-grained and unstratified clay is often called *Ancylus clay* (MUNTHE 67), though, as pointed out by DE GEER (22), the formation of such clays cannot be assigned to the *Ancylus* period only.¹⁾ Being a phenomenon directly connected with the melting of the ice sheet, similar clays must have already been deposited during the preceding stages of the melting; therefore all such clays should justly be counted among late-Glacial deposits.

Late-Glacial clays consist of rock fragments formed by mechanical disintegration of the old crystalline bedrocks through the action of the ice. TAMM (106, 107) has recently shown by experiment that chemical disintegration must have occurred to some extent simultaneously. Viewed under the microscope, silt and clay particles in late-Glacial clays are seen to be sharp-edged, whereas sand grains are generally subrounded. A few diatoms have been found in varved clays and in some localities shells of *Yoldia arctica*, lending the corresponding period its name. As a whole organic remnants are very sparse and most commonly none are found at all, though analysis reveals a slight content of organic matter. A bottom sample, whether distinctly laminated or not, in which no diatoms are found, and which, examined under the microscope, presents a purely minerogen appearance, may be attributed to the late-Glacial period.

With the close of the Ice Age the abundant formation of fresh rock detritus came to an end. The materials of the *Ancylus* and *Litorina* sediments, referred to as post-Glacial, were partly the normal products of erosion and partly, and to the greatest extent, the rich deposits of the Glacial period, which during the transgressions and regressions in the *Ancylus* and *Litorina* periods became covered and again uncovered by water, and thus repeatedly came under the influence of moving water, streams, wave-action, currents. True *Ancylus* sediments are characteristic of the conditions prevailing after the close of the Ice Age. They contain a great many fresh-water diatoms and in the south part of the Baltic the characteristic mollusc *Ancylus fluviatilis*. *Litorina* sediments finally abound in salt water diatoms; on the ancient shores from that period, shellbanks of various molluscs, amongst others, the species of *Litorina* are found. In both kinds of sediment the content of organic matter may be high.

¹⁾ The soft water stage of the *Ancylus* period is here — in the manner hitherto accepted — considered to begin directly after a very short salt water stage (*Yoldia* period), thus long before the final melting of the ice sheet.

Until recently it was considered that determination of the diatoms made it possible to distinguish *Ancylus* and *Litorina* sediments from each other. Modern investigations, however, have shown that in this respect great prudence should be observed. In sub-*Ancylus* clay from the Carelian Isthmus, HYYPÄ (51) recently found diatoms hitherto considered as characteristic of the *Litorina* period, which shows that the proof by means of diatoms alone is not reliable. In the present work it was hoped that mechanical composition would give a clue, and for this reason especially the silt and clay fractions of the sediments were studied in detail. Sediments deposited in water with coagulating properties should be less well sorted than sediments deposited in soft water. From the experiments recorded in Section 20 it was concluded that an apparent particle size of $20\ \mu$ may be regarded as the probable upper limit for coagulated flocks formed of fine-grained material. Therefore the silt and clay groups of *Yoldia* and *Litorina* sediments should be poorly sorted whereas clays deposited in the Baltic Ice Lake or the *Ancylus* Lake should be well sorted. A number of perfectly unsorted post-Glacial sediments have in fact been met with in the Baltic and, on the other hand, some extremely fine-grained and well-sorted late-Glacial clays, dating from the Baltic Ice Lake, but as for the influence of coagulation, which ought to be apparent in clays deposited in the brackish water of the *Yoldia* Sea it is unnoticeable. From the particle size distribution it is difficult so far to draw any conclusions as to the nature of the water in which a sediment was deposited.

As will be seen from the List of Samples many clays of undoubtedly late-Glacial origin have been met with in the present work, revealing their character by more or less pronounced stratification, a very low content of organic matter (about 1 % or less) and absence of diatoms. In addition, mechanical analysis has proved that the fine-grained kinds possess a characteristic distribution of particle sizes. The stratified clays which were found in the Baltic are seldom as distinctly laminated as those occurring on land. Even the «coarse layers» are generally very fine-grained, rendering it difficult to distinguish a single varve and to measure its thickness. As a rule the thickness does not seem to exceed a few millimetres. With one exception (F 31E, 1928), sandy layers of measurable thickness have not been observed within a late-Glacial clay, whereas most clays are covered by a layer of sand from a few millimetres to some centimetres thick. This interesting sandy layer is not restricted to coastal areas, but is found as well in localities far from land.

As fine and coarse layers do not shrink in the same degree, stratification is especially noticeable when a sediment has dried; the profile

of the sample, from being smooth when wet, becomes more or less uneven when dry. Very often the only sign of varves in the wet state are diffuse brownish streaks in the grey clay, and sometimes even when dry the sample is apparently uniform, but shows a tendency to break along parallel lines, thereby revealing lamination. These parallel lines are often not horizontal, but more or less convex as a result of the pressure of the bottom sampler when cutting through the plastic sediment. An instance of this kind is sample F 77 1925 shown in Fig. 3.

In the following, samples of late-Glacial origin, especially characterized by a low content of organic matter and absence of diatoms, will be called sands, silts or clays, according to which grain size the distribution diagram reveals to be dominating, (see page 52) whereas post-Glacial sediments will be referred to as muds (see below).

As has been shown above, it is important from a geological point of view to ascertain whether a sediment belongs to late-Glacial or post-Glacial deposits. From a biological and a purely morphological standpoint the organic matter content, as such, is of greatest interest and indeed in a decisive manner determines the outward appearance of a sediment.

The sediments containing the highest amount of organic matter are those analogous to Blue mud. MURRAY and HJORT (68) in the following way characterize Blue mud and its mode of formation: »The Blue mud areas which are of vast extent, afford a most important example of the reduction of submarine clay after deposition. We may indeed divide the floor of the sea, according to the relative abundance or paucity of dissolved oxygen in the bottom waters, into oxidizing and reducing areas. Reducing conditions will prevail wherever there is a larger excess of putrifiable organic matter than can be coped with by whatever supply of oxygen (depending on the circulation of the area) may be available. In general, therefore the coast-lines of continents are girdled by reducing areas, and it is here that Blue muds characteristically occur. Oxidization of the organic matter is here effected at the expense of ferric ion, probably by bacterial agency. — — — there are bacteria, which, whilst living on sarcodic matter seize on the dissolved sulphates of sea water and reduce them to sulphides; the latter react with whatever ferruginous material is present, and produce the highly insoluble compound ferrous sulphide. — — — The retention of sulphur in bottom deposits can only occur where there is plenty of decaying organic matter, where the bottom waters are stagnant, or nearly so, and not well aerated, and where there is not a copious hail of calcareous tests; that is mainly in the lower layers of muddy bottoms at shallow and

medium depths. — — — It may be that sulphur plays an intermediate part in the formation of Blue muds, but the end product is simply a clay, in which some or most of the iron has been reduced to the ferrous state, containing one or two percent of amorphous black organic substance. To these two factors the distinctive dark colour is due».

The above applies entirely to the muds of the Baltic, but it might be added that, especially in deeper layers of a sediment, a high amount of organic matter is not necessarily accompanied by a dark colour and that instead of 1 or 2 the total amount may be nearly 10 percent of the air dry sample. Besides rock fragments, remnants of plant and animal life, and more or less dark, greenish black flocks of undefinable shape, a black or dark grey sample, when viewed under the microscope, shows small black globules, often imbedded in shells of diatoms or other remnants, but also lying free. These are the sure signs of the presence of ferrous sulphide: the globules of pyrite described in all investigations of lacustrine and marine muds. Concerning the conditions of formation of black muds, TRASK (115) is of the opinion that an entire lack of oxygen is not necessary; on the contrary »the essential requisite seems to be occasional temporary replenishments of oxygen in the overlying water». This opinion he supports not only by referring to the mode of occurrence of black sediments, but also by an observation made during work on bottom samples rich in organic matter. Many of the freshly gathered sediments turned black after they had been stored in the laboratory for some time in a moist condition. This discoloration commenced at the top and worked downwards, but never did it reach the bottom of the container. »The formation of hydrogen sulphide indicated that the action was partly anaerobic, but since the discoloration began at the surface and never at the bottom, the process cannot be considered as being entirely anaerobic». EKSTRÖM (25) states too that many »gyttjas» (muds) turn dark when first exposed to the air. The views of TRASK find support in recent investigations by HECHT (46) on the conditions of life of certain marine benthonic animals which show that even the presence of hydrogen sulphide in the bottom water does not necessarily mean complete absence of oxygen. Baltic and Russian investigations, cited by ANDRÉE (5), treating the curative muds along the west coast of Estonia and the Limans of the Black Sea, have evidenced that the mode of formation of black muds is extremely complicated. The formation of hydrogen sulphide may occur by decomposition of organic substance or by reduction of sulphates, in either case, with or without the aid of various bacteria. The process is further complicated by the presence of sulphobacteria which

need hydrogen sulphide for their existence, oxidizing it to free sulphur and sulphuric acid, but which, on the other hand, cannot live without a certain supply of oxygen. Mud eating bottom animals too participate in the decomposition of organic detritus.

In this connection it may be noted that THOULET (111) ascribes the blueish colour not to ferrous sulphide alone, but to ferrous compounds in general. This would explain the extreme facility with which oxidization takes place. Blue mud, however dark, becoming grey when dried. Oxidization, on the other hand, does not affect the globules of pyrite, which are always found when the dried sediment is examined under the microscope.

In the Baltic the colour of the sediments is seldom blueish; the most characteristic type of this kind is black or greyish black. A transitional type, however, is most common; it is partly black, partly greenish grey, and becomes uniformly grey when dried.

In limnology, sediments having a high content of organic remnants, more or less decomposed, and sometimes, though not necessarily, a dark colour from ferrous sulphide, are known internationally by the Swedish word »gyttja». The most pronounced form, in a state of advanced putrefaction in a reducing milieu, is also called *sapropel*, though there is no general agreement about the definition of this type (NAUMANN 72, WASMUND 120, 121). In his investigation of the sediments of the Danish Sound, SJÖSTEDT (100) introduced the limnological terminology. Though the analogy with lacustrine sediments is evident and naturally so in the Baltic with its brackish water, I have preferred the word *mud*, long used in oceanography, and in its German form of »Mudd» already applied to Baltic deposits by APSTEIN (7) and recently adopted by PRATJE (89).

The definition of the different kinds of »gyttja» soils in limnological textbooks (see e. g. NAUMANN 72 or LUNDQVIST 59), as well as the definition given by SJÖSTEDT and the description of the mud by APSTEIN, all emphasize that the mud is to the greatest extent made up of organic detritus. APSTEIN gives the following definition: »Der Mudd ist schwarz. Er besteht aus allerfeinsten bis größeren Organismenresten, die in Zersetzung begriffen sind». He coloured the mud with methyl green and was thus able to estimate exactly the total amount in a sample. Or rather, he seems to have estimated the visible minerogen grains, counting all the rest of the sample as mud. In this way he arrives at the result that, for instance, at station A96 (57°16'N, 20°04'E) having almost the same position as F81, the mud amounted to 94.1 %, and at Kl 94 (58°42'N, 18°25'E), corresponding to F78 (Landsort Deep), it constituted 90 % of the sample. It should, how-

ever, be noted and will be shown in Section 32 that about 50 % of the minerogen component of the muds of the North Baltic are made up of particles smaller than 1μ in diameter. Particles of such dimensions, necessarily flocculated, cannot be distinguished from the organogen component when viewed under the microscope, but will, on the contrary, tend to increase the apparent volume of the latter. Chemical analysis of the organic matter in air dry samples from the same localities, made in connection with this work, gave as result 7—8 % by weight at F81 and 3.6 % at F78. The only guidance to explain the enormous discrepancy with the results of APSTEIN is supplied by the fact that the latter did not take into account the high water content of the samples. However, he determined himself the amount of water in a typical mud (station 02, $54^{\circ}30'N$, $10^{\circ}02'E$) and found it to be 81.06 %. It is obvious that in a certain volume of a sample, consisting of water up to perhaps 80 % by weight, the volume of the minerogen component will seem quite insignificant. If this component is, say, 20 % by weight and has a specific gravity of 2.7, the ratio of its volume to that of the total will be 7/87, the specific gravity of the water plus organic detritus taken as equal to unity. In other words, the minerogen component will constitute about 8 % by volume of the whole. It seems unjustified, however, to regard all the rest, including the water, as organic in origin, or still more to call it «organic matter» as SPETHMANN (101) did, who cited APSTEIN's analyses. Moreover, the water content of the mud or the «gyttja» depends as much on the physical and colloidchemical properties of the minerogen component as on those of the organogen one. That is why, to a non-linnologist, the current definitions of the «gyttja» seem somewhat misleading, not making any allowance for the part of the water in the apparent bulk of organic detritus.

A description of the mud, such as it is found in the Baltic in its most pronounced form, would be the following: The mud is black, and sometimes, though not always, reeking with hydrogen sulphide. It is made up of more or less decomposed organic detritus, minerogen substance and water. It is of a loose consistency, either gelatinous if the minerogen component is fine-grained, or of an almost liquid appearance if that component is silty or sandy. Sometimes, during storage in a wet condition, gas is produced making the sediment seem foamy and porous. The black colour is caused by amorphous ferrous sulphide. When dried the sediment shrinks considerably and assumes the outward properties of the minerogen component, the colour becoming different shades of grey, or purely brown, as a result of the content of ferric hydroxide which is either initial or formed

during drying. In comparatively well aerated waters the uppermost part is sometimes oxidized even in the wet state. The water content is considerable, constituting roughly three fourths of the sample. The content of organic matter as revealed by analysis of the air dry sample, varies. The highest amount found is about 10 %, the lowest which may still be accompanied by a black colour, about 2 %.

As already pointed out, uniformly black muds are found at some localities in the Baltic, but the most common type of sediment is partly black, greenish black or blueish black, and partly different shades of grey. In the Gulf of Finland the top part of a glass tube sample is often black, this layer being up to 5 centimetres thick, then follows a dark grey layer stretching to 10—15 cm below the surface, finally the bottom part is brownish or greenish grey. A similar stratification was observed by SJÖSTEDT. Analysis shows that the bottom part may be richer in organic matter than the dark layers. An instance of this kind was the sample F62 1924, already described page 21. A black colour consequently, is not in itself a sure sign of a high content of organic matter. It indicates the incidental conditions prevailing in the sediment, rather than a permanent property thereof. Such conditions may occur quite locally, in that samples otherwise uniformly grey may have black spots or lumps in any part of the profile. These lumps are sometimes discernible when the sample is still in the glass tube, but usually they appear only after it has been divided into two parts, so that the interior is revealed¹⁾. Very often the black parts have the appearance of layers either thick or thin, the whole sample making a decidedly stratified impression. SJÖSTEDT observed this kind of mud stratification and described it in his work on the Danish Sound. He calls it a »biological yearly stratification». STÅLBERG (104) using the bottom sampler and working method of SJÖSTEDT, also followed in our work here, found a similar stratification in the muds of Lake Vättern. In the beginning of this work the author was sure of having met with the same phenomenon in the muds of the North Baltic, but as the work progressed it became more and more evident that in many cases, if not in all, the stratification was only apparent, caused partly by the method of examination of the fresh samples, partly by the small diameter of the glass tubes used. It should be noted that this kind of stratification is never seen clearly through the glasstube, it appears only after the profile has been removed from it and divided, the layers then beginning a little inside the edge of the section. Obviously, when the profile is divided into two parts

¹⁾ See first examination of samples p. 11.

with pairs of microscopic slides, the joint edge of the slides will spread out to streaks whatever small black lumps they meet, thereby giving them the appearance of thin layers. Often on one half of a profile there is a «layer», which is not to be found on the other, and when the profile is cut crosswise it is found that the «layer» does not fill the section, but is either a thin streak or else has the appearance shown in Fig. 20. Characteristic of the black spots is the sharp outline against the grey surrounding. In many cases the apparent layer does fill the section, but as the contrary is so often the case and as the diameter of the tube is only 1.5 cm, one is not justified in concluding that the supposed layer has any considerable horizontal extent. The very varying thickness of the layers is easily explained as being caused by different sized black lumps in the sediment. The doubt as to the reality of the observed stratification was greatly confirmed, when it was found that «stratified» bottom samples may quite easily be produced artificially. Some clay was coloured with lampblack and mixed with uncoloured clay, but quite superficially. The mixture was sucked into a glass tube of the kind used in the bottom sampler of SJÖSTEDT, then taken out in the ordinary manner, allowed to dry on filter paper for some time and divided as usually with pairs of microscopic slides. Fig. 21 shows two samples prepared in this way, having exactly the ordinary appearance of stratified muds.

Fig. 20.
Cross section
of sample
F25A.

Consequently, one must be very cautious in drawing any conclusions about sedimentation from apparently stratified muds. The black lumps may have a tendency to spread out horizontally, and in some cases met with this seems probable. All sedimentation, whether regular or accidental, naturally develops more in the horizontal than in the vertical direction, and consequently also the phenomena depending thereon. Lense shaped black concretions, about 1 cm in diameter, have been found in mud samples, though their original position in the sample was not noted. On the whole it seems highly questionable, whether the phenomenon observed in the muds of the Baltic deserves the name «stratification», which implies a considerable expansion in the horizontal direction. It does not follow, though, that the dissimilarity of the biological constituents, observed by SJÖSTEDT and STÅLBERG in black and grey parts of a sediment, is without importance for the colour distribution. The process is apparently purely biological, as no traces of disparity in the mechanical composition can be observed in the dry sediment, this kind of stratification disappearing altogether on drying, leaving perhaps a brownish

patch in places that were particularly rich in ferrous sulphide. The black lumps, whether big or small, may be regarded as »reducing areas» in a very restricted sense of the expression used by MURRAY and HJORT for the Blue mud forming areas, in which, incidentally, from biological reasons not known in detail, formation of ferrous sulphide has occurred.

The views set forth above, which apply to the uppermost 30 cm of the muds, seem to contradict the results of PERFILEW (83—86). The latter found a distinct stratification in the muds of many Russian lakes, and developed a theory of microzones on a detailed study of these. Later he found stratified muds in German and Italian lakes and states (85) that an expedition under the leadership of Professor DERJUGIN has proved their occurrence in the Gulf of Finland. In the opinion of PERFILEW this stratification is the complex result of various forms of sedimentation, which are all assumed to have a yearly period, and thus directly or indirectly to depend on solar radiation. Physico-chemical precipitation (CaCO_3 , CaSO_4), excessive production of plankton, inorganic erosion, may all give rise to yearly layers, which form so-called »sedimentation microzones» (Ablagerungsmikrozonon). SCHOSTAKOWITSCH (97) who studied part of the material of PERFILEW, regards the strata to result principally from inorganic erosion and thus to be analogous to the varves of late-Glacial clays. But unlike the latter, mud varves, according to SCHOSTAKOWITSCH are easy to date. Being caused by a phenomenon still in process, yearly layers are formed continuously and dating is simply a question of counting back from the year of collection. By comparing the variations in thickness of the layers with the yearly variations of certain geophysical data SCHOSTAKOWITSCH was able to establish a relationship and thus to control the correctness of the calculations. In the muds of Lake Pert in East Carelia he thus identified all the yearly layers from the year 600 to 1928.

To a similar interpretation the majority of the »stratified muds» of the Baltic examined here would certainly not lend themselves. Their macroscopically visible »layers» are obviously analogous to what PERFILEW calls »transformation microzones» (Umwandlungsmikrozonon), which in the words of PERFILEW (86) are formed »infolge der gegenseitigen Einwirkung der Schlammlösungen in verschiedenen Tiefen und der bereits im Schlamm abgelagerten Teilchen, durch Abschichtung der gesamten Schlamdecke». He states that great difficulties are met with in determining the yearly layers in muds »von einem höherem Gehalt an organischen Substanzen und günstigen Verhältnissen für die Entwicklung der Bakteriefloora. Der

Fig. 21. Artificially stratified bottom samples.

Fig. 22. Iron concretions found in the Baltic ($\frac{1}{2}$ of natural size). Figures refer to List of Iron Concretions, Section 23.

durch diese Entwicklung hervorgerufene verwickelte Komplex biochemischer und physikalisch-chemischer Umwandlungen kann öfters eine vollständige Umarbeitung der ursprünglichen Produkte, aus welchen der Schlamm zusammengesetzt ist bedingen». In the opinion of the author this is what has happened in most of the muds of the Baltic. Any real stratification, which may originally have existed, has disappeared and the »layers» have been united to »reducing areas» of varying dimensions.

Further investigations from a biological point of view, made with the modern technical outfit of PERFILEW, are necessary for a decision as to the real nature and the cause of the »stratification» observed in the muds of the North Baltic. In the List of Samples this kind of stratification whether real or apparent will be referred to as biological stratification.

An attempt has been made above to characterize the different kinds of mud found in the Baltic. Classification is easy in extreme cases, but transitional types being most common, it is often difficult to decide whether a sample should justly be considered as a clay or a mud. Distinctions, such as between »muddy clay» and »clayey mud», are arbitrary and not satisfactory. In dubious cases the author preferred to let the presence or absence of diatoms decide the question, thereby giving recognition to the fact that mud formation is of a biological nature. Broadly speaking the limit was drawn between late-Glacial and post-Glacial sediments. This way is less arbitrary than fixing the limit at a certain percentage of organic matter, at which the characteristic mud properties begin to be outwardly noticeable; particularly as a high percentage of organic matter is not necessarily associated with a typically muddy appearance. The nature of the minerogen component of the mud may be indicated by stating whether the mud is sandy, silty or clayey.

Thus in the List of Samples and in Table 19 the terms sand, silt, clay are restricted to samples the properties of which depend essentially on mechanical composition, whereas the term mud, used when organic matter content is high and diatoms are found in the sample, indicates that organic matter to a greater or lesser extent influences the properties thereof.

In the case of sands this definition cannot always be followed; although there are sandy muds, which present all the properties of the mud, there are, on the other hand, diatom containing sands which cannot justly be called muds. Such samples will always be referred to as sands and the question of the period of deposition is left open.

Besides sands, clays, and muds, the bottom sampler or the lead of the sounding line sometimes brings up concretions of iron and probably manganese. These are of the same type as those described from lakes in Finland and Sweden. Fig. 22 shows a few specimens found in the Baltic.

Such concretions occur at all depths, down to over a hundred metres, and in very varying shapes, from amorphous flocks of rust colouring the sediment, or crusts of limonite hardening it, to large flat brown pieces with a marked structure, deposited round a foreign body, or almost black roundish globules formed in concentric layers round a centre lighter in colour, but without a distinctive nucleus. Time has not permitted a detailed study of these formations. In the List of Samples the finds will be noted, and, in an Additional List, finds of the same kind made during earlier cruises of the s/s Nautilus.

It seems very doubtful whether the limnological explanation for the formation of iron ores in lakes (AARNIO 1, NAUMANN 70, 71) applies to these marine occurrences. According to the generally adopted view, the iron is transported from the surroundings of the lake with the ground water, humus compounds, either chemically bound or in colloidal solution, acting as protection against precipitation until contact with the lake water. In the sea, on the other hand, the origin of the iron must probably be sought in the sediment itself, in the immediate surrounding of the place of deposition; it would be a far-fetched explanation to suppose a transport with ground water at all the various localities and depths where iron ores have been found, moreover a difficult supposition to prove. The formation of iron concretions in the sea is probably best studied in connection with the similar manganese problem, manganese concretions of various shapes being found in lakes as well as in the sea, even down to the greatest depths. A bottom sampler should be used which takes the concretions «in situ» together with the surrounding sediment, making analysis of the latter possible. A study of the concretions alone would probably not lead to definite results.

22. LIST OF SAMPLES.

Below will be given a short description of each of the samples examined. First will be given, in the order in which they are enumerated, station and year of collection, position, depth in metres, bottom sampler used, length or weight of sample and general character thereof, (for terminology see page 97); when samples are of late-Glacial origin this will be indicated. Distribution diagrams are found on Fig. 31—41, p. 192—202.

GULF OF BOTHNIA.

F1 1924. 65°38'N, 23°47'E. 35 m. Glass tube, 16 cm. Sandy mud.

Described as blackish green when hauled in; almost dry and brown in colour when brought to the laboratory, glass tube having cracked. The lowest 5 cm more greyish than the rest. Divided into two parts, analyzed separately: a) top 11 cm, b) bottom 5 cm. Both parts dusty sand. Distribution diagram of top shows high max. in 20—50 μ group. Median 27 μ . Organic matter 1.0 and 0.8 % respectively. Top very rich, bottom poorer in diatoms. (Diagram 2).

F1 1925. 40 m. Glass tube, 7 cm. Dark grey, very fine sand.

Dark grey. When dried, light grey with brown patches, median 62 μ , somewhat coarser than foregoing, though from same locality. Top a few diatoms, bottom only fragments of such. Mechanical analysis: < 50 μ 37.3 %, 50—100 μ 42.9 %, > 100 μ 19.8 %.

F1A 1925. 65°05'N, 25°11'E. 53 m. Glass tube, 19 à 20 cm. Sandy mud.

Top 2 cm brown, rest dark greyish brown. Size distribution very like that of F1 1924, median 21 μ , dusty sand. Diatoms very sparse. Organic matter 1.3 %. (Diagram 1).

F3 1925. 65°10'N, 23°14'E. 89 m. Glass tube, 17 cm. Silty mud.

Top, 2 or 3 cm, brown; rest of profile dark grey; bottom, a few centimetres, quite black. Very loose. Apparent biological stratification in light and more or less dark layers. Divided into two parts: a) top 3 cm, b) bottom 14 cm. Top, slight content of CO₂ 0.23 %, more than generally found in Bothnian Bay; organic matter 4.1 and 3.8 % respectively. Top and bottom diatoms.

F3 1928. 65°10'N, 23°15'E. 107 m. Iron tube, 10 gr dry weight. Silty mud.

Kept from sample sent to Dr TRASK. Median 7 μ , mode of symmetrical distribution 5—10 μ . No diatoms found though organic matter 4.4 % (Diagram 33).

F6 1925. $64^{\circ}28'.5N$, $23^{\circ}38'E$. 43 m. Iron concretions and sand.

Probably from lead of sounding line. A few brownish black fragments of iron concretions, flat, about 2 mm thick and from 0.4 to 1 square cm. Some sand. Not examined further.

F7 1925. $64^{\circ}33'.5N$, $23^{\circ}13'E$. 77 m. Glass tube, 5 cm. Fine sand.

Fine grey sand with yellow patches, coarse gravel and iron concretions (not considered in mechanical analysis) on top. Max. of distribution diagram at $50-100\mu$, but median 120μ because of strong admixture of medium and coarse sand. A subrounded concretion with dark centre near bottom. Top a few diatoms, bottom none; organic matter 0.4 %. (Diagram 6).

F8 1925. $64^{\circ}40'.5N$, $22^{\circ}44'E$. 100 m. Glass tube, 12 à 13 cm. Silty mud.

Top, 4 cm, brownish grey; bottom 9 cm dark grey, lowest part, 2 cm, black. Biological stratification. Very fine silt with sharp maximum at $2-5\mu$, median 2.9μ . Divided into two parts a) top 4 cm, b) bottom 9 cm. Organic matter 7.0 and 5.7 % respectively. Top and bottom diatoms. (Diagram 34).

F8 1929. 93 m. Iron tube, mud.

A few grams kept of sample sent to Dr TRASK. Only organic matter determined, 5.2 %.

F9 1924. $64^{\circ}42'.5N$, $22^{\circ}04'E$. 96 m. Glass tube, 15 cm. Silty mud.

Almost black mud. Biological stratification. Size distribution very similar to that of F8, 1925, median 3.2μ . Top and bottom diatoms. Organic matter 5.0 %. (Diagram 35).

F9 1925. 113 m. Glass tube, sand with iron concretions.

Insignificant in volume, muddy sand, small round concretions. Though from same locality as the foregoing, apparently much coarser.

F9 1925. 86 m.

On lead of sounding line, a few pea shaped dark concretions (iron, manganese?), the biggest 1.5 cm in diameter. Not examined further.

F10 1924. $64^{\circ}44'N$, $21^{\circ}33'E$. 66 m. Glass tube, 2 cm. Sandy mud.

Dry when brought home, described as brown and black mud when taken. No diatoms found. Organic matter 2.1 %.

F12 1925. 64°13'N, 22°04'E. 112 m. Glass tube, 14 cm. Silty mud.

Brownish grey with black lumps, lowest part almost black. Very loose. Lower half, biological stratification in thin layers, seems real. Median 2.7μ , size distribution with sharp maximum at $2-5 \mu$, very like that of F8. Top and bottom diatoms. Organic matter 5.4 %. (Diagram 36).

F12 1927. 108 m. Silty mud.

Caught on lead of sounding line. Very different from foregoing. A big lump of silty mud. Nearest to lead 1—2 cm vividly brown from limonite, below grey when wet, but brown after drying. The minerogen component seems to be dusty sand or coarse silt. Divided into 2 parts: a) brown surface layer b) grey layer. Organic matter of a) 5.2 %, b) 5.3 %, diatoms.

F13 1924. 63°47'5N, 21°29'E. 64 m. Glass tube, 7 cm. Coarse silt.

Grey mud. Unsymmetrical size distribution has sharp maximum at $20-50 \mu$, median however lies at 17μ , owing to presence of much material $< 20 \mu$. Organic matter 2.3 %, diatoms. (Diagram 5).

F15 1926. 63°29'5N, 21°22'E. 48 m. Gilson sampler. Very fine sand.

About 40 gr of very fine sand. Distribution diagram applies only to sample, not to sediment, as Gilson sampler was used. Sharp maximum at $50-100 \mu$, median 90μ . Organic matter 0.7 %, diatoms. (Diagram 7).

F16 1926. 63°30'5N, 20°54'E. 27 m. Gilson sampler. Medium sand.

Amount insignificant.

F17 1925. 63°33'5N, 20°34'E. 31 m. Glass tube, 2 cm. Sand.

Sample dry when examined. Light grey with brown tinge. Fine sand 65 %, mixed with gravel and small pebbles 17 %, coarse and medium sand 18 %. Median $< 0.5 \text{ mm}$. Organic matter 0.6 %.

F18 1925. 63°19'5N, 20°18'E. 91 m. Glass tube, 14 cm. Clayey mud.

Dark grey with black lumps. Very loose. Biological stratification. Quite unsorted, about same amount of all particle sizes from $0.2-20 \mu$, median 2μ ; very fine silt or stiff clay. Top and bottom diatoms, organic matter 3.3 %. (Diagram 73).

F18 1928. 63°19'5N, 20°20'E. 100 m. Iron tube. Clayey mud.

About 80 gr kept of sample sent to Dr TRASK. Taken 2'E of preceding. A little more sorted, but median the same, 2μ . Organic matter 3.5 %, diatoms. (Diagram 37).

F19 1925. 63°09'N, 19°27'E. 179 m. Glass tube, 12 cm. Clayey mud.

Dark grey with black lumps. Biological stratification, seems real. Distribution curve, sharp maximum from 0.5—2 μ , median 1.4 μ , stiff clay. Top and bottom diatoms, organic matter 3.8 %. (Diagram 38).

F21 1925. 62°36'N, 20°36'E. 43 m. Glass tube, 12 cm. Late-Glacial, sand and varved silt.

The most northern specimen of varved clay. Top, 2 cm, pebbles, gravel and sand mixed with silt, greyish brown; then pure grey layer 2 mm, distinct black layer 1 mm, pure grey 2 mm, rest diffusely varved; top of varved part, 2 cm, more brownish than rest, 7.5 cm. Organic matter of silt 0.8 %, no diatoms here, but a few on top of sandy layer. Median of sand 750 μ ; if gravel > 2 mm not considered, 200 μ . Distribution curve of varves shows that coarse layers must be very thin, only 21.5 % being > 20 μ ; median 3 μ . Divided into two parts: a) sand, b) silt. (Diagrams 9 and 14).

F22 1924. 62°36'N, 20°01'E. 125 m. Fine sand and pebbles.

About 2.5 gr of fine sand and gravel taken from water sampler. Contained a pebble of sandstone, and grains of sandstone. Besides usual faceted and subrounded quartz grains there were strikingly round and smooth ones. Grains > 2 mm, 40 %, median of smaller grains 100 μ . A few diatoms.

F22 1926. 93 m. Pebbles.

A few pebbles caught on lead of sounding line.

F23 1925. 62°39'N, 19°31'E. 130 m. Glass tube, 13 cm. Clayey mud.

Grey with some black lumps. Size distribution similar to that of F24 and especially F25A below, median 1.5 μ . Top and bottom diatoms, organic matter 3.4 %. (Diagram 39).

F23 1925. 80 à 100 m. Concretions and clayey mud.

Near the station, from the lead of sounding line a few stratified dark concretions, imbedded in clayey mud.

F24 1925. 62°50'N, 18°56'E. 198 m. Glass tube, 20 cm. Clayey mud.

Grey with black lumps. Biological stratification. Size distribution sharp maximum at 1—2 μ , median 1.2 μ . Almost no grains > 20 μ . Top and bottom diatoms, organic matter 3.3 %. (Diagram 40).

F25A 1925. 63°0'N, 18°51'E. 166 m. Glass tube, 16 cm. Clayey mud.

Top, 1 cm, brown, the rest grey and black. Biological stratification, but only apparent. Cross section see Fig. 20. Size distribution very like preceding, median 1.5 μ . Top and bottom diatoms, organic matter 3.2 %. (Diagram 41).

F26 1925. 61°59'N, 20°04'E. 137 m. Glass tube, 13.5 cm. Clayey mud.

Dark brownish grey, unstratified. Top, 1 or 2 cm, shade lighter. A few black spots. Size distribution high max. from 0.2—2 μ . Median 0.9 μ , very stiff clay. Organic matter 3.8 %, no carbonates. Top and bottom diatoms, but mostly broken shells. (Diagram 42).

F26A 1929. 61°30'N, 18°30'E. 63 m. Pebbles.

Glass tube sampler brought nothing, but lead of sounding line caught 10 small pebbles — of which 7 were of Silurian limestone — and a few grains of limestone sand.

F28 1925. 61°07'5N, 20°55'E. 54 m. Glass tube, 31 cm. Late-Glacial, varved clay.

Purely grey clay. Top strongly mixed with sand. Stratified in thin diffuse layers, more distinct after drying. Contains carbonates, but unevenly distributed, partly in form of concretions. Near surface concretion $\frac{3}{4}$ cm long, $\frac{1}{2}$ cm broad, light grey with dark centre. HCl dissolved crust, but not center. Twenty cm below the surface a pebble with thin crust of carbonates. The clay surrounding pebble hardened, containing 3.2 % carbonates. Near the bottom another hardened place containing 9 % carbonates, with a centre of sand grains. When half dry, carbonate concretions were very distinct, occurring in the shape of small white lumps, disseminated all over the clay, treated with HCl they left residue of quartz grains. (In other clays, F30 and F32 A, also containing carbonates, there were similar white lumps, which however showed no effervescence when treated with HCl). It seems as if the carbonates of this sample for some reason had been partly dissolved, formed saturated solution and had precipitated again around grains above a certain size occurring in the sediment (pebble, sand grains). A few pebbles of limestone found. Divided into three parts: a) top 7.5 cm, b) middle part 16 cm, c) bottom 7.5 cm. Organic matter about 1 %. Distribution curves of the three parts very like each other, all having maxima at 0.5—1 μ , thus all three very stiff clays; a) contains 20 % grains > 20 μ , b) and c) only 4.3 and 6.5 respectively. In the fractions > 50 μ of a) no grains of limestone were found, whereas among the sand of b) and c) there were plenty of red and grey limestone grains. The medians were 1.2, 0.9 and 1.0 μ . The «coarse layers» must have been very thin and fine. Top a few diatoms, rest of profile none.

