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THE ORIGIN OF THE „WADDEN" MUD

by

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The origin of the sedimentary mud is a very important problem for the land reclamation on the „Wadden", the tidal flats North of the province of Groningen. This land reclamation is undertaken by the „Technische Dienst der Domeinen" (Technical Service of the Domains). In 1935 a research service was added to this „Technische Dienst" in order to investigate the problem of the origin of the „Wadden" mud. The research service tried to solve this problem in several ways. One of the suitable methods of investigation is the mineralogical analysis. Dr R. D. CROMMELIN was given this task to perform. First he applied the determination of the so-called heavy fraction of the sediment after the method of EDELMAN (3). From this investigation (1) it appeared that the coarser material ($>40\ \mu$) of the „Wadden" is of marine origin.

Whether this conclusion holds good for the whole sediment must be determined by investigating the finer material. For this, however, another method is necessary. Above a grain size of $10\ \mu$ the microscopical method is used; below $10\ \mu$ the X-ray method after Debije-Scherrer must be applied. The further investigation as to the origin of the whole sediment was therefore carried out by Dr CROMMELIN, who used the microscopical method, in collaboration with the author of this paper, who carried out the X-ray investigation. [1])

As the „Wadden" mud may be composed of material originating from the North Sea or from the rivers Eems, Wezer or Elbe, various samples have been examined, viz. „Wadden" mud, mud suspended in water from the North Sea and from the above named rivers (besides the Rhine) and some sea-bottom samples.

The mud originating from the old clay-banks on the „Wadden" may effect the composition of the „Wadden" mud; samples of the mud of these banks were also investigated.

It is not impossible that in the „Wadden" mud transformations occur on which the animal organism exerts an influence; thus samples of mud of musselbanks and musselfaeces were investigated.

With regard to the comparison of the „Wadden" mud with the mud of the tidal flats in the province of Zeeland („Schorren") also the composition of a number of samples from Zeeland was determined.

Table 1 gives a survey of the examined samples; the places where the samples

[1]) This investigation has been carried out in the years 1940–1943 but publication was not possible until now.

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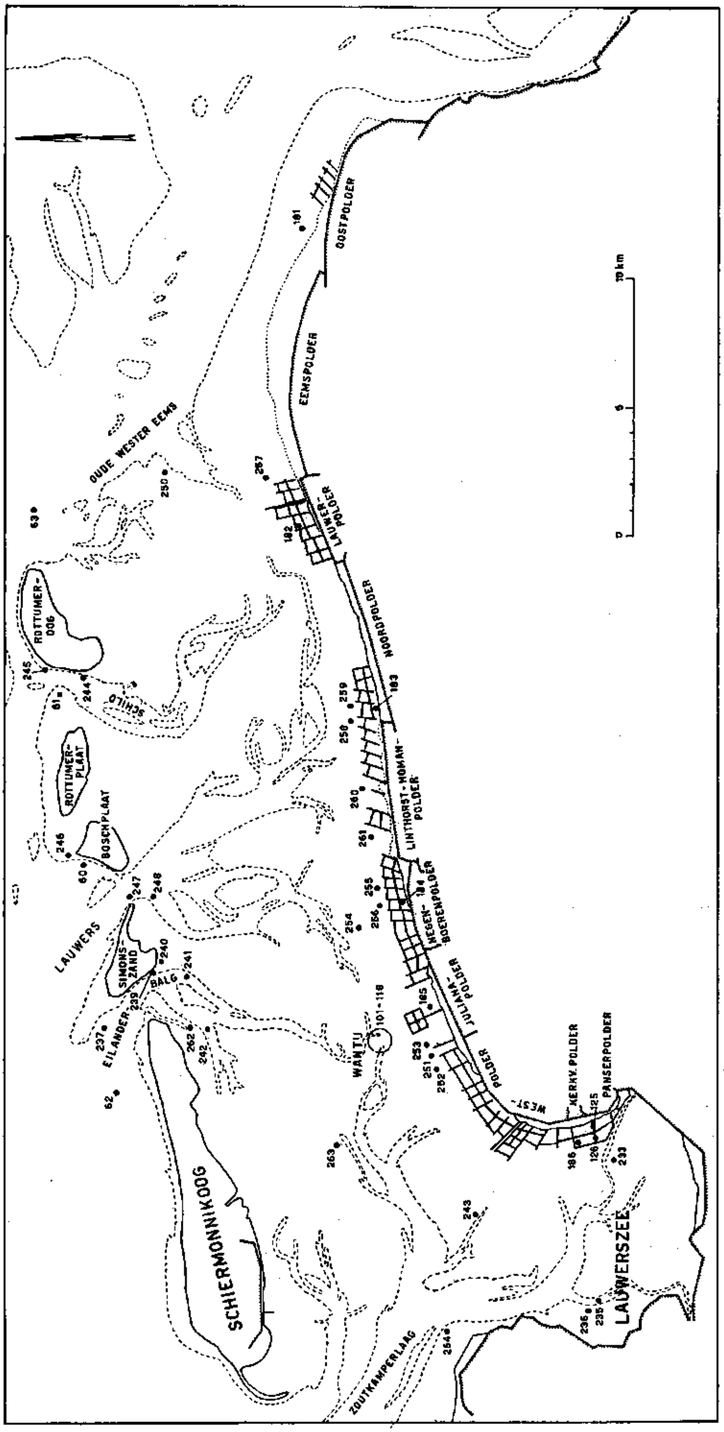

Fig. 1. Map of the „Wadden" of Groningen (with sample localities)

were collected are given in Fig. 1 (samples from the „Wadden") and Fig. 2 (samples from Zeeland).