The evenness of the mechanical composition of the clay throughout the sample is clearly seen, when the analyses are recalculated on grains < 20 μ . The following result is obtained (Diagrams 17—19):

	a)	b)	c)
20—10 μ	5.1 %	5.2 %	5.7 %
10—5 μ	4.0 »	4.4 »	6.4 »
5—2 μ	13.0 »	12.0 »	14.0 »
2—1 μ	19.6 »	21.2 »	20.0 »
1—0.5 μ	23.8 »	25.1 »	22.0 »
0.5—0.2 μ	26.0 »	27.3 »	27.2 »
< 0.2 μ	8.3 »	4.4 »	4.6 »

F29 1925. 61°03'N, 20°16'E. 104 m. Glass tube, 15 cm. Clayey mud.

Dark greyish brown, not stratified, but somewhat uneven in colour. Very poorly sorted, median $1.2\ \mu$, stiff clay. Organic matter 3.9 %, no carbonates. Top and bottom a few diatoms. (Diagram 45).

F29A 1928. 61°06'N, 20°41'E. About 70 m. Gilson sampler, 300 gr dry weight. Late-Glacial, varved silt.

Much coarser than F28 though from greater depth. Contained stones up to 3 cm in diameter, partly quite sharp-edged, partly subrounded. In places brown and quite hard, these parts when washed free of the clay, turned out to be more or less large, flat concretions, partly very dark and without a distinct structure, up to 5 or 10 centimetres in diameter (broken when examined). The concretions seem to be in different stages of development. The coarse varves probably not more than 1—2 millimetres thick though difficult to judge, as layers dislocated because of sampler used. The average composition determined from two portions, the one electrolyzed, the other dialyzed which gave about the same result, except for the smallest grain classes (see Fig. 15, page 67). Distribution curve shows 2 maxima: one at 2—5 μ , another at 20—50 μ , median 7.5 μ . The fine layers are thus very fine silt, coarse layers dusty sand; the latter however also contain coarse sand and gravel. Like F28 this sample contained carbonates, about 3 %; sand and gravel, but not larger pebbles, also partly consisted of red and grey limestone. Organic matter 0.8 %, no diatoms found. (Diagram 15).

F30 1925. 61°04'5N, 19°35'E. 104 m. Glass tube, 18 cm. Late-Glacial, very stiff clay.

Sample dry when examined, tube having cracked. Purely grey in colour, about $\frac{1}{2}$ cm of top seems to have been darker. Probably varved, because profile had a tendency to break along parallel sections, colour of clay at these places being partly much lighter; as in F28 there were small disseminated white lumps of the size of a pin's head, which however showed no effervescence with HCl. Carbonate content only 0.41 %. A very fine-grained sample, median only 0.75 μ , 85 % smaller than 2 μ ; very sharp maximum at 0.5—2 μ . Organic content 1.3 %, no diatoms found. (Diagram 20).

F30 1926. 120 m. Glass tube, 15 cm. Clayey mud.

Though from same station as foregoing, from greater depth and very different. Black and grey throughout, biological stratification but certainly only apparent, cross sections being spotted black and grey. Less well sorted and not as fine-grained as foregoing, median 0.95 μ , 70 % < 2 μ , maximum at 1—2 μ , very stiff clay. Organic matter 3.4 %, carbonates 0.48 %, top and bottom diatoms. (Diagram 43).

F30A 1928. 61°04'N, 20°13'E. About 100 m. Gilson sampler, 125 gr dry weight. Clayey mud.

Examined dry. In clay concretions in the making like those at F29 A, but also small dark brown, almost black lumps, not more than 2 mm in diameter,

disseminated all over the clay. These have apparently a high content of manganese, observed during electro dialysis (see page 67). Mechanical composition almost identical with that of foregoing, median 1.1μ , organic matter also the same 3.5 %, carbonates only 0.23 %. Diatoms. (Diagram 44).

F31 1924. $61^{\circ}11'N$, $18^{\circ}37'E$. 62 m. Glass tube, 8 cm. Late-Glacial, dusty sand mixed with coarse sand.

When dry, very light in colour and hard, contains 41.6 % of carbonates; coarser on top, median 25μ . Organic matter 0.5 %, no diatoms. (Diagram 3).

F31 1925. 60 m. Glass tube, 6 cm. Fine sand.

Fine grey sand, coarser on top, median 150μ . No carbonates, though theoretically from the same locality as foregoing. The limy clay here is probably covered by lime-free sand, varying in thickness. On top a roundish iron concretion, partly hollow, with grey porous centre. Organic matter 0.9 %. No diatoms. (Diagram 8).

F31 1926. 54 m. Gilson sampler. Pebbles and iron concretions.

Some large, flat, dark brown iron concretions, diameter of largest about 5 cm. Stones and pebbles. No limestone.

F31A 1925. $61^{\circ}11'N$, $18^{\circ}39'E$. About 35 m. Glass tube, 6 cm. Late-Glacial, sand and silt.

Top 2 cm, fine grey sand mixed with gravel; then 2 cm fine and coarse sand; bottom 2 cm, a more compact layer of dusty sand or coarse silt containing 23.7 % carbonates. The colour of the limy layer different light shades of grey and light brown, also small white lumps. Divided into two parts: a) top, 4 cm, only 0.55 % carbonates, a few diatoms, b) bottom 2 cm, no diatoms.

F31B 1925. $61^{\circ}11'N$, $18^{\circ}35'E$. 50 à 60 m. Glass tube, 17.5 cm. Late-Glacial, coarse silt with gravel.

Coarse silt mixed with sand and gravel, — mostly, especially towards the bottom, of sharp-edged pieces of grey and red limestone. Gravel also contained fragments of fossils. Divided into 2 parts: a) top, 7.5 cm, carbonates about 7 %, b) bottom, 10 cm, carbonates about 36 %. Because of uneven distribution of carbonates, individual analyses differed considerably. The distribution curve of b) shows a very wide range of particle sizes with maximum in the coarse silt group, median 16μ . Organic matter of b) 0.4 %. No diatoms. (Diagram 4).

F31C 1926. $61^{\circ}09'N$, $18^{\circ}58'E$. 64 m. Glass tube, 11 cm. Late-Glacial, clay.

a) Top, 2 cm, fine lime-free sand mixed with some clay, then b) 3.5 cm, dark grey, hard and fine-grained clay with minute white spots, c) bottom,

5.5 cm, light grey and reddish grey clay, apparently coarser than the grey clay. Bottom part perhaps varved, but layers in that case distorted and differing more in colour than in grain-size. a) only 0.9 % carbonates, b) 7.8 %, c) 31.6 %. Diatoms only in the sand. Organic matter 1.1, 1.0, 1.1 % respectively.

Also dredged with Gilson sampler a few grams of fine lime-free sand.

F31D 1926. 61°07'N, 18°34'E. 34 m. Gilson sampler, 290 gr. Late-Glacial, pebbles, gravel and sand,

to about 14 % consisting of red and grey limestone and fragments of fossils; 80 % of sample > 2 mm.

F31E 1928. 61°08'N, 19°08'E 45 m.¹⁾ Gilson sampler, 500 gr dry weight. Late-Glacial, varved clay.

Distinctly varved clay, which unfortunately, because of the sampler used, could not be investigated closely. The varves seem to consist throughout of very stiff grey clay and very fine brownish sand, each layer being a few millimetres thick, sandy layers probably thicker than others. The distribution curve of an average sample shows 2 maxima, one at 0.5—1 μ , another and more pronounced at 50—100 μ . The median 30 μ , lies on the coarse side, confirming the view that the coarse layers dominate. Carbonate content on the whole very low, an average sample only gave 0.2 %, though some pieces show a weak but distinct reaction, when treated with HCl. A pebble of red limestone found. This sample is remarkable because it differs very much from F31C its nearest neighbour 10' W, the bottom part of which is light reddish grey and contains about 32 % carbonates. Both samples are undoubtedly of late-Glacial origin, but must have been formed of material from very different sources. Organic matter 1.2 %, no diatoms found. (Diagram 16).

Finngrunden I 1925. 60°58'5N, 18°27'E. 14 m. Gilson sampler.

Four stones, one a piece of grey limestone (20 gr) and another a small piece of red limestone.

Finngrunden II 1925. 61°0'N, 18°27'5E. 20 m. Gilson sampler, 75 gr. Late-Glacial, pebbles, gravel and coarse sand.

Gravel of limestone about 25 %, fossils, 3.5 gr, about 5 %. 70 % of sample > 2 mm.

Finngrunden III 1926. 61°0'N, 18°30'E. 18 m. Gilson sampler, 240 gr. Late-Glacial, pebbles, gravel, sand and clay.

Gravel of limestone and fossils about 25 % of whole. Composition of sample: > 2 mm 31 %, 2—0.05 mm 41 %, < 50 μ 28 %. Carbonate content

¹⁾ In the expedition records the depth of this sample is given as 45 m; but according to the sea chart, depths in the neighbourhood range from 60 to 100 metres. As the bottom configuration in this area is very uneven the reported depth was nevertheless considered correct.

of latter group 38 %. Besides this, two pieces of limestone weighing 655 gr and 58 gr.

F32 1925. 61°12'N, 17°52'E. 67 m. Glass tube, 13 cm. Clayey mud covered with sand.

Top, 1 cm, very fine sand, rest dark greyish brown, lime-free mud; median 1.3μ , stiff clay. Organic matter of sandy layer 1.9 %, that of mud 4.3 %. In spite of high organic content no black lumps, but as usual black globules of pyrite. Top a few diatoms, bottom no diatoms found! Divided into two parts: a) sand, b) mud. (Diagram 46).

F32 1926. 67 m. Glass tube, 14 cm. Clayey mud covered with sand.

Very similar to foregoing, top, 2 cm, very fine sand. Top and bottom diatoms. Divided into three parts: a) sand, 2 cm, b) mud, 6 cm, c) mud, 6 cm. Organic matter increasing with depth: a) 2.4 %, b) 5.9 %, c) 6.6 %. Between b) and c) no visible difference.

F32A 1926. 61°06'N, 18°10'E. 68 m. Glass tube, 29 cm. Late-Glacial, clay.

Top, 3 cm, very fine brownish grey sand, then 12 cm fairly homogeneous looking grey clay; when wet, indistinctly stratified in lighter and darker layers; when dry, showing silty looking streaks and breakage along parallel sections; also containing disseminated small white lumps, which do not contain carbonates, but are simply formed of grains coarser than surrounding clay. Bottom, 15 cm, when dry on the whole more silty looking and uneven in colour, different shades of light grey, also indistinctly varved like top part. Small samples examined under microscope showed that grain size on the whole increases towards bottom of profile. (Fig. 3). Only in sandy layer were diatoms found. Carbonates 12.4 % at the bottom, decreasing to none at top. Organic matter about 1 % throughout. Divided into 5 parts: a) sand, 3 cm, b), c), d), e) clay, 6.5 cm each. An average sample of clay coagulated partly during mechanical analysis (see Fig. 19 p. 83). It was evident, however, that median $< 2 \mu$, not more than 20 % $> 5 \mu$, and that difference in grain size between fine and coarse layers was not pronounced enough for development of two maxima in size distribution. There was probably a single maximum below 2μ .

F33 1925. 60°33'5"N, 18°55'E. 106 m. Glass tube, 28 cm. Late-Glacial, clay.

Top, 2 cm, fine grey sand mixed with gravel, then clay, 26 cm; still wet, diffusely stratified in grey and brownish grey streaks. About 9 cm below surface a somewhat darker layer, 1 to 1.5 cm thick. Everywhere small white lumps disseminated in clay. This sample had high content of carbonates, about 30 % directly under sand. No diatoms found in clay, nor in sand. Divided into 4 parts: a) sand, 2 cm, b) clay 6.5 cm, c) clay 13 cm, d) clay 6.5 cm. Fraction c) subjected to mechanical analysis. Very fine-grained, median 1μ , max. at $0.5-2 \mu$; small secondary max., probably accounted for by «coarse layers»,

lies at 10—20 μ . Median of a) 250 μ . Organic matter about 1 % throughout the clay. (Diagrams 10 and 21).

F33 1926. 79 m. Glass tube, 23 cm. Late-Glacial, clay.

Top, 2 cm, fine sand, then clay, 21 cm; a black patch seen near bottom, when sample was still in tube. Both wet and dry, diffusely stratified in lighter and darker layers, each varve 1 to 2 mm thick; high content of carbonates almost white in colour and unevenly distributed. Colour of first 10 cm seem on the whole darker than bottom part (see Fig. 3). Divided into 4 parts: a) sand, 2 cm, b), c), d) clay, 7 cm each. Carbonates increasing towards bottom being in a) 3.7 %, b) 19.7 %, c) 23.7 % and d) 29.6 %. Only d) similar to foregoing sample from same locality. Organic matter about 1 % throughout. Fractions b) and c) joined subjected to mechanical analyses but partly coagulated (see Fig. 19). However, not more than 21 % were $> 5 \mu$. No diatoms found.

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F36 1924. 60°39'N, 28°37'E. 13 m. Glass tube, 12 cm. Silty mud.

Both wet and dry, evenly brownish grey. Organic matter 6.8 %. Mineral component very poorly sorted, median 3.7 μ , very fine silt. Diatoms. (Diagram 74).

F37 1924. 60°35'N, 28°27'E. 27 m. Glass tube, 8 cm. Silty mud.

Evenly grey; when wet about 2 cm of top somewhat darker; when dry, top part seems more sandy than rest. Size distribution of mixed sample very like that of F36 but still less sorted, an equal amount of all particle sizes from 0.2 to 100 μ , median 3.5 μ . Organic matter only 2.2 %, lower than at F36 and next sample from same locality. Diatoms abundant on top; bottom, no diatoms found. (Diagram 75).

F37 1925. 60°35'N, 28°28'E. 25 m. Ekman-Birge sampler. Clayey mud.

Some experiments were made with an EKMAN-BIRGE bottom sampler¹⁾ of brass plate. On account of its small weight it could be used, however, only at very moderate depths. The sample now under consideration consisted of a few grammes, dry weight, of black silty mud, containing 7.7 % organic matter and thus very different from the foregoing collected 1' W. Diatoms.

From lead of sounding line a number of dark brown, pea-shaped concretions.

F38 1924. 60°30'N, 28°26'E. 28 m. Glass tube, 10 cm. Sand.

Examined dry, very fine sand mixed with fine grains of limonite. Organic matter 2.6 %. Diatoms.

¹⁾ The EKMAN-BIRGE bottom collector was kindly lent to the Thalassological Institute by Prof. K. M. Levander, Helsingfors.

F40 1924. 60°06'5N, 28°48'E. 40 m. Glass tube, 12 cm. Clayey mud.

Top, 10 cm, grey and black, very dark, reeking of hydrogen sulphide, bottom brownish grey with sharply defined upper limit. Organic matter of bottom not analyzed separately, mean content 5.7 %. No carbonates. Maximum of size distribution at 5—10 μ , but rather poorly sorted, median 2 μ , very fine silt or stiff clay. Top and bottom diatoms abundant. (Diagram 49).

F40 1925. 37 m. Glass tube, 17 cm. Clayey mud.

Similar to foregoing, grey and black, biological stratification, organic matter 5.7 %. Very loose; bottom, 1 cm, more compact and brownish grey, sharply defined upper limit. Size distribution almost identical with foregoing, median 2 μ . Top and bottom diatoms abundant. (Diagram 50).

F41 1924. 60°07'N, 28°04'E. 51 m. Glass tube, 11 cm. Silty mud.

Dry when examined, brownish grey. Less sorted than foregoing and wider range of particle sizes, median 2.4 μ , very fine silt. Slight content of carbonates 0.59 %, organic matter 4.6 %. Throughout the profile, diatoms abundant, different species of *Chaetoceras* sp. (Diagram 51).

F42 1924. 60°07'N, 27°29'E. 61 m. Glass tube, 8.5 cm. Mud.

Clayey or silty mud. Three distinct layers, top 4 cm dark grey and black, biological stratification, then 2.5 cm dark grey, bottom, 2.5 cm, light brownish grey. Organic matter 5.0 %, carbonates 0.56 %. Top and bottom diatoms. No mechanical analysis.

F42 1928. 64 m. Iron tube, 250 gr dry weight. Late-Glacial, very stiff clay.

When dry purely grey. Very different from foregoing, organic matter only 0.7 %, carbonates 0.23 %, extremely fine-grained, median only 0.6 μ ; the distribution curve has high maximum at 0.2—0.5 μ , 80 % < 2 μ and only 8 % > 5 μ . At this locality obviously late-Glacial clay is partly covered with post-Glacial deposits. (Diagram 25).

F43 1924. 60°20'N, 26°58'E. 38 m. Glass tube, 2.5 cm. Mud.

Silty or clayey mud, brownish grey. Diatoms. Organic matter 5.6 %. No carbonates.

F43 1925. 38.5 m. Glass tube, 14 cm. Late-Glacial, varved silt.

a) Top, 1 cm, fine sand mixed with gravel, b) varved silt. Distribution curve of sand has maximum at 0.5—1 mm, but median is 330 μ , that of silt 2 maxima at 0.2—0.5 μ and at 10—50 μ . The coarse layers seem to predominate, second maximum being higher and broader than first; median of silt 6 μ . Sand a few diatoms, bottom none. Organic matter of sand 1.3 %, of silt 0.7, no carbonates. The two samples from F43 form another case similar to that of F42. The one taken 1924 is post-Glacial, the present one late-Glacial. (Diagrams 12 and 23).

F43A 1924. 60°17'N, 27°12'E. About 25 m. Glass tube, 14 cm. Late-Glacial, very stiff clay.

Top, a few millimetres, sand; then very stiff clay; has tendency to break along parallel sections. Bottom half, darker than top. Size distribution almost identical with that of F42, 1928, median 0.6 μ . Organic matter 0.6 %, no carbonates. (Diagram 26).

F44 1924. 60°7'5N, 26°58'E. 63 m. Glass tube, 11 cm. Clayey mud.

a) Top, 1.5 cm, black, b) 6 cm, dark grey and black, biological stratification, c) bottom 3.5 cm, brownish grey. Similar to F42 1924. Organic matter of a) 3.1 % of b) and c) 6.1 % and 6.3 % respectively, no carbonates; b) and c) joined for mechanical analysis. Median 1.4 μ , stiff clay. In all parts diatoms abundant. (Diagram 52).

F45 1924. 59°57'N, 27°0'E. 72 m. Glass tube, 13 cm. Clayey mud.

Top, 1 cm, black sandy mud, then 4 cm, dark grey, clayey mud, biological stratification; bottom 8 cm, lighter grey, somewhat uneven in colour. Divided into two parts: a) sand, b) rest of profile. Organic matter in a) 2.8 %, in b) 5.1 %, no carbonates. Median of b) 0.9 μ , minerogen component thus very stiff clay. Like foregoing, sample has small secondary max. on coarser side, however no sign of different sized layers were to be seen. Throughout profile diatoms abundant. (Diagram 53).

F49 1924. 59°52'N, 26°17'E. 84 m. Glass tube, 2 cm. Silt.

Coarse silt with some gravel, organic matter 1.7 %, no diatoms found.

F49 1925. 85 m. Glass tube, 15 cm. Clayey mud.

Dry when examined. Mixed with some sand on top. Poorly sorted, median 1.1 μ , stiff clay. Organic matter 3.6 %, no carbonates. Top and bottom diatoms. (Diagram 54).

F50 1924. 59°50'N, 25°37'E. 85 m. Glass tube, 16 cm. Clayey mud.

a) Top, 1 cm, brownish, b) rest of profile, when wet, grey with darker streaks, especially towards top; bottom almost purely grey. Organic matter 3.9 % and diatoms throughout. No carbonates. Distribution curve of b) has two max., one at 1—2 μ , another and lower at 5—10 μ , median 0.9 μ , thus, on the whole, very stiff clay. (Diagram 55).

F52A 1925. 60°01'N, 24°58'E. 41 m. Glass tube, 4 cm. Late-Glacial, clay.

Diffusely varved clay, on top half mixed with coarse sand. Divided into two parts: a) top, 2 cm, b) bottom 2 cm. Organic matter of a) 1.2 %, of b) 1.1 %, no carbonates. Top a few diatoms, bottom none.

F53 1924. 59°51'5N, 24°50'E. 80 m. Glass tube, 19 cm. Clayey mud.

Different shades of grey throughout. Biological stratification, in lighter and darker grey streaks, the colour differences on the whole very slight. Organic

matter of average sample 3.8 %. Top and bottom diatoms. No carbonates. Distribution curve shows that sample is very fine-grained, but absolutely unsorted below $2\ \mu$, median only $0.7\ \mu$, very stiff clay. (Diagram 56).

F54 1924. $59^{\circ}43'N$, $25^{\circ}01'E$. 90 m. Glass tube, 24 cm. Late-Glacial, varved clay.

Top, 0.5 cm, blackish grey, rest of profile, when wet, diffusely stratified in grey and brownish grey layers; when dry, distinctly varved, bottom part on the whole more brownish than top. Distribution curve also shows that sample is varved, though difference in size very slight. There are two maxima, one at $0.5-1\ \mu$, another and higher at $2-5\ \mu$. Median $1.1\ \mu$, only 3 % of sample $> 10\ \mu$. Organic matter on an average 1.1 %, diatoms only in black surface layer. Sample shows slowness of sedimentation in the sea. Station F54 lies in a comparatively sheltered depression, yet the entire sedimentation since the Ice Age is represented by the 0.5 cm thick black surface layer! (Diagram 24).

F54 1925. 108 m. Glass tube, 6 cm. Fine sand.

Fine grey sand, with some gravel, which distribution curve reveals as possibly stratified. Two maxima, one at $50-100\ \mu$, another at $0.5-1\ \text{mm}$, median $250\ \mu$. Organic matter 1.2 %. (Diagram 13).

F55 1924. $59^{\circ}37'.5N$, $25^{\circ}11'E$. 90 m. Glass tube, 24 cm. Late-Glacial, very stiff clay.

When wet, homogeneous grey clay with irregular brownish streaks. Extremely fine-grained, median $0.55\ \mu$, distribution curve has high max. at $0.2-0.5\ \mu$, 18 % being $< 0.2\ \mu$ and only 10 % $> 5\ \mu$. Organic matter 0.7 %, carbonates likewise 0.7 %. No diatoms found. (Diagram 27).

F56 1924. $59^{\circ}36'.5N$, $24^{\circ}21'E$. 85 m. Glass tube, 12 cm. Clayey and sandy mud.

Biological stratification throughout. Top almost black, colour of layers gradually changing into brownish grey at bottom. Bottom part, 4 cm, almost evenly brownish grey. Contrary to rule for samples with high content of organic matter, stratified also when dry; sandy layers especially towards bottom. Divided into two fractions: a) top half, b) bottom half. Organic matter of a) 3.2 %, b) 3.6 %. Carbonates of a) and b) joined 1.31 %. Size distribution of a) and b) joined shows max. at $20-100\ \mu$, but perfectly even distribution of particle sizes below $20\ \mu$. Median $8.0\ \mu$ lies in fine silt group, but sample is obviously a stratified mixture of unsorted clay and dusty and very fine sand (see below). Top and bottom diatoms. (Diagram 81).

F56 1925. 81 m. Glass tube, 11 cm. Clayey and sandy mud.

Top, 1 or 2 cm, brownish grey; the rest dark grey with black lumps, visibly stratified neither when wet nor dry, colour just uneven. Distribution diagram shows max. at $20-50\ \mu$ and lower secondary max. at $0.2-0.5\ \mu$, but on the whole distribution similar to that of foregoing, though not so even in height. The grain class $20-50\ \mu$ possibly occurring more on top of profile, as under mic-

roscope top seems coarser than bottom, median $11\ \mu$. Organic matter 2.8 %, carbonates 2.65 %. Top and bottom diatoms. (Diagram 82).

F56 1928. 80 m. Iron tube, 140 gr dry weight. Clayey and sandy mud.

Similar to two preceding, taken at same locality, median $6\ \mu$. Organic matter 3.2 %, carbonates 3.1 %. Comparison of the three samples shows varying carbonate content from 1.3 to 3.1 %, whereas organic matter is fairly constant, varying from 2.8 to 3.6 %. Diatoms. (Diagram 83).

F57 1924. $59^{\circ}30'N$, $23^{\circ}44'E$. 88.5 m. Glass tube, 13 cm. Clayey mud.

a) Top, 11 cm, dark grey, with lighter and still darker streaks, biological stratification, b) bottom, 2 cm, brownish grey. Organic matter of a) 4.2 % of b) 4.4 %. Carbonates 1.05 % and 1.94 % respectively. Size distribution of a) quite unsorted, similar to that of F56 1924, but without marked admixture of sand, median $2\ \mu$. Top and bottom diatoms. (Diagram 76).

F57 1925. 104 m. Glass tube, 22 cm. Clayey mud.

Evenly grey with black lumps at bottom, A few dark streaks 3—4 cm from top, two pebbles on top. Five cm from bottom a brown lump in the clay containing a flat iron concretion. Organic matter less than foregoing only 2.5 %, carbonates 2.0 %. The distribution diagram comprises a wider range of particle sizes than foregoing; on the whole more fine-grained, median $1.2\ \mu$; two maxima, one at 0.2—0.5 μ , another at 10—20 μ . Diatoms abundant. (Diagram 57).

F58 1925. $59^{\circ}47'N$, $23^{\circ}0'E$. 36 m. Fine sand.

A small amount of fine grey sand. No diatoms found.

F59A 1924. $59^{\circ}38'5N$, $23^{\circ}05'E$. 48 m. Glass tube, 18 cm. Late-Glacial, very stiff clay.

When wet grey throughout with reddish brown layers, 2 to 3 mm thick, at a distance of from 3.5 to 1.5 cm from each other. Dry diffusely stratified, but coarse layers so fine that distribution diagram does not reveal them; median only 0.85 μ , very stiff clay. Organic matter 1.1 %, no carbonates. No diatoms found. (Diagram 28).

F61 1924. $59^{\circ}26'N$, $23^{\circ}09'E$. 101 m. Glass tube, 11 cm. Clayey mud.

Grey throughout with a few brownish streaks, but stratified neither when wet nor dry, median $1\ \mu$, very stiff clay. Organic matter 4.1 %, carbonates 1.41 %. Top and bottom diatoms. (Diagram 58).

F61 1925. 98 m. Glass tube, 9 cm. Clayey mud.

Top, 2 cm, brownish grey, rest almost black, not stratified. Organic matter 4.7 %; carbonates, like foregoing, 1.41 %. Top and bottom diatoms.

F61 1928. 95 m. Iron tube, 112 gr dry weight. Clayey mud.

When dry purely grey. Size distribution similar to that of F61 1924, but still more fine-grained, median 0.8μ . Organic matter 3.9 %, carbonates 1.52 %. Diatoms. (Diagram 59).

F62 1924. $59^{\circ}19'5N$, $23^{\circ}16'E$. 82.5 m. Glass tube, 17 cm. Clayey and sandy mud.

When wet a) top, 2 cm black, b) 13 cm, dark grey, c) bottom, 2 cm brownish grey, (see page 23). Layer b) has light and dark streaks. Stratified also when dry. Size distribution of b) somewhat similar to that of F56, 1924, which was stratified though containing diatoms and much organic matter. High max. at $50-100 \mu$, and size group $20-50 \mu$ also abundant. The rest poorly sorted clay and silt, median 20μ on limit between sand and silt. Organic matter of a) and b) 2.6 % of c) as much as 5.1 %; carbonates unevenly distributed 2.55, 3.07 and 1.70 % respectively. Top and bottom diatoms abundant. (Diagram 84).

Pojo V 1926. $60^{\circ}01'N$, $23^{\circ}29'5E$. 36 m. Glass tube, 20 cm. Clayey mud.

Top dark grey, changing into almost black at bottom, biological stratification throughout, but only apparent. Distribution diagram shows high max. at $0.2-0.5 \mu$, median 0.8μ . Organic matter 5.1 %, perhaps a slight content of carbonates as 0.10 % carbonate- CO_2 found. Diatoms abundant throughout. (Diagram 60).

Pojo XI 1926. $59^{\circ}52'5N$, $23^{\circ}16'5E$. 28 m. Glass tube, 12 cm. Clayey mud.

Top, about 1 cm, black, rest of profile dark grey, no stratification but colour somewhat uneven. Organic matter 6.2 %. No carbonates. Top and bottom diatoms.

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F64 1925. $60^{\circ}11'5N$, $19^{\circ}09'E$. 294 m. Glass tube, 26 cm. Late-Glacial, very stiff clay.

Extremely fine-grained sample, 85 % being $< 2 \mu$, median only 0.5μ . Size distribution similar to that of unstratified late-Glacial clays. Grey with big and small black lumps, giving part of sample stratified appearance, obviously no real stratification. On top also coarse sand grains in clay. Organic matter only 1.1 % in spite of black lumps. No carbonates. Top a few diatoms, bottom none. (Diagram 29).

F64 1928. 288 m. Glass tube, 18 cm. Clayey mud.

Top, 4 cm evenly greyish brown, rest of profile banded, greyish black and dark grey alternately, each band 2 or 3 cm; biological stratification within darkest bands. Less fine-grained than foregoing, only 65 % being $< 2 \mu$, also less well sorted, median 1μ , a small secondary max. above 20μ . Under microscope coarse grains also seen in middle and bottom of profile. Organic matter 4.3 %, no carbonates. Top and bottom diatoms. (Diagram 63).

Lumparen I 1926. 60°10'6N, 20°11'8E. 16 m. Glass tube, 20 cm. Clayey mud.

Top grey, towards bottom darker, biological stratification throughout. Size distribution has low maximum at 0.5—2 μ , median 0.9 μ . Organic matter 4.3 %, no carbonates. Top and bottom diatoms. (Diagram 61).

Lumparen II 1926. 60°08'9N, 20°08'2E. 18 m. Glass tube, 15 cm. Clayey mud.

Almost evenly dark grey, no black lumps, top a few mm brown. Below 5 μ very poorly sorted, median 1.4 μ , small secondary max. above 10 μ , 17 % sand. Organic matter 3.7 %, no carbonates. Top and bottom diatoms. (Diagram 62).

Lumparen III 1926. 60°07'6N, 20°05'7E. 18.5 m. Glass tube, 21 cm. Clayey mud.

Similar to foregoing, dark grey. Top and bottom diatoms. Organic matter 3.8 %, no carbonates.

Lumparen IV A 1926. 60°06'N, 20°04'E. 18 m. Glass tube, 17 cm. Clayey mud.

Dark grey, top half somewhat brownish, biological stratification in bottom half. Top and bottom diatoms. Organic matter 4.7 %, no carbonates.

Lumparen IV B 1926. 18 m. Gilson sampler. Clayey mud.

Dark grey with black lumps. Size distribution determined on electrolyzed sample (see Table 11), 71 % < 2 μ . Organic matter 5.2 %, diatoms.

F65A 1928. 60°02'5N, 22°14'E. 72 m. Iron tube, 175 gr dry weight. Clayey mud.

Size distribution has max. at 0.2—0.5 μ ; sample poorly sorted, but fine-grained, median 0.8 μ . Average organic matter only 1.6 %, diatoms. (Diagram 64).

F65B 1925. 60°07'N, 21°41'E. 66 m. Glass tube, 18 cm. Late-Glacial, varved clay.

a) Top, 2 cm, sand and gravel mixed with clay, b) rest of profile purely grey, varved clay. Distribution diagram of b) shows that fine layers consist chiefly of very stiff clay, 0.2—0.5 μ , and coarse layers of dusty and very fine sand 20—100 μ . Median 1.6 μ shows that fine layers predominate. Organic matter comparatively high 1.4 % in a) and 2.1 % in b). Mechanical composition of a): > 2 mm 26.6 %, 2—1 mm 6.5 %, 1—0.5 mm 6.1 %, 0.5—0.1 mm 24.2 %, 0.1—0.05 mm 4.5 %, < 50 μ 32.1 %; median 250 μ . No diatoms found. (Diagrams 11 and 22).

F66 1924. 60°05'N, 20°57'E. 80 m. Glass tube, 11 cm. Clayey and sandy mud.

Almost dry when examined, grey, no black lumps. Seems stratified in finer and coarser layers. This impression is supported by distribution curve

which is similar to that of F56 and F62, having high max. at 20—100 μ and low secondary max. in clay group; median 5 μ indicates that coarse and fine grains have about equal parts in the sediment. Organic matter 3.8 %, no carbonates. Top and bottom diatoms. (Diagram 85).

F67 1926. 59°59'N, 19°46'E. 210 m. Gilson sampler. Clayey mud.

A few grams of grey mud. Organic matter 4.2 %. No carbonates, diatoms.

F67 1930 I. 210 m. Glass tube, about 20 cm. Clayey mud.

Black throughout, when examined frothy because of gas formation during storage. Organic matter 4.7 %, carbonates 0.23 %. Diatoms throughout.

F67 1930 II. 210 m. Iron tube. Clayey mud.

About half a litre of black mud. Size distribution almost identical with that of F64 1928, shows that sample is fine-grained, but rather poorly sorted; max. at 0.2—0.5 μ , median 0.9 μ . As is the case with so many other fine-grained mud samples there is small secondary max. in dusty sand group. Organic matter 4.2 %, carbonates 0.20 %; diatoms. (Diagram 65).

F68 1925. 59°56'5N, 19°14'E. 122 m. Glass tube, 13 cm. Clayey mud.

Almost black, apparent biological stratification throughout. Size distribution somewhat similar to foregoing with max. in the clay group and a secondary max. in the 20—50 μ group, median 1.1 μ . Organic matter 3.6 %, no carbonates. Top and bottom diatoms. (Diagram 67).

F68 1928. 120 m. Iron tube, 50 gr. dry weight. Clayey mud.

Size distribution very similar to that of foregoing from same locality, median 1 μ . Organic matter 4.1 %, no carbonates; diatoms. (Diagram 66).

F69 1925. 59°46'N, 19°47'E. 150 m. Glass tube, 15 cm. Clayey mud.

Dark brownish grey with black lumps. Seems stratified when dry having a tendency to break along parallel sections. Size distribution shows two maxima, one at 0.5—2 μ in poorly sorted clay group, another equally high, but more pronounced in dusty sand group, median 1.6 μ . Organic matter 3.6 %, no carbonates; diatoms. (Diagram 86).

F69 1930. 169 m. Iron tube. Clayey mud.

About half a litre of dark grey mud with blueish black lumps. Size distribution very similar to that of foregoing, median 1.5 μ . Organic matter 3.5 %, no carbonates; diatoms. (Diagram 87).

NORTH BALTIC.

F71 1925. 59°30'.5N, 20°24'E. 155 m. Glass tube, 22 cm. Clayey mud.

Black throughout, when examined frothy because of gas formation during storage, biological stratification. From a locality where oxygen content of

bottom water as a rule very low, often nil. Size distribution shows poor sorting in clay group, low secondary max. at 20—50 μ , median 1.3 μ . Organic matter 3.7 %, carbonates 0.34 %; diatoms abundant. (Diagram 78).

F71 1929. 156 m. Iron tube. Clayey mud.

A few grammes kept of sample sent to Dr TRASK. Organic matter 3.5 %, carbonates 0.20 %; diatoms.

F71 1930. 155 m. Iron tube. Clayey mud.

About 600 c.c. of black mud. Size distribution similar to that of F71 1925, quite unsorted below 2 μ ; median 1.2 μ . Organic matter 3.0 %, carbonates 0.23 %, diatoms abundant. (Diagram 77).

F72 1924. 59°14'5N, 22°11'E. 124 m. Glass tube, 17 cm. Silty mud.

Consists of three layers, when wet: top, 3 cm, black; middle 8 cm, dark grey, biological stratification; bottom, 6 cm, much lighter, brownish grey. Seems stratified even when dry in coarser and finer layers. Divided into 2 parts: a) Top, 11 cm, b) bottom, 6 cm. Mechanical analyses of the two parts separately shows essentially same composition, very poor sorting with small max. at 0.2—0.5 μ ; top part has another max. in dusty sand group, median of a) 2.1 μ , of b) 2.0 μ . Organic matter a) 4.7 %, b) 4.9 %. Carbonates a) 3.96 %, b) 3.54 %. Diatoms abundant throughout. (Diagrams 79 and 80).

F73 1924. 59°0'5N, 21°52'E. 87 m. Glass tube, 13 cm. Clayey and sandy mud.

Black and grey mud, biological stratification when wet and also plainly stratified when dry. Mechanical composition of the type of F56 and F62. Quite unsorted below 10 μ with high max. in dusty sand group, median 11 μ . Organic matter 3.2 %, carbonates 6.27 %. Diatoms abundant throughout. (Diagram 88).

F74 1925. 59°01'N, 21°05'E. 176 m. Glass tube, 15 cm. Clayey mud.

Top half almost black, bottom half grey and black, biological stratification. Very fine-grained with max. at 0.2—0.5 μ , median 0.8 μ . Organic matter 4.1 %, carbonates 1.07 %. Diatoms throughout. (Diagram 68).

F74 1930 I. 195 m. Glass tube, 36 cm. Late-Glacial, very stiff clay.

Very different from foregoing, grey clay. When divided, found to be finely stratified in lighter and darker shades of grey. Top part, about 13 cm, somewhat lighter in colour and brownish. Dry profile had tendency to break along parallel sections, somewhat lighter in colour, thus sample probably varved. Divided into 5 equal fractions, about 7 cm each. Organic matter of a) 1.9 %, of b), c), d) and e) 1.0 %. Carbonates throughout, but unevenly distributed: a) 2.30, b) 4.59, c) 3.96, d) 5.43 and e) 2.71 %. Diatoms on top. Also, 13 cm deep, in bottom part of brownish layer a disc-shaped diatom found; rest of profile no diatoms. No mechanical analysis.

F74 1930 II. 195 m. Iron tube. Late-Glacial, very stiff clay.

About 0.75 litres of grey clay, similar to foregoing. A lump of small pea shaped concretions in the clay, when dry seen to be rust coloured crusts covering small pebbles. Pebbles and sand also found in the lump. Like foregoing very finely layered, the difference in grain size between fine and coarse layers being very small. Coagulated partly during mechanical analysis (see fig. 19). But the result shows that not more than 5 % were $> 10 \mu$ and at least 63 % $< 2 \mu$. Organic matter 1.0 %, carbonates 2.60 %.

F75 1925. $58^{\circ}54'N$, $20^{\circ}07'E$. 178 m. Glass tube, 10 cm. Clayey mud.

Grey and black mud, apparent biological stratification. Very fine-grained; distribution curve has a max. at $0.5-1 \mu$, median 0.7μ , only 5 % $> 5 \mu$ and 78 % $< 2 \mu$. The minerogen component is thus well sorted, very stiff clay. Organic matter 4.3 %, carbonates only 0.27 %. Diatoms throughout. (Diagram 47).

F76A 1924. $59^{\circ}05'5N$, $19^{\circ}37'E$. 96 m. Glass tube, 30 cm. Late-Glacial, very stiff clay.

Grey throughout, when wet stratified in lighter and darker layers from 1 cm to a few mm thick, colour differences being very slight. Seems stratified also when dry, probably finely varved. Coagulated partly during mechanical analysis. However it is evident that 18% were $> 5 \mu$, and at least 65 % $< 2 \mu$, small secondary max. is to be seen in $10-20 \mu$ group (see fig. 19). Organic matter 1.2 %, carbonates 2.45 %, no diatoms found.

F76A 1930 I. 99 m. Glass tube, 23 cm. Late-Glacial, very stiff clay.

An interesting sample which has characteristics both of a clay and a mud. While still in the tube, top of sample grey with black patches; divided, apparent biological stratification especially in top half; bottom, 4 cm, not stratified. When dry, top, 1.5 cm, was seen to consist of fine sand, rest had rust coloured crusts in clay, except in bottom part, which was purely grey. Bottom part shows certain signs of being varved, as there are some parallel convex cracks in dry clay. No mechanical analysis was made, but evidently as fine-grained as next sample taken at same locality, the dry clay being extremely hard. Divided into 4 parts: a) top, 1.5 cm, sand, b), c), d) about 7 cm each. Organic matter of b) c) and d) 1.0 %; no carbonates. Diatoms found at top and bottom of sand, and in clay just below sand, but not in rest of sample.

F76A 1930 II. 99 m. Iron tube. Late-Glacial, very stiff clay.

About 0.75 litre of dark grey clay with black lumps. These are, however the only mud characteristics of the sample. It is extremely fine-grained, the median being only 0.4μ ; 91 % are $< 2 \mu$, 80 % $< 1 \mu$ and 25 % consist of colloidal clay $< 0.2 \mu$. It constitutes the most fine-grained sample found in the Baltic. The organic content is only 1 %, there are no carbonates, nor were diatoms found. (Diagram 30).

F77 1925. 58°47'N, 19°07'E. 152 m. Glass tube, 24 cm. Late-Glacial, very stiff clay.

Top, 2 cm, sand mixed with clay, rest grey clay with a few darker streaks. In middle of profile a pebble, 0.5 cm in diameter. (Fig. 3). Size distribution of b), c), d) joined very similar to that of foregoing, median 0.5 μ , 84 % < 2 μ , 72 % < 1 μ , 23 % colloidal clay. Divided into four parts: a) sand, b), c), d) about 7 cm each. Organic matter of a) 1.2, of b), c), d) 1 %. No carbonates, no diatoms found. (Diagram 31).

F78 1924. 58°42'N, 18°26'E. 410 m. From the water sampler. Clayey mud.

From Landsort Deep. About 150 c.c. of black and grey mud. Size distribution resembling that of F75 1925; median 0.6 μ , 81 % < 2 μ and 65 % < 1 μ . Organic matter 3.6 %, no carbonates. Diatoms. (Diagram 48).

F79 1926. 58°27'N, 20°20'E. 105 m. Glass tube, 12 cm. Clayey mud.

Black and dark grey. Apparent biological stratification. Organic matter 5.6 %, carbonates 0.34 %. Top and bottom diatoms. No mechanical analysis.

F79 1928. 105 m. Iron tube, 175 gr dry weight. Late-Glacial, very stiff clay.

Though from same locality as foregoing very different from that sample. Examined when dry. Grey clay, extremely fine-grained, perhaps finely layered. Distribution curve of the type of F77 1925, median 0.55 μ , 80 % < 2 μ and 68 % < 1 μ . Organic matter 0.7 %, carbonates 0.43 %, small piece of limestone found in clay. No diatoms. (Diagram 32).

F79 1930. 117 m. Iron tube. Clayey mud.

About 0.3 litre of grey mud with black spots, similar to F79 1926. Distribution curve shows sample less well sorted than foregoing, maximum in clay group being much lower, but amount of colloidal clay, 23 %, higher than in any other sample examined. Median 0.6 μ , 70 % < 2 μ , and 60 % < 1 μ . Organic matter 4.7 %, no carbonates. Diatoms. (Diagram 69).

F80 1930 I. 58°0'N, 19°54'E. 189 m. Glass tube, 24 cm. Clayey mud.

Somewhat frothy because of gas formation during storage. Dark grey and black, biological stratification throughout. Divided into three parts: a), b), c) about 8 cm each. Organic matter a), b), c) 5.3 %. Carbonates in a) 1.68 %, b) 1.84 % and c) 2.47 %. Diatoms throughout. No mechanical analysis.

F80 1930 II. 189 m. Iron tube. Clayey mud.

About 0.3 litre of black mud. Somewhat coarser than preceding samples. Size distribution shows max. at 0.5—1 μ , median 1.1 μ ; secondary max. at 10—50 μ . Organic matter 5.8 %, carbonates 3.78 %. Diatoms. (Diagram 70).

F81 1926. 57°22'N, 19°57'E. 215 m. Glass tube, 12 cm. Clayey mud.

Greyish black throughout. Size distribution shows broad max. in clay group with 23 % of colloidal clay, also two secondary maxima, median 0.7 μ . Organic matter 8.0 %, carbonates 1.14 %. Top and bottom diatoms. (Diagram 71).

F81 1930 I. 220 m. Glass tube, 23 cm. Clayey mud.

Greyish black mud, somewhat darker in top half, which has biological stratification in black, greyish black and grey layers. Divided into three parts: a), b) and c), about 8 cm each. Organic matter of a) 6.7 %, b) 6.9 %, c) 9.9 %. Carbonates: a) 1.43 %, b) 0.95 %, c) 1.29 %, thus organic matter as well as carbonates unevenly distributed. Diatoms throughout. On top, shells of *Bosmina maritima* were found in abundance, but none at bottom. The distribution of *Bosmina* shells was therefore followed throughout profile. It was found that 16 cm below surface there were still entire shells, at 17 cm there were only claws left and lower down no distinct remains. However there occurred characteristic green flocks, which had the shape of shells. It thus seems as if the shells were gradually destroyed in the mud, disappearing after the length of time necessary for the formation of about 20 cm of sediment. As in most mud samples from the Baltic, pollen grains were found in all parts of the profile, here and at station F80 abundantly. No mechanical analysis.

F81 1930 II. 220 m. Iron tube. Clayey mud.

About 0.3 litre of greyish black mud. Size distribution similar to that of F81, 1926, median 0.8 μ . Organic matter 7.3 %, carbonates 1.32 %. Pollen abundant, but in spite of persistent search for diatoms in various samples, only one distinct diatom and a few fragments found. (Diagram 72).

23. ADDITIONAL LIST OF IRON CONCRETIONS.

Collected during various cruises of the s/s Nautilus.

1. F38 1904. 60°30'N, 28°25'E. 17 m.

Twenty gr of peashaped brown concretions of almost uniform size, about 0.5 cm in diameter.

2. Willingefjärd 1904. 60°10'N, 25°10'E.

210 gr of flat iron concretions from 1—5 cm in diameter, mostly formed around large pebbles as centres.

3. Porkala 1904. 59°58'N, 24°30'E. 21 m.

260 gr of flat round iron concretions up to about 5 cm in diameter.

4. Kobbaklintar —. 60°02'N, 19°56'E. 215 m.

A single, peashaped dark brown concretion from water sampler.

5. F48 1905. $59^{\circ}32'5''\text{N}$, $26^{\circ}54'\text{E}$. 36 m.

22 gr of oval peashaped concretions together with a few flat ones, 2—3 cm in diameter.

6. F43 1912. $60^{\circ}20'\text{N}$, $26^{\circ}58'\text{E}$. 38 m.

1.5 gr of small, peashaped concretions 2—3 mm in diameter.

7. Outside Hundören 1914. $60^{\circ}06'\text{N}$, $24^{\circ}52'\text{E}$.

160 gr of more or less flat, irregularly shaped, iron concretions.

8. F55 1923. $59^{\circ}37'5''\text{N}$, $25^{\circ}11'\text{E}$. Ca. 70 m.

3 gr of dark brown concretions 1 à 2 cm in diameter (manganese?).

24. LIST OF ANALYSES.

TABLE 19.

- (1) Designation of sample. (Position, bottom sampler used, length or weight of sample and fractions to be found from the List of Samples).
- (2) Depth in metres.
- (3) Percentage of oxygen saturation in bottom water, (within 1—2 metres from bottom). Mean of ten determinations on water samples collected during the summer cruises of the s/s Nautilus in the years 1922—1931 (64). When number of analyses less than ten, number given in brackets.
- (4) Salinity (‰) of bottom water when sample collected.
- (5) Salinity (‰) of air dry sample, calculated from chlorine content by application of factor 1.805.
- (6) Water content (‰) of air dry sample.
- (7) Minimum initial water content (‰) of sample in natural state, calculated from values in columns (4) and (5).
- (8) Organic carbon (‰).
- (9) Organic matter, from (8) by application of factor 1.724.
- (10) Nitrogen (‰). 1) Analysis by Dr TRASK.
- (11) Ratio C/N calculated from values in columns (8) and (10).
- (12) Carbon dioxide from carbonates (‰).
- (13) Carbon dioxide calculated as calcium carbonate.
- (14) Diatoms, + presence of, — diatoms not found.
- (15) General character, for terminology see p. 95.
- (16) Median of size distribution (μ).
- (17) Character of minerogen component on basis of distribution diagram, or estimated, when no mechanical analysis made.

Table

Consecutive number	(1) Station	(2) Depth m	(3) Bottom water		(5) Salinity ‰	(6) Water content		(8) Organic carbon %	(9) Organic matter %
			O ₂ %	Salinity ‰		air dry sample %	minimum initial %		
1	F1 1924 a)	35	90	3.10	0.18	0.51	37	0.60	1.0
2	b)	—	—	—	—	—	—	0.44	0.8
3	F1 1925	40	90	2.86	—	—	—	—	—
4	F1A 1925	53	—	2.77	0.19	0.62	41	0.77	1.3
5	F3 1925 a)	89	88	3.66	—	—	—	2.35	4.1
6	b)	—	—	—	—	—	—	2.24	3.9
7	F3 1928	107	88	3.77	0.72	—	66	2.56	4.4
8	F7 1925	77	89	3.60	0.09	0.20	20	0.25	0.4
9	F8 1925 a)	100	88	3.93	0.76	2.60	66	4.03	7.0
10	b)	—	—	—				3.32	5.7
11	F8 1929	93	88	3.91	—	—	—	3.01	5.2
12	F9 1924	96	88	4.18	0.44	—	51	2.88	5.0
13	F10 1924	66	85	3.75	—	—	—	1.22	2.1
14	F12 1925	112	89	4.11	1.00	2.74	71	3.13	5.4
15	F12 1927 a)	108	89	4.20	—	—	—	3.00	5.2
16	b)	—	—	—	—	—	—	3.05	5.3
17	F13 1924	64	(s) 94	3.68	0.27	0.74	42	1.34	2.3
18	F15 1926	48	(9) 95	4.70	—	—	—	0.40	0.7
19	F17 1925	31	(9) 90	5.25	—	—	—	0.33	0.6
20	F18 1925	91	79	5.97	0.79	0.54	57	1.89	3.3
21	F18 1928	100	79	5.93	1.05	2.28	64	2.03	3.5
22	F19 1925	179	75	6.37	0.99	1.66	61	2.22	3.8
23	F21 1925 a)	43	92	5.70	—	—	—	—	—
24	b)	—	—	—	0.28	1.00	33	0.49	0.8
25	F22 1925	125	78	6.33	—	—	—	—	—
26	F23 1925	130	(9) 76	6.26	0.76	1.73	55	2.00	3.4
27	F24 1925	198	75	6.37	0.98	2.00	61	1.93	3.3
28	F25A 1925	166	(s) 74	6.5	0.60	1.78	48	1.84	3.2
29	F26 1925	137	74	6.51	0.57	1.96	47	2.20	3.8
30	F28 1925 a)	54	89	5.75	0.39	1.26	—	0.23	0.4
31	b)	—	—	—	0.41	1.57	42	0.61	1.1
32	c)	—	—	—	0.37	1.42	—	0.58	1.0
33	F29 1925	104	(9) 89	6.40	0.63	1.76	50	2.28	3.9
34	F29A 1928	ab. 70	—	ab. 6.0	0.32	0.61	35	0.48	0.8
35	F30 1925	104	83	6.51	0.69	1.68	52	0.73	1.3
36	F30 1926	120	83	6.49	0.70	2.04	52	1.97	3.4
37	F30A 1928	ab. 100	—	ab. 6.4	1.26	2.79	66	2.05	3.5
38	F31 1924	62	94	5.57	0.11	0.52	17	0.29	0.5
39	F31 1925	60	94	5.54	0.13	0.45	19	0.50	0.9
40	F31A 1925 a)	ab. 35	—	—	—	—	—	—	—
41	b)	—	—	—	—	—	—	—	—
42	F31B 1925 a)	50 à 60	—	ab. 5.5	—	—	—	—	—
43	b)	—	—	—	0.12	0.67	18	0.25	0.4
44	F31C 1926 a)	64	—	—	—	—	—	0.61	1.1
45	b)	—	—	—	—	—	—	0.58	1.0
46	c)	—	—	—	—	—	—	0.63	1.1
47	F31E 1928	45	—	ab. 5.5	0.29	1.03	35	0.69	1.2

¹⁾ Analysis by Dr. TRASK.

19.

(10) Nitrogen %	(11) C/N	(12) Carbonates		(14) Diatoms	(15) General character	(17) Minerogen component		Consecutive number
		CO ₂ %	Calculated as CaCO ₃ %			Median μ	Character	
0.060	10.0	0.03	0	+	} Sandy mud	27	} dusty sand	1
—	—	0	0	+		—		2
—	—	0.03	0	+	very fine sand	62	very fine sand	3
0.067	11.5	0.03	0	+	sandy mud	21	dusty sand	4
—	—	0.23	0	+	} silty mud	—	} silt	5
—	—	0.04	0	+		—		6
0.28 ^a	9.1	—	—	—	silty mud	7	fine silt	7
—	—	0.02	0	+	fine sand	120	fine sand	8
—	—	—	—	+	} silty mud	2.9	very fine silt	9
—	—	—	—	+				10
0.29 ^b	10.4	—	—	—	mud	—	—	11
—	—	—	—	+	silty mud	3.2	very fine silt	12
0.081	15.1	—	—	—	sandy mud	—	very fine sand	13
0.24	13.0	—	—	+	silty mud	2.7	very fine silt	14
—	—	0.07	0	+	} silty mud	—	} silt	15
—	—	0.06	0	+		—		16
—	—	0.02	0	+	silty mud	17	coarse silt	17
—	—	—	—	+	very fine sand	90	very fine sand	18
—	—	—	—	—	sand	—	fine sand and gravel	19
—	—	0.05	0	+	clayey mud	2.0	stiff clay	20
0.21 ^b	9.7	0.02	0	+	clayey mud	2.0	stiff clay	21
0.22	10.1	0.07	0	+	clayey mud	1.4	stiff clay	22
—	—	—	—	+	sand	750	medium sand and pebbles	23
—	—	0.01	0	—	varved silt	3.0	} very fine silt and } very fine sand	24
—	—	—	—	—	fine sand and pebbles	100		25
—	—	—	—	+	clayey mud	1.5	stiff clay	26
0.19	10.2	0.02	0	+	clayey mud	1.2	stiff clay	27
0.19	9.7	0.02	0	+	clayey mud	1.5	stiff clay	28
0.23	9.6	0.03	0	+	clayey mud	0.93	very stiff clay	29
—	—	1.25	2.84	+	sand and clay	1.2	very stiff clay with sand	30
0.055	11.1	0.70	1.60	—	} indistinctly } varved clay	0.9	very stiff clay	31
0.054	10.7	0.82	1.86	—		1.0	very stiff clay	32
0.24	9.5	0.05	0	+	clayey mud	1.2	stiff clay	33
—	—	1.39	3.16	—	varved silt	7.5	very fine silt and dusty sand	34
0.060	12.2	0.19	0.43	—	varved? clay	0.75	very stiff clay	35
0.19	10.4	0.21	0.48	+	clayey mud	0.95	very stiff clay	36
0.20	10.3	0.10	0.23	+	clayey mud	1.1	stiff clay	37
—	—	18.3	41.6	—	dusty sand with coarse sand	25	dusty sand	38
—	—	0.02	0	—	fine sand	150	fine sand	39
—	—	0.24	0.55	+	fine sand and gravel	—	fine sand and gravel	40
—	—	10.4	23.7	—	dusty sand	—	dusty sand	41
—	—	3.1	7.0	—	} coarse silt with gravel	—	} coarse silt	42
—	—	ab. 16	36.5	—		16		43
—	—	0.40	0.91	+	sand	—	fine sand	44
—	—	3.45	7.84	—	} clay	—	stiff clay	45
—	—	13.9	31.6	—		—	clay	46
—	—	0.10	0.23	—	varved clay	30	stiff clay and very fine sand	47

Table 19

Consecutive number	(1) Station	(2) Depth m	(3) (4) Bottom water		(5) Sali- nity %	(6) (7) Water content		(8) Or- ganic carbon %	(9) Or- ganic matter %
			O ₂ %	Sali- nity ‰		air dry sample %	mi- nim- um initial %		
48	F32 1925 a)	67	93	5.50	—	—	—	1.12	1.9
49	b)	—	—	—	0.52	2.18	49	2.47	4.3
50	F32 1926 a)	67	93	5.50	—	—	—	1.39	2.4
51	b)	—	—	—	—	—	—	3.43	5.9
52	c)	—	—	—	—	—	—	3.80	6.6
53	F32A 1926 a)	68	—	ab. 5.5	—	—	—	0.49	0.8
54	b)	—	—	—	—	—	—	0.71	1.2
55	c)	—	—	—	—	—	—	0.61	1.1
56	d)	—	—	—	—	—	—	0.58	1.0
57	e)	—	—	—	—	—	—	0.63	1.1
58	F33 1925 a)	106	92	6.53	—	—	—	0.34	0.6
59	b)	—	—	—	—	—	—	0.56	1.0
60	c)	—	—	—	0.17	1.94	21	0.60	1.0
61	d)	—	—	—	—	—	—	0.64	1.1
62	F33 1926 a)	79	92	6.55	—	—	—	0.38	0.7
63	b)	—	—	—	—	—	—	0.65	1.1
64	c)	—	—	—	—	—	—	0.61	1.1
65	d)	—	—	—	—	—	—	0.61	1.1
66	F36 1924	13	(5) 65	0.73	0.43	4.40	85	3.94	6.8
67	F37 1924	27	(9) 58	4.51	0.27	1.89	37	1.30	2.2
68	F37 1925	25	58	5.03	—	—	—	4.46	7.7
69	F38 1924	28	(8) 60	5.41	—	—	—	1.48	2.6
70	F40 1924	40	(9) 50	6.17	0.70	3.12	53	3.30	5.7
71	F40 1925	37	50	6.06	0.63	3.40	51	3.31	5.7
72	F41 1924	51	(6) 48	6.8	1.10	4.37	62	2.64	4.6
73	F42 1924	61	(9) 48	7.07	0.93	—	57	2.87	5.0
74	F42 1928	64	48	6.94	0.61	2.17	47	0.41	0.7
75	F43 1924	38	55	6.65	—	—	—	3.27	5.6
76	F43 1925 a)	38.5	55	6.00	—	—	—	0.76	1.3
77	b)	—	—	—	0.31	1.28	34	0.40	0.7
78	F43A 1924 a)	ab. 25	—	—	—	—	—	—	—
79	b)	—	—	—	—	2.22	—	0.33	0.6
80	F44 1924 a)	63	(7) 50	7.12	—	—	—	1.81	3.1
81	b)	—	—	—	} 1.03	3.80	59	3.53	6.1
82	c)	—	—	—				3.63	6.3
83	F45 1924 a)	72	50	7.30				1.61	2.8
84	b)	—	—	—	0.62	2.89	46	2.94	5.1
85	F49 1924	84	(9) 36	7.61	—	—	—	1.01	1.7
86	F49 1925	85	36	8.95	1.25	3.13	58	2.07	3.6
87	F50 1924 a)	85	(9) 36	8.04	—	—	—	2.35	4.1
88	b)	—	—	—	0.72	3.17	47	2.24	3.9
89	F52A 1925 a)	41	(9) 77	6.22	—	—	—	0.69	1.2
90	b)	—	—	—	—	—	—	0.64	1.1
91	F53 1924	80	(9) 48	7.79	0.76	3.52	49	2.21	3.8
92	F54 1924	90	(9) 31	8.39	0.50	2.12	37	0.61	1.1
93	F54 1925	108	31	8.28	0.19	0.36	19	0.70	1.2
94	F55 1924	90	(9) 32	8.57	0.69	2.32	45	0.42	0.7
95	F56 1924 a)	85	(8) 33	9.00	} 0.64	2.31	42	1.88	3.2
96	b)	—	—	—				2.09	3.6
97	F56 1925	81	33	9.80				1.02	1.85

(continued).

(10) Nitrogen %	(11) C/N	(12) Carbonates		(14) Diatoms	(15) General character	(16) (17) Minerogen component		Consecutive number
		CO ₂ %	Cal- culated as CaCO ₃ %			Median μ	Character	
0.10	11.2	0	0	+	sand	—	fine sand	48
0.23	10.7	0.06	0	—	clayey mud	1.3	stiff clay	49
0.092	15.1	0	0	+	sand	—	very fine sand	50
0.28	12.2	0	0	+	} clayey mud	—	} stiff clay	51
0.33	11.5	0	0	+		—		52
—	—	0	0	+	very fine sand	—	very fine sand	53
} 0.069	9.1	0	0	—	} indistinctly varved clay	—	} stiff clay and very fine silt	54
		1.74	3.96	—		—		55
		3.09	7.02	—	} indistinctly varved clay	—	} stiff clay	56
		5.17	12.4	—		—		57
—	—	1.65	3.75	—	fine sand	250	fine sand	58
0.041	13.7	13.0	29.5	—	} indistinctly varved clay	1.0	} stiff clay	59
—	—	13.0	29.5	—		—		60
—	—	12.3	27.9	—	fine sand	—	fine sand	61
—	—	1.61	3.66	—	} indistinctly varved clay	—	} stiff clay	62
—	—	8.65	19.7	—		—		63
—	—	10.1	23.7	—	} indistinctly varved clay	—	} stiff clay	64
—	—	13.0	29.6	—		—		65
0.34	11.6	—	—	+	silty mud	3.7	very fine silt	66
0.096	13.5	—	—	+	silty mud	3.5	very fine silt	67
0.59	7.6	—	—	+	clayey mud	—	clay	68
0.13	11.4	—	—	+	sand	—	very fine sand	69
0.36	9.2	0	0	+	clayey mud	2.0	stiff clay	70
0.29	11.4	0	0	+	clayey mud	2.0	stiff clay	71
—	—	0.26	0.59	+	silty mud	2.4	very fine silt	72
0.31	9.3	0.24	0.55	+	mud	—	—	73
0.055)	8.2	0.10	0.23	—	very stiff clay	0.62	very stiff clay	74
0.32	10.2	0	0	+	mud	—	—	75
—	—	0	0	+	fine sand	330	fine sand	76
—	—	0	0	—	varved silt	6	coarse silt and very stiff clay	77
—	—	—	—	—	sand	—	sand	78
—	—	0	0	—	very stiff clay	0.62	very stiff clay	79
—	—	0	0	+	} clayey mud	—	} stiff clay	80
} 0.36	10.0	—	—	+		1.4	} stiff clay	81
		—	—	+	sandy mud	—		82
—	—	—	—	+	clayey mud	0.90	very stiff clay	83
0.25	11.8	0.03	0	+	clayey mud	—	fine sand	84
—	—	0	0	—	silt	—	very stiff clay	85
0.18	11.5	0.04	0	+	clayey mud	1.14	stiff clay	86
—	—	—	—	+	} clayey mud	—	} very stiff clay	87
0.21	10.7	0.04	0	+		0.93		88
—	—	—	—	+	clay and sand	—	clay and sand	89
0.021	30	0	0	—	varved clay	—	clay, silt	90
0.21	10.5	0.04	0	+	clayey mud	0.72	very stiff clay	91
—	—	0	0	—	varved clay	1.1	very fine silt and very stiff clay	92
0.049	14.3	0.04	0	—	fine sand	250	fine sand	93
—	—	0.32	0.72	—	very stiff clay	0.55	very stiff clay	94
} 0.21	9.5	0.58	1.31	+	} clayey and sandy mud	} 8.0	} clay with dusty sand	95
		1.16	2.64	+				96
—	—	—	—	+	clayey and sandy mud	11	clay with dusty sand	97

Table 19

Consecutive number	(1) Station	(2) Depth m	(3) (4) Bottom water		(5) Sali- nity %	(6) (7) Water content		(8) Or- ganic carbon %	(9) Or- ganic matter %
			O ₂ %	Sali- nity ‰		air dry sample %	mi- nimum initial %		
98	F56 1928	80	33	9.43	1.71	1.97	65	1.84	3.2
99	F57 1924 a)	88.5	(5) 26	8.77	0.87	2.55	50	2.46	4.2
100	b)	—	—	—	—	—	—	2.55	4.4
101	F57 1925	104	26	9.38	0.87	2.52	48	1.42	2.5
102	F59A 1924	48	70	7.41	0.40	1.94	35	0.63	1.1
103	F61 1924	101	(8) 18	10.17	1.15	3.72	53	2.35	4.1
104	F61 1925	98	18	10.07	—	—	—	2.72	4.7
105	F61 1928	95	18	9.83	1.59	2.62	62	2.25	3.9
106	F62 1924 a)	82.5	(8) 29	8.06	—	—	—	1.48	2.6
107	b)	—	—	—	0.57	1.92	41	1.52	2.6
108	c)	—	—	—	—	—	—	2.96	5.1
109	Pojo V 1926	36	—	4.83	0.76	3.62	61	2.94	5.1
110	Pojo XI 1926	28	—	6.19	—	—	—	3.61	6.2
111	F64 1925	294	(9) 84	6.82	0.62	2.93	48	0.63	1.1
112	F64 1928	288	84	7.00	0.66	2.63	49	2.48	4.3
113	Lumparen I 1926 ..	16	—	—	0.97	3.07	—	2.49	4.3
114	Lumparen II 1926 ..	18	—	—	0.56	2.48	—	2.16	3.7
115	Lumparen III 1926 ..	18.5	—	—	—	—	—	2.22	3.8
116	Lumparen IV A 1926 ..	18	—	—	—	—	—	2.70	4.7
117	Lumparen IV B 1926 ..	18	—	—	—	—	—	3.00	5.2
118	F65A 1928	72	—	6.62	0.87	2.31	57	0.90	1.6
119	F65B 1925 a)	66	—	—	—	—	—	0.82	1.4
120	b)	—	—	—	0.53	2.07	—	1.19	2.1
121	F66 1924	80	(1) 81	6.60	0.79	2.61	55	2.18	3.8
122	F67 1926	210	(9) 87	6.87	—	—	—	2.45	4.2
123	F67 1930 I	210	87	6.83	—	—	—	2.73	4.7
124	F67 1930 II	210	87	6.83	1.16	3.21	63	2.41	4.2
125	F68 1925	122	86	6.69	1.04	3.13	61	2.10	3.6
126	F68 1928	120	86	6.76	2.01	3.00	75	2.38	4.1
127	F69 1925	150	64	8.08	1.05	3.23	56	2.09	3.6
128	F69 1930	169	64	8.22	1.11	2.86	57	2.04	3.5
129	F71 1925	155	10	9.56	1.43	2.70	60	2.13	3.7
130	F71 1929	156	10	9.87	—	—	—	2.01	3.5
131	F71 1930	155	10	9.49	1.66	2.78	64	1.74	3.0
132	F72 1924 a)	124	(9) 20	10.35	0.97	2.54	48	2.72	4.7
133	b)	—	—	—	1.21	2.92	54	2.84	4.9
134	F73 1924	87	(6) 71	10.05	0.82	2.23	45	1.83	3.2
135	F74 1925	176	(9) 23	9.20	1.53	3.10	62	2.40	4.1
136	F74 1930 I a)	195	23	10.35	—	—	—	1.09	1.9
137	b)	—	—	—	—	—	—	0.60	1.0
138	c)	—	—	—	—	—	—	0.61	1.0
139	d)	—	—	—	—	—	—	0.60	1.0
140	e)	—	—	—	—	—	—	0.58	1.0
141	F74 1930 II	195	23	10.35	0.75	1.84	42	0.60	1.0
142	F75 1925	178	(8) 22	ab. 10	1.18	3.10	54	2.47	4.3
143	F76A 1924	96	(9) 28	9.90	0.79	2.55	44	0.71	1.2

(continued).

(10) Nitrogen %	(11) C/N	(12) Carbonates		(13) Cal- culated as CaCO ₃ %	(14) Dia- toms	(15) General character	(16) (17) Minerogen component		Consecutive number
		CO ₂ %					Median μ	Character	
—	—	1.36	3.09	+	+	clayey and sandy mud	5.8	clay with dusty sand	98
0.22	11.2	0.85	1.94	+	+	} clayey mud	2.0	} stiff clay	99
—	—	0.46	1.05	+	+		—		100
0.15	9.5	0.88	2.00	+	+	clayey mud	1.2	stiff clay	101
0.029	22	0.04	0	—	—	varved? clay	0.85	very stiff clay	102
0.25	9.4	0.62	1.41	+	+	clayey mud	1.0	very stiff clay	103
—	—	0.62	1.41	+	+	clayey mud	—	very stiff clay	104
0.24 ⁴)	9.4	0.67	1.52	+	+	clayey mud	0.8	very stiff clay	105
0.19	7.8	1.12	2.55	+	+	} clayey and sandy mud	—	} clay with fine and dusty sand	106
0.20	7.6	1.35	3.07	+	+		20		107
0.30	9.9	0.75	1.70	—	—	clayey mud	—	very stiff clay	108
0.31	9.5	0.10	0.23	+	+	clayey mud	0.84	very stiff clay	109
0.41	8.8	0.05	0	+	+	clayey mud	—	very stiff clay	110
0.104	6.1	0.03	0	—	—	very stiff clay	0.51	very stiff clay	111
0.28	8.9	0.03	0	+	+	clayey mud	0.95	very stiff clay	112
0.28	8.9	0.02	0	+	+	clayey mud	0.90	very stiff clay	113
0.27	8.0	0	0	+	+	clayey mud	1.4	stiff clay	114
0.26	8.5	0	0	+	+	clayey mud	—	stiff clay	115
0.30	9.0	0	0	+	+	clayey mud	—	stiff clay	116
—	—	0	0	+	+	clayey mud	—	stiff clay	117
0.08 ⁴)	11.3	0.04	0	+	+	clayey mud	0.83	very stiff clay	118
—	—	—	—	—	—	sand	250	fine sand with gravel	119
0.12	9.9	0.03	0	—	—	varved clay	1.6	dusty and very fine sand, very stiff clay	120
0.31	7.0	0.08	0	+	+	clayey and sandy mud	4.9	very stiff clay with dusty and very fine sand	121
0.31	7.9	0	0	+	+	clayey mud	—	very stiff clay	122
0.33	8.3	0.10	0.23	+	+	clayey mud	—	very stiff clay	123
—	—	0.09	0.20	+	+	clayey mud	0.90	very stiff clay	124
0.21	10.0	0	0	+	+	clayey mud	1.1	stiff clay	125
0.28	8.5	0	0	+	+	clayey mud	1.0	very stiff clay	126
0.29	7.2	0.08	0	+	+	clayey mud	1.6	very stiff clay with dusty sand	127
0.23	8.9	0.02	0	+	+	clayey mud	1.5	very stiff clay with dusty sand	128
0.22	9.7	0.15	0.34	+	+	clayey mud	1.3	stiff clay	129
0.22	9.1	0.09	0.20	+	+	clayey mud	—	stiff clay	130
0.26	6.7	0.10	0.23	+	+	clayey mud	1.2	stiff clay	131
0.27	10.1	1.74	3.96	+	+	clayey mud	2.1	very fine silt	132
—	—	1.55	3.53	+	+	clayey mud	2.0	very fine silt	133
0.24	7.6	2.76	6.27	+	+	clayey and sandy mud	11.0	very stiff clay with dusty sand	134
0.31	7.7	0.47	1.07	+	+	clayey mud	0.8	very stiff clay	135
0.086	12.7	1.01	2.30	+	+	clayey mud	—	—	136
—	—	2.02	4.59	—	—	} varved? clay	—	} very stiff clay	137
—	—	1.74	3.96	—	—		—		138
—	—	2.39	5.43	—	—	} varved? clay	—	} very stiff clay	139
—	—	1.19	2.71	—	—		—		140
—	—	1.14	2.60	—	—	varved? clay	—	very stiff clay	141
—	—	0.12	0.27	+	+	clayey mud	0.67	very stiff clay	142
—	—	1.08	2.45	—	—	varved? clay	—	very stiff clay	143

Table 19

Consecutive number	(1) Station	(2) Depth m	(3) (4) Bottom water		(5) Sali- nity ‰	(6) (7) Water content		(8) Or- ganic carbon %	(9) Or- ganic matter %
			O ₂ %	Sali- nity ‰		air dry sample %	mi- nimum initial %		
144	F76A 1930I a)	99	28	9.51	—	—	—	—	—
145	b)	—	—	—	—	—	—	0.91	1.6
146	c)	—	—	—	—	—	—	0.90	1.6
147	d)	—	—	—	—	—	—	0.91	1.6
148	F76A 1930II	99	28	9.51	0.84	3.10	47	0.60	1.0
149	F77 1925 a)	152	(3) 23	10.59	—	—	—	0.72	1.2
150	b)	—	—	—	} 0.69	2.30	39	0.60	1.0
151	c)	—	—	—				0.62	1.1
152	d)	—	—	—				0.66	1.1
153	F78 1924	410	(4) 25	10.64				2.09	3.6
154	F79 1926	105	(9) 24	10.55	—	—	—	3.24	5.6
155	F79 1928	105	24	10.68	0.77	2.01	42	0.41	0.7
156	F79 1930	117	24	10.17	1.32	3.12	56	2.75	4.7
157	F80 1930I a)	189	(8) 12	11.37	—	—	—	3.08	5.3
158	b)	—	—	—	—	—	—	3.05	5.3
159	c)	—	—	—	—	—	—	3.06	5.3
160	F80 1930II	189	12	11.37	2.72	3.91	70	3.38	5.8
161	F81 1926	215	(8) 8	12.27	1.77	3.63	59	4.64	8.0
162	F81 1930I a)	220	8	11.98	—	—	—	3.88	6.7
163	b)	—	—	—	—	—	—	4.00	6.9
164	c)	—	—	—	—	—	—	5.72	9.9
165	F81 1930 II	220	8	11.98	2.27	3.67	65	4.23	7.3

(continued).