To solve the posed problem the above mentioned samples must be mutually compared. For this the mineralogical composition had been chosen as criterion. Therefore it is necessary to separate the samples into fractions of different grain size; below 50 μ the method of Atterberg was used, above 50 μ the fractions were obtained by sieving.

At first little attention was paid to the choice of the fraction limits; 2 μ was taken as the lowest limit and the coarser material was separated into three fractions. However, during the investigations it appeared to be desirable to choose narrow fraction limits, both for the microscopical and the X-ray investigation. Owing to this the counting of mineral grains by the microscopical investigation gets a more quantitative signification; at the same time the mineralogical composition of the fractions becomes more simple, because some correlation exists between mineralogical composition and grain size. A typical example is the quartz content of the fine fractions of the marine sediments: the fraction 0.5–2 μ contains 30–40% quartz, the fraction <0.5 μ generally less than 5%.

The preparation of a large number of fractions takes rather much time. However, it was very important that detailed data were obtained about the granular composition of the samples and that now both the mineralogical and the granular composition could be used for the determination of the origin of the mud.

The mineralogical (microscopical) investigation of the coarser fractions has already been published by Dr Crommelin (2).

In this article the results of the granulometric analysis of the samples and of the X-ray investigation of the finer fractions will be discussed.

A. Granulometric analysis

The examined samples were dispersed as completely as possible (without affecting the clay minerals or polluting the samples chemically). To attain this purpose organic matter and calcium carbonate must be removed. First the samples are treated with 10% H_2O_2 on a boiling water-bath. If more resistant organic matter (peat, fibrous material in river mud) is present the treatment must be repeated.

For removing $CaCO_3$ and adsorbed Ca-ions the samples were treated with an excess of 0.2 N HCl. This treatment was carried out at room-temperature, because some clay minerals are strongly attacked by HCl at higher temperature; it appeared that the attack by 0.2 N HCl at room-temperature is much smaller than by boiling 0.05 N HCl (an often used method). The electrolytes are removed by sucking off the suspension on a membrane-filter and washing out the residue.

When organic matter and $CaCO_3$ (and Ca^{++}) have been removed a very good peptization is obtained with NaOH better than with sodium citrate or sodium oxalate without preceding removal of $CaCO_3$ and Ca^{++}. The rate of peptization with NaOH shows an optimum at a concentration of about 0.005 N.

The separate fractions below 50 μ were obtained by means of sedimentation cylinders after Atterberg. The influence of temperature on the rate of fall of the particles was eliminated by changing the height of fall or the settling-time. Large fluctuations of temperature during sedimentation could be prevented by putting the sedimentation cylinders in a case with insulating walls.