(10)	(11)	(12) Carbonates		(13)	(14)	(15)	(16)		(17) Minerogen component	Consecutive number
Nitrogen %	C/N	CO ₂ %	Cal- culated as CaCO ₃ %	Diatoms	General character	Median μ	Character			
—	—	0.07	0	+	fine sand	—	fine sand	144		
0.085	10.7	0.05	0	—	} varved? clay	—	} very stiff clay	145		
0.100	9.0	0.06	0	—		—		146		
—	—	0.04	0	—	} very stiff clay sand	—	} very fine sand	147		
—	—	0.02	0	—		0.40		148		
—	—	0.06	0	—	} very stiff clay	—	} very stiff clay	149		
} 0.046	13.7	0.09	0	—		} 0.48		150		
				—				151		
0.22	9.5	0.04	0	+	clayey mud	0.61	very stiff clay	152		
0.31	10.5	0.15	0.34	+	clayey mud	—	very stiff clay	153		
0.07 ¹	5.9	0.19	0.43	—	very stiff clay	0.55	very stiff clay	154		
—	—	0.03	0	+	clayey mud	0.58	very stiff clay	155		
0.29	10.6	0.74	1.68	+	} clayey mud	—	} stiff clay	156		
—	—	0.81	1.84	+		—		157		
—	—	1.09	2.47	+	} clayey mud	—	} stiff clay	158		
0.31	10.9	1.66	3.78	+		1.15		159		
0.62	7.5	0.50	1.14	+	clayey mud	0.70	very stiff clay	160		
0.40	9.7	0.63	1.43	+	} clayey mud	—	} very stiff clay	161		
—	—	0.42	0.95	+		—		162		
0.83—	7—12	0.57	1.29	+	} clayey mud	—	} very stiff clay	163		
0.47				+		—		164		
—	—	0.58	1.32	+	clayey mud	0.84	very stiff clay	165		

VI. DISCUSSION.

25. ORGANIC MATTER AND CHARACTER OF SEDIMENTS.

In the preceding chapter the general character of the sediments of the Baltic has already been described. It was pointed out that in many cases an examination under the microscope is sufficient to determine to which of the two outstanding groups, late-Glacial or post-Glacial sediments, a sample should be assigned. A purely statistical treatment of the analyses of organic matter reveals how well defined and different from each other these two groups actually are. Transitional types form exceptions. That is why the organic matter content will be discussed now, even before the distribution of the sediments has been described. As to the latter, it may merely be noted in this connection that late-Glacial and post-Glacial sediments occur side by side, that late-Glacial clays are found at all depths, and finally that only in great outline is a relation between character of sediments and topography of the sea bottom to be discerned. At localities where late-Glacial clays are still found at the surface of the sea bottom, where consequently no post-Glacial sediments have been deposited, sedimentation since late-Glacial times has either been interrupted or the localities in question have been subjected to erosion, supplying the material for post-Glacial sediments in the neighbourhood. The former is more probable in localities where the sediments consist of that fine-grained and unstratified clay which forms the uppermost part of varved clays where the series of late-Glacial sediments is complete. At such places sedimentation was practically interrupted when the excessive supply of mineral detritus ceased in consequence of the withdrawal of the ice-sheet. Just as late-Glacial clays are still found uncovered by younger deposits, so we may expect *Ancylus* and *Litorina* sediments to form the surface layer of the bottom. But besides the ready sediments we would expect transitional types, especially as regards the content of organic matter. A gradual change in conditions of settling, marked by a gradual rise in the organic matter content of the sediments, would be the natural development. Very few of the samples examined allow of such conclusions. As may be seen from the List of Analyses, some late-Glacial clays, of which several fractions were analyzed separately, show a somewhat higher content of organic matter in the uppermost part (F32A, F74 1930I), which part may therefore be interpreted as a transitional

zone, but in post-Glacial sediments organic matter, on the contrary, generally increases with depth in sediment¹⁾. With a few exceptions which will be discussed below, we find in the area investigated either late-Glacial sediments or fully developed post-Glacial ones.

The adequateness of the statements given above is seen from Fig. 23, which contains all the analyses of organic matter statistically arranged. Along the abscissa the different values of organic matter occurring in the sediments, from 0 to 8 %, are marked by points and above each point as many circles for clays or silts, and as many crosses for sands, as the number of corresponding analyses. Laminated, unlaminated and diatom containing samples are marked in different ways. The figure contains all analyses recorded in the List of Analyses, but equal values found in adjacent parts of a sample and obviously referring to the same kind of deposit are quoted only once. A single high value 9.9 %, referring to F81 is not included. It will be seen that the values referring to silts and clays form two principal groups, one comprising values below 1.5 %, the other values above 3 %. Between the two there is a very small transitional group. To the

¹⁾ Information given to Dr PARKER D. TRASK (115 p. 207) to the effect that organic matter in the Baltic decreases with depth in sediment, was sent when only part of the samples had been analyzed and the final results could not yet be surveyed.

first group belong only diatom free samples, to the second, with two exceptions, only such as contain diatoms; moreover, with only one exception, all more or less distinctly laminated samples belong to the first group. The sharp difference between late-Glacial and post-Glacial sediments could not be illustrated more clearly. A closer examination of the transitional group (diatoms, mechanical composition) reveals that samples F37 1924, F13, F57 1925, F62 and F56 1925, with organic contents above 2.2, undoubtedly belong to the post-Glacial group. As to the others, which refer to stations F76A 1930 I, F74 1930 Ia), F65A, F65B and F49 1924, all, except the last, belong to localities freed from ice just before or during the Yoldia period, and thus perhaps reflect the change in organic life which followed on the opening of the connection with the Ocean over Central Sweden at Mount Billing. In that case they would represent the only truly transitional types between late-Glacial and post-Glacial sediments. The value 1.7 referring to F49 in the Gulf of Finland forms an exception. It was included for the sake of completeness, but refers to an insignificant sample, only 2 cm long, consisting of coarse silt with some gravel. Comparison with F49 1925 shows that it is most probably post-Glacial. The nature of the samples in the intermediate group will be treated more fully below (Section 26).

The present writer is unaware whether a sharp difference in organic content between late-Glacial and post-Glacial sediments may also be observable in sediments now occurring on land; especially in post-Glacial deposits, forming the surface layer of the soil, changes caused by the influence of the atmosphere, by the vegetation or by leaching, may have given rise to intermediate values filling up the gap between the two groups. The existence of this gap, when only such sediments are considered as have been permanently covered by water, reveals, beside the mere fact that there are two distinct groups of sediments, the marked change which occurred in the balance between inorganic and organic sedimentation when late-Glacial sedimentation came to an end.

In spite of the scarcity of recognizable organic remnants in late-Glacial clays, analysis invariably reveals the presence of organic matter in the sediments, and thus of organic life in the water from which they were deposited. The organic content of late-Glacial sediments varies within very narrow limits. Most clays examined contained 1.0 % or 1.1 %, silty kinds, obviously deposited nearer to the ice-margin, somewhat less. Four extremely fine-grained samples, F42 1928, F43A 1924, F55 1924 and F79 1928, which judging from the localities where they were taken, date from the time of the Baltic

Ice lake, were found to hold 0.7 %, F43A 1924 even 0.6 % only. The balance between inorganic and organic sedimentation at some distance from the ice-margin (i. e. where fine-grained, only indistinctly varved sediments were deposited) thus led to a sediment containing roughly 1 % of organic matter. In post-Glacial sediments, on the other hand, the normal balance seems to have been 3—4 % in fine-grained specimens, and 2—3 % in sandy ones. Higher values are obviously due to accumulation and may be accounted for by a consideration of the special conditions at the place of deposition. The well-known fact that organic matter tends to accumulate on the bottom of basins and in sheltered bays near land is well illustrated by the organic contents of the muds investigated. At the same time the influence of currents is noticeable and gives the explanation why in certain basins no accumulation seems to take place. The survey of the distribution of the different kinds of deposits given in Section 26 will best show these relationships. If about 4 % is taken as the «normal» value of post-Glacial muds, this means that the latter contain about four times as much organic matter as late-Glacial clays. It seems admissible to suppose that the decrease in inorganic sedimentation, when post-Glacial conditions set in, was at least equally large.

Thus the remarkable post-Glacial increase in organic matter does not necessarily imply a change in the biological conditions of the water, but may be ascribed to the decrease in inorganic sedimentation. Only from comparisons within the same group of sediments, whether late-Glacial or post-Glacial, are any conclusions as to changes in biological conditions possible, as only in that case may the inorganic component be considered as constant and safely left out of consideration.

As for the lack of recognizable organic remnants, especially diatoms, in late-Glacial deposits, as against the abundance in post-Glacial ones, attention may be drawn to the well-known scarcity of diatoms in Arctic as well as Antarctic sediments (PHILIPPI 69, 87, BÖGGILD 12 and recently STETSON 102) in spite of the abundance of them in the overlying water. It is true that the comparison is somewhat imperfect in that sea-water, even Arctic, is highly saline, whereas the waters of the Glacial period were soft, but conditions in the vicinity of an ice border may exercise an influence which cannot now be estimated. Very little is known as to distribution of dissolved silicates in sea-water and factors influencing it, and consequently in what circumstances solution of silica may be expected.

In this connection there is reason to touch upon a circumstance, which may have been important. The favourable climatic conditions

which on land followed at some distance upon the retreating ice margin and gave rise to a rich vegetation, cannot from an oceanographical point of view be considered to have *eo ipso* influenced life production in the sea, unless at the same time the supply of nutrient salts in the latter was increased. This is evident from modern investigations of marine biological conditions (see e. g. HARVEY 43) which have shown that life in the sea from the lowest to the highest forms, depends on the presence in the water of minute quantities of nutrient salts, chiefly phosphates and nitrates. These are necessary primarily for the growth of planktonic algae, which serve as food for marine animals, and thus indirectly for all forms of life in the sea. Where these stuffs are not present in sufficient quantities — in present day oceanic sea water the amounts of them range from a few milligrams to a couple of hundreds per cubic metre — the water is poor in organic life, and favourable conditions of temperature and light have then no influence. Thus in the tropics the surface water is almost depleted of nutrient salts throughout the year owing to lack of vertical mixing and consequently plankton production is many times smaller here than in higher latitudes, where an upwelling of water rich in nitrates and phosphates takes place, although in high latitudes production is limited to the summer months only. Arctic sea temperatures, 1° — 4° , on the other hand, are not inimical to life production where sufficient amounts of nutritious salts are available. As long as life in the Baltic Ice Lake depended on whatever nutrient salts might be brought down by ice water currents and affluents its quantitative increase can only have been very slow and improvement of climate alone could not augment it. A considerable change could only be brought about by connection with the ocean with its enormous supply of food stuffs. Thus as long as the Närke Sounds existed the amount of nutrient salts in the Baltic increased, and when the connection finally was cut off the newly formed Ancylus Lake started its existence with a greater supply of them than that of the former Ice Lake. What the addition meant in comparison to the already existing supply, and what share it had in the post-Glacial increase of organic matter in the sediments, cannot be estimated, as simultaneously the velocity of inorganic sedimentation underwent that radical change which was a consequence of the transition from late-Glacial to post-Glacial conditions.

An interesting feature of late-Glacial clays is the layer of more or less fine sand, generally from 1 to 2 cm thick, by which most of them are covered. Out of 18 late-Glacial samples collected with the SJÖSTEDT glass tube sampler (showing original order of layers), 13 or 72 % were covered by sand. On the other hand out of 41 post-Glacial

muds only 3 or 7 % had a distinct sandy layer on top. Samples from the Bothnian Bay, where no late-Glacial deposits were met with, or from the Bay of Wiborg, as well as purely sandy specimens collected elsewhere, are not included in these figures. The surface sand on late-Glacial sediments sometimes contains diatoms and may have an organic content up to 1.4 %, but generally holds much less. Post-Glacial muds covered by fine sand were collected northwest of the Finngrundén banks in the Bothnian Sea at F32, 67 m, where the sand contained 1.9 % and 2.4 % of organic matter, and further at F45, 72 m, just south of Hogland Island, where as much as 2.8 % was noted. In the diagram Fig. 23 the post-Glacial sands together with the sandy muds in the Bothnian Bay and the Bay of Wiborg form a distinct group, separated from the «late-Glacial sands» with their low content of organic matter.

The simplest explanation of the fact that the sand occurs almost exclusively on late-Glacial deposits would be to ascribe its origin to some late-Glacial catastrophical event causing currents of an unusual transporting capacity. This thought would find support in a circumstance pointed out by SAURAMO (94) and BRENNER (15), i. e. that in the extensive clay fields of Southwestern Finland a more or less sandy layer is almost invariably found at the limit between post-Glacial and late-Glacial sediments. But as surface sand is found in the Gulf of Finland as well as in the Baltic and in the Bothnian Sea even as far north as at F21, it could not be ascribed to one and the same late-Glacial event, but two or three different events would have to be assumed to account for it. If we consider, on the other hand, that, owing to the upheaval of land, the depth of the North Baltic of to-day is about 150 metres less than at the end of the late-Glacial period and its area considerably smaller, it is clear that littoral sands washed out from the coast are transported much further down now than in earlier periods. Part of the sand may derive its origin from late-Glacial clays, which in the vicinity of the coast are more easily liable to destruction than in deeper water. The fine-grained parts of these clays are transported further out and deposited where in post-Glacial times conditions have been favourable for the formation of fine-grained sediments. The bottom specifications on nautical charts, which are too uncertain to be of use for estimating the distribution of late-Glacial and post-Glacial clays, can probably be relied upon as to the distribution of sands. Fine sands may be taken for clays; but the opposite cannot be the case. On examining such a chart we find that all the localities, where sand covered late-Glacial clays have been found, are within fair distance of sandy deposits. In some cases, at

stations far from land, the sand may be very fine (F76 and F77) or even lacking (F74).

If upheaval of land is supposed to account for the presence of sand, where at late-Glacial times only clay was deposited, then sand ought to occur on most post-Glacial muds as well. But considering the generally much looser consistency of the mud it is probable that sand grains would not accumulate on top of it, but would gradually sink into it and become mixed up with it. Only on comparatively compact sediments could a distinct layer of sand accumulate. Nevertheless, a certain amount of fine sand ought to be present in the majority of muds. As a matter of fact the distribution diagrams (Fig. 37—39 p. 198) of muds generally show a certain content of dusty and very fine sand. In some cases distinct sandy layers have been found within post-Glacial muds, (F56, F62, F66, F72 and F73, see next section). That the sandy component is independent of the rest of the sediment is revealed by the distribution diagrams of the very fine-grained Baltic muds, which often have two maxima, the principal one below $2\ \mu$ and a small secondary maximum in the dusty sand group ($20\text{--}50\ \mu$). The minimum between the two is generally to be found in size-group $10\text{--}20\ \mu$.

A natural explanation of the «top sand» is thus to declare it a more or less recent effect of the upheaval of land. In that case we must conclude that practically the whole of the Baltic is at present within reach of sands.

On the basis of the statistical diagram (Fig. 23) of the analyses of organic matter, it was concluded above that the «normal» or fundamental amount occurring in fine-grained post-Glacial sediments is 3—4 %, and that higher amounts are due to accumulation, where favourable conditions have prevailed. This assumption is of course a very crude generalization of a complicated question. The survey in the following section will show that the «normal» value occurs especially in depressions over which currents prevent excessive accumulation of organic matter. The «normal» value is thus in a way a minimum value. The factors influencing it and organic matter content on the whole are for biologists to discuss. The problem involves many questions of general bearing. First of all the «mud» or «gyttja» problem, which in this connection might be defined by the following question: Is the organic content (in air dry samples) of a grey mud, with the outward appearance of a clay as to composition and rate of decomposition, comparable to that of a black gelatinous looking mud? In the List of Samples there are many instances which prove that clay-like muds may have a much higher organic content than loose black

specimens. Another problem of interest is that of the influence of grain size. It has repeatedly been stated above that »fine-grained» post-Glacial as well as late-Glacial sediments contain more organic matter than the corresponding »coarse-grained» ones. But no precise definition was given as to which is in this connection the difference between »fine-» and »coarse-»-grained sediments. As for post-Glacial deposits, the difference is noticeable between sands on the one hand and silts and clays on the other; whereas among late-Glacial sediments there is a small difference between clays and silts, while the more or less recently deposited »top sand» may contain about as much organic matter as the clays, but holds considerably less than sandy muds. The difference between sands and other sediments was brought out in Fig. 23 by marking the analyses referring to sandy samples in a different way from the others, but no attempt was made to show the difference numerically, (e.g. by mean values) the material being too uniformly fine-grained for that purpose. However TRASK (115) has also established that a relation exists between texture and organic content of sediments. He compared 80 samples from the Channel Islands region outside California as to their content of nitrogen, (which he considers as an equally good indicator of organic matter as organic carbon) and found that clays contained about four times as much as sands and twice the amount of silts. Even if the same relation does not hold good in the Baltic, still the observations on the Baltic material are confirmed.

Summary.

A statistical diagram (Fig. 23) reveals that there is a marked difference in organic matter content between late-Glacial and post-Glacial sediments. Late-Glacial clays contain less than 1.5 % of organic matter, post-Glacial muds 3—4 %, sometimes more. Transitional types with organic contents from 1.5 to 3 % are very rare. This is explained as a consequence of the changed balance between inorganic and organic sedimentation, which followed the withdrawal of the ice border from a certain locality. When the excessive supply of glacial detritus ceased, inorganic sedimentation became suddenly very much slower than before. Even if organic sedimentation remained the same, its share in the sediments must have increased considerably. — After the opening of the Närke Sounds over Central Sweden the amount of nutrient salts in the Baltic increased and thus organic life may have become richer too. The lack of recognizable organic remnants, especially diatoms, in late-Glacial clays is mentioned and reference made to the fact that Arctic as well as Antarctic sediments are

known to be very poor in diatoms, although these occur abundantly in the overlying water. — The occurrence of sand on top of most late-Glacial clays is explained as an effect of the upheaval of land. In loose post-Glacial muds the corresponding recent addition of sand is revealed by a small secondary maximum in the distribution diagram. — It is shown that organic matter content is influenced by grain size, clays as a rule containing more than silts and these more than sands.

26. ORGANIC MATTER AND DISTRIBUTION OF SEDIMENTS.

In the preceding section the importance of analyses of organic matter for classification of Baltic sediments was emphasized. It was found that late-Glacial and post-Glacial sediments form two outstanding groups which have to be discussed independently of each other. The reasons for the variations in organic content in late-Glacial sediments have to be looked for in the early history of the Baltic i. e. the events which accompanied the melting of the ice-sheet after the last glaciation. In comparison with this the topography of the sea bottom seems to have been of lesser importance; a comprehensible fact considering the very much greater depth of the Baltic at that period (about 100 metres more than at present at the height of Gotland, and at least 200 metres in the Bothnian Bay, see SAURAMO 94). Since the definite improvement in climate, which caused and followed the melting of the ice, conditions in the Baltic have, indeed, varied but have remained the same in character. The most notable change, which took place at the close of the Ice Age, was the radical decrease of inorganic sedimentation. The excessive supply of inorganic detritus, formed by the action of the ice-sheet on the underlying bedrock, was exhausted and afterwards new deposits were formed only from the normal products of erosion and from such parts of late-Glacial deposits as were disaggregated again by wave action or currents. Inorganic sedimentation in the sea now became much slower than before, and this led to a new equilibrium between inorganic and organic sedimentation, an equilibrium in which the share of organic sedimentation was about four times greater than formerly. However, part of the change may have been due to the influence which the new post-Glacial conditions exercised on organic sedimentation.

The conditions influencing the distribution of organic matter in post-Glacial sediments are essentially those still active at the present day. The only factor which has changed notably since the beginning of post-Glacial sedimentation is that of depth. But depth being a relative, not an absolute factor, this circumstance is more important

Fig. 24. Vertical sections of the Gulf of Bothnia, the Gulf of Finland and the North Baltic. Figures at surface indicate hydrographical stations; at bottom, mean saturation percentage of oxygen in bottom water.

in the coastal region than in the open sea where the majority of the samples now examined were taken. As already pointed out in the preceding section, post-Glacial sediments illustrate the well-known fact that organic matter tends to accumulate at the bottom of basins and in sheltered bays near land, and in addition the influence of currents is clearly noticeable. The latter even seem to be the most important factor, as in cases where depth and currents act in opposite directions, currents are apt to have the greater influence. This is comprehensible considering the slight inclination of slopes in the Baltic, the gradient of the steepest slopes being only about 1 : 50 (see Fig. 24).

Since the opening of the connection with the ocean through the Danish Sounds in the Litorina period, circulation in the Baltic may be

trusted to have taken place essentially in the same way as at present. Before describing the distribution of late-Glacial and post-Glacial sediments over the area investigated, a survey will therefore be given of the present circulation in the Baltic as revealed by modern investigations. For this purpose Fig. 25 was borrowed from a work by PALMÉN (81) treating current measurements made on board Finnish, Swedish and Estonian light vessels during the years 1923—1927. A similar picture is presented by the current charts in the Atlas of Finland (32) 1910 computed by WITTING on earlier

Fig. 25. Resulting circulation in the Baltic. Length of arrows indicate strength of resulting current; a length of 0.2 cm corresponds to a velocity of 1 cm/sec.

material and that of 1925 (PALMÉN). The surface water in the Baltic has a low salinity owing to abundant admixture of soft water from the many rivers, which fall particularly into the Gulf of Bothnia and the Gulf of Finland. Circulation depends on the outward moving tendency of the surface water of low salinity, the inward moving depth current of high salinity through the Danish Sounds and, finally, the deviation to the right, caused by the rotation of the earth. The resulting movement of the water masses is, on the whole, a horizontal circulation of a cyclonal character, no pronounced difference existing between the movement of the surface and the depth water. In the Gulf of Bothnia prevailing winds contribute to the maintenance of the circulation observed. Fig. 25 refers to the resulting circulation; at any particular period the currents thus may present a picture quite different from that of the figure. The arrows show the direction and the strength of the resulting current. A length of 0.2 cm corresponds to a velocity of 1 cm/sec. The numbers are relative values for the stability of the current (for particulars see original paper). The highest stability and at the same time the greatest velocities occur in the Åland Sea and along the Swedish coast in the North Baltic. Here we have resulting velocities up to 5 cm/sec; the actual velocities, even in the depth, may be many times greater. In the Gulf of Bothnia the inward movement takes place along the Finnish, the outward movement along the Swedish side. In the Gulf of Finland the inward current has more or less the character of a depth current along the deeper Estonian side, the outward current that of a surface current along the shallower Finnish side. The currents are strongest along the coasts; in the middle of the basins we find areas with practically no currents, which may be regarded as eddies on a large scale. Such areas occur in the Bothnian Bay, the Bothnian Sea, the inner part of the Gulf of Finland and in the Baltic above the Gotland Deep (not shown in the figure). These act as centres of accumulation, and here we find the highest amounts of organic matter. It may be noted that these centres do not necessarily coincide with the deepest parts of the basins.

Below, the distribution of the different kinds of deposits over the area investigated will be described and an attempt will be made to explain the variations occurring in the organic matter content.

The distribution is shown in Fig. 26 and 27, the symbols of which are easily understood. Considering to begin with the Gulf of Bothnia, north of the threshold at the North Kvark, we find that here only post-Glacial sediments occur. Round the coasts there are sands or sandy muds with comparatively low organic contents. Further out

Fig. 26. Content of organic matter in Baltic sediments

organic matter increases with depth, being about 1 % at F1, 4 % at F3 and from 5 to 7 % at F8, F9 and F12, the depth at the four latter stations reaching about 100 m. Here the sediments are finer, but still retain a silty character — a lower median than 2.7μ has not been met with in the Bothnian Bay. At F13, 64 m there is sandy mud again with 2.3 % of organic matter, at F15, 48 m and F17, 31 m pure sands. South of the Kvarck we find station F18 in an isolated depression which goes down to about 100 m. However, in two samples from F18 the organic content did not exceed 3.5 %. Likewise in the Hårnösand Deep, the greatest depression (see Fig. 1) in the Gulf of Bothnia, which reaches nearly 300 m, no higher value than 3.8 % was found. At F24, 198 m, we have 3.3 %, at F19, 179 m 3.8 %, at F23, 130 m 3.4 % and at F25A, 166 m 3.2 %. This is remarkable considering the much greater depth here than in the depression north of the Kvarck, where at F8, 100 m, an organic content up to 7 % was noted. A consideration of the current chart, Fig. 25, affords an explanation: the middle of the Bothnian Bay is a centre of accumulation, where organic matter gathers in excess of the normal amount, whereas over the Hårnösand Deep strong currents on the contrary prevent accumulation. Similar phenomena were met with in the Baltic over the depressions at F71 and F78.

In spite of its character of accumulation centre the high amount of organic matter in the central basin of the Bothnian Bay is all the same remarkable. According to HESSLE (47) the production of bottom animals is very poor in the whole of the Bothnian Bay (and in the Bothnian Sea below a depth of 50 m), and, as for plankton, LEVANDER (57) states that the Bothnian Bay is almost sterile. BUCH (17) saw the reason for this in a marked lack of phosphates in the water of the Gulf of Bothnia on the whole, and especially in the Bothnian Bay. On the other hand, the ammonia content is rather higher both at the surface and especially in the depth than elsewhere in the Baltic and the supply of nitrate quite sufficient for plankton production. BUCH supposed the origin of the nitrogen to be humus stuffs which in great quantity are brought down by the rivers from the extensive peat-bogs of Northern Finland. These humus compounds sooner or later precipitate and become mineralized, delivering part of their nitrogen to the water. The examination of the bottom muds gives support to BUCH's hypothesis. Not only is the percentage of organic matter remarkably high considering the lack of plankton and bottom animals, but also the composition of the mud points to terrigenous rather than to marine origin. As will be shown in Section 26, the ratio between carbon and nitrogen in the bottom muds is higher in the Bothnian

Bay than elsewhere in the Baltic, the mean value being 11.5 against 10.2 in the Gulf of Finland and 9.1 in the Baltic proper. TRASK found a mean C:N ratio of 8.4 in marine deposits, while the mean for soils is 10 and that for peat much higher (KIVINEN 52). The high value in the Bothnian Bay would thus imply a strong influence of land humus.

As a sign of the scarcity of plankton in the Bothnian Bay may finally be noted that in a sample, F3 1925 containing 4.4 % of organic matter, in spite of persistent search for diatoms, none were found.

Proceeding south from the North Kvarck we find at F21, 43 m, near the Finnish coast, the first specimen of varved silt, covered by sand. It is more remarkable that sand and pebbles still occur at F22 at a depth of 125 m. The sample from this station was taken from the water sampler and nothing therefore can be said about the character of the bottom underneath. A fact of geological interest is that the sand contained pebbles of sandstone and well rounded quartz grains. — Unfortunately only one sample was taken from the middle part of the Bothnian Sea, from station F26, 137 m. It proved to be a post-Glacial mud with 3.8 % of organic matter. — A few samples collected on section F28 to F32 contained in part high amounts of carbonates. As the Bothnian Sea is known to conceal a Silurian area, sediments taken in this region are of unusual interest. From this reason about 20 samples in all were collected at and between the regular stations. Not far from the Finnish coast were taken two late-Glacial samples with a slight carbonate content: a very fine-grained specimen from F28, 54 m and a somewhat coarser varved silt from F29A, about 70 m. Next come F29 and F30A from an isolated depression, which goes down to about 100 m. Both were almost carbonate-free post-Glacial muds with 3.9 and 3.5 % of organic matter respectively. At F30 late-Glacial and post-Glacial sediments occur side by side. In 1925 a very fine-grained diatom-free late-Glacial clay with 1.3 % of organic matter was taken here from a depth of 104 m, while in 1926, at 120 m, was found a diatom-containing sample with an entirely different distribution of particle sizes and 3.4 % of organic matter. Similar cases have been met with elsewhere (F64, F74, F79, F42, F43) and bring to mind the distribution of late-Glacial and post-Glacial sediments in the extensive clay fields of Southwestern Finland. AARNIO (2) states that the character of the sediments in the coastal region (below the 50 m isobase) varies notably within small areas. At some places post-Glacial sediments seem preferably to have gathered at the bottom of valleys and small depressions, while at others no relation to the topography of the place of deposition is discernible. It is obvious

that a similar distribution of the sediments in the sea may render illusory the bottom specifications on nautical charts, especially when the difference in origin is accompanied by a marked difference in exterior, as was noted for instance at F30. The post-Glacial specimen, judged by the outward properties, would undoubtedly have been described as a mud; while the late-Glacial sample was clearly a clay. The occurrence of late-Glacial clay in the central depression of the Bothnian Sea, as in other depressions in the Baltic, shows that post-Glacial sediments, though preferably gathering at the bottom of slopes, are not necessarily predominant here, but are probably, as on land, confined to restricted areas, the extension of which depends on local conditions (topography, currents, etc.). This circumstance also shows the scarcity and accidental character of post-Glacial sedimentation at localities which after the Ice Age have been permanently covered by water.

West of F30 follow a number of late-Glacial samples collected north of and in the vicinity of the East Bank of the Finngrundén. The majority of these have a high content of carbonates, up to 40 %, for which reason they will be treated in detail in Section 30, treating the Silurian area of the Bothnian Sea. How far north and south the carbonate-containing sediments extend, has not been ascertained, but at F26A, lat $61^{\circ}30'$, a few pebbles of limestone were collected and at F33, lat $60^{\circ}33'.5$, a clay with 30 % of carbonates, while the late-Glacial sample of F64, proved to be lime-free. Northwest of the Finngrundén two samples of post-Glacial mud were collected at F32, 67 m. Both were covered by a thin layer of sand which contained about 2 % of organic matter while the mud held 4.3 and 6.6 % respectively. An interesting feature of this mud was the evenly brownish grey colour and lack of black lumps, in spite of the high organic content.

In the Åland Sea samples were collected at F64, 288 and 294 m, F67, 210 m, F68, 120 m and F69, 150 and 169 m, all of which were post-Glacial with organic contents from 3.5 to 4.7 %, with the exception of the already mentioned late-Glacial duplicate sample from F64, 294 m.

From its outward appearance the latter sample was first considered as post-Glacial. It was grey with black lumps which gave part of it an appearance of being biologically stratified, and the black lumps, when treated with hydrochloric acid, gave out a strong smell of hydrogen sulphide. However, it was found to be entirely sterile, when examined as to its content of diatoms and the organic matter content was only 1.1 %. The sample was thus no doubt of late-Glacial origin. The abundant occurrence of ferrous sulphide is possibly due

[Fig. 27. Distribution of sediments in the Baltic. Figures indicate median of size distribution (μ).

to a later immigration of the various bacteria necessary for its production, perhaps under the influence of post-Glacial sediments in the vicinity. A late-Glacial clay collected at F76A in the North Baltic presented the same peculiarity (see below).

The rather surprising occurrence of late-Glacial clay at F64, in the deepest part of the Åland Sea, may possibly be explained by the fact that the Åland Sea is an area of strong currents which in the deep channel, where F64 is situated, go right down to the bottom. A sign of circulation at this depth is the high amount of oxygen in the bottom water, the mean saturation percentage being 84 % (Table 19); which shows that the water here is constantly being renewed.

In the Archipelago three samples were collected which, though interesting in themselves, of course do not give any idea of the general distribution of sediments here. These were F65A, 72 m, F65B, 66 m, and F66, 80 m. F65A was a fine-grained sample containing a few diatoms, but with an organic content of 1.6 % only; F65B contained no diatoms and was distinctly varved, but had 2.1 % of organic matter underneath the top sand and F66, finally, seemed varved, but contained diatoms and 3.8 % of organic matter. All three consequently had characteristics both of late-Glacial and post-Glacial sediments. From the discussion of size distribution types in Section 32 it will appear that F65A has a typically post-Glacial distribution and consequently in spite of the low organic content cannot be late-Glacial; the late-Glacial character of F65B is, on the other hand, proved by two distinct maxima in the distribution diagram (diagram 22 Fig. 33) and by the absence of diatoms and, finally the post-Glacial character of F66 is shown by the high organic content and abundance of diatoms.

In the Bay of Lumparen, which stretches far into the Island of Åland, five samples, Lumparen I—IV, were collected from depths of 16—18 m with a view of ascertaining whether the bottom muds here contain carbonates, an outcrop of Silurian limestone having been discovered on the bottom near shore. These samples, however, proved to be entirely lime-free post-Glacial muds with organic contents from 3.7 to 5.2 %, the highest amount being found in the innermost part of the bay.

In the Gulf of Finland, as elsewhere in the Baltic, the hydrographical stations are preferably situated over depressions. For this reason the post-Glacial samples collected here are probably more numerous in comparison to the late-Glacial ones than would have been the case if more samples had been taken from slopes and ridges. East of Hogland Island most post-Glacial sediments have high amounts

of organic matter. Thus we find 5.7 % at F40, 40 m, 4.6 % at F41, 51 m, 5 % at F42, 61 m, 5.6 % at F43, 38 m, up to 6.3 % at F44, 63 m and 5.1 % at F45, 72 m, while west of this lower values mostly occur. The inner part of the Gulf is a natural centre of accumulation; here a rich growth of plankton develops every spring on the store of nutrient salts brought from the depths of the Baltic by the inflowing water which rises here to the surface (BUCH 17). After the end of the vegetation period part of the plankton deposits here, and part is carried by the outflowing surface water into the Baltic, where it sinks to the bottom, adding to the high amounts of organic matter there. However, even in the middle of the Gulf, east of Hogland Island, late-Glacial deposits are met with. In addition to the post-Glacial mud mentioned above, a very fine-grained late-Glacial clay was collected at F42, with only 0.7 % of organic matter. Further north another late-Glacial clay, almost identical as to mechanical composition, was taken at F43A about 25 m, and finally a more coarse grained varved silt at F43, 38.5 m.

In the Bay of Wiborg the sediments are comparatively coarse-grained and contain in part very high amounts of organic matter, 6.8 % having been found at F36, 13 m and 7.7 % at F37, 25 m.

Late-Glacial deposits would probably have been found in abundance if more samples had been collected along the Finnish coast. As it is, samples were taken on three cross sections: F43 to F45, F52A to F55 and F58 to F62, as well as in the middle of the Gulf on a longitudinal section from F40 to F61 (see Fig. 1). On section F52A to F55 only one sample, F53, 80 m, proved to be post-Glacial; while F52A, 41 m and F54, 90 m were finely varved clays with 1.1 % of organic matter, and F55, 90 m a very stiff clay with only 0.7 %, like that at F42. On section F58 to F62 there was sand at F58, 36 m, outside Hangö; late-Glacial clay at F59A, 48 m; and post-Glacial mud at the deeper stations near the Estonian coast, F61, about 100 m, and F62, 82.5 m. The organic contents of the post-Glacial muds on the longitudinal section west of Hogland Island were 3.6 % at F49, 4.0 % at F50, 2.8—3.6 % at F56, 2.5—4.4 % at F57 and 3.9—4.7 % at F61, thus on the whole lower than in the innermost part of the Gulf.

Two samples from the Bay of Pojo, east of Hangö, were both post-Glacial with high amounts of organic matter, 5.1 % and 6.2 % resp. They resemble in this respect the muds in the Bay of Lumparen and the Bay of Wiborg. Obviously the nearness of land and the sheltered position accounts for the high organic content.

In the Baltic proper, samples were taken at eleven hydrographical stations, F71 to F81, most of them situated over more or less deep

depressions. In spite of this fact late-Glacial clays were collected at four stations, viz. at F74, 195 m, F76A, 96 and 99 m, F77, 152 m and F79, 105 m. At two of these, F74, 176 m and F79, 105 and 117 m, post-Glacial muds were found as well. We thus meet in the middle of the Baltic the same phenomenon as in the Bothnian Sea and the Gulf of Finland, i. e. late-Glacial and post-Glacial sediments occur side by side and even in depressions the late-Glacial clay is not entirely covered by younger deposits.

Two late-Glacial samples taken on the same occasion at F76A presented the same peculiarity as the late-Glacial clay from F64. Both were grey with black lumps and seemed to be biologically stratified. The organic content in one was unusually high for a late-Glacial sample, being 1.6 % throughout (top sand not considered); but the other had the normal amount of 1.0 % only. The absence of diatoms and the mechanical composition (diagram 30, Fig. 33) definitely proved their late-Glacial origin. Another late-Glacial sample from the same station differed from the two others in that it was purely grey and contained 2.45 % of carbonates, organic content being 1.2 %. The other late-Glacial samples collected in the Baltic were likewise purely grey; those from F74 and F77 had 1 % of organic matter, with the exception of the top parts which held 1.9 and 1.2 % respectively. The organic content of sample F79 1928 was 0.7 % only. Judging from its position this sediment was deposited during the Baltic Ice Lake period, that is before the opening of the connection with the Atlantic over Central Sweden. In accordance with this the organic content was low, and almost exactly the same as at stations F55, F42 and F43A, the sediments of which undoubtedly date from the Ice Lake period (see successive positions of ice-margin, SAURAMO 94). Equally low organic amounts have not been found elsewhere in fine-grained late-Glacial clays. If the amount of 1 % is considered as characteristic of sediments deposited after the drainage of the Baltic Ice Lake, then sedimentation at F77, F74, F59A and F54 had not yet been interrupted, when the drainage occurred. The distance of these points from the supposed position of the ice-margin is about 50 km, and from F79 about twice that distance. DE GEER (22) states that clay deposited after the final drainage is more brown in colour than earlier formed clay. Without wanting to draw any conclusions from a single observation, it may be stated that the top part of glass tube sample F74 1930I, the length of which was 36 cm, was, when wet, to a depth of 13 cm, more brownish in colour than the rest. The topmost fraction of this sample (7 cm), however, also presented another peculiarity, in that it contained 1.9 % of organic matter, in which

respect it resembled sample F76A 1930I containing 1.6 % throughout and a specimen collected further north in the Archipelago, F65B 1925, which was distinctly varved and contained 2.1 % underneath the top sand (see page 147). These values seem to mark the climax of organic life during the Yoldia period during which oceanic water entered into the Baltic. Later, organic life in the vicinity of the ice border seems to have declined somewhat, judging from the fact that the fine-grained late-Glacial clays collected in the Bothnian Sea again have the normal organic content of about 1 %.

As for post-Glacial sediments in the Baltic, the highest amount of organic matter was found in the Gotland Deep, where at F81, 220 m, from 6.7 % to 9.9 % were noted. North of this we find from 5.3—5.8 % at F80, 189 m, 4.7—5.6 % at F79, 117 and 105 m, 4.3 % at F75, 178 m, 4.1 % at F74, 176 m, 3.2 % at F73, 87 m, thus a slow decrease with decreasing depth, but no proportionality. At F72, 124 m, situated north of Dagö Island, not far from F73, but about 40 m deeper, organic matter increases to 4.7—4.9 %. The two latter samples present a peculiarity already mentioned as regards F66. In spite of the high organic content and abundance of diatoms, these samples were distinctly stratified in finer and coarser layers; the same was noted at stations F62 and F56. In four of the cases observed, the locality of collection was thus situated at the mouth of the Gulf of Finland, on the Estonian side where the depth current from the Baltic is strongest; and these localities were all similar in character, being situated at the bottom of depressions not far from shallow water. We must conclude that sedimentation here has been uneven, that at times when currents or wave action have been particularly strong a considerable amount of coarse grains have been washed out from the coastal region and transported to the foot of the slope, where normally only clay particles are deposited. The sand found on late-Glacial deposits may be due to a similar intermittent sedimentation.

A few words remain to be said about the sediments at F71 and F78. In both cases we should expect high organic contents. F71 is situated in a small depression reaching down to 155 m, just outside the Bogskär Lighthouse in the North Baltic. The bottom water here is stagnant and often entirely depleted of oxygen. We should expect organic matter to be washed down here and to accumulate at the bottom. All the same in three samples, collected at different occasions, contents of only 3.0—3.7 % were found, thus not above the «normal» post-Glacial amount. Likewise, in the deepest depression of the Baltic, the Landsort Deep or hydrographical station F78, 410 m, an organic content of only 3.6 % was found. In this case only one sample was

examined; others may have revealed higher contents. However, if we consider that above Landsort Deep occur some of the strongest currents observed in the Baltic, the comparatively low amount becomes comprehensible.

From the foregoing description it is evident that the bottom samples collected are not numerous enough to allow of general conclusions as to the extension of the areas within which late-Glacial and post-Glacial sediments occur. But it is clear, on the other hand, that a very great number of samples would have been needed for that purpose. The fact that in six cases late-Glacial as well as post-Glacial sediments were collected at the same station, thus at theoretically the same point, shows this most clearly. We must conclude that post-Glacial sediments do not form large continuous areas, but are distributed more or less in patches, even in depressions. We should for instance expect post-Glacial sediments to fill the narrow northern depression of the Åland Sea, which goes down to 300 m, but even here a late-Glacial clay was collected. A study of the bottom specifications on nautical charts confirms the impression of the extreme variety of the bottom. We cannot, however, make use of such charts to determine the distribution of the sediments, as the terms «clay» and «mud» used for fine-grained sediments cannot simply be identified with «late-Glacial» and «post-Glacial», as has been done in this work. If we did so, our own «muds» would in many cases appear as sole representatives of their kind within large areas of «clays», and even *vice versa*. The distinctions «mud» and «clay» obviously refer to colour and consistency of the sediments, typical mud being loose and black and typical clay firm and grey. On Swedish charts appears a third term, «slick», which is probably neither a clay nor a mud, but that mixture of both as to outward appearance, of which so many instances have been met with in the present work. A decision as to which of the three kinds a small sample, caught in the hollow of the sounding lead, should be assigned, cannot be easy and in practice is probably often rather accidental. It is all the same striking that on charts of the Bothnian Sea and the Baltic the term «clay» appears much more frequently than «mud» or «slick». On the latest Finnish chart of the Bothnian Sea (1926, scale 1 : 350 000) the terms «clay» and «mud» appear 142 times in all between latitudes 60°30' and 63°30', of which «clay» forms 73 % and «mud» 27 % of the total number. On a Swedish chart (1882, scale 1 : 500 000) of the North Baltic «clay» forms even 83 % of the 306 cases of «clays», «slicks» and «muds» between latitudes 57° and 59°30' (Bay of Riga not included). In spite of the vagueness of the terminology this circumstance may perhaps be regarded as a

support of the view expressed above, that post-Glacial sediments as a matter of fact do not occupy large or continuous areas.

In the Gulf of Finland conditions seem to be different. The terms »clay» and »mud» appear 129 times in all east of long. 23° on the latest Finnish chart (1922, scale 1 : 285 012), but of these only 9 or 7 % refer to »clay». In the Gulf of Finland »mud» thus seems to be predominant among the fine-grained sediments. But here a circumstance must be taken into account, the influence of which in the Baltic proper is not as manifest. The terms »sand» and »stones» occur on the chart even more frequently than »mud»; but it is obvious that this sand often forms only a thin layer on top of fine-grained sediments. This is evident from the fact that many sand-covered late-Glacial clays, when placed in position on the chart, come to be surrounded by »sands» and further that, as repeatedly mentioned, all late-Glacial samples collected, with a few exceptions only, were covered by sand (a few centimetres thick). Thus late-Glacial clays no doubt occur much more abundantly in the Gulf of Finland than appears from the few scattered cases when the bottom is specified as clay on nautical charts.

On the basis of the available material it is thus impossible to trace in detail the areas within which the various kinds of deposits occur in the North Baltic and its bays. We must content ourselves with the general description given above and the survey on Fig. 27.

Summary.

The distribution of late-Glacial and post-Glacial sediments is described (Fig. 27). Post-Glacial sediments occur preferably in depressions and in sheltered bays near land. But even in depressions late-Glacial deposits are found at the surface of the bottom. The organic content of post-Glacial sediments is influenced by currents. Circulation in the Baltic is described. In the Bothnian Bay only sands and post-Glacial muds have been found; in the Bothnian Sea muds occur in the Härnösand Deep, at F32, and in the central depression; in the south part of the latter, late-Glacial clay has also been met with. On section F28 to F32 several late-Glacial samples with a high carbonate content were collected, likewise at F33. In the Gulf of Finland post-Glacial muds occur preferably in the innermost part and in the deep channel along the Estonian side. In the Baltic special areas for late-Glacial and post-Glacial deposits cannot be traced. At two stations, F74 and F79, both kinds were collected; at two others only late-Glacial clay, and at the rest post-Glacial sediments. In the Åland Sea and the Archipelago most samples were post-Glacial. Three late-Glacial clays from the North Baltic had about 2 % of organic matter, while

1 % is the rule; this is ascribed to increase of organic life in the sea as a result of opening of connection with the Ocean over Central Sweden at the beginning of the Yoldia period. Some post-Glacial samples collected in the deep channel leading into the Finnish Bay were distinctly laminated. Ascribed to intermittent sedimentation, sands being washed out from the coast when water particularly agitated because of storms or strong currents. — Nautical charts cannot be made use of for determining distribution of sediments, as the terms »clay» and »mud», used for fine-grained sediments, cannot be relied upon to coincide with »late-Glacial» and »post-Glacial», even if in many instances this may be the case.

27. ORGANIC MATTER AND DEPTH IN SEDIMENT.

In the preceding section no mean values of organic matter in different kinds of deposits or in different parts of the Baltic have been given. One of the reasons for this was the very varying value of the different analyses as an indicator of the average amount of organic matter in the sediments. Some analyses refer to small glass tube samples, a few centimetres in length, while others were made on long cores taken with the iron tube and presumably representing the average of the entire sample. In some cases a sample was divided in several parts, each of which was analyzed separately. When different parts were found to contain widely differing amounts, obviously because of different origin or different texture, it became clear that average values calculated on such diverse material would not be very exact. In Fig. 23 the difficulty was overcome by introducing all the different analyses (with certain restrictions, see p. 131), whether they referred to the whole of a sample or to a part of it. Each analysis was thus considered to belong to a different deposit. This brought out clearly the fundamental difference between late-Glacial and post-Glacial sediments, but the same procedure could not be followed in calculating mean values, as some samples would then have entered into the mean with several values; while other much bigger samples would have occurred only once. Even if only the mean value of each sample had been entered into the general mean, there would still have remained the great disparity in size between the samples; some referring only to a thin surface layer of the bottom, others reaching deep into it. A mean value calculated on such premises would have been entirely devoid of the exactitude it alleged. The existing relationships, and the order of magnitude of the organic content in different kinds of deposits, are all the same fully evident from the survey in the foregoing section and from Fig. 23.

Below will be presented in Table 20 a number of cases in which several analyses were made on different parts of samples taken with the glass tube sampler. In some cases the analyses refer to samples with different coloured layers, at least outwardly uniform as to grain-size; in a few others to seemingly uniform cores. The table contains the data for post-Glacial sediments only. In the List of Analyses are to be seen several similar series of analyses referring to late-Glacial clays; but the variations occurring in these proved to be so small as to lie almost within the analytical errors. Down to the depths reached by the glass tube sampler (about 20—35 cm), late-Glacial clays may be said to be uniform as to organic content. Two exceptions found in the North Baltic have already been treated in the foregoing section.

As for post-Glacial sediments, the analyses seem to indicate that organic matter within the first 20 cm of the bottom decreases with depth in sediment in the Bothnian Bay, but increases with depth elsewhere in the area investigated. The analytical material refers to 12 samples only, and the result therefore cannot be taken as definitive, though it finds support in the distribution of colours in the samples, which likewise points to a difference between the Bothnian Bay and the rest of the area.

Most samples taken in the Bothnian Bay were more or less brown or greyish brown in colour to a depth of 2 à 4 cm (probably more near shore); then below this oxidized surface layer followed a dark grey layer, which in samples from the middle of the bay turned into black about 15 cm below the surface. The existence of the brown surface layer is confirmed by HESSLE (47), who points out that the bottom along the Swedish coast, especially in the north part of the Bothnian Bay, is reddish brown from limonite. South of the North Kyvark this brown layer is lacking, the muds found at the deep stations in the Bothnian Sea being mostly dark grey with or without black lumps and biological stratification. If below this dark grey layer a black one follows, it begins deeper than 15 à 20 cm in the mud. In the Gulf of Finland the succession of colours is different. Here the surface layer is black (1—4 cm), then follows a dark grey layer, mostly with biological stratification, and finally a greenish or brownish grey layer much lighter in colour, beginning from 5 to 15 cm below the surface. This colour change was observed at the following stations: F40, F42, F44, F45, F50, F56, F57 and F62. Only in a few cases were the sediments evenly dark grey without biological stratification, and in a few others the top part was brownish. But the general character of muds in the Gulf of Finland may be said to be that just described. The mud found at F72 in the Baltic also belongs to this type. The

other muds in the Baltic and the Åland Sea were all black or very dark grey and black; nowhere did the bottom sampler reach down to a lighter layer, similar to that found in the Gulf of Finland. The top part of a sample taken at F64 was evenly greyish brown.

Table 20. *Distribution of organic matter with depth in sediment.*

Sample	Character of minerogen component	Colour of layer	Thickness of layer cm	Organic matter %	Difference %
F1, 1924	a) } dusty sand	brown	11	1.0	-0.2
	b) }	grey	5	0.8	
F3, 1925	a) } silt	brown	3	4.1	-0.2
	b) }	grey and black	14	3.9	
F8, 1925	a) } very fine silt	grey	4	7.0	-1.3
	b) }	dark grey and black	9	5.7	
F32, 1926	a) } very fine sand	—	2	2.4	+0.7
	b) }	dark grey	6	5.9	
	c) } stiff clay		6	6.6	
F44, 1924	a) }	black	1.5	3.1	+3.0
	b) } stiff clay	grey and black	6	6.1	+0.2
	c) }	brownish grey	3.5	6.3	
F50, 1924	a) } very stiff clay	brownish grey	1	4.1	-0.2
	b) }	dark grey	15	3.9	
F56, 1924	a) } clay with	black	6	3.2	+0.4
	b) } dusty sand	brownish grey	6	3.6	
F57, 1924	a) } stiff clay	dark grey	11	4.2	+0.2
	b) }	brownish grey	2	4.4	
F62, 1924	a) } clay with	black	2	2.6	+2.5
	b) } fine and	dark grey	13	2.6	
	c) } dusty sand	brownish grey	2	5.1	
F72, 1924	a) } very fine silt	black and dark grey	11	4.7	+0.2
	b) }	brownish grey	6	4.9	
F80, 1930I	a) }	grey and black	8	5.3	
	b) } stiff clay	» » »	8	5.3	
	c) }	» » »	8	5.3	
F81, 1930I	a) }	grey and black	8	6.7	+0.2
	b) } very stiff clay	» » »	8	6.9	
	c) }	» » »	8	9.9	

Returning now to Table 20, we find that light-coloured layers, whether in the Bothnian Bay or the Gulf of Finland, are always comparatively richer in organic matter than adjoining dark or black layers. Consequently organic matter decreases with depth in sediment in the Bothnian Bay and increases in the Gulf of Finland. One exception to the latter rule was found at F50, which also deviates as to colour succession, for the higher value refers to the brownish surface layer, 1 cm thick!

The sediments in the Bothnian Bay thus seem to follow the general rule established by TRASK, to the effect that marine deposits, on an average, lose 15 % of their organic matter within the first 30 cm.

Slow decomposition with time or increased rate of decomposition at »dark mud»-forming conditions, or both, may be the explanation. In the Gulf of Finland and the Baltic, the situation is more complicated. It is true that in all cases an increase is noticeable in the lowest light-coloured layer in comparison to the layer above, but in one case, F44 1924, a much greater increase occurred within the dark layers, the thin black surface layer of this sample containing 3.1 %, the dark grey layer 6.1 % and the brownish grey one 6.3 %. In one other case an equally high increase, from 2.6 to 5.1 %, was observed, viz. at F62; but in this case the light-coloured layer held the highest amount. In the Baltic increase with depth, but without colour change, was observed at F81, while a sample from F80 was uniform down to 24 cm in the mud. Three equally thick layers (8 cm) at F81 held 6.1, 6.9 and 9.9 % respectively; the latter was the highest organic amount noted anywhere in the area investigated. At F32 in the Bothnian Sea increase was noted within a uniformly grey mud, one of the samples taken here containing 5.9 % beneath the surface sand, and 6.6 % somewhat lower in the mud.

Increase of organic matter with depth in sediment has thus been observed in 1) black muds, 2) uniformly grey muds, 3) partly dark grey and brownish grey muds, in the last case independently of the colour limit and simultaneously with it. The increase thus occurs at the most varied conditions, which suggests that it is a phenomenon independent of the processes involved in the colour change, i. e. independent of the biological conditions of the sediment. As in each case only one analysis of the dark part of samples from the Bothnian Bay was made, the question remains open whether within this part increase of organic matter occurred. From the available material, it appears, however, that there have been two influences acting in opposite directions upon the organic content of the muds; one being the decrease with depth caused by time of burial and biological conditions (bacteria, lack of oxygen), and the other the increase with depth due to changed conditions of sedimentation.

The fact that the first of these influences is noticeable especially in the Bothnian Bay may be due to the good aeration of the water throughout this basin, since even the bottom water is saturated with oxygen to about 90 %, against about 20 % in the North Baltic and 30—50 % in the Gulf of Finland. These numbers refer to the situation in the summer, which is shown on Fig. 24 giving the mean saturation percentage of oxygen in the bottom water (within 1—2 m of the bottom) as found from analyses (64) made during the years 1922—1931. The abundant supply of oxygen in the Bothnian Bay favours

oxidization of the surface layer and thus prevents the black discoloration which is due to reducing conditions, prevailing deeper in the mud, from reaching the surface of the bottom. The analyses in Table 20 seem to infer that decomposition at oxidizing conditions leads to a slower loss of organic carbon than at reducing conditions. In the Gulf of Finland and the Baltic the much lower oxygen content in the bottom water cannot as a rule maintain an «oxidized», i. e. grey or brownish grey, surface layer; here reducing conditions command even the surface of the bottom, and consequently the surface layer is black or very dark grey from ferrous sulphide.

The existence of light coloured mud 5—15 cm below the surface seems to indicate that conditions in the Gulf of Finland have not always been the same as at present. If reducing conditions were already present at the time when the light coloured layer was formed, then this was originally black and a colour change has taken place subsequently; but considering the fact that only an ample supply of oxygen, with or without the aid of bacteria, can have caused oxidization of the black ferrous sulphide into ferric compounds, it is not probable that such a change can have occurred after deposition, if reducing conditions were uninterruptedly prevailing in the surface layer of the sediment. We must consequently conclude that reducing conditions were not yet present when the sediment was deposited. SjöSTEDT (100), who observed a similar succession of colours in bottom samples from Öresund, states that the light coloured layer contains diatoms partly belonging to an earlier geological period. This brings us to the second factor influencing organic content; the one which caused increase of organic matter with depth in sediment, a factor the influence of which has been noted, as stated above, in outwardly widely differing deposits in the Baltic. If, as before, we consider the ready sediment as a product of the balance between inorganic and organic sedimentation, increase of the organic component with depth may be due either to formerly slower inorganic, or more abundant organic sedimentation. In the present case both contingencies seem probable. The diminished depth and advanced shore line resulting from the upheaval of land must, at least theoretically, cause a slow increase in the rate of inorganic sedimentation, though it is impossible to express any opinion as to the magnitude of the effect; for sedimentation in the sea is on the whole extremely slow and entirely dependent on local conditions at the place of deposition. On the other hand the broader and deeper connection with the ocean during the Litorina period, which facilitated the water exchange between the Baltic and the Atlantic and caused the salinity in the Baltic to rise, naturally

also furthered the entrance of nutrient salts. Together with the favourable climate of the period, these created the necessary conditions for the development of an intense organic life in the sea, evidence of which may be seen in the shell banks still occurring on the ancient shores of the Litorina Sea. Viewed from this angle the increase of organic matter with depth in sediment does not seem surprising. It is not proved, however, that the bottom parts of the samples, where the highest organic contents were found, actually date from the Litorina period. Even if this were not impossible on account of the slowness of sedimentation, a decision in this direction can only be given by an additional biological analysis of the sediments.

Summary.

Late-Glacial clays are uniform as to organic content down to a depth of 20—35 cm (depth in sediment reached by glass-tube sampler). In post-Glacial sediments organic matter, within the first 20 cm, decreases with depth in the Bothnian Bay, but increases elsewhere in the Baltic (Table 20). Light-coloured layers as a rule contain more than neighbouring dark layers. In the Bothnian Bay succession of colours is: greyish brown, dark grey, black; in the Gulf of Finland the colour change is reversed, the surface layer being black. In the Bothnian Sea and the Baltic proper the muds are grey, grey and black or black, but a regular succession of colours has not been observed. Existence of an oxidized light-coloured surface layer in the Bothnian Bay is ascribed to oxygen content of water, even bottom water here being saturated with oxygen to about 90 %, against 20 % in the North Baltic and 30—50 % in the Gulf of Finland. Two influences have acted upon organic content in opposite directions, one being decrease with depth caused by time of burial and biological conditions (bacteria, lack of oxygen), the other increase due to changed conditions of sedimentation. A formerly more important share of the organic component in balance between inorganic and organic sedimentation may be due to formerly slower inorganic or more abundant organic sedimentation. Both contingencies seem probable. Upheaval of land, resulting in diminished depth and advanced shore line, causes, at least theoretically, slow increase in rate of inorganic sedimentation. On the other hand, organic life in the sea was richer during the Litorina period than at present, evidence of which is afforded by the shellbanks still occurring on the ancient shores of that period. The question remains open whether the lowest parts of the samples where the highest organic contents were noted, actually date from the Litorina period.

28. RATIO OF CARBON TO NITROGEN.

Nitrogen analysis has lately been adopted by many workers as a method of determining organic matter, since extensive work has shown that the ratio between carbon and nitrogen in soils is almost constant. Nitrogen analysis, moreover, is less time-consuming than determination of organic carbon. The mean C/N ratio in soils is 10. As already stated in Section 5 WAKSMAN'S (119) investigations have shown that the constancy of the ratio is to be ascribed to a certain decomposition equilibrium of soil organic matter. Decomposition leads to accumulation of resistant substances of plant origin, chiefly lignins and similar compounds and those of bacterial origin i. e., proteins and protein-like substances. As decomposition advances the ratio between carbon and nitrogen in the product tends to become constant, and once this state has been reached, more or less remains so on further decomposition.

With a view to ascertaining if the decomposition equilibrium of organic matter in marine deposits is the same as in soils, TRASK and co-workers subjected 108 bottom samples to analysis of both organic carbon and nitrogen. Of these samples, 85 originated from widely differing depths in the Channel Islands area in California, and the rest from various localities along the coasts of North and South America. The mean C:N ratio in these samples was found to be 8.4, thus notably lower than for soils. This means that marine deposits are comparatively richer in resistant nitrogenous compounds. TRASK confirmed this result by analyzing in detail a number of bottom samples according to the method of WAKSMAN, and ascribed it to differences in origin of the organic constituents, organic matter in marine muds being largely derived from phytoplankton, which contains less cellulose than land plants.

Having adopted nitrogen-analysis as his general method of determining organic matter, TRASK also determined the nitrogen content in the bottom samples from the Baltic collected for him by the Thallassological Institute of Helsingfors. In 9 of these organic carbon was determined here, and the ratio of carbon to nitrogen calculated with the aid of TRASK'S nitrogen data. The mean was found to be 9.1, thus somewhat higher than the value of 8.4 for oceanic deposits, which indicated that Baltic deposits in this respect perhaps present a systematical difference. Considering the restricted area of the Baltic and the importance of the affluents, of which the majority transport large quantities of humus stuffs into the sea, such a difference would not be surprising. In order to elucidate this point, nitrogen was determined in 21 samples or part of samples from the

Gulf of Bothnia, 25 from the Gulf of Finland and 30 from the Åland Sea and the Baltic proper. The analyses are recorded in the List of Analyses, which also gives the corresponding C:N ratios.

A survey of the result is given in Table 21, containing the means for different areas and different kinds of deposits. The ratios calculated on TRASK's nitrogen data are also included, whereas two abnormally high values, 30 and 22 resp., referring to two late-Glacial clays taken at F52A and F59A in the Gulf of Finland, in which only 0.02 and 0.03 % of nitrogen were found, were omitted. The organic content of these samples was normal, 1.1 % in both. Whether there was an error in the nitrogen determinations or whether these samples really differed from the rest, the C:N ratios in question are obviously not comparable to the others. Nevertheless, as the determinations were done in duplicate and belong to good series of analyses, they were not rejected altogether, but included in the List of Analyses.

Before discussing the C:N ratios given in Table 21, there is reason to point out that nitrogen seems to be unevenly distributed, at least within sediments with a high amount of organic matter. In some samples with high organic contents double analyses differed more than usual and, when repeated, gave values, agreeing perhaps within themselves, but with neither of the earlier values. As already mentioned in Section 5, the same phenomenon was observed as to organic carbon content, but in a much lesser degree. In order to find out the reason for this variability, double analyses were made on some very small adjacent fractions of a sample. For this purpose 2.5 cm of the lowest part of sample F81 1930I was divided in four equal parts, each of which was analyzed separately. The percentage of organic matter in this fraction was 9.9 %, being the highest amount observed in any of the samples examined. The result shows that the nitrogen content actually varied within wide limits within this short fraction of a sample. The following result was obtained, in which No. 4 refers to the lowest portion:

	1.	2.	3.	4.
% Nitrogen	{ 0.83	{ 0.72	{ 0.52	{ 0.47
	{ 0.82	{ 0.70	{ 0.53	{ 0.47
Ratio C/N	6.9	8.0	10.9	12.2

The double analyses thus agree very well within themselves, but the nitrogen amount of the lowest part is little more than half that of fraction 1. That the high value of the latter is not characteristic of the entire upper part of the sample is proved by the nitrogen content of fraction a), an average sample of which was found to hold

0.40 %. Nitrogen may thus be quite unevenly distributed. This fact recalls an observation recorded in Section 21, which treats the general character of Baltic deposits. It was pointed out that the stratification in lighter and darker layers, which was observed in a great many post-Glacial samples, as a matter of fact was only apparent, and was due to uneven distribution of black lumps forming small »reducing areas» within the sediment. As according to WAKSMAN the nitrogen content of organic matter is chiefly of bacterial origin, the uneven distribution of nitrogen points to uneven distribution of micro-organisms and suggests that the similarly uneven distribution of black lumps may be due to their being centres of bacterial activity.

As described in Section 3 the samples were prepared for chemical analysis in such a way that the analytical results presumably represent average values for the sample or part of sample they refer to. From the detailed analysis of sample F81 it follows that in the case of the highest organic contents or of big iron tube samples, which on account of the manner in which they were kept had to be treated as average samples, the result may not always be the one intended.

However, the unevenness of the material seems to be fairly well smoothed out in the mean C:N ratios given in Table 21, these ratios varying regularly in a way which cannot be accidental. Table 21 shows primarily that the mean of all C:N ratios is 10.0; or exactly the same as for soils in general and for arable soils in Southwestern Finland. Secondly, we see that there is no marked difference between post-Glacial and late-Glacial deposits, the mean of the post-Glacial being likewise 10.0, and that of the late-Glacial 10.2; the latter number referring, it is true, to only 13 samples against 68 post-Glacial ones. On the other hand, when examining the values for different parts of the area, we perceive regular differences. The mean ratio of all samples from the Gulf of Bothnia is 11.1, from the Gulf of Finland 10.2 and from the North Baltic with the Åland Sea 9.1.

Table 21. *Ratio of carbon to nitrogen in Baltic deposits.*

	Entire area	Bothnian Bay only	Gulf of Bothnia	Gulf of Finland	North Baltic including Åland Sea and Archipelago
All samples	10.0 (81)	11.5 (6)	11.1 (24)	10.2 (25)	9.1 (32)
Post-Glacial muds and surface sands	10.0 (68)	11.5 (6)	10.0 (19)	10.2 (24)	8.9 (25)
Late-Glacial clays	10.2 (13)	—	11.4 (5)	— (1)	9.7 (7)
				East of F 57	Includ. Gulf of Finl. until F57
All samples				10.7 (17)	9.0 (40)

¹⁾ The figure in brackets refers to the number of determinations entering in the mean.

The highest ratio is thus found in the Gulf of Bothnia, and a still higher one when samples from the Bothnian Bay only are considered; the mean for 6 samples from the latter area being 11.5. If the individual values in the Gulf of Finland are examined, we note that all values above 10 are found in the inner part of the Gulf, whereas from F57 onwards only lower values occur. The mean for stations east of F57 is 10.7, for those west of it 9.0. From the standpoint of C:N ratios we may thus divide the whole area in three parts: 1) Gulf of Bothnia, 2) Gulf of Finland east of F57 and 3) Baltic proper with Åland Sea, Archipelago and Gulf of Finland as far as F57. In the two first the C:N ratio is roughly 11, in the third 9. The mean ratios of post-Glacial and late-Glacial deposits separately, present a similar peculiarity, in that the highest means are found in the Gulf of Bothnia, the lowest in the Baltic. Besides this, late-Glacial values are seen to be somewhat higher than the corresponding post-Glacial ones, indicating perhaps a greater loss of nitrogen in the older deposits or a greater initial carbon content, but, as pointed out above, the material is too small for any definite conclusions. It may be stated merely that TRASK, who found that organic matter as a rule decreases with depth in sediment, or, in other words, with time of burial, observed that the nitrogen content decreases a little more rapidly than does organic carbon. The few analyses made here on several parts of the same sample and recorded in the List of Analyses, do not quite seem to agree with this result, but their number is too low to allow of any conclusions, and besides this they refer to post-Glacial sediments the organic matter of which, in the Baltic, generally increases with depth in sediment.

As for the difference observed in C:N ratios in the two gulfs on the one hand, and the Baltic proper on the other, attention may be drawn to the work of BUCH (17, see Section 26) dealing with the distribution of nutrient salts in the Baltic. BUCH explained the high nitrogen but low phosphate content in addition to marked infertility in the Bothnian Bay, as an effect of the large quantities of humus stuffs, which are carried down by the rivers from the vast peat-bogs in Northern Finland. These humus stuffs become partly mineralized, delivering their decomposition products, including the nitrogen, to the water, where the latter accumulates, not being used up for plankton production. The C:N ratio of peat is high. KIVINEN (52) records a great number of analyses on different kinds of peat from various parts of Finland and found mean values ranging from 17 to 37. Consequently it seems probable that the C:N ratio of the humus stuffs, which in more or less colloidal solution are carried down to the sea — this ratio depends largely on the solubility of the various constituents of peat — is also high, and that the comparatively high ratios of

the bottom deposits which derive their organic content from them may be explained in this manner.

In order to get an idea of the quantities of humus stuffs brought down by the rivers to the different parts of the Baltic, and thus to be able to judge to what extent land humus accounts for the varying C:N ratios, the following Table 22 was calculated. ASCHAN (8) estimated the total amount transported to the sea by Finnish rivers at 1.4 million tons. Both for the water transport and the content of organic matter in the river waters there are, however, more accurate values now than in 1908, when ASCHAN made his calculation, and a renewed calculation seemed therefore justified.

In Table 22 the values in columns 1 and 4, are those calculated and used by WITTING (135) in his work on the position of the water level and the upheaval of land in the Baltic basin. The organic contents of the Finnish river waters are mean values calculated from tables published by BLOMQUIST, LEVANDER and WITTING (10). The value for the Bothnian Bay is the mean for 13 rivers, and refers to conditions in the summer. For the Kemi and Ule rivers there are also yearly means, 21 and 23 mgr/lresp., which almost exactly coincide with the values with which these rivers enter in the general mean. The value for the Bothnian Sea is the yearly mean of the Kuono river¹⁾,

Table 22. *Annual transport of humus stuffs to the Baltic.*

	(1) Annual Affluence km ³	(2) Mean org. content of river water gr/m ³	(3) Annual addition of org. matter million tons	(4) Area km ²	(5) Mean Annual addition gr/m ²
Bothnian Bay			Total	37 000	67
Finland	54.5	31	1.69	2.48	
Sweden	60.7	13	0.79		
Bothnian Sea				66 600	38
Finland	13.1	36	0.47	1.89	
Sweden	79.1	18	1.42		
Gulf of Finland				29 500	117
Finland	19.4	30	0.58	3.44	
Neva river	70	20	1.40		
Estonia	24.4	60	1.46		
Baltic Sea				236 200	19
Finland	3	30	0.09	4.38	
Sweden	21	30	0.63		
Rest of area ...	122	30	3.66		
Total	467.2		12.19	369 300	

¹⁾ Since the above was written, Dr H. RENQVIST kindly put at the disposal of the author extensive analytical material which will be published in the near future (HOLMBERG, L. Ergebnisse optischer und chemischer Wasseranalysen 1911-31. Hydrografischen Toimiston Tiedonantoja, Meddelanden från Hydrografiska Byrån V, Helsingfors 1934). From this material, which treats the water of rivers falling into the Gulf of Bothnia, the value for the Kuono river in Table 22 was derived, while for the Bothnian Bay exactly the same value was obtained as from the older material.

which stands for 75 % of the affluence from the Finnish side. For the Gulf of Finland 30 mgr/l was used, which is a little higher than the yearly mean, 27 mgr/l for the Kymmene river, which transports somewhat more than half the water quantity from the Finnish side, but lower than the mean summer value 34 mgr/l for 4 smaller rivers.