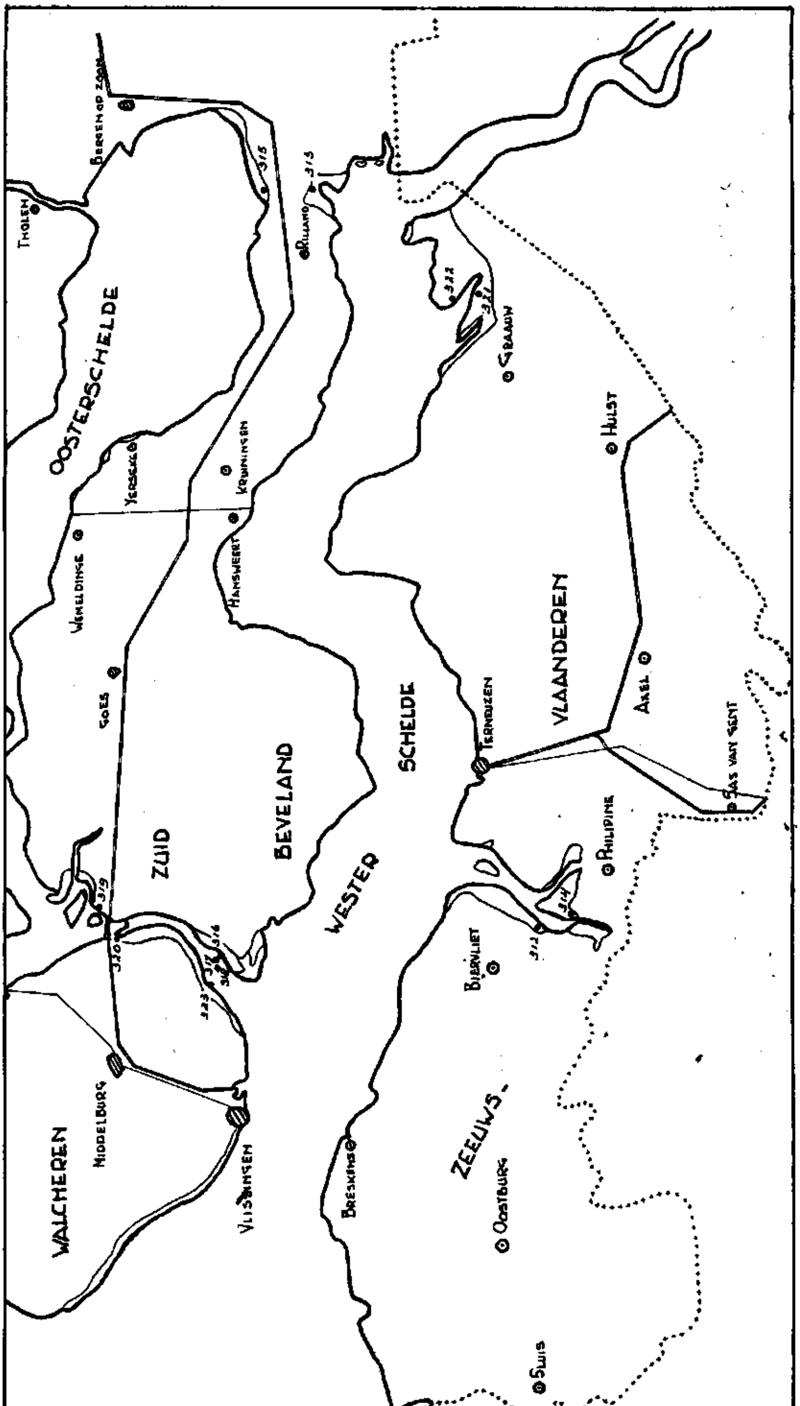

Fig. 2. Map of the „Schorren" of Zeeland (with sample localities)

The finer fractions ($<100\,\mu$) were dried at room-temperature above a saturated solution of $K_2CO_3 . 2\,H_2O$ (relat. humidity at room-temperature: 44%), after the removal of the greater part of liquid water above anhydrous $CaCl_2$.

Table 2 gives the results of the granulometric analysis in percents of the so-called mineral parts.

The comparison of granular compositions is always difficult, as appears from the various ways found in literature. This holds true especially if, as in our case, a number of samples with strongly differing granular compositions must be examined for similar components. These compositions expressed in percents are therefore not suitable.

It seemed probable to us that the determination of the ratios between the quantities of the separate grain fractions would give useful data for our purpose. Since this investigation refers to the origin of the fine material of the „Wadden" mud we have determined the ratios of the percentages of the fractions with regard to the percentage of the finest fraction ($<0.5\,\mu$). Though these ratios are well usable for direct comparison it is disadvantageous that they are dependent on the fraction limits. This disadvantage can be avoided by determining the ratios (with regard to the fraction $<0.5\,\mu$) for the cumulative percentages (Table 3) and plotting them against the logarithms of the fraction limits. The curves coincide in the area in which the finer material has the same granular composition.

Conformity in granular composition may also appear by using logarithmic cumulative curves: the logarithms of the cumulative percentages of the fractions are plotted against the logarithms of the fraction limits. For samples of which up to a given grain size the ratios between the quantities of the fractions are equal, these curves go parallel up to that grain size. This method gives a picture which is not so clear as that of the ratio-curves, but it requires less calculations; besides, an impression of the real granular composition is obtained, just as by ordinary cumulative curves.

Fig. 3 a, b and c are examples of different ways of representing the granular composition, i.e. ordinary cumulative curves, ratio-curves and logarithmic cumulative curves.