Likewise for the small Finnish affluence to the Åland Sea and the Archipelago the value 30 mgr/l was used, in view of the notable constancy of organic content in Finnish waters. The water of the Neva river contains less than the latter, Lake Ladoga acting as a clarifying basin. The value 20 mgr/l was used (PRSCHIBYTEK 90). For the greatest of the Estonian rivers the Narowa, LEPPIK (56) gives the value 63 mgr/l, which is an autumn value. As the detritus amount is said to be higher in spring, a mean of 60 mgr/l for Estonian rivers is perhaps not too high. ERIKSSON (26), who computed the very large Swedish analytical material, collected in the years 1909—1925 at 69 different stations and referring to 29 Swedish rivers, found the highest values for both inorganic and organic detritus in rivers running through calcareous soil. The high amount in Estonian rivers may therefore be due to the Silurian rocks of the country. The values given for the Swedish affluents are based on ERIKSSON's work. The mean for the Bothnian Bay is calculated from the mean values for 6, that for the Bothnian Sea, from the means for 7, and finally that for the Baltic proper from the means for 5 rivers. Each of the individual means are based on a great number of analyses (generally 50—100). The mean for the Swedish affluents to the Baltic proper has been used for the whole of the Baltic, as no data were available for the Dūna and the German rivers. The total for the Baltic is thus rather a minimum value, since there is no reason to suppose that the affluents from the plains east and south of the Baltic carry less organic detritus than the Swedish rivers. — Finally a word may be said about the method of analysis. Both as regards the Finnish and the Swedish material, organic matter was determined as ignition loss on evaporation residue of filtered water. In Finland additional analyses were made for organic content in suspended matter, the results of which, ranging from 1—3 mgr/l were added to the ignition loss values. As the humus stuffs are in more or less colloidal solution, it rather depends on the quality of the filters used how much of the organic matter will be considered to be «suspended» and how much to be «in solution»; for which reason it seems most correct for the present purpose to use the total amounts. The Finnish and the Swedish values for the organic contents per litre are thus not quite comparable — the Swedish values would have to be increased by about 10 %, — but in view of the inevitable uncertainty of the calculations no corrections were applied.

Table 22 shows that Finnish rivers on an average carry about the same amounts of organic matter, whether they fall into the Bothnian Bay or the Gulf of Finland; whereas the Swedish material clearly shows the transition from the highlands in the north to the plains in the south, in that the northern rivers transport per litre less than half the quantity of the southern rivers and of Finnish rivers in general. The total amount carried to the sea by Finnish rivers is, according to the present calculations, 2.83 million tons or double the amount estimated by ASCHAN, who based his calculations on a mean organic content of 20 gr/m³ and an affluence of 70 km³. The total contribution from the Swedish side is almost the same, or 2.84 million tons. ERIKSSON estimated in a different way the total annual organic denudation of Sweden at 3.93 million tons. This leaves 1.09 million tons for the west coast of Sweden, which seems a likely proportion. In view of the very varying areas of the different parts of the Baltic, the total amounts of organic matter are hardly comparable. We note for instance that the Gulf of Finland receives three fourths of the amount transported to the Baltic, though the area of the former is only one eighth of that of the latter. In order to get an idea of the importance of the annual contributions to the different basins, the last column of Table 22 was calculated. It gives the amounts which would accumulate during one year on every square metre of the sea bottom, if the whole of the organic matter were precipitated as such. This shows the order of magnitude of the yearly supply of land humus and affords relative values suitable for comparison purposes. In reality only a fraction of the total amount settles at the bottom, the main part becoming mineralized on the way down, — a sign of this process may be seen in the low pH-values of the bottom waters —, besides which the part finally settling does not become evenly distributed, but accumulates where conditions are favourable.

The values in the last column of Table 22 bring us back to the purpose for which the table was calculated. Having found that the mean C:N ratio was highest in the Bothnian Bay and lowest in the Baltic proper, and having explained this as an effect of land humus on the composition of organic matter, we wanted to estimate the relative influence of this in the different basins. The table shows that the total annual addition per square metre is 67 gr (dry weight) in the Bothnian Bay, 28 gr in the Bothnian Sea, 117 gr in the Gulf of Finland and 19 gr in the Baltic proper. From these numbers we should expect the greatest influence in the Gulf of Finland and the smallest in the Baltic. As the C:N ratio of 9 in the Baltic shows, conditions here are actually most like those in oceanic deposits; but the high C:N

ratio of 11.5 in the Bothnian Bay indicates the greatest influence here and not in the Gulf of Finland. However, if we take into account the scarcity of plankton in the Bothnian Bay and the abundance in the Gulf of Finland (LEVANDER 57), it becomes evident why the influence is relatively greater in the Bothnian Bay¹). Also for the whole of the Gulf of Bothnia the C:N ratio was slightly higher than that for the Gulf of Finland. In spite of the low direct annual addition of land humus to the Bothnian Sea, 28 gr/m², we must expect conditions here to be largely influenced by the Bothnian Bay, which, though occupying little more than half the area of the Bothnian Sea, receives 25 % more water from the affluents, the excess of which is carried off into the Bothnian Sea.

Before leaving the subject of the influence of land humus on the organic content of Baltic deposits, we will make yet another calculation in order to show the order of magnitude of the annual addition of humus stuffs in comparison to the actual amounts found in the bottom deposits. If a sediment is supposed to contain 60 % of water, 38 % of inorganic constituents and 2 % of organic matter (5 % of air dry sample), then a 10 cm thick layer of the bottom will contain 2.6 kgr of organic matter per square metre, as simple calculation shows, whereby the specific gravity of the minerogen component is taken as 2.7 and that of the organogen one as equal to unity. An annual addition of 117 gr/m², as in the Gulf of Finland, thus constitutes roughly 5 % of the organic content per 10 cm layer of the sediment. The amount actually deposited naturally remains far below this value.

Summary.

Nitrogen was determined in 76 bottom samples or part of samples. The mean C:N ratio of all was found to be 10.0 or exactly the same as for soils. Regionally, differences are observable. The mean for the Gulf of Bothnia is 11.1, for the Gulf of Finland 10.2 and for the North Baltic with the Åland Sea 9.1. The highest value occurs in the Bothnian Bay, for which a ratio of 11.5 was found. From the standpoint of C:N ratios, the Gulf of Finland from F57 onwards may be counted to the Baltic. The difference in C:N ratios is ascribed to varying influence of land humus on organic sedimentation, the C:N

¹) No quantitative data can be given for the distribution of plankton in Baltic waters, since there is only one investigation dealing with the subject (CAROLINE LEEGAARD 54); this refers to a single period (May, 1912), and thus does not allow of general conclusions. We must therefore content ourselves with the general indication given above.

ratio of humus stuffs from peat-bogs being high (17—37, KIVINEN). ASCHAN estimated the amount of humus stuffs annually transported to the Baltic by Finnish rivers at 1.4 million tons. A recalculation is made on the basis of modern material, whereby the value of 2.83 million tons is arrived at. Almost the same value, or 2.84 million tons, is found for the total contribution from the Swedish side and 6.52 million tons for the rest of the Baltic, thus a total annual contribution of about 12 million tons of humus stuffs. (Table 22.) The annual addition to the different basins per square metre is calculated (last column of table). The highest influence of land humus may be expected in the Gulf of Finland, but is counteracted here by a very rich plankton growth. Both plankton and animal life being poor in the Bothnian Bay, the greatest effect is noticed here, in spite of lower addition of humus stuffs. The lowest annual contribution was noted in the Baltic, for which the lowest C:N ratio was found. As was to be expected, conditions here mostly resemble those prevailing in the ocean.

29. CALCIUM CARBONATE AND BALTIC SEA WATER.

In discussing the carbonate content of the bottom samples collected by the Swedish Hydrographical Expedition of 1877, MUNTHE (66) traces the lines along which future investigations should go and finishes with the following words: »Only through comparative investigations of this kind will it be possible to arrive at definite results in the question, an important one, yet hitherto scarcely dealt with, as to the cause of the varying carbonate content of recent sediments, within that area, in many respects interesting, from the Gulf of Bothnia to the Skagerrack. — — — Since the carbon dioxide content of the water layers is doubtless of no little importance for the carbonate content of the sediments, it will be of interest to attach the investigation of the carbonate content of the sediments to the results, which will be obtained by investigations of this kind within the Baltic area also; and there is in this connection reason to point out, that a preliminary experimental investigation of the influence effected by water of varying salinity and carbon dioxide content upon carbonate containing clays, would be of a special interest.»

Since 1894, when these words were written, much information has been collected as to the mutual relationships of sea water, carbon dioxide and calcium carbonate, and the time seems to have come when it is possible to view from a theoretical standpoint conditions prevailing in the Baltic. An attempt in this direction will be made

below. It is only of a preliminary nature, for data are still lacking for an exhaustive treatment of the subject.

It is a well-known fact that the water of the Baltic has a tendency to dissolve carbonate of lime. LUTHER (60) states that shells of dead molluscs washed up on the shores in the Finnish Archipelago always present different stages of destruction. Nowhere to-day are banks being formed similar to those dating from the Litorina period, which are now found on land, and which contain well preserved shells of species that still belong to the fauna of the neighbourhood. LUTHER concludes that the carbonate dissolving faculty of the present Baltic is greater than that of the Litorina Sea. MUNTHE (66) found a very low content of carbonates in bottom deposits from the South Baltic, but rising values when passing into the Cattegat and the Skagerrack, the mean content of 17 samples referring to the southern two thirds of the Baltic (below lat. about $57^{\circ}30'$) being 1.16 %, but that of 12 samples from the north Cattegat and the Skagerrack 9 %. In samples from the Cattegat and the Skagerrack calcareous shell fragments of marine animals occurred abundantly, whereas they were entirely lacking in the Baltic proper, only epidermis fragments of molluscs being sometimes found in Baltic deposits. Discussing the possible causes of the dissolving properties of Baltic water, LUTHER mentions the presence of carbon dioxide in the water, but in view of the fact that the Baltic contains considerably less carbon dioxide per litre than e. g. the Skagerrack, where accumulation of carbonate rich sediments is possible, he is inclined to consider carbon dioxide as a secondary factor, and ascribes the principal effect to the humus stuffs of an acid character («humus acids», ASCHAN 8), which are present in such great quantities in the water (see Section 28). He finds a third factor in the low salinity of the Baltic, THOULET (109) having shown that powdered shells of molluscs are dissolved more quickly in distilled than in sea-water (oceanic).

The problem of the calcium carbonate solubility in Baltic water is a part of the general problem of the mutual relationship of calcium carbonate and sea water. It has been a long discussed question whether sea water is saturated with calcium carbonate or not. The answer was finally given by WATTENBERG (123), who showed that Atlantic surface water (down to 100—500 metres) is always oversaturated with respect to calcium carbonate, while in the depth slight undersaturation is present. He found that sea water at such pH-values as occur in the surface layers, when for a long time shaken with calcium carbonate powder, loses part of its alkalinity and that

at the same its pH decreases¹⁾. This he interpreted as due to suppression of an oversaturation, the loss in alkalinity indicating that calcium carbonate had settled out of the water, and the decrease in pH, i. e. the increase in acidity, being a consequence of the disappearance of carbonate ions from the water. WATTENBERG then determined the constant governing the calcium carbonate equilibrium in sea water at different chlorinities and different temperatures. For numerical calculations a knowledge of the calcium content of sea water and of the first and second dissociation constants of carbonic acid in sea water is further necessary. The latter were recently determined by a Commission appointed by the International Council for the Exploration of the Sea (BUCH and co-workers 18). In oceanic water the total calcium content is also well-known. It is closely proportional to the salinity and may be expressed by the equation

$$c_{Ca} \text{ gr/kg} = 0.02156 \cdot Cl \text{ ‰}.$$

A water of 19.5 ‰ contains 0.42 gr calcium per kg. All the data necessary for determining the state of oceanic sea water with respect to calcium carbonate, are thus at hand and were used by WATTENBERG, for studying in detail conditions in the Atlantic.

WATTENBERG having determined the equilibrium constant of calcium carbonate for low salinities too, such as occur in the Baltic, it is now possible to grasp and to express numerically the real nature of the carbonate dissolving properties of its water. It is true that the calcium content of Baltic waters is but incompletely known. There are in all about forty analyses of old date by FORCHHAMMER (28), STRUVE (103), GLASENAPP and SCHMIDT (96) most of which deal with surface water. Though the analytical methods used naturally do not satisfy modern requirements as to accuracy, these analyses all the same show plainly that calcium content is higher in the Baltic, in comparison to chlorinity, than in the open ocean. A survey of

¹⁾ The «alkalinity» or «excess base» of sea water, generally given as milliequivalents per litre, is equal to the surplus of bases over strong acids. The weak acids making up for the deficiency consist of about 80 % of carbonic acid and of about 20 % of boric acid; pH is the negative logarithm of the hydrogen ion concentration, or — more correctly speaking — the hydrogen ion activity, which is a measure of the concentration. Pure water has a pH of 7, the product of the concentrations of the hydrogen and hydroxyle ions being 10^{-14} . Acidities are given in terms of pH when they are too small to be expressed in the ordinary measures of analytical chemistry. The pH of sea water depends largely on the carbonic acid present, i. e. the mutual relationships of the free carbon dioxide and the bicarbonate, carbonate and hydrogen ions, which relationships are determined by the two dissociation constants of carbonic acid.

the material is given by STRUVE, who calculates a mean of 0.043 for the ratio CaO/Cl , corresponding to 0.0307 for that of calcium to chlorine. Some analyses recorded by SCHMIDT bring down the ratio to 0.0301. Consequently the following preliminary relation may be used for calculating the calcium content of Baltic surface water from the chlorinity:

$$\begin{aligned} c_{\text{Ca}} \text{ gr/kg} &= 0.03 \text{ Cl } \text{‰} \\ c_{\text{Ca}} \text{ mmol/l} &= 0.75 \text{ Cl } \text{‰} \end{aligned}$$

It is probable that future and more accurate analyses will show that the calcium and chlorine contents are not directly proportional in the Baltic, but for the purpose of estimating the over- or under-saturation with respect to calcium carbonate, the above relation gives the order of magnitude of the Ca-concentration with sufficient accuracy. With the data at hand it is now possible to calculate what calcium contents Baltic water should have at current pH-values and temperatures, in order to be saturated with calcium carbonate.

A word must first be said about the factors which determine the pH of surface water. Besides being influenced by chlorinity¹⁾ and temperature, which influence the dissociation constants, and by alkalinity, on which the sum of carbonate and bicarbonate ions in the water depends, pH is influenced by the tension of the free carbonic acid, which in surface water is roughly in equilibrium with that of the atmosphere. Naturally other factors, such as the presence of »humus acids» in the water, may also influence pH; but from the standpoint of the carbonic acid equilibrium it is unimportant from what source the hydrogen ions are derived. As is well-known, the pressure of the atmospheric carbon dioxide is about $3 \cdot 10^{-4}$ atm.; the tension of the free carbon dioxide in the water tends to adjust itself to this value; when from biological or hydrographical reasons the tension rises above $3 \cdot 10^{-4}$ atm., then carbon dioxide is given off to the atmosphere; when it sinks below that value, carbon dioxide is, on the contrary, taken up. In the depth, where the regulating influence of the atmosphere is lacking, much higher tensions may occur. According to still unpublished observations made during the yearly cruises arranged by the Thalassological Institute, the carbon dioxide tension of the surface water is in July usually slightly over that of the atmosphere in the Gulf of Bothnia, somewhat below

¹⁾ As a matter of fact not the chlorinity, but the total amount of electrolytes, i. e. the salinity, influences the dissociation constants; but the chlorinity being the actually determined quantity, it is convenient to use it as a measure of the salinity.

that value in the Gulf of Finland, and in equilibrium with the atmosphere in the Baltic proper, while in the bottom waters higher values, even up to $50 \cdot 10^{-4}$ have been observed.

The pH-values, which correspond to equilibrium with the atmosphere, are affected by temperature and chlorinity in such a way that decreasing temperatures and chlorinities cause decreasing pH-values at equilibrium. Atlantic water is in equilibrium with the atmosphere at pH about 8.2 at temperatures of 10° — 20° C. If such water is diluted to 1 ‰ Cl with distilled water the equilibrium pH goes down to 7.3. We should thus expect very low surface pH-values in the Bothnian Bay and the inner part of the Gulf of Finland, where equally low chlorinities are current, but the effect is counteracted by the relatively higher alkalinities in the Baltic. Atlantic water diluted to 1 ‰ Cl has an alkalinity of 0.12 mequ/l, while for similar water in the Bothnian Bay and the Gulf of Finland values of about 0.3 and 0.8 mequ/l respectively are found. On the basis of the actually observed alkalinities in the different parts of the Baltic was calculated the following Table 23 giving the «normal» pH-values of surface water of varying chlorinities and temperatures when in equilibrium with the atmosphere¹⁾. For these same pH-values the calcium concentrations corresponding to saturation with calcium carbonate were calculated and introduced in the table. We thus get a survey of the conditions which determine over- or undersaturation with respect to calcium carbonate in the surface water of the Baltic.

The table was calculated for the temperatures 4° , 12° and 20° C, and chlorinities from 0.5—4.0 ‰. The actual Ca-contents according to the relation given above are also included. By comparing the latter values with the amount necessary for saturation we may judge of the degree of saturation. The table shows that Baltic surface water at low temperatures, prevailing during the greater part of the year, is undersaturated with respect to calcium carbonate. Only in the summer

¹⁾ The calculation was based on the equilibrium equations of carbonic acid (BUCH and co-workers), and on that of calcium carbonate in sea water (WATTENBERG). The calcium concentration necessary for saturation was calculated from the following final equation:

$$\frac{c_{Ca} \cdot A}{\alpha_H + 2K_2'} = C'$$

where c_{Ca} is the calcium concentration, A the alkalinity, α_H the num log of the pH-value, K_2' the apparent 2nd dissociation constant of carbonic acid, and C' a constant determined by WATTENBERG, the two latter varying with chlorinity and temperature.

is slight oversaturation possible. In the table the values which are lower than the respective actual Ca-contents and thus indicate possible oversaturation are printed in fatfaced types. Water of 3 ‰ Cl may be oversaturated when temperature rises above 12°, and even at lower temperatures if pH, as is possible, rises above the value corresponding to equilibrium with the atmosphere. Surface water of 4 ‰ Cl, such as occurs in the south part of the Baltic, is more often slightly oversaturated. In the Gulf of Finland, where surface salinity varies between 2 and 3 ‰ Cl, saturation is possible at the highest summer temperatures, especially as pH here often rises above the equilibrium value, but directly temperature goes down the general state of undersaturation is restored. It is, as a matter of fact, remarkable how great an influence temperature has on the state of saturation. In the Gulf of Bothnia summer saturation is perhaps possible in the southern part, but in the Bothnian Bay it is certainly never attained.

As repeatedly stated, the above applies to the surface water. It was, however, mentioned that in the bottom water, high tensions, or what amount to the same, low pH-values are common. In fact, a drop of 0.2 pH-units within 10 metres at the discontinuity layer is the rule. As at the same time temperature decreases considerably, this change is enough to transform a state of slight oversaturation into one of decided undersaturation. In comparison with this the effect of possibly somewhat higher Ca-content and alkalinity in the depth is of no consequence. We may thus conclude that Baltic water below the discontinuity layer is always undersaturated with respect to calcium carbonate.

It may be noted that the actual amount of undersaturation, i. e. the quantity of calcium carbonate, which a water of certain chlorinity, pH and temperature might still dissolve, if shaken with calcium carbonate powder, cannot be found simply by subtracting the actual Ca-content from the amount necessary for saturation. When calcium carbonate dissolves, not only does the Ca-content increase, but also that of the alkalinity and the carbonate ions, which again causes a displacement of the carbonic acid equilibrium and a rise of pH. The amount actually dissolved remains less than the amount apparently necessary according to the table.

The equilibrium constants of carbonic acid and calcium carbonate are not known accurately enough for very low salinities to allow of reliable calculations; but as is well-known, the solubility of calcium carbonate in soft water is high. We may safely extend also to soft

Table 23. *Ca-concentrations needed for saturation of Baltic surface water with calcium carbonate at pH-values corresponding to equilibrium with the atmosphere.*

		0.5 ‰		1.0 ‰		2.0 ‰		3.0 ‰		4.0 ‰	
		pH	Ca mmol/l	pH	Ca mmol/l	pH	Ca mmol/l	pH	Ca mmol/l	pH	Ca mmol/l
Gulf of Finland	4°	7.9	8.1	8.0	5.8	8.1	4.2	8.2	3.1		
	12°	8.0	4.6	8.1	3.3	8.1	2.9	8.2	2.2		
	20°	8.0	3.2	8.1	2.3	8.2	1.7	8.2	1.5		
Baltic	4°							8.1	4.1	8.2	3.3
	12°							8.2	2.4	8.2	2.4
	20°							8.2	1.6	8.2	1.6
Gulf of Bothnia	4°	7.6	30.0	7.8	14.7	8.0	6.7	8.1	4.4		
	12°	7.7	16.9	7.9	8.3	8.0	4.8	8.1	3.2		
	20°	7.8	9.4	7.9	5.7	8.1	2.7	8.2	1.7		
Actual Ca-content of water.			0.4		0.8		1.5		2.2		3.0

waters the conclusions we have reached: e. g. the considerable influence of temperature on the state of saturation. An indication in the water itself of the continuous process of dissolution may be seen in the high calcium contents and alkalinities, in proportion to salinity, in Baltic waters compared to oceanic water. This is of course partly due to the lime content of the water in certain of the affluents which come from limestone areas; but in view of the fact that most of the affluents are poor in lime, a considerable part of the effect must be that of solution from whatever supplies of carbonates the water is in contact with.

As for the existence of shell banks dating from the Litorina period, we must conclude from the possibility of their formation that at least the surface water of the Litorina Sea, like that of the present Atlantic, was on the whole oversaturated with respect to calcium carbonate. Theoretically we might even calculate what lowest salinity this corresponded to, provided some relation between Ca-content and chlorinity in the Litorina Sea were postulated. It is, however, wise to postpone such a calculation until the Ca-content of the present Baltic is better known.

In the foregoing, the different behaviour of oceanic and Baltic water towards calcium carbonate has been traced to the difference in chlorinity, on which the equilibrium constants of carbonic acid and calcium carbonate depend; and in the bottom water, moreover, to the low pH-values and consequently high carbonic acid tensions prevailing there. The former may be due, if not to the high-molecular humus stuffs themselves, at least partly to carbonic acid formed at

their decomposition. Of the three carbonate dissolving factors suggested by LUTHER, salinity and carbonic acid have thus been shown to be the most important. It now becomes obvious why carbonate content is on an average higher in Cattegat and Skagerrack deposits than in Baltic ones. The further we move from the Baltic into the North Sea, the more do conditions become equal to those in the At-

Fig. 28. Percentage of calcium carbonate in Baltic sediments.
When there are several samples from the same station highest amount given.

lantic; the more oversaturation gets the upper hand over undersaturation, the greater consequently is the chance that limy detritus, especially shells of calcareous organisms accumulating on the bottom, will escape solution before being definitely imbedded in the sediment.

The above examination of the state of saturation with respect to calcium carbonate was made with the object of making clear the conditions to which carbonate-containing sediments in the Baltic

are subjected. As appears from the List of Analyses, Baltic bottom deposits are not altogether devoid of carbonates, which thus, except perhaps during the Litorina period, were deposited against the dissolving power of the water. There are two regions where carbonates occur; the one comprising the south part of the Bothnian Sea, where chiefly late-Glacial deposits contain carbonates, the other the north part of the Baltic and the Gulf of Finland along the Estonian coast, where both late-Glacial and post-Glacial deposits may have a certain carbonate content. (Fig. 28). The amounts found here in post-Glacial samples are even on an average higher than those noted by MUNTIE in »sediments younger than the Litorina period» — these are equivalent to the post-Glacial samples of the present investigation — in the southern part, while in the Bothnian Sea, near the submarine banks of Finngrundén, percentages up to 42 % have been noted, which is more than anywhere else in the Baltic.

In spite of the dissolving properties of the water, notable amounts of carbonates have thus been able to accumulate on the bottom and are probably still accumulating there. But the origin of the lime is not, as in the Atlantic and even in the Skagerrack and the Cattegat, to be sought in calcareous marine organisms. Firstly, such organisms are scarce — obviously because of the quality of the water — and secondly, their shells are too easily soluble in that water. The origin of the lime in late-Glacial as well as post-Glacial deposits may be ascribed exclusively to limestone detritus, i. e. to the Silurian formations in and around the Baltic depression, and to some extent to the crystalline limestones in the Swedish and Finnish Archipelago. The correctness of this statement is proved by the position of the carbonate-containing deposits. As for the Bothnian area, it is a well-known fact that Silurian limestone occurs as solid rock on the bottom of the Bothnian Sea; and in the Baltic the localities where limy deposits occur indicate that the Silurian of Estonia and Gotland chiefly accounts for the lime content. Another proof is the fact already mentioned: that the mean carbonate content of the post-Glacial deposits in the North Baltic is higher than in the southern part, where the Silurian formations are less important.

From the List of Analyses it will be seen that besides the samples, which obviously contained carbonates, a great many others showed a low content of carbon dioxide — really lying within the admissible analytical error —, the reality of which, however, became quite evident when bigger portions of the samples (1—2 gr) were analyzed. It is probable that in all samples a slight carbon dioxide content would have been found if, from the beginning, attention had been given to

these very low amounts. As it is, the first analyzed samples are reported in the List of Analyses to be free of carbon dioxide, while for the later ones the low amounts actually found are given. These were, however, not calculated as CaCO_3 , as this carbon dioxide may derive its origin partly from the sea water originally contained in the sample, and partly from decomposed organic matter.

The carbonate-containing samples collected in the Bothnian Sea will be treated in Section 30, and in the following Section 31 those taken in the Gulf of Finland and the Baltic proper.

Summary.

The tendency to dissolve calcium carbonate, often observed in Baltic sea water, is discussed. On the basis of the equilibrium constant for calcium carbonate, determined by WATTENBERG for sea water of varying salinity and temperature, Table 23 was calculated, containing the calcium concentrations necessary for saturation with calcium carbonate at salinities, temperatures and pH-values occurring in Baltic surface water; the pH-values corresponding to a free carbonic acid tension of $3 \cdot 10^{-4}$ atmospheres, i. e. to equilibrium with the atmosphere. By comparing the values of the table with the calcium contents actually observed in the water, an idea is obtained of the state of saturation with respect to calcium carbonate. It is shown that Baltic surface water, as a rule, is undersaturated. Only in the summer is slight oversaturation possible. From the low temperatures prevailing below the discontinuity layer and the lower pH-values observed here, it may be concluded that the bottom water of the Baltic is always undersaturated with respect to calcium carbonate.

WATTENBERG has recently shown that Atlantic surface water, down to a depth of 100—500 metres, is always oversaturated with respect to calcium carbonate; while in the depth slight undersaturation is present. The pronounced undersaturation in the Baltic depends partly on the lower salinity here, the equilibrium constants of carbonic acid and calcium carbonate varying with the salinity; and partly on the low pH-values occurring in the depth. Yet Baltic bottom deposits are not altogether devoid of carbonates. In the southern part of the Bothnian Sea late-Glacial deposits occurring in the neighbourhood of the submarine banks of Finngrundén contain 30—40 % of carbonates. In the Baltic proper and the Gulf of Finland along the Estonian coast, late-Glacial as well as post-Glacial sediments have a low carbonate content. The origin of the carbonates is in both cases ascribed

to limestone detritus from the occurrences at the bottom and on the coasts of the Baltic.

30. THE SILURIAN AREA OF THE BOTHNIAN SEA.

It has long been known to geologists that the Bothnian Sea covers a Silurian area, though nothing definite is known about its extension. The present investigation has revealed that its influence on the composition of the sediments stretches northwards to at least lat. $61^{\circ}30'$, where at F23A, 63 m, pebbles of limestone were collected, and eastwards to near the Finnish coast, where at F28, 54 m and F29A, about 70 m, late-Glacial clay with 2—3 % of carbonates was found. The greatest influence was noted at and around the submarine banks of Finngrunden. The highest amount of carbonates was noted at station F31, 62 m, north of the banks, a sample from which contained 41.6 % and two others, collected near by, over 30 %. At the Finngrunden themselves limy clay, gravel, pebbles and many large pieces of limestone were dredged at depths of 14—20 m. No samples were taken immediately south of the banks, but at F33, 79 and 106 m, at a distance of about 50 km, the late-Glacial clay still contained nearly 30 % of carbonates. A high amount was also found in the bottom part of F31C, 64 m, where 31.6 % was noted. This point seems to mark the eastern limit for the high carbonate content, since a late-Glacial sample, F31E, 45 m, collected 10' east, was of an entirely different character. (See below). A 29 cm long core of late-Glacial clay taken at F32A, 68 m, north of Finngrunden and WSW from F31, proved to be carbonate-free in the top part, but to contain increasing amounts towards the bottom, though not more than 12.4 % in the lowest portion. Northwest of F32A at F32, 67 m, lime-free post-Glacial mud was found. The distribution of carbonates in the deposits around Finngrunden is shown on Fig. 28 and 29. None of these samples was distinctly varved, though they were rather coarse-grained; the median of F31 1924 being $25\ \mu$, and that of F31B, $16\ \mu$. The median of F33 1925 was $1\ \mu$, the distribution curve of this sample resembling that of F28 (see below and Fig. 33 p. 194). As already mentioned, sample F31E, though late-Glacial, was quite different from the others collected near the Finngrunden. It was more coarse-grained, the median being $30\ \mu$, and distinctly varved in clayey and sandy layers; consequently it was deposited near to the ice border. As it was collected at a slightly lesser depth, than the others, 45 m, it may originally have been covered by finer layers, now eroded; but what is more remarkable than its coarseness is the very low

percentage of carbonates in it. In an average sample only 0.2 % was found, though some pieces showed a faint effervescence with hydrochloric acid. We must conclude, notwithstanding, that the glacial streams at the time of its formation carried detritus chiefly from a lime-free area. Further east, in the central basin of the Bothnian Sea, two almost lime-free and very fine-grained samples were collected at station F30; one a late-Glacial one from 104 m, the other a post-Glacial specimen from 120 m. Both contained about 0.5 % of carbon-

Fig. 29. Distribution of calcium carbonate in samples from the South Bothnian Sea. Figures indicate percentage of calcium carbonate.

ates. Two more lime-free post-Glacial samples, F30A, about 100 m, and F29, 104 m, were taken in an isolated depression further east. Nearer to the Finnish coast carbonates are found again. The varved silt at F29A, about 70 m, had a median of 7.5μ and contained 3.2 % of carbonates; the very fine-grained clay, collected at F28, 54 m, had a median of about 1μ and 2—3 % of carbonates, unevenly distributed. Finally it may be noted that an exceedingly fine-grained late-Glacial clay, having a median of only 0.5μ , taken at station F64, 294 m, from the deepest part of the Åland Sea, proved entirely lime-free.

A characteristic feature of late-Glacial samples from the South Bothnian Sea were the small white soft lumps, often not bigger than

a pin's head, disseminated all over the clay and giving it a somewhat «disorderly» appearance. In some cases the lumps contained carbonates, leaving a residue of quartz grains when treated with hydrochloric acid; but in others they were found to consist exclusively of mineral grains, which, being coarser than the surrounding clay, seemed lighter in colour. The lumps occurred in samples both rich and poor in carbonates. Professor M. SAURAMO drew my attention to the fact that Uppsala clay, samples of which are in the possession of the Mineralogical Collection of the University of Helsingfors, shows just the same peculiarity, though the lumps of that clay seem bigger and more varying in size. GUSTAFSSON (40) studied the «spotted zone» of Uppsala clay in detail, and found the lumps to be the residue of small completely weathered pieces of limestone originally imbedded in the clay. In some cases the centre of the lumps were found to consist of material as yet unweathered. The «spotted zone» was about 5 cm thick, but in the very fine-grained clay above were also to be seen some minute white spots. According to GUSTAFSSON, the crushed Silurian material of this zone was transported by ice-bergs to the place of deposition, and the zone was formed when the ice border had retreated as far north from Uppsala as the present coast of the Bothnian Sea. DE GEER (20) states that a spotted zone has been met with at numerous localities in Uppland. The white lumps observed in sea-bottom samples from this area would thus indicate that floating icebergs had once deposited Silurian gravel all over the southern part of the Bothnian Sea. Like the carbonate-content, this circumstance proves the importance of the Silurian occurrences in this area; but it also testifies to the activity of icebergs in this period, and thus confirms DE GEER's view on the rapid withdrawal of the ice sheet over the Bothnian Sea. In samples taken with the Gilson sampler, larger boulders of limestone and primitive rocks were met with; but these of course cannot be expected in glass tube samples. — Samples with disseminated white lumps were collected at the following stations: F28 near the Finnish coast, F30 in the central depression, F31A, F31C, F32A, north of Finngrunden, and F33 south of it. Sample F31E had a few white spots, but much less than the other samples. Clay of this kind thus covers practically the whole southern part of the Bothnian Sea, though it is at some points covered by younger deposits.

Weathering did not always attack the imbedded pieces of limestone. The grey limestone gravel of sample F31B and the coarse silt of F31 1924 consisted chiefly of perfectly fresh looking and sharp-edged pieces. HÖGBOM (48, 49) has shown that the ratio between the content of magnesium carbonate (or rather dolomite) and carbonate

of lime in a clay, may be regarded as a measure of the length of time during which the sedimenting clay particles were exposed to the dissolving action of the water. As calcium carbonate dissolves more easily than dolomite, the relative amount of magnesium carbonate increases in a deposit in proportion as the time of sedimentation becomes longer. This effect is noticeable even within a single varve, the fine-grained upper part having as a rule a lower content of carbonates and a higher ratio than the sandy layer. It might be added that the decrease of temperature during the winter months must have notably increased the rate of solution, Table 23 showing that the solubility of calcium carbonate increases considerably with decreasing temperature. Regionally, the same effect manifests itself in the fact that clays with a low percentage of lime, i. e. those deposited far from the source of the carbonates, always present high ratios between the carbonates. On the basis of an extensive analytical material, HÖGBOM calculated the mean ratios for different parts of the area in the provinces of Uppland, Västmanland and Sörmland, where carbonate containing late-Glacial clays appear. The lowest ratios were found in the north-eastern part of Uppland, where the highest carbonate contents occur; the highest ratios were in the south and southwest, where carbonate content is low. The normal ratio (parts magnesium carbonate on 100 parts of calcium carbonate) was 4.7 for clays with a carbonate content of 20—30 %, and 3.0 for those containing 30—40 %. In connection with the present work, the content of magnesia was determined in four cases only. The results were given in Table 1 (p. 18). It will be seen that the ratios are still somewhat lower than those found in the Uppland clays. As for sample F31B in particular, the ratio for the clay, 1.5, was exactly equal to that of the pieces of limestone imbedded in it. This value, moreover, is identical with that found by HÖGBOM for so-called »Baltic limestone»¹⁾. From this fact, we may conclude that the sample in question was never subjected to weathering, i. e. to the dissolving influence of the water; consequently, it must have been formed within a very short period of time. This circumstance, as well as the absence of any stratification, indicates that the clay at F31B is not of a fluvio-glacial origin, but rather morainic in character. The same is probably the case with the adjacent sample F31, 1924, for which a ratio of 2.1 was found. The gravel of limestone in the latter was finer; but like F31B, it did not have any white lumps testifying to weathering, for it was evenly light grey in colour. On the other

¹⁾ Swedish »Östersjökalk», a facies of limestone found abundantly in erratic blocks from the Silurian area of the Bothnian Sea.

hand, weathering was obvious in samples F31A and F31C, which in the top parts, poor in lime, had disseminated white lumps, while in the bottom parts, rich in lime, they were partly almost white and light red in colour. In these samples the magnesia content was not determined; whereas it was so for F33 1925, for which a ratio of 3.0 was found, indicating that weathering had begun and the possibility that the material from which the deposit was formed had originally had a still higher carbonate content.