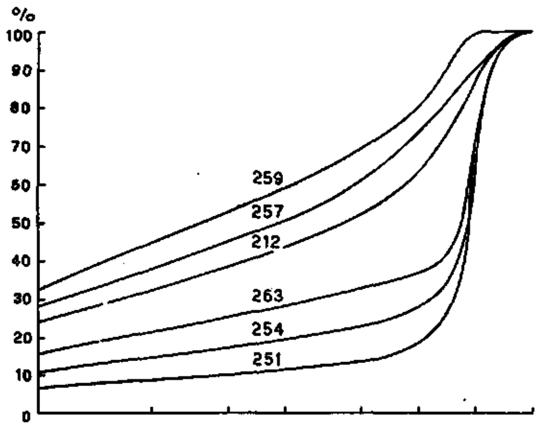

Fig. 3a. Cumulative curves

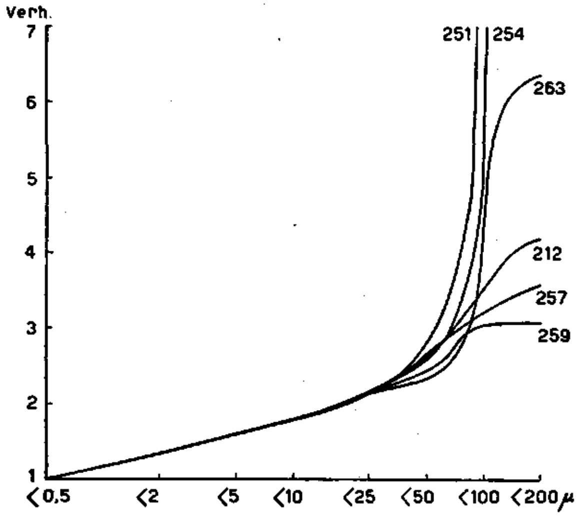

Fig. 3b. Ratio curves

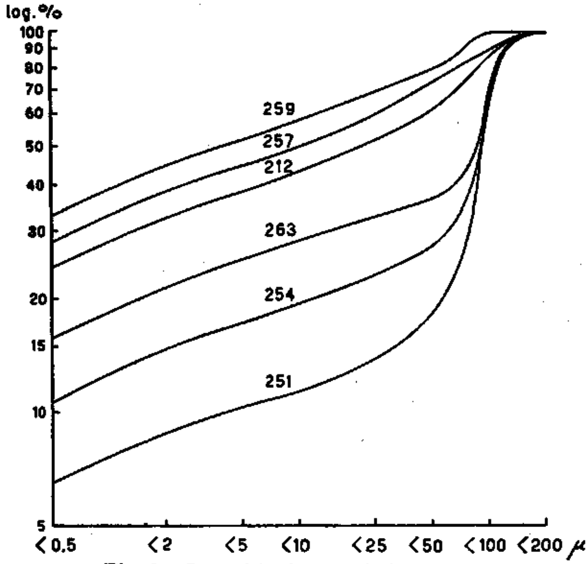

Fig. 3c. Logarithmic cumulative curves

For reducing the number of diagrams only for some typical cases logarithmic cumulative and ratio-curves will be given. All samples will be represented in triangular diagrams; the application of these diagrams will be treated in the discussion of the granular composition of the samples.

Discussion of the granular composition of the samples

I. New „Wadden" mud (R 125, 126 and 181–186) originating from the reclaiming works before the Kerkvoogdij-, Oost-, Lauwer-, Noord-, Negenboeren- and Julianapolder (polder = diked marsh) (Fig. 4a and b).

It is remarkable that, notwithstanding the great variation in granular composition, the ratios of the quantities of the subfractions below about 25 μ of most of the samples lie between narrow limits, as appears from the following survey:

<0.5	0.5–2	2–5	5–10	10–25 μ
1	0.29–0.34	0.24–0.26	0.20–0.24	0.36–0.54

Only of the very sandy samples R 181 and 185 (2% <0.5 μ) the ratios for

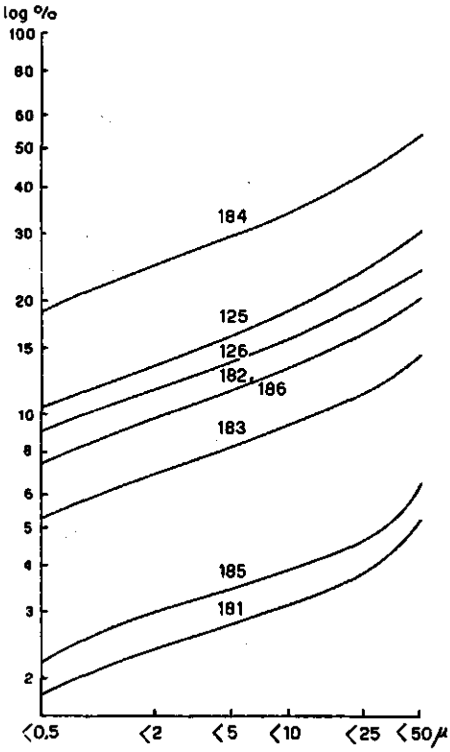

Fig. 4a. New „Wadden" mud (logarithmic cumulative curves)

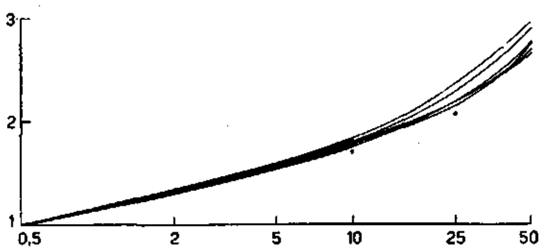

Fig. 4b. New „Wadden" mud (ratio curves)

the fractions 2–5 and 5–10 μ are slightly smaller, viz. 0.20 and 0.16. In Fig. 4b the deviating ratios of these samples are marked by points.

The variations increase already for the fraction 10–25 μ and for the coarser fractions the ratios differ strongly.

II. Mud from sea-water (R 60–63).

The mud content (after removal of organic matter and calcium carbonate) amounted to respectively 9.8, 11.7, 10.7 and 23.5 mg/l (during the transport part of the watersample R 63 has been lost; the mud had already settled for the greater part, the content therefore being far too high).

Also this mud shows constant ratios for the subfractions $<25\ \mu$ (Fig. 5a and b):

<0.5	0.5–2	2–5	5–10	10–25 μ
1	0.35–0.40	0.27–0.30	0.23–0.25	0.30–0.35

III. Just the same can be said of the sea-bottom samples (R 127–129, 140, 142, 145 and 150). Here also the very sandy samples R 145 and 150 (with less than 2% $<0.5\ \mu$) deviate.