The pebbles of limestone found imbedded in some of the samples, and in greater quantities dredged at the Finngrunden, consisted of different varieties of Silurian limestone. The colours were different shades of grey and red. Many were seen to contain small fragments of fossils. Such fragments were also found lying free in the clay or the sand, the biggest being about 2 cm, though the majority were only a few millimetres in diameter. The limestone in which they had been imbedded had in some cases been completely dissolved, while in others it was partly remaining. Doctor G. TROEDSSON of Sweden, who kindly examined the fossils, declared the fauna to be Ordovician, probably Middle-Ordovician. Of two bigger pieces of limestone, dredged at Finngrunden III, weighing 58 gr and 655 gr resp., the first was likewise Middle-Ordovician; while the second, somewhat younger and Upper-Ordovician, consisted of »Baltic limestone». On account of the small size of the fragments and the scarcity of the material, a further examination of the fossils so far has not been made. Fossils were found in samples F31B, F31D, Finngrunden II and III.

What conclusions as to the extent of the Silurian area may be drawn from the present material? From the distribution of Silurian boulders in Uppland, WIMAN (134) concluded that Silurian limestone belonging to different stratigraphic series occurs as solid rock in various restricted areas immediately north and east of the coast of Uppland; while GUSTAFSSON, from a study of the »spotted zone», concluded that the Silurian formation occupies an extensive and continuous area in the south part of the Bothnian Sea. The present material shows that the Silurian occurrences are undoubtedly more important than WIMAN supposed; but they are not necessarily confined to one area only.

To begin with, let us see what information can be afforded by the successive positions of the ice border in the southern Bothnian Sea, as to the direction from which material was supplied to the localities where carbonate-containing sediments have been collected. According to DE GEER (20), a change in the normal direction of the ice border, WSW—ENE, occurred when the melting had reached northern Upp-

land; so that here a »Finiglacial Gävle Bay» was formed. Perhaps we may suppose that a local retardation of the melting occurred when the ice margin first reached the depression of the present Bothnian Sea, while on land¹⁾ the withdrawal continued with the normal yearly amount. The direction of the striae shows that the transport of glacial detritus in this bay occurred from the north and NNE. The Finiglacial Bay of Gävle did not mark a prolonged retardation of the melting. When further east the ice border had reached the central depression of the Bothnian Sea, the rate of the disappearance of the ice sheet increased with unprecedented rapidity (DE GEER 21). The increased lifting power of the water caused a great calving bay to be formed here; while over the less deep western part, to begin with, a retardation occurred. From this calving bay emanated the great number of icebergs which spread their detritus all over the Bothnian sea and the adjacent parts of the present land, then covered by water. Within 200 years this second bay had become so extensive as to comprise the whole of the Bothnian Sea to the vicinity of the North Kvark. Over the shallow Kvark the melting took place more slowly. The melting on land once more gained on that in the sea, and 500 years later at the end of the Fini-Glacial period, i. e. in the year 0 of the Swedish chronology, the ice border, according to the latest determinations by DE GEER (cited after SAURAMO 95), passed just north of the Kvark in a west-easterly direction.

As already repeatedly mentioned, two limy samples were taken at depths of 106 and 79 metres at station F33, situated in the northern end of the narrow channel leading into the Bothnian Sea. As both were only indistinctly varved, the median of one being $1\ \mu$, they cannot have been deposited in the immediate neighbourhood of the ice border. Yet both had a high content of carbonates; F33 1925 having 30 % throughout the 26 cm-long core, F33 1926 the same amount 14 cm below the surface.²⁾ The $\text{MgCO}_3/\text{CaCO}_3$ ratio indicated that the initial carbonate content had probably been still higher. The thickness of a single varve in sample F33, 1926 was not more than 1 to 2 mm; since the core was 21 cm long, this means a time of deposition of 100 to 200 years. We do not know how deep into the bottom the diffusely varved clay may go. But from the length of the cores actually taken, we may conclude nevertheless that the area from which the limy detritus was supplied must have had a considerable extension. GUSTAFSSON

¹⁾ The expressions »land» and »sea» are used here in the sense of »present land» and »present sea».

²⁾ In this connection the layer of sand covering the late-Glacial clay is not considered. The surface sand was discussed in Section 25 and found to be post-Glacial, an effect of the upheaval of land on sedimentation.

estimated the number of regular distinct varves in Uppsala clay at about 200. According to DE GEER (21) the ice border receded here at a rate of about 300 à 350 metres a year; this indicates that the formation of indistinctly varved clay began when the ice border had receded at least 60 km. At F33 conditions may have been the same, as the rapid melting over the Bothnian Sea cannot yet have begun at this period; here we should rather expect a retardation, because of the formation of the Finiglacial Bay of Gävle. A distance of 60 km from F33 takes us north of the Finngrundén. Here we should thus expect an extensive Silurian area. As we have seen, actual proofs of its existence have been found in the form of boulders at the Finngrundén, morainic clay at F31 and F31B, and limestone pebbles at F26A. Whether limestone forms part of the solid rock foundation of the Finngrundén banks themselves, remains so far an open question. GUSTAFSSON calculated that the »spotted zone» in Uppsala clay was formed about 350 à 400 years after the deposition of the first varve at Uppsala. Reckoning on a retreat of 200 metres a year, he placed the Silurian area immediately north or east of the coast of Uppland. A retreat of 300 à 350 metres a year, as given by DE GEER, again takes us to the vicinity of Finngrundén. The »spotted zone» of Uppsala clay would thus have been formed when the ice border had retreated at least as far as the Finngrundén, and when icebergs had begun forming here; while the origin of the carbonates in the regular varves of the Uppland clays, directly or indirectly, would be the several isolated occurrences of solid limestone, which in the opinion of WIMAN are to be sought along the coast of Uppland.

The limestone boulders and the limy clay on the Åland Islands have been ascribed partly to local occurrences of solid limestone at the bottom of certain bays and immediately north of the islands, (METZGER 65, HAUSEN 44) and partly to a more extensive area at a greater distance in the Bothnian Sea (HAUSEN 45), from which especially the boulders of Baltic limestone, spread by icebergs all over the Åland Islands and the Archipelago, and even as far as the coast of the Finnish mainland, (GYLLING 41) would derive their origin. This more distant area might very well be identical with the Finngrund area. On the other hand, the lime content of the varved clays in southern Norrland from Gävle to Söderhamn can hardly derive its origin from the same area (except in the most fine-grained part), as this would mean a transport of fluvioglacial detritus in an east-westerly direction, which seems improbable in view of the shape of the ice border here and the course of the melting over the Bothnian Sea. Local occurrences along the coast seem again more probable (Silurian boulders at the Kultebo Lake, v. ECKERMANN 23).

Some information as to the extent of the Silurian area in the west-easterly direction may be inferred from samples F32A and F31C and E. F32A testifies to rather peaceful conditions. The carbonate content of this 26 cm-long core, which in the bottom part was 12.4 %, decreased slowly to none in the last 7 cm. As there were white spots in the lime-free part also, solution may have contributed to the low lime content; but it is evident nevertheless that long before sedimentation ceased here, detritus was being supplied chiefly from a lime-free area, which can only have been situated west or north of the Silurian one. Further east, that is, nearer to the central depression of the Bothnian Sea, conditions were more complicated. In sample F31C dark grey, fine-grained clay with only 8 % of carbonates covered, without a transitional zone, light coloured clay holding nearly 32 %, and 10' east the distinctly varved clay from F31E was practically lime-free. When this was being deposited, the whole of the Silurian area was perhaps still covered by ice; but in any case it seems evident that the latter cannot stretch as far east as this point. A considerable extension in the northern direction is more likely. The carbonates in sample F28 and F29A might very well have been transported by icebergs over the great calving bay of the Bothnian Sea from a distant Silurian area situated in a northwesterly direction; whereas a transport in a purely easterly direction from the vicinity of the Finngrunden seems less probable. Moreover, Silurian occurrences far north is proved by the fact that Silurian boulders have been found in abundance on the islands of Brämön and Gran, not far from Sundsvall (SCHÖN 98).

The above discussion thus leads us to the conclusion that the principal Silurian area of the Bothnian Sea extends from the Finngrunden in a northerly direction. There is no direct proof as to whether it continues south of the banks also; but an indication to the contrary may be found in a statement by GUSTAFSSON, to the effect that the finely stratified clay which follows below the »spotted zone» in Uppsala clay is *p o o r i n l i m e*, which proves that the detritus from which it was formed chiefly originated from a lime-free area, situated between the area delivering the lime of the regular varves and that of the »spotted zone».

Finally, a conjecture as to the extent of the Silurian area suggested by the bottom configuration of the Bothnian Sea, may be formed here. As seen from map Fig. 1 the 50 metres isobath encloses a shallow area which stretches in a north-easterly direction from the Bay of Gävle to the Finngrunden banks, and from these, divided in two parts, northwards to somewhat above lat. 62°. Almost within the whole of this area the character of the bottom is specified on nautical charts

as »sand» or »stones». Within the two northern areas the depth varies from 35 to 50 metres, the 55 metres isobath uniting them into a single area; thus they form together a remarkably even plateau with partly steep slopes. At the northern end it rises abruptly 30 to 40 metres over the surrounding bottom. Between the Finngrunden and the Gävle Bay depth is more varying; the least depth at the banks is 0.5 metres. The three areas constitute together a continuous bank; west of it depth goes down to 80 à 100 metres, in the east more slowly to 100 à 150 metres in the parallel valley formed by the central depression of the Bothnian Sea. It seems a natural conjecture to suppose that this low but extensive elevation on the sea bottom holds what is left of the Silurian formation, though only at its extremity in the Gävle Bay has an outcrop of Silurian rock been established. The even surface of the »plateau», perhaps marks the actual extent of the Silurian formation north of the Finngrunden.

Summary.

The distribution of carbonate-containing sediments over the south Bothnian Sea is described (Fig. 28). The occurrence of a Silurian area in this neighbourhood is a fact well-known to geologists. The present investigation has shown that its influence on the sediments stretches in a north-southerly direction from F26A to F33, and in an east-westerly from F28 to F32A. The highest content of carbonates was found north of the submarine banks of Finngrunden at F31, where 41.6 % was noted. Other neighbouring samples contained over 30 %, which amount was also found as far south as at F33. The distribution of carbonates within the samples is shown on Fig. 29. A common feature of samples from this area, whether rich or poor in lime, is the abundant occurrence of small white lumps, disseminated all over the clay. These are connected with the »spotted zone» in Uppsala clay, described by GUSTAFSSON. The lumps, which are sometimes carbonate-free, consist of mineral grains coarser than the surrounding clay. They form the remains of completely weathered pieces of limestone originally imbedded in the clay. According to DE GEER limestone detritus from the Silurian areas was spread by icebergs, formed in especially great number during the rapid retreat of the ice-border over the Bothnian Sea. Weathering did not always attack the limestone detritus. Sample F31B contained quite fresh-looking and sharp-edged pieces, but no white lumps. Reasons are given for considering this sample, as well as sample F31 1924 to be *morainic* in character. — In samples F31B, F31D, Finngrunden II and III were found fragments of fossils, partly lying free in the clay. These

were examined by Dr G. TROEDSSON of Sweden, who declared the fauna to be Ordovician, and probably Middle-Ordovician. — The site and extension of the Silurian area is discussed. WIMAN assumed the existence of local occurrences immediately north and east of the coast of Uppland. The finds of limestone boulders and morainic clay at the Finngrunden banks and north of them, as well as of limestone pebbles at F26A, prove that there is yet another extensive limestone area north of the Finngrunden. It is shown that this area probably has a greater extension in the north-southerly direction than in the east-westerly. A conjecture as to its extent, founded on the configuration of the sea bottom, is furnished.

31. CARBONATE CONTENT OF SAMPLES FROM THE NORTH BALTIC AND THE GULF OF FINLAND.

It was shown in Section 29 that the character of Baltic sea water precludes the formation of carbonate-containing sediments at the bottom, otherwise than from inorganic limestone detritus, grains of which are washed out into the sediment, become imbedded there, and thus escape rapid solution. Shells of molluscs are completely dissolved long before the necessary state of mechanical disintegration is reached. For this reason the lime content of the bottom samples collected in the Gulf of Finland and the North Baltic may be attributed to the Silurian formations of Estonia and Gotland; and in addition, for the late-Glacial clays of the Baltic, a more northern provenience of the lime may be possible.

The percentage of calcium carbonate in samples from this area is shown in Table 24 and on Fig. 28. On the latter, stations are also marked where carbonate-free samples were collected. We note that from F56 onwards, except in the Åland Sea and the Archipelago, a slight carbonate content in the sediments is the rule. At some stations in the Baltic both lime-free samples and samples with a low lime content were collected. The highest amount was found at F73, the post-Glacial sample taken here containing 6.3 %.

The first column of Table 24 refers to late-Glacial samples. It will be seen that only two such samples from the Gulf of Finland had a slight content of carbon dioxide, viz. F42 1928, 64 m, and F55 1924, 90 m, containing 0.23 and 0.72 % resp., calculated as CaCO_3 . It is doubtful whether the low amount of carbon dioxide in F42 1928 should really be ascribed to calcium carbonate; but that of F55, taken in a depression quite near the Wrangel Islands, is obviously

Table 24. Carbonate content in samples from the North Baltic and the Gulf of Finland.

Late-Glacial		Post-Glacial		
Sample	CaCO ₃ %	Sample	CaCO ₃ %	Mean
F42 1928	0.23	F41 1924	0.59	2.35
F55 1924	0.72	F42 1924	0.55	
		F56 1924 ¹⁾	1.31	
		F56 1925 ¹⁾	2.64	
		F56 1928 ¹⁾	3.09	
		F57 1924 ¹⁾ a)	1.94	1.50
		b)	1.05	
		F57 1925 ¹⁾	2.00	1.45
		F61 1924 ¹⁾	1.41	
		F61 1925 ¹⁾	1.41	
		F61 1928 ¹⁾	1.52	
		F62 1924 ¹⁾ a)	2.55	
		b)	3.07	2.44
		c)	1.71	
		F71 1925	0.34	0.26
		F71 1929	0.20	
		F71 1930	0.23	
		F72 1924 ¹⁾ a)	3.96	3.75
		b)	3.53	
F74 1930I a)	2.30	F73 1924 ¹⁾	6.27	2.89
b)	4.59	F74 1925 ¹⁾	1.07	
c)	3.96	F75 1925 ¹⁾	0.27	
d)	5.43	F79 1926 ¹⁾	0.34	
e)	2.71	F80 1930I ¹⁾ a)	1.68	
F74 1930II	2.60	b)	1.84	1.23
F76A 1924	2.45	c)	2.47	
F79 1928	0.43	F80 1930II ¹⁾	3.78	1.23
		F81 1926 ¹⁾	1.14	
		F81 1930I ¹⁾ a)	1.43	
		b)	0.95	
		c)	1.29	
		F81 1930II ¹⁾	1.32	

¹⁾ Carbonate content observed in calculating mean value for the Baltic carbonate area.

due to carbonates washed out from the coast. Further out, carbonate-containing late-Glacial clay was not found until F74, 195 m. The two samples collected here had mean contents of 3.8 and 2.6 %. The 36 cm-long core of the former was divided into 5 parts, each of which was analyzed for carbonates with the following result: a) 2.30, b) 4.59, c) 3.96, d) 5.43, e) 2.71 %; which shows that the carbonates were unevenly distributed. The lime content of this sample, as of that collected further west at F76A, 96 m, possibly derives its origin from the limestone occurrences at the Åland Island; but in this case we must take into account the possibility that it may originate from crystalline, not Silurian, limestone, since crystalline limestone frequently occurs as solid rock in the Finnish and Swedish Archipelago. In this con-

nection it may be noted that late-Glacial clay at the Islands of Svenska Högarne, and Svenska Stenarne rising from the ridge which separates the Baltic from the Åland Sea, has a carbonate content of 20—22 % (HOLST 50), which is higher than on the adjacent mainland. The lime content at F76A may be of the same origin. A slight carbonate content was finally noted in the late-Glacial sample F79 1928, 105 m.

Turning now to the post-Glacial deposits, we find in the inner-part of the Gulf of Finland a slight lime content only at the stations F41, 51 m and F42, 61 m, where 0.59 and 0.55 % were noted. All other post-Glacial samples proved to be lime-free, until proceeding westwards we come to station F56 about 80 m, at the mouth of the gulf. In three samples collected here amounts from 1.3—3.1 % were determined. At stations F57, F61 and F62, which like F56 are situated in the deep southern part of the Gulf at depths of 80—100 metres, the muds likewise had carbonate contents of the same order of magnitude. Of the two samples F73, 87 m, and F72, 124 m, collected northwest of Island Dagö, the first, as already mentioned, showed the highest amount observed in post-Glacial muds, or 6.3 %, while F72 contained about 3.7 %. The latter value agrees well with that of a sample taken during the Swedish Hydrographical Expedition in 1877, quite near F72 at station »Klint 84»; this sample at a distance of 20 cm from the surface contained 3.1 % of carbonates. Varying amounts were further noted at F74, 176 m, F80, 189 m, and F81, 220 m, while F75, 178 m, F79, about 110 m, and F78, 410 m were practically lime-free. The same was the case with all samples from the Åland Sea and the Archipelago. In none of these was a notable carbonate content evident.

The mean content at the 11 stations between F56 and F81 (marked especially in Table 24), which together may be said to form a carbonate-containing area, was 2.20 %, or almost the same as the mean 2.31 %, calculated by MUNTHER for the area between Gotland and Latvia on the basis of his own and BEHRENS' (9) analyses; the two highest values (5.8 and 4.0 %) entering in the latter mean probably belong, however, to late-Glacial samples. In calculating the mean, only one value was entered for each station; thus if there were analyses on various parts of the same sample, or several samples from the same station, only the corresponding means were used. When all samples collected in the Baltic proper are considered — including stations F56, F57, F61 and F62, which in this respect belong to the Baltic — the mean goes down to 1.78 %; but all the same it remains higher than the value 1.16 % given by MUNTHER for the South Baltic. Mean values, however, do not have much significance if the single values

entering in them differ considerably. For this reason importance can be attached only to the mean 2.20 % of the post-Glacial samples, which all had carbonate contents of the same order of magnitude and came from the same kind of environment (central depression of the North Baltic and its continuation into the Gulf of Finland).

The lack of carbonates in the sediments of the Åland Sea and the Archipelago is noteworthy; but another result would perhaps have been arrived at, if a greater number of samples had been available for analysis. An outcrop of Silurian limestone having been discovered in the Bay of Lumparen, five bottom samples were collected in this bay, with a view to ascertaining whether the bottom muds also contained carbonates. As was to be expected, all these samples proved to be post-Glacial, and moreover entirely lime-free.

It was pointed out in Section 29 that the water of the Litorina Sea probably represented a higher state of saturation with respect to calcium carbonate than the present Baltic. We should therefore expect a higher lime content in Litorina sediments than in the recent sediments covering them; or in other words, increase of lime content with depth in sediment, just as organic matter was found to increase with depth. However, no such effect has been noted. Where several parts of a sample were analyzed (see Table 19) the lime content was always found to vary irregularly. Neither increase nor decrease with depth could be established. This may be due to solution. It is obvious that the chance of solution is much greater in post-Glacial samples with their high content of decaying organic matter—especially in those in which the «black mud» character is developed—than in late-Glacial clays. Solution may for this reason occur unevenly, just as the black «reducing areas» (see Section 21) often seem to be accidentally distributed over a sediment. In this way any signs of a former higher carbonate content may have been obliterated.

Summary.

A slight carbonate content is the rule in samples collected near the Estonian coast in the Gulf of Finland and in the North Baltic. (Table 24). The lime content is attributed chiefly to the Silurian formations of Estonia and Gotland. The amount is about the same in post-Glacial and late-Glacial deposits. Carbonate-free deposits also occur. No carbonates were found in samples from the Åland Sea and the Archipelago. This may be due to the low number of samples from these regions. The mean for post-Glacial [sediments from 11 stations lying between F56 and F81 (especially marked in Table 24), which together may be said to form a carbonate containing area, was

2.20 %; while the mean of all samples from the North Baltic and the Gulf of Finland as far as F56 was 1.78 %, or somewhat higher than the value 1.16 % calculated by MUNTZ for the South Baltic. The carbonate content was found to vary irregularly within the sediments; neither increase nor decrease with depth could be established.

32. MECHANICAL COMPOSITION.

In the foregoing discussion only casual reference to the mechanical analyses has been made. For the purposes of classification the organic matter content, together with a statement as to the presence or absence of diatoms, proved entirely sufficient. Nevertheless the mechanical analyses offer valuable additional information for the characterization of the sediments, even if classification on the basis of these analyses alone would have been difficult on account of the complexity of factors influencing sedimentation in the sea.

Most of the mechanical analyses made are presented in the shape of distribution diagrams on Fig. 31—41. The actual analytical data are also given. In drawing the diagrams the figures were rounded off to the nearest half-percent. For each sample the two quartiles, the median, the coefficient of sorting So and the coefficient of skewness Sk were calculated and marked on the diagram, which thus contains all the data of the mechanical analysis. Coefficients of skewness below unity, that is indicating better sorting on the coarse side of the median, are given as fractional numbers in order to facilitate comparison with values above unity; coefficients equal to a and $1/a$ indicating same degree of skewness.

As for the order in which the diagrams are given it would have been simplest to make it the same as that of hydrographical stations beginning by F1 and ending by F81. In that way local similarities would have been brought out and any particular diagram would have been easily found. But on the other hand it would have been difficult to get a survey of the different types which undoubtedly exist among the sediments. For this reason the diagrams were arranged according to types or other common characteristics. Within the separate groups the order of stations is generally observed.

For the sake of a better survey, seven characteristic diagrams are given on Fig. 30. Most distributions may be referred to one of these or form transitional types. A glance at Fig. 30 shows that the frequency distribution within the clay group forms a very important feature of most sediments and that consequently subdivision of the clay fraction into several subgroups is absolutely necessary for a good

Fig. 30.

Seven typical distribution diagrams.

characterization of fine-grained sediments. A clear idea could not have been obtained of any of the seven types if the percentage of particles within the clay group had been given simply as a square at the end of the diagram.

Type 1 first attracted notice in some samples of dusty sand from the Bothnian Bay. Its characteristic feature is the very strong asymmetry of the distribution, the range of particle sizes being markedly wider on the left than on the right side of the mode. Thus the shape of the curve in the first and fourth quartiles attributes to the characterization of the type, whereas the coefficients of sorting and skewness are not particularly characteristic. A consequence of the lack of symmetry is that the drop from the mode group is markedly steeper on the right than on the left side of the mode. A similar arrangement of particle sizes may often be recognized within a certain part of a frequency distribution, though the distribution as a whole cannot be assigned to this type. Instances of *type 1* are diagrams 1, 2 and 5

Fig. 32.

Fig. 33.

Fig. 31.

Fig. 35.

Fig. 36.

Fig. 37.

Fig. 38.

Fig. 39.

Fig. 40.

Fig. 41.

(Fig. 31) referring to samples of dusty sand or coarse silt from the Bothnian Bay. In all of these the high mode lies in the dusty sand group, the range stretching just beyond $100\ \mu$ on the right side, but reaching on the left down to the smallest grain sizes. In diagrams 3 and 4, which belong to two specimens of morainic clay (see p. 180) found at stations F31 and F31B north of the Finngrunden this type may also be distinguished, though both of them show on the coarse side of the median an ample admixture of sand grains of all grades. The steep right side and slowly declining left side of the mode are nevertheless recognizable. Further instances of the same character of the mode are to be seen in diagrams 21 (Fig. 33) 49, 50 and 55 (Fig. 37), as well as in many others, though less well developed.

Of all types of sediment probably *type 1* best reflects the sorting capacity of moving water. Though it would lead too far to discuss in this connection the theoretical shape of the distribution curve under various conditions of settling an attempt will be made below to show the principal features of the problem.

A current of constant velocity V and height h carries detritus of constant composition. The amount of a single particle size with radius r , that passes through a cross section L of the current, is a function $f(r)$ of r (Fig. 42).

The settling velocity v of a particle with radius r is Cr^2 (law of STOKES) where C is a constant. A particle at the surface of the current reaches the bottom after the time $\frac{h}{v}$. On reaching the bottom it has simultaneously been carried by the current the distance $V \frac{h}{v}$.

Thus, the smaller the particle, that is, the smaller the settling velocity, the further will the particle be carried before reaching bottom. Particles which are not at the surface of current

Fig. 42.

Deposition from moving water.

when passing cross section L, will have a shorter way to settle and will arrive at the bottom nearer to L. If all particles of radius r were evenly distributed over L, they will also be evenly distributed over the distance $V \frac{h}{v}$ on the bottom. In one unit of time the amount $V f(r)$ of particles with radius r passes through L. Consequently the amount

$$\frac{V \cdot f(r)}{V \cdot \frac{h}{v}} = \frac{C}{h} f(r) r^2 \quad (1)$$

in one unit of time becomes deposited in every point of the distance $V \frac{h}{v}$. It is noteworthy that expression (1) is independent of the velocity V of the current. In other words, independently of possible variations of the velocity

V the amount deposited at any point of the bottom in one unit of time will be the same, provided the composition $f(r)$ of the detritus that passes the cross section L remains the same. Let us consider a certain point P situated at the distance l from the cross section L. Of all grain sizes passing through L those for which the distance $V \cdot \frac{h}{v}$ is greater than l , will become deposited in P. The biggest grains still reaching P will be those for which

$$V \cdot \frac{h}{v} = V \cdot \frac{h}{Cr^2} = l, \quad \text{for which consequently } r = \sqrt{\frac{V \cdot h}{C \cdot l}} \quad (2)$$

All smaller grain sizes will become deposited in P. The sum of all particles deposited in P in unit of time will therefore be

$$F(r) = \int_0^{\sqrt{\frac{V \cdot h}{C \cdot l}}} \frac{C}{h} f(r) r^2 dr \quad (3)$$

Consequently the distribution curve $F(r)$ of the sediment formed in P will be given by the equation

$$F(r) = \frac{C}{h} f(r) r^2. \quad (4)$$

If $f(r)$ is a constant, that is if equal amounts of all grain sizes pass through the cross section L, equation (4) will be that of a parabola. The diagram will stretch from the origin to radius $r = \sqrt{\frac{V \cdot h}{C \cdot l}}$.

Fig. 43 shows the shape of such a diagram, drawn in the ordinary manner to a logarithmic scale. It is evident that equation (4) represents a very strong sorting of the material and moreover an extremely skew distribution.

It was shown above that even if the velocity of the current is varying, the amount of sediment deposited in P will be constant provided the amount that passes through cross section L remains constant. But the size of the biggest grains deposited in P, that is the upper limit of S , will vary with the velocity, and consequently with time, and in order to determine the total amount of particles deposited in P during a certain interval of time we have to integrate S over time. The equation of the distribution curve can easily be deduced if a linear relation between velocity of current and time is assumed. It is found that even in this case the distribution of the sediment formed in P will be extremely skew.

Fig. 43.
Theoretical distribution
curve.

The form of the function $f(r)$ does not markedly influence the distribution. The factor r^2 in equation (4) will always predominate, unless the function $f(r)$ itself is very skew (e.g. has the form $f(r) = \frac{K}{r^2}$, which is hardly a natural assumption).

We thus come to the conclusion that a current moving in constant direction and carrying detritus of constant composition will always bring about a very skew distribution. The more exclusively the sorting capacity of the water makes itself felt, that is the less subjected to chance variations it is, the more skew will the distribution be.

Of the few distributions of *type 1* met with, those having medians in the dusty sand or coarse silt group (20—50 μ) are best developed. Here we find the lowest coefficient of sorting occurring in any of the samples analyzed, viz. 1.95 in sample F1 1924 a); in the same sample the height of a primary subgroup (see p. 50) reaches 29 %, or the highest value observed in any sediment. The latter two facts are of course interrelated, both indicating that the sediment is highly sorted. It is true that in diagram 7 the height of the 50—100 μ group reaches 41 %, but sample F15 1926 having been taken with the Gilson sampler the diagram only applies to the sample, and not to the sediment. —

In Section 25 the layer of sand which almost always covers late-Glacial deposits was discussed and found to be a consequence of the upheaval of land. The depth of the Baltic being now about 150 metres less than at the end of the late-Glacial period and its area considerably smaller, littoral sands, washed out from the coast or from sandy banks by wave action and currents, are now being transported very much farther down than in earlier periods and may become deposited in almost any part of the Baltic. It is therefore not surprising that the thin layer of sand occurring on top of late-Glacial deposits often shows an irregular distribution of particle sizes, being the result of intermittent sedimentation, when wave action or currents have been particularly powerful. Diagrams 8—13 (Fig. 31—32) show instances of this kind of sedimentation. We see that their medians vary from 150—750 μ and the coefficients of sorting from 3.1 to 10.7, while those of diagrams 1—5 are more constant, varying only from 1.95 to 2.87.

Type 2 on Fig. 30 illustrates the distribution of a varved clay. It shows clearly the occurrence of two maxima, corresponding to »fine» and »coarse» layers of the clay, otherwise the diagram chosen for Fig. 30 is not particularly characteristic, varved clays, as is natural, showing a variety of distributions, depending on the relative thicknesses of the various layers and their respective sets of particle sizes.

Instances of *type 2* are diagrams 14—24 (Fig. 32—33), showing the composition of a number of more or less distinctly varved clays, with greatly varying coefficients of sorting and skewness. Diagrams 14—21 refer to samples from the Bothnian Sea, 22 to sample F65B from the Archipelago and 23—24 to samples from the Gulf of Finland. Diagrams 17—21 belong to indistinctly varved, carbonate-containing clays from the south part of the Bothnian Sea. They may be said to form a transition to the following *type 3*, but are slightly less fine-grained than typical sediments belonging to the latter group, their mean median diameter being $1\ \mu$ against 0.5 for *type 3*.

Type 3 represents the most fine-grained kind of non-varved late-Glacial deposits. Some of the clays belonging to this group (Diagrams 25—27 and 32 Fig. 34) were formed in the soft water of the Baltic Ice Lake, while others were collected at localities where sedimentation had probably not yet ceased when sea water penetrated into the lake as a result of the opening of the Närke Sounds. Yet all have essentially the same composition. A study of Fig. 34 shows that the mode of all distributions of this type lies in subgroup $0.2\text{--}0.5\ \mu$, except that of sample F59A, the distribution of which rather resembles diagrams 17—21. In subgroup $0.5\text{--}1\ \mu$ almost the same height is attained as in the mode group, but after that there is a marked drop to subgroup $1\text{--}2\ \mu$. Thus it is clear that sorting has occurred even within the clay group, causing a pronounced accumulation of particles smaller than $1\ \mu$. When comparing diagrams 17—21 to those of *type 3*, we note that in both a primary subgroup attains about the same maximum height or 20—25 % (mean height of all non-varved clays 22 %) and the coefficients of sorting are about the same, but the mode of the samples from the Bothnian Sea is slightly displaced to the right into subgroup $0.5\text{--}1\ \mu$, and correspondingly the sharp drop occurs only in passing from subgroup $1\text{--}2\ \mu$ to that of $2\text{--}5\ \mu$. The principal range of particle sizes in samples from the south Bothnian Sea thus comprises grain sizes from $2\ \mu$ downwards, while in those of *type 3* occurring in the Gulf of Finland and the North Baltic, the predominating grain sizes lie below $1\ \mu$. One might be tempted to interpret this as a systematical difference, possibly connected with the entrance of salt water into the Baltic, but as at least one sample of *type 3* (F64 1925) was deposited in the Yoldia Sea an inference of this kind would not be correct. However, though the number of fine-grained late-Glacial clays collected in the Bothnian Sea is too small to allow of general conclusions, the fact that among post-Glacial samples, also, the most fine-grained ones were found in the North Baltic points to the reality of the observed difference.

The astounding uniformity over wide areas in the composition of clays of *type 3* is seen from Table 25 which shows the frequency distribution within the clay group of six late-Glacial samples of which three from the Gulf of Finland, two from the North Baltic and one from the Åland Sea.

Table 25. *Frequency distribution within the clay group of six non-varved late-Glacial clays.*

Sample	2—1 μ %	1—0.5 μ %	0.5—0.2 μ %	< 0.2 μ %	1—0.2 μ %	Median
F42 1928	14.7	21.5	28.4	15.4	49.9	0.62
F43A 1924	13.4	20.3	28.3	14.9	48.6	0.62
F55 1924	13.1	19.4	29.2	18.0	48.6	0.55
F77 1925	11.9	21.1	28.8	22.6	49.9	0.48
F79 1925	12.6	20.6	28.8	18.3	49.4	0.55
F64 1925	15.6	20.6	28.4	21.0	49.0	0.51

The table shows that the percentages of particles in subgroups 1—0.5 μ and 0.5—0.2 μ are practically identical for all samples and their sum only varies between 48.6 % and 49.9 %. In group 2—1 μ the agreement is not quite so good, the range being 11.9 to 15.6 %, while the amount of particles < 0.2 μ seem to increase when passing from the Gulf of Finland into the Baltic. — The table does not include the most fine-grained sample of all F76A 1930II (Diagr. 30, Fig. 34) in which subgroup 0.5—0.2 μ attains 32.4 %, group 1—0.5 μ 22.8 %, and the colloidal clay — < 0.2 μ — amounts to 24.8 %. With its median of 0.4 μ and its coefficient of sorting of 2.07, it is more fine-grained than any other late-Glacial or post-Glacial sample analyzed.

It is of considerable interest to compare the composition of clays of *type 3* to that of an »Ancyclus» clay, analyzed by ODÉN and REUTERSKIÖLD (78). The latter was obviously not an Ancyclus clay in the strict sense of the expression, but belonged to the group of clays which of old have been given that name (MUNTHE 67), though in reality they complete the series of late-Glacial deposits, being formed of the most fine-grained part of the glacial detritus (DE GEER 22). These clays are thus of exactly the same kind as the fine-grained non-varved late-Glacial clays of the present investigation and should have a composition similar to that of *type 3*. As a matter of fact the agreement is surprisingly good. The author recalculated ODÉN's analytical data as they were given in a form not allowing of direct comparison. The percentages of particles within each of ODÉN's subgroups were first calculated and these added up into the subgroups used in the present work. As the smallest grain size determined by ODÉN was 0.34 μ

(radius 0.17μ), the amount of particles in subgroup $0.5-0.2 \mu$ had to be extrapolated. This was done by continuing the summation curve downwards with the same inclination as between 0.34 and 0.50μ , which operation in practice meant multiplying the percentage of particles between 0.34 and 0.50μ (11.7%) by the factor $0.40/0.17$. The following result was obtained:

»Ancyclus» clay, ODÉN:

$> 10 \mu$	$10-5 \mu$	$5-2 \mu$	$2-1 \mu$	$1-0.5 \mu$	$0.5-0.2 \mu$	$< 0.2 \mu$
% 4.4	8.5	11.5	15.5	17.4	27.6	15.0

We see that the composition does in fact strongly resemble that characteristic of *type 3*. The mode of the distribution lies in the same subgroup $0.5-0.2 \mu$ and, though extrapolated, the percentage of particles within this group is almost the same as that common in clays of *type 3*. The similarity in composition may also be seen by comparing Fig. 44 with the diagrams on Fig. 34. The median is slightly higher and the sorting somewhat less in the »Ancyclus» clay, but the connection with *type 3* is unmistakable.