IV. The following samples of river-water have been examined:

Eems and *Wezer*. The samples were taken (in duplicate) from two places, viz. there where the tides are just perceptible and about 50 km up-stream.

Elbe. Here the samples were taken in the same way, but more widely spread, over a distance of 40 km.

Rhine. Some samples of Rhine-water were examined for comparison. The place where the samples were taken was always the same (Lexkes Veer near Wageningen). However, they were taken on differing moments: R 272 (at high

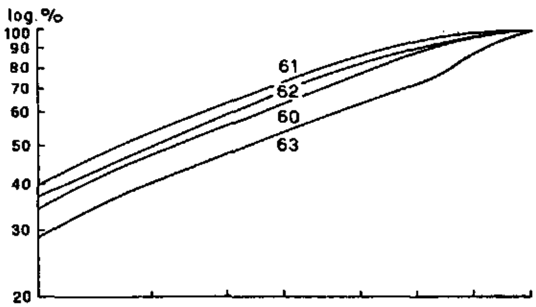

Fig. 5a. Mud from sea-water (logarithmic cumulative curves)

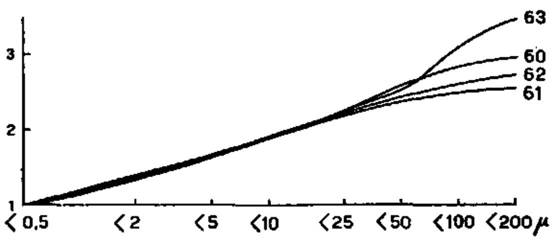

Fig. 5b. Mud from sea-water (ratio curves)

water) on 8-11-1940; R 330, 332 and 334 respectively on 27, 29 and 31-1-1941 (R 330 and 332 at rising stage, R 334 at the highest stage); R 443 on 26-3-1942 (at high water).

The following values were found for the mud content (after removal of organic matter and calcium carbonate):

Eems	277 and 278	16.8 mg/l
	279 and 280	13.9 „
Wezer	344 and 345	53 „
	275 and 276	180 „
Elbe	346 and 347	6.5 „
	348 and 349	27.6 „
Rhine	330	109 „
	332	114 „
	334	76 „

The granular composition of the mud in the river-water samples gives another picture than that of the samples described under I–III. The samples of Rhine-water show this very clearly. If the ratios for the fractions are compared it is obvious that for river-mud generally no constant ratios can be found, even not for the samples R 330, 332 and 334, taken within a short course of time.

This fact can also be observed for the samples of the Wezer (R 275 and 276, 344 and 345) and more or less for those of the Elbe. Only for the samples of the Eems the ratios are nearly constant, even up to about 50 μ.

The logarithmic cumulative curves and the ratio curves are shown in Fig. 6a and b.

V. As for the origin of the „Wadden" mud also the mud of old clay banks can play a part, samples of this mud were also examined (R 233–248). These samples too show a constant granular composition below a grain size of 25 μ. The same can be said of a number of clay clods that drifted on the isle of Ameland (R 69–73).

VI. The granular composition of the material $<25\,\mu$ of the mud of mussel banks (R 250–264) and of shell clay (R 212) gives the same picture as that of the mud from sea-water and the „Wadden". So the mussels do not effect the granular composition of the fine material. This was proved by an investigation of mussel faeces (R 231 and 232); these contain little coarse material, even less than the mud in sea-water, but the fraction ratios for the particles $<25\,\mu$ do not show deviations. So the presence of little coarse material in mussel faeces is not caused by a change of coarse material into fine during the digestive process; obviously the coarser material is taken up by the mussels to a smaller extent (which is in agreement with the results of culture experiments carried out by the Research Service of the Domains). Fig. 3a, b and c show the granular composition of some of these samples.

VII. The results of the investigation of a number of samples from the wan-tide S. of Schiermonnikoog (R 101–118) are in agreement with those of the mud from sea-water and the „Wadden"; only for two samples (R 108 and 118) with a very small content of particles $<0.5\,\mu$ (respectively 0.9 and 0.4%) the ratios of the fractions deviate slightly.

For these samples a clear connection was found between the granular composition and the sample-place with regard to the situation of the wan-tide. The content of fine material decreases strongly from Schiermonnikoog to the coast of Groningen, just as to the sides of the wan-tide (to E. and W.).

Sample R 101 originates from an ebb-gully and therefore it may contain more fine material than corresponds with its situation with regard to the other samples.

VIII. To be able to make a comparison with mud deposits in the province of Zeeland also samples from the „Schorren" were examined (R 312–323).

For these samples the uniformity of the granular composition of the material

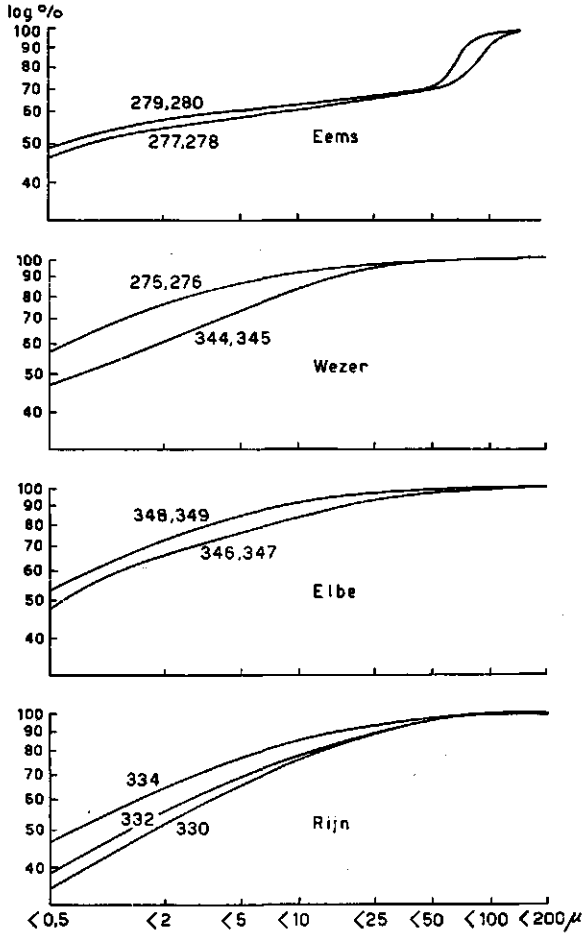

Fig. 6a. Mud from river-water (logarithmic cumulative curves)

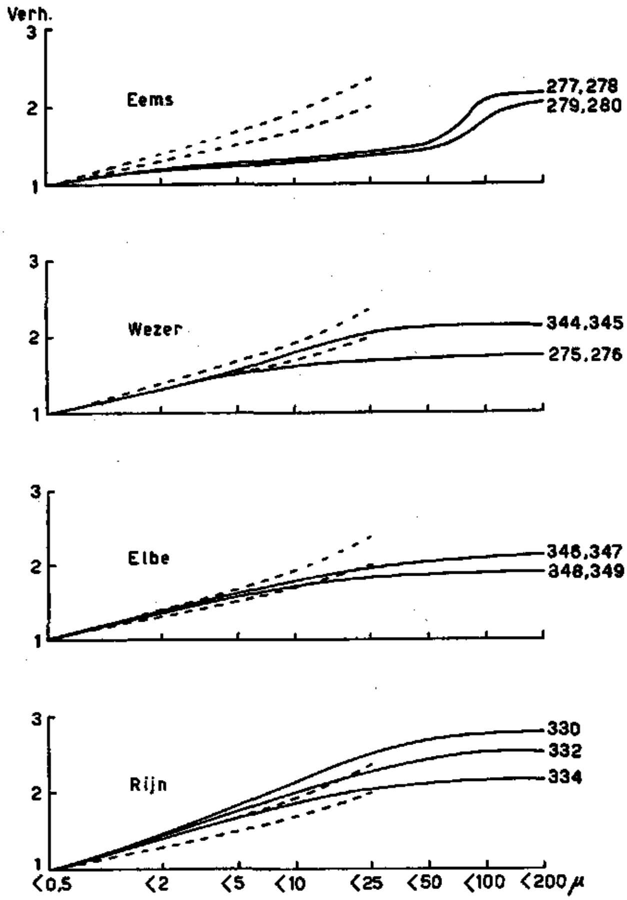

Fig. 6b. Mud from river-water (ratio curves)

$<25\ \mu$ is very marked, notwithstanding rather great variations in the content of this material and the extent of the area of sampling. The fractions of the samples originating from the „Schorren" along the East Scheldt show just the same ratios as those from the West Scheldt. So any influence of the river Scheldt on the deposition of mud on the „Schorren" was not found.

Conclusions

From these results it has appeared that the material below about 25 μ, as well of the mud in sea-water and of sea-bottom samples, as of the samples from the „Wadden" and the „Schorren" of Zeeland, has an almost constant granular composition. For each sample the content of this material may vary but its granular composition is the same.

If for all these samples the ratios of the subfractions $<25\ \mu$ (with regard to the fraction $<0.5\ \mu$) are compared it appears not only that they are constant for similar samples but that the values are nearly equal for all samples. They lie between the following limits:

<0.5	0.5–2	2–5	5–10	10–25 μ
1	0.3–0.4	0.2–0.3	0.2–0.3	0.2–0.5

Thus below about 25 μ these samples exist of material of nearly equal granular composition.

In contrast with this the mud present in river-water generally does not show such a constant granular composition, even not for a smaller grain size. The ratios of the finer fractions (with regard to the fraction $<0.5\ \mu$) differ not only for different rivers but they may vary strongly even for one and the same river. This is shown by the samples of Rhine-water (R 330, 332 and 334) taken from the same place with intervals of one day.