Fig. 44. Distribution diagram of »Ancyclus» clay (ODÉN).

In all clays of *type 3* the coefficient of skewness slightly exceeds unity. This indicates that the range of particle sizes is somewhat wider on the coarse than on the fine side of the median. But as in the case of *type 1*, the coefficient of skewness does not give a good idea of the actual skewness of the distribution, this being so pronounced that in most cases the median lies slightly outside the mode group. A better idea is obtained when comparing the amount of particles on either side of the mode group. We then come to the result that the percentage of particles smaller than the mode group constitute on an average 18 %, while those bigger than the mode make out about 53 % of the sample. The mode has thus a very skew position.

— The diagrams are drawn so as to give an idea of the smallest grain sizes occurring in the samples. A study of Fig. 34 indicates that about $50\ \mu$ may be taken as a probable lower limit for late-Glacial clays.

It was pointed out above that some of the clays belonging to *type 3* were probably deposited in saline water. This was undoubtedly the case with sample F64 1925 from the deep northern part of the Åland Sea and with the above mentioned «Ancylys» clay from the neighbourhood of Uppsala, the localities of which were still covered by ice when the connection with the Ocean over Central Sweden was formed. Yet their composition is quite the same as that of the Baltic Ice Lake deposits. A natural assumption would be that sediments formed in saline water should be poorly sorted, i.e. comprise a wide range of particle sizes, as the sorting process would be prevented by the formation of rapidly settling aggregates. On this assumption SAURAMO (93) founded his views in the effects of coagulation on the structure of certain series of varved clays in Southern Finland. In the case of clays of *type 3*, however, sorting was obviously not prevented, these clays belonging to the best sorted sediments occurring in the Baltic (mean $So\ 2.4$) and we must therefore conclude that either coagulation took place after the sorting process had ceased, or aggregates of varying sizes were formed which did not prevent continued sorting of the material. Distributions of *type 3* probably reflect the composition of the detritus remaining in the water when the sorting process had ceased and what was left slowly settled to the bottom in practically stagnant water, but whether the final deposition occurred in a coagulated condition or not the diagrams do not reveal.

In planning the mechanical analyses of the present work one of the reasons for subdividing the silt and clay groups into several subgroups was the wish to ascertain whether any influence of coagulation on the composition of the samples could be detected. If such an influence had been evident one would have obtained a clue for distinguishing Baltic Ice Lake and Yoldia sediments as well as Ancylys and Litorina sediments from each other. A marked difference in sorting between clays deposited in the Baltic Ice Lake and the Yoldia Sea would have been especially convincing as the character of such clays could already be inferred from the locality of collection and there only remained to establish a possible difference in composition. As no such difference has been detected, where it ought to have been evident, we are hardly entitled to interpret poor sorting where it does appear as a result of coagulation. Thus we must explain the often very poor sorting in post-Glacial sediments as due to other circumstances.

It may be emphasized that the above result cannot be used as an argument against ODÉN's (75) and SAURAMO's assumption that the exceptional thickness of the varves in certain fine-grained clays in Uppland and Southern Finland has to be ascribed to the coagulating power of the water of the Yoldia Sea, causing rapid precipitation of detritus that normally would have spread over a wide area. The distribution diagram reveals the relative composition of the sediments, which composition has been found the same in fine-grained clays, and whether these were deposited before or after the opening of the Närke Sounds; but it cannot tell anything about the actual quantity of the material and, as already pointed out, leaves open the question as to under what conditions it was deposited.

However, we can hardly escape assuming that even independently of a possible salinity in the water, some kind of coagulation process must have had a part in the formation not only of fine-grained non-varved late-Glacial clays, but also of the varved ones. The thought is not new (ANTEVS 6, BRENNER 15) that coagulation accounts for the presence in varved clays of considerable amounts of particles so fine that we cannot figure their settling to the bottom at all, within the course of a year, without the co-operation of an accelerating factor. It is true that for the last late-Glacial deposits in which no varves are conspicuous we need not assume a yearly sedimentation period. Deposition may have taken place extremely slowly during a long period and a single grain may have needed years to arrive at the bottom. But considerable amounts of very small particles have also been found in nearly all distinctly varved clays examined. Thus sample F21 contained 17 %, F31E 16 % (Fig. 32), and samples F43 and F54 (Fig. 33), both deposited in the Baltic Ice Lake, 21 % and 31 % respectively, of particles smaller than 0.5μ . Thus even if we figure the Baltic Ice Lake as permanently turbid from very slowly settling particles, it is still a fact that considerable amounts yearly settled out of this suspension. According to КÖНН, grain sizes 0.5 and 0.2μ (sp. gr. 2.7, temp. 5°) need 7.5 and 47.5 days respectively for a 10 cm fall, corresponding to approximately 2 and 13 years for 10 metres, while grain size 1μ covers 10 metres in 0.5 years. Now it is not necessary to assume that every particle individually covered the distance from the surface layers of the water column to the bottom (200 to 300 metres in the Baltic of the late-Glacial period), on the contrary, it is more probable that currents and vertical mixing carried the suspended matter to the vicinity of the bottom within a relatively short time and that the true sedimentation process only began after practically stagnant water had been reached. As a matter of fact

the mere presence of fine-grained detritus in the water must have caused vertical mixing as it added to the specific gravity of the water masses in which it was suspended. But even for a moderate fall of one metre particles less than 0.2μ would have needed over a year. Therefore, we cannot but conclude that they must have already been in a partially coagulated condition when settling. The nearest explanation would be to ascribe coagulating properties to the water of the Baltic Ice Lake. Considering the importance of the Silurian areas that had been covered by ice, the Lake water may have had a considerable content of calcium ions, which, as is well-known, are strongly coagulating, but we may also go one step further back and consider conditions at the very formation of the glacial detritus. TAMM (106, 107) has recently shown experimentally that a certain amount of weathering must always have accompanied the process of mechanical disintegration by which the materials of late-Glacial deposits were formed. Consequently electrolytes were dissolved, which to begin with were in immediate contact with the detritus formed. According to modern views on the structure and properties of clay particles (see Section 15), it seems probable that aggregation of the smallest grain sizes occurred even at this stage. The smallest grains would thus have been in a state of partial coagulation from the very beginning of their existence and in that state they would in due time have become deposited. Judging from the fact that in distributions of *type 3*, sorting is evident even within the clay group, the size of the aggregates can hardly have exceeded 0.5 to 1μ , but this already marks a greatly increased settling velocity for the very smallest grain sizes.

The following four types on Fig. 30 all refer to post-Glacial samples. *Type 4* as given on Fig. 30 is in a way the model of a distribution such as we would expect it in the sea. It is almost symmetrical, S_k being 1.03, it is well sorted, S_o being 2.4, and the decrease on either side of the mode agrees well with the frequency distribution of the »probability curve» (see below). Thus the transporting capacity of the water at the place of deposition has effected deposition chiefly of grain sizes between 2 and 5μ and the occurrence of smaller or bigger grains on either side of the mode may be considered as due to random variations. A few well developed distributions of this kind have been found in the Gulf of Bothnia (Fig. 35), but the type may be said to be rare. In most cases met with the mode of the distribution lies in the silt group; when it becomes displaced into the sand group the distribution seems to become asymmetrical (*type 1*) and the same tendency is seen when the mode lies in the clay group. In that case

it is difficult to establish the type at all, as we are then near the limit of determinable grain sizes; if the opinion expressed above is correct — which naturally also applies to post-Glacial sediments — that the smallest grains are always deposited in the shape of aggregates, then a symmetrical distribution, the mode of which lies in the clay group is hardly possible unless the sorting is very good. The best sorted distributions of *type 4* (*So* 2.3—2.4) are diagrams 34, 36 and 40 on Fig. 35; while further diagrams 41, 47, 51, 54 and 61 are more or less symmetrical. Because of their poor sorting the three last mentioned, however, rather belong to *type 5*. All distribution diagrams referring to post-Glacial samples from the Gulf of Bothnia (except those belonging to *type 1* and diagram 73, *type 6*) are given on Fig. 35 and 36. Some of the diagrams on Fig. 35 are less detailed than usually. This is due to the fact that determination of the smallest grain classes would have been illusory in samples which showed a tendency to develop fine layers in the top part of the cylinders during mechanical analysis. This was the case with many samples from the Gulf of Bothnia, especially with those samples from the Bothnian Bay, which had a notable content of limonite. — A study of diagrams 33 to 46 shows that most samples from the Gulf of Bothnia are fairly well sorted. The fineness increases in passing from the Bothnian Bay into the Bothnian Sea, but even here no lower median than 0.9μ has been observed, while in the Baltic medians down to 0.6μ are found. Thus the same rule is valid for post-Glacial as for late-Glacial deposits (see p. 206). The analogy is, however, not surprising if we take into account that the material of post-Glacial sediments must to a great extent be that of late-Glacial ones in the same surroundings. The mean coefficient of sorting in the Gulf of Bothnia (*type 1* included) is 2.9, the range being 2.0 to 4.0 while the mean of typical post-Glacial samples from the Gulf of Finland and the North Baltic is 3.8 and that of all post-Glacial samples from these areas as high as 4.6. The mean height of the distribution diagrams is 20 % in the Gulf of Bothnia, but 15 % in the rest of the area.

Outside the Gulf of Bothnia only two well sorted post-Glacial samples (*type 7* not considered) have been met with. These are samples F75 1925 and F78 1924, which both attain a height of 20 % and the coefficients of sorting of which are 2.6 and 2.5 respectively (diagrams 47 and 48 Fig. 36). These two, as well as sample F26 1925 (diagram 42), besides being well sorted, are also very fine-grained and therefore from the point of view of the frequency distribution, might be taken for late-Glacial. With regard to other post-Glacial

samples no mistake is possible as all others are either too coarse-grained or too poorly sorted or both, to be able to figure as late-Glacial. If we consider the localities where the above mentioned three samples were collected we understand that absence of coarse particles and consequent good sorting is not accidental. Sample F26, 137 m was taken from the central depression of the Bothnian Sea, thus far from land or shallow water; the same applies to F75, 178 m, from the middle part of the North Baltic, while sample F78, 410 m, came from the greatest depression of the Baltic, the Landsort Deep, to the depths of which coarse particles obviously seldom penetrate.

Type 5 is the most common type for post-Glacial sediments. Its chief characteristic, already mentioned in the foregoing, is the poor sorting, the maximum height of the distribution being generally about 15 %. Still less sorted are *types 6* and *7*, which in a way form extremes of *type 5*. While *type 6* may be said to be absolutely unsorted, the percentages of all grain sizes being about the same, *type 5* has generally a low mode in the clay group. Very often there is a small secondary maximum in the dusty sand or coarse silt group, the amount of particles $> 50 \mu$, however, seldom exceeding a few per cent. The range is thus the same as in non-warved late-Glacial clays, but the proportion between the various grain sizes is different. It is noteworthy that the abundance of colloidal clay is of the same order of magnitude as in late-Glacial clays, although the other subfractions in the clay group are considerably smaller, as in fact is natural in view of the low maximum height of the distribution.

A striking demonstration of the fundamental difference between late-Glacial and post-Glacial sediments, not only as to organic content and diatoms, but also regarding mechanical composition, is afforded by comparison of distribution diagrams of samples collected at theoretically the same point in the sea, but in reality of different origin. Diagrams 20 and 43, 29 and 63, 32 and 69 form instances of this kind. In all three cases the difference is marked and leaves no room for hesitation as to which group of sediments the respective samples should be assigned to. The two samples from F79 are especially interesting. Both are extremely fine-grained, having about the same median: 0.55μ for the late-Glacial and 0.58μ for the post-Glacial specimen; but while in the former a primary subgroup attains 21.5 %, it does not exceed 14.5 % in the latter; and while the former has a coefficient of sorting of 2.43, that of the latter is 4.20!

Most sediments of *type 5* were collected in the Gulf of Finland and the North Baltic, although in the Gulf of Bothnia a few poorly sorted specimens were also found. A number of more or less typical

distributions are given on Fig. 37—39. The mode of the three first diagrams (49—51) which refer to stations F40 and F41 in the inner part of the Gulf of Finland lies in the fine silt group, but in all other cases there is a low mode in the clay group. The height of the mode varies from 13 to 17 %, only in 2 out of the 24 cases attaining 19 %. The mean coefficient of sorting is 3.8 and the range 3.4 to 5.1.

The somewhat puzzling occurrence of two maxima in the distributions of post-Glacial sediments has already been discussed in Section 25 (p. 136). The secondary maximum was regarded as analogous to the layer of sand, which is almost invariably found on top of late-Glacial clays (see also p. 205). It was found that conditions of settling in the Baltic must have undergone a slow change since late-Glacial times, both the area and the depth having decreased considerably as a result of the upheaval of land. Sands have gradually been transported further and further out from the coast and have become partly deposited on top of earlier sediments, partly mixed up with them, in the latter case causing the small secondary maximum of the distribution.

The transporting agencies for post-Glacial sediments are currents and waves. These vary in strength and direction and may sometimes carry coarse, sometimes fine particles to a place of deposition; especially if the latter is protected from the moving water by a zone of quiet water, all kinds of grain sizes will become deposited there in the course of time. The more varying the transporting capacity of the water, the greater will be the range of the particle sizes deposited, and consequently the higher the value of the coefficient of sorting. While a late-Glacial clay was the result of a sorting process taking place within a body of water for a long time moving in the same direction and constantly fed with fresh detritus, a post-Glacial sediment is thus the chance result of a great many varying influences. In this circumstance may probably be seen the reason for the generally bad sorting of fine-grained post-Glacial sediments in comparison to late-Glacial ones. A certain transporting capacity in the water may predominate, leading to deposition preferably of a definite grain class; if then the deposition of smaller or bigger grains is due entirely to chance variations, the distribution curve of the resulting sediment will coincide with the so-called »probability curve». The curve will be higher or lower according to whether the transporting capacity has kept more or less constant.

In accordance with the definition of the coefficient of sorting its logarithm is equal to the »semi-interquartile range» of the »probability curve» when the latter is given as a function of the logarithm of grain

size. The »semi-interquartile range» may easily be calculated for curves of different heights.

The area enclosed between the »probability curve» and the X-axis (Fig. 45) is equal to $y_0 \sigma / \sqrt{2\pi}$ where y_0 is the greatest ordinate and σ the standard

Fig. 45. Probability or normal curve.

deviation (»root-mean-square deviation from the mean», see G. UDNY YULE: *An Introduction to the Theory of Statistics*, London, 1929). As in the present case the area equals 100 %, σ may be calculated from the equation

$$\sigma = \frac{100}{y_0 \sqrt{2\pi}};$$

σ is here expressed in terms of subgroups, for which log 2 or 0.30 was chosen as a basis (see p. 50). The »semi-interquartile range» or »probable error» is 0.674σ . Consequently the coefficient of sorting of a »normal» size distribution may be found from the equation:

$$\log So = 0.674 \frac{100}{y_0 \sqrt{2\pi}} \cdot 0.30$$

$$So = \text{num log } \frac{8.066}{y_0}.$$

In this way the following normal coefficients of sorting were calculated for a number of different heights (values of y_0):

Height of distribution diagram %	13	15	17	19	21	23	25	27
corresponding »normal» So	4.17	3.45	2.98	2.66	2.42	2.24	2.10	1.99.

By comparing these calculated coefficients to actually determined ones we are able to judge whether in a natural sediment the distribution corresponds to probability.

It would of course be more correct to calculate a fitted probability curve and thus to take into account the whole distribution, but the calculations involved are rather toilsome and in view of the

low number of subgroups, the accuracy attained would be only apparent. The calculation was carried out for one sample only F12 1925 (Fig. 30), which was chosen for illustrating *type 4*. Comparison of a coefficient of sorting with the corresponding «normal» coefficient has any sense only providing the coefficient of skewness approximates unity and the distribution is thus fairly symmetrical. Table 26 illustrates a few cases which show good agreement between actual and normal coefficients of sorting.

Table 26. *Comparison of normal and actual coefficients of sorting.*

Number of diagram Station	33 F3	34 F8	36 F12	44 F30A	21 F33	48 F78
Height of distribution diagram %	14.5	22	21	18	23	20.5
actual <i>So</i>	3.63	2.35	2.41	2.83	2.21	2.45
corresponding normal <i>So</i>	3.60	2.33	2.42	2.81	2.24	2.48

Only the last sample in Table 26 refers to the Baltic, all others are from the Gulf of Bothnia. In the Baltic and in the Gulf of Finland distributions as a rule are not normal, as is already evident from the frequent occurrence of a small secondary maximum at the coarse end of the distribution. Here at least two main influences have asserted themselves in the formation of the sediments. One is deposition of normal erosion products and of detritus from destroyed sediments of earlier periods, another the above mentioned recent transport of fine sand from the coast or from shallow banks downwards to greater depths. But yet another influence may be detected: that of weathering. It was already pointed out above that in spite of the low total height of the distribution diagram the percentage of colloidal clay ($< 0.2 \mu$) is of the same order of magnitude in post-Glacial as in non-varved late-Glacial sediments. This means that in post-Glacial sediments colloidal clay makes out a relatively greater part of the entire clay group. Table 27 contains the total amount of clay, as well as the percentage of colloidal clay therein in late-Glacial (*type 3*) and post-Glacial sediments (*type 5*).

The range of colloidal clay is 19 to 27 % in late-Glacial and 19 to 40 % in post-Glacial sediments; the mean values are 23.2 and 28.2 % respectively. The amount of colloidal clay in typical post-Glacial sediments is thus about 20 % higher than in the most fine-grained kind of late-Glacial clays. This fact seems to imply that weathering has occurred, increasing the amount of colloidal clay at the expense

Table 27. *Percentage of colloidal clay in total clay of late-Glacial and post-Glacial sediments.*

Sample	Total amount of clay %	Percentage of colloidal clay in total	Sample	Total amount of clay %	Percentage of colloidal clay in total
Late-Glacial:			Post-Glacial:		
F42 1928	80.0	19.3	F57 1925	58.3	26.4
F43A 1924	76.9	19.4	F61 1924	63.0	20.6
F55 1924	79.7	22.6	F61 1928	67.3	29.9
F64 1925	85.6	24.6	Pojo V	65.0	22.9
F76A 1930 II ..	91.1	27.2	Lumparen I	66.9	28.7
F77 1925	84.4	26.8	Lumparen II ...	57.4	19.0
F79 1928	80.3	22.8	F64 1928	63.7	26.8
Mean		23.2	F65A 1928	67.0	26.7
Post-Glacial:			F67 1930II	65.3	26.5
F40 1924	50.2	25.5	F68 1928	62.3	29.8
F40 1925	49.6	22.0	F68 1925	61.7	26.6
F41 1924	46.9	32.4	F74 1925	67.3	27.8
F44 1924	57.5	31.0	F79 1930	69.4	40.5
F45 1924b	65.2	32.2	F80 1930II	60.2	18.6
F49 1925	60.6	30.2	F81 1926	67.1	34.7
F50 1924	68.5	32.0	F81 1930II	63.9	32.6
F53 1924	70.5	34.0	Mean		28.2

of the other grain sizes in the clay group. Thus the low total height of the diagram is due not only to the addition of coarse particles at the right side of the mode but also to the levelling influence of weathering at the extreme left. The weathering may be due mainly to two reasons: on the one hand the very slow rate of settling of post-Glacial sediments and on the other the complicated biological and chemical processes taking place within them as a result of the high amount of organic matter.

As both colloidal clay and organic matter have a high water-capacity the gelatinous looking appearance of many black muds is probably due to the simultaneous abundance of these substances.

FRÖDIN (29) has published detailed analyses of the mechanical composition of post-Glacial sediments from the valley of the Göta river in Sweden, executed according to the ATTERBERG method by JOHANSSON and LARSSON. Though the Göta valley sediments may have been deposited in conditions of settling entirely different from those prevailing in the Baltic, it would have been interesting to compare their composition to that of the post-Glacial sediments of the present work as until now there has been very little detailed material available for comparison. However, except for the extreme group on the left, for which the analytical data are given, the analyses are presented

only in the shape of distribution diagrams in which the uneven upper line of the separate groups has been replaced by a smooth curve. For this reason comparison with the extreme group only is possible, which is that of colloidal clay. At first sight the clays of the Göta valley seem to be of an extremely fine-grained kind, the percentage of colloidal clay in many instances exceeding 40 %. As 28 % is the highest amount observed in the Baltic (F79 1930, diagram 69, Fig. 39), the Göta valley clays would thus be markedly more fine-grained. Another characteristic of these clays is the occurrence of two maxima in the distribution, a fact, which, as we have seen, is not peculiar in itself, but becomes so because of the position of the intermediate minimum. This is in most cases situated in the clay group between 0.6 and 2μ ; in the present investigation, on the other hand, minima in the clay group have been observed very rarely and never well developed ones.

If we examine the settling times used for the determination of the two smallest grain sizes we get the explanation both of the fineness and of the existence of the minimum. For the particle sizes 0.2 and 0.6μ , settling times of 100 and 25 hours respectively for a 10 cm fall were used. However, according to the law of STOKES these settling times correspond to grain sizes 0.6 and 1.2μ (temp. 20° , see e.g. GESSNER 33). The amount of colloidal clay in JOHANSSON'S analyses would thus, if anything, be comparable to the percentage of particles $< 0.5\mu$ in the Baltic sediments. As a matter of fact the two percentages are of quite the same order of magnitude and the Göta valley sediments are consequently not more fine-grained than the Baltic ones. If grain size 0.2μ in JOHANSSON'S analyses in reality corresponds to 0.6μ , the whole amount of particles which in the diagrams occupy the interval between 2 and 0.2μ should really be contained in the space between 2 and 0.6μ , or where in most cases the minimum is situated. A reconstruction of the diagrams on these lines would probably in many cases change the minimum into a maximum, but, analytical data lacking, it is difficult to judge of the final height of the diagram. However, as far as can be judged, there does not seem to exist any fundamental difference between the post-Glacial Göta valley clays and the Baltic ones.

There remains to be said a few words about the last post-Glacial types, 6 and 7. Both may be considered as extreme forms of *type 5*. In *type 6* the principal maximum of *type 5* is completely levelled and the secondary maximum has risen to a height equal to that of the other groups. This type may therefore be said to be completely unsorted, in the sense that no grain size is favoured at the expense of the others, there being equal amounts of all sizes. The distribution

diagram is higher or lower according to the range of grain sizes occurring. At localities where sediments of *type 6* have been deposited the transporting capacity of the water has thus varied within wide limits and chances have been equal for the deposition of all grain sizes. *Type 6* has generally a very high coefficient of sorting, and a coefficient of skewness approximating unity. — Instances of *type 6* are given on Fig. 40: the two belonging to station F71 might almost equally well have been referred to *type 5*. The most extreme case is that of F37 1924 (diagram 75), also given on Fig. 30. In this sample there are equal amounts of all grain sizes from 0.2 to 100 μ and the percentages of particles < 0.2 μ and > 100 μ are also about the same, 12.9 and 9.7 % respectively. Distributions of *type 6* seem to be formed preferable at sheltered localities where detritus is supplied from a restricted area only, and where consequently the sorting capacity of the water has hardly been able to exert itself. Thus F18, 91 m and F71, 155 m both lie in depressions of very small extent, F72, 124 m, not far from shallow water, F36 and F37 finally, in the narrow waters of the Bay of Wiborg.

The last *type 7* (Fig. 30) belongs to visibly stratified post-Glacial sediments. It consists of two well-defined parts, a very poorly sorted fine-grained part, which shows a likeness to *type 6*, and a coarse-grained part forming a sharp maximum in the dusty or fine sand group. In some cases there is some sorting in the clay group and then the diagram might almost be taken for that of a varved clay. A doubt as to the post-Glacial character of this type is nevertheless impossible, as the amount of organic matter is always high and diatoms occur abundantly. Instances of *type 7* (Fig. 41) were found in sediments from the mouth of the Gulf of Finland (F56, F62, F73) as well as in samples from stations F66 and F69. It is difficult to commit oneself to any definite opinion about the mode of formation of *type 7*. Like the foregoing it seems to occur mostly in sediments from restricted depressions or those situated near shallow water. We can only establish the fact that at some points of the sea bottom intermittent sedimentation has occurred. The most obvious explanation would be that currents of unusual strength or moving in an unusual direction have sometimes deposited fine sand where normally only clay particles settle. *Type 7* might be described as a modification of *type 5*, in which the small secondary maximum has grown to form the principal maximum of the distribution. *Type 7* has always a high coefficient of sorting; but a very varying coefficient of skewness.

In the foregoing an attempt has been made to describe the different types of sediments occurring in the Baltic and their distribution

over the area investigated. On the basis of the present material the following general picture is obtained. The coarsest sediments occur in the Bothnian Bay, where only post-Glacial sands and silts have been collected. The mean median diameter of the five sandy samples analyzed is 64μ , that of the five silts 6.6μ , no lower median than 2.7μ having been observed. In the Bothnian Sea the post-Glacial samples, mostly collected in the Härnösand Deep and the great central depression, are considerably more fine-grained, the median of eleven samples being 1.4μ and the extremes 0.9 and 2μ . The fine-grained late-Glacial samples have a median of 0.9μ , and the several varved specimens collected medians varying from 3 to 30μ . The lowest median or 0.75μ belongs to the late-Glacial sample collected at F30. In the Gulf of Finland the composition of the post-Glacial samples is more varying. The mean median of all 19 samples analyzed is 3.6μ , the range being 0.7μ to 20μ . If samples of *type 7*, which are markedly more coarse-grained than the rest, are not taken into consideration the mean median goes down to 1.6μ and the range is then 0.7μ to 3.7μ . As some of the samples from the Gulf of Finland were collected comparatively near land while those from the Bothnian Sea were all taken in the open sea, the sediments from the Gulf of Finland, may, as a matter of fact, be considered as equally fine-grained as the others. The mean median of the post-Glacial samples from the Åland Sea and the Archipelago is the same as in the North Baltic or 1.1μ , the range of the 20 samples analyzed being 0.6 to 2.1μ (*type 7* not considered). As is natural the most fine-grained of all post-Glacial samples (range 0.6 — 0.8μ) were found in the middle of the North Baltic at stations F75 and F79, as well as in the Landsort Deep, station F78, and in the Gotland Deep, station F81. — Outside the Gulf of Bothnia only two distinctly varved late-Glacial clays (F43, F65B) were collected, but several non-varved specimens. The mean median of the eight samples analyzed is 0.6μ , and that of the three from the Baltic proper 0.5μ . Thus both as regards late-Glacial and post-Glacial sediments the smallest average grain size is found in the Baltic. The result of the mechanical analyses of clays and silts, late-Glacial as well as post-Glacial, is summarized in Table 28 below, which comprises 62 out of the 90 analyses executed. Those not entering in the table refer to sands, varved clays or stratified post-Glacial muds.

The mean of all analyses entering in Table 28 is 1.6μ , and thus this value indicates the average median diameter of fine-grained Baltic sediments, as far as can be judged from the present investigation. It is possible, even probable, that a higher mean value would have been found if the hydrographical stations, where most of the

Table 28. *Mean median diameters of clays and silts, (types 2 and 7 not considered).*

	Bothnian Bay		Bothnian Sea		Gulf of Finland		Åland Sea and Archipelago		North Baltic	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Late-Glacial .	—	—	0.9 (3)	0.75—1 —	0.7 (4)	0.55—0.85 —	0.5 (1)	—	0.5 (3)	0.40—0.55 —
Post-Glacial .	6.6 (5)	2.7—17 —	1.4 (11)	0.9—2 —	1.6 (15)	0.7—3.7 —	1.1 (9)	0.9—1.6 —	1.1 (11)	0.6—2.1 —

(Figures in brackets refer to the number of analyses entering in mean).

samples were collected, had not for preference been situated over depressions. This fact which has already once or twice been referred to in the foregoing discussion may be seen from the cross sections on Fig. 24. The value 1.6μ forms in a way an average value for the most fine-grained sediments occurring in the different basins.

When compared to the mechanical composition of marine bottom sediments in general, Baltic deposits seem to possess a high degree of fineness. TRASK's extensive work on possible future source beds of petroleum comprised 166 mechanical analyses of bottom samples, preferably from localities adjacent to the coasts of North and South America, but also from various other parts of the world. Many of these samples came from sheltered bays or river deltas. Yet, only 4 of them or 2.5 % had medians below 2μ , while 58 out of 90 Baltic samples analyzed or 64 % showed that degree of fineness. Though it may be said that the Baltic samples came from a restricted area with uniform sediments, while those analyzed by TRASK belonged to widely differing localities of deposition, the difference in average fineness is still so marked that there is reason to believe that some special circumstance has contributed to it. The fact that TRASK's method of preparing the suspensions for analysis (see Section 19) was entirely different from the method used here may be suggested as a possible explanation. This assumption gains in probability by comparison of TRASK's analyses on Baltic deposits (Table 14) with the results attained here. The two sets of analyses are therefore hardly comparable. Nor, because of the difference in preliminary treatment, is the present material comparable to ODÉN's (74) analyses of deep-sea deposits, executed before TRASK's. The results arrived at by ODÉN implied that the general notion of the exceptional fineness of such deposits is not in accordance with facts. The same result may be inferred from THORP's (108) analyses of deep-sea deposits from the Western North Atlantic. As neither ODÉN nor THORP removed the sea salts present in the samples, it

remains an open question, however, how much of the lack of fineness is to be ascribed to this circumstance.

Some bottom samples from the Arctic Basin collected by the »Nautilus» Expedition of 1931 and analyzed by STETSON (102) proved to be more fine-grained than deep-sea deposits in general. STETSON's method of preliminary treatment resembled the one used here in that sea salts were removed by prolonged washing; as the samples moreover had a low content of organic matter, the fact that they were not treated with an oxidizing agent probably did not markedly affect the dispersion of the final suspensions. Each of the seven samples, 34 to 44 cm in length, were divided in 4 or 5 parts which were analyzed separately. The variations within a single core were quite marked, but in all except one there were parts having medians below 2μ ; the range was 1.0 to 7.2μ and the mean median diameter of all 2.6μ . Compared to deep-sea deposits, as analyzed by ODÉN, THORP and TRASK, these Arctic sediments are very fine-grained. Yet they do not surpass the Baltic ones in fineness. As far as can be judged from comparison with available analytical material, Baltic bottom deposits seem to belong to the most fine-grained sediments yet observed in the sea.

Summary.

It is shown that Baltic bottom deposits, in their mechanical composition, may be referred to seven different types (Fig. 30). The characteristic feature of *type 1* is a very strong asymmetry of the distribution, the range of particle sizes being very much wider on the left than on the right side of a well developed mode, mostly situated in dusty sand group. Maximum height of diagram 20—30 %. *Type 1* presumably best reflects the sorting activity of moving water. — *Type 2* is that of varved clays. It has generally two maxima corresponding to fine and coarse layers of the clay and shows a variety of shapes, depending on the relative thickness of the layers and their respective sets of particle sizes. Diagrams 14—24 (Fig. 32—33) show composition of more or less distinctly varved clays. Diagrams 17—21, forming transition to following *type 3*, belong to fine-grained (mean median 1μ) indistinctly varved clays from the South Bothnian Sea. — *Type 3* represents most fine-grained kind of non-varved late-Glacial clays (Fig. 34), showing uniform composition over wide areas (Table 25) in North Baltic and Gulf of Finland. Mode of *type 3*, mostly 21—22 % high, is always situated in subgroup $0.5\text{--}0.2\mu$, mean median diameter is 0.5μ ; the distribution is strongly asymmetrical as amount of particles smaller than mode on an average 18 %, while

53 % bigger than mode. *Type 3* is compared to composition of an »Ancyclus» clay, analyzed by ODÉN. Agreement found to be surprisingly good (p. 208). Though, according to modern views on development of Baltic in late-Glacial times some of the clays of *type 3* were undoubtedly deposited in saline water, no trace of coagulation may be detected in composition. If coagulation had effected formation of rapidly settling aggregates, sorting should be poor, yet *type 3* belongs to best sorted sediments of Baltic (mean $So = 2.4$). *Type 3* probably reflects composition of detritus remaining in water when sorting process had ceased and what was left slowly settled to the bottom in practically stagnant water. Nevertheless, the idea is set forth that the smallest grains of late-Glacial clays were in a state of partial coagulation from the very beginning of their existence.

Types 4—7 refer to post-Glacial sediments. *Type 4* is symmetrical and agrees well with the »probability curve», that is, distribution of particle sizes on either side of the mode may be ascribed entirely to random variations of transporting capacity of the water at place of deposition. Best developed distributions of *type 4* (So 2.3—2.4) are diagrams 34, 35 and 40 (Fig. 35) belonging to samples from Bothnian Sea. The mode is generally situated in silt group. *Type 5* is the most common post-Glacial type (diagrams 49—72): its chief characteristic is very poor sorting (mean So 3.8) and frequent occurrence of a small secondary maximum in sand group. Height of diagram seldom exceeds 15 %. Occurs in Gulf of Finland and North Baltic, including Åland Sea and Archipelago. Within the whole of this area only two well-sorted post-Glacial samples were found, viz. at stations F75, 178 m and F78, 410 m. The low mode of *type 5* is generally in clay group. A good idea of difference between late-Glacial and post-Glacial sediments is obtained by comparing samples theoretically from the same point in the sea but in reality of different origin. Diagrams 20 and 43, 29 and 63, 32 and 69 form instances of this kind. — The small secondary maximum in sand group of *type 5*, as well as layer of sand generally covering late-Glacial sediments is explained as a consequence of the diminished area and depth of the Baltic resulting from upheaval of land. — The general mode of formation of post-Glacial sediments is discussed: likewise formation of symmetrical distributions corresponding to »probability curve». Normal coefficients of sorting for symmetrical distributions of varying height are calculated and some instances of »normal» sorting are given in Table 26. — It is shown that post-Glacial sediments contain relatively more colloidal clay ($< 0.2 \mu$) than late-Glacial clays (Table 27). — Composition of post-Glacial sediments from the valley of the Göta river in Sweden (FRÖDIN)

are compared to Baltic deposits. — *Types 6 and 7* may be considered as extremes of *type 5* (Fig. 40 and 41). *Type 6* is absolutely unsorted, all grain sizes occurring in equal amounts. The maximum height of the diagram varies with range of particle sizes: *So* generally very high. *Type 6* is generally formed at sheltered localities where detritus supplied from restricted area only, so that sorting capacity of water has not been able to exert itself. — *Type 7* belongs to visibly stratified post-Glacial sediments. It has a poorly sorted clay group and a high maximum in the sand group. *So* is always very high. Occurs like *type 6*. *Type 7* may be described as modification of *type 5*, where small secondary maximum has risen to principal maximum of distribution. — In Table 28 mean median diameters of fine-grained sediments are shown (*types 2 and 7* not considered). The table comprises 62 out of 90 samples analyzed, the mean median of all is 1.6μ . It is shown by comparison with analyses of deep-sea deposits executed by ODÉN, TRASK, THORP and STETSON that Baltic deposits belong to the most fine-grained yet observed in the sea.

ERRATA.

Page 24, line 3 from foot, *for* Table 3 *read* Table 4,

» 27, » 13, *for* page 48 *read* page 50,

» 27, » 14, » page 95 » page 97,

» 94, » 16, » page 21 » page 23,

» 112, » 13, *for* 1.05 % and 1.94 % *read* 1.94 % and 1.05 %,

» 121, » 4 from foot, *for* p. 95 *read* p. 97,

» 143, » 2 » » , *for* Section 26 *read* Section 28.

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