The ratios for the river-mud deviate more or less from those found for the mud from sea-water and the „Wadden". This is shown in Fig. 6b, in which dotted lines represent the limits of the ratios for the mud from sea-water and the „Wadden". The difference is very marked for the mud from the Eems; also there is a difference for the mud from the Wezer and the Rhine. Only for the mud from the Elbe the ratio-curves lie for a greater part in the area marked by dotted lines. However, it is probable that this similarity is more or less accidental and that mud samples from the Elbe taken under other circumstances would show differing ratios.

On account of the preceding data it is plausible that the constant granular composition of the fraction $<25\ \mu$ is characteristic for the examined marine sediments. In this respect the „Wadden" mud corresponds completely with the mud from sea-water, not however with the mud from Eems, Wezer or Elbe. From this we may conclude that the „Wadden" mud – at least in the main – is of marine origin.

The samples from the „Schorren" of Zeeland show exactly the same fraction ratios as those from the „Wadden". So this points to a marine origin of the mud of the „Schorren". In the discussion of these samples it has already been mentioned that differences in granular composition between the samples of the East and West Scheldt were not observed. So the mud of the river Scheldt has no perceptible influence on the granular composition of the mud from the „Schorren". The quantity of mud deposited by the Scheldt is probably too small with regard to the quantity of mud originating from the sea.

This characteristic property of marine sediments enables us to use another method for comparing granular compositions, viz. by means of triangular diagrams. These diagrams have the advantage of being very surveyable; however, application is only possible if fraction limits are used which are characteristic for the composition of the samples. From the preceding it has appeared that the material below 25 μ of marine sediments has a nearly constant granular composition and so the percentages of particles <0.5, 0.5–25 and $>25\ \mu$ can be used for representing the composition in triangular diagrams. For sediments with a constant ratio between the fractions <0.5 and 0.5–25 μ the points lie on a straight line going through the angular point „100% $>25\ \mu$".

Naturally the triangular diagrams show a less detailed picture than the ratio curves, the latter ones giving a survey of the complete granular composition, the triangular diagrams only showing the composition with regard to two fractions.

The granular compositions of the examined samples are represented in triangular diagrams in Fig. 7–11. All points (except for the mud from river-water) lie within an area (marked by dotted lines) for which the ratio $\frac{0.5\text{–}25\,\mu}{<0.5\,\mu}$ lies between 1.0 and 1.3.

In view of the small content of particles $<0.5\,\mu$ in Fig. 7 a quartei of the triangle has been represented in twice its original size.

Fig. 8 shows the granular compositions of the mud from sea-water and river-water. The points for the river-mud fall nearly all out of the area for the marine sediments (only one of the five samples Rhine-mud lies inside).

B. X-RAY INVESTIGATION OF THE FRACTIONS $<10\,\mu$

The fractions <0.5, 0.5–2 and 2–10 μ were examined; for some samples of river-mud the fraction 2–10 μ has been separated into 2–5 and 5–10 μ.

From this investigation (for the applied method see FAVEJEE (4)) it soon appeared that the samples are not sufficiently characterized by their qualitative mineralogical composition, differences in this composition occurring only rarely. Therefore it was necessary to determine also the quantitative composition.

The mineralogical compositions of the examined samples are mentioned in Table 4 and 5. Table 4 gives a survey of the compositions of the different kinds of mud; Table 5 gives an idea of the occurrence of the minerals in the fractions.

It must be noted that, if the content of montmorillonite has been indicated

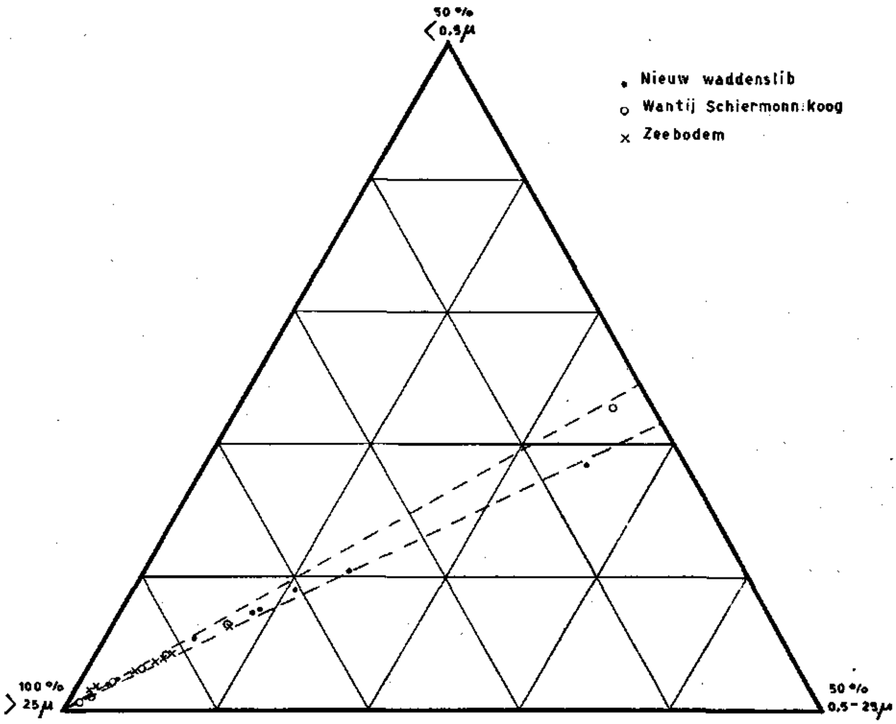

Fig. 7. New „Wadden" mud (.), wan-tide (o) and sea-bottom (x) samples

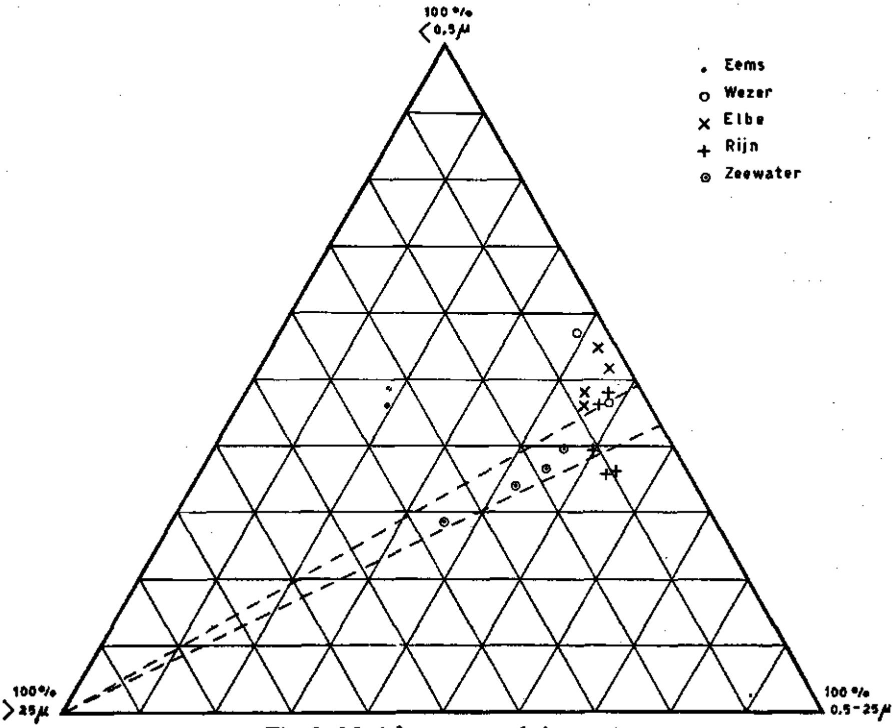

Fig. 8. Mud from sea- and river-water

by <3%, it is not sure that the sample indeed contains this mineral. In that case the central background of the X-ray photograph is so disturbing that no certainty can be obtained as to the presence of small amounts of montmorillonite. We can only say that the content is in no case higher than 3%.

The results of the X-ray investigation lead to the following remarks.

Illite, kaolinite, montmorillonite and quartz are found as components of the fraction <0.5 μ. Besides, muscovite occurs in the fractions 0.5–2 and 2–10 μ and felspar in the fraction 2–10 μ.

The content of *illite* predominating in the fraction <0.5 μ decreases with increasing grain size. The determination of its content in the fractions >2 μ is difficult, for in these fractions the mica content is small and besides muscovite forms an important part of this content. As the reflections of illite coincide with strong muscovite reflections determination of the illite content is not possible.

On the X-ray photograph of the mud from the Eems illite shows a deviating diagram caused by broadening and fading of some reflections, a low intensity of the reflections and the presence of a strong diffuse scattering, owing to a high content of iron. The mud seems to contain nontronite but from measurements it appeared that the reflections correspond pretty well with those of illite and not with those of nontronite. So the mud from the Eems in all probability contains a type of illite in which for a considerable amount Fe has been substituted for Al. This having a great influence on the intensities of the reflections it is not possible to dermine the quantitative composition of the fractions with any certainty. In this case, for the quantities of the minerals, is used the notation: very much, much, rather much, little and very little.

The *kaolinite* content of the fraction <0.5 μ usually amounts to 5–10% (for the mud from the Wezer it is slightly lower and in this fraction of the mud from the Eems kaolinite has not been found). It shows a weak maximum (about 10%) in the fraction 0.5–2 μ.

Of the clay minerals *montmorillonite* shows the most variations in its content. In the examined samples of river-mud it occurs, at the utmost, in very small quantities. For the other samples, however, the content in the fraction <0.5 μ can amount even to 15%; in the fractions >2 μ it is lower.

The *quartz* content increases strongly with increasing particle size. In the fraction <0.5 μ it is of little importance (usually not higher than 5%), but in the fraction 0.5–2 μ the content amounts already to 25–40% and in the fraction 2–10 μ to 50–70%. As quartz gives a great number of strong X-ray reflections it is recommendable in investigations on the nature of the clay minerals to choose the limits for the finest fraction as low as possible and certainly not above 0.5 μ.

Muscovite generally does not occur in the fraction <0.5 μ (only in the mud from the Rhine this fraction contains a very small quantity), but it does in the coarser fractions.

Felspar is usually only found in the fractions >2 μ, but in some cases in the fraction 0.5–2 μ. X-ray investigations of coarse fractions containing much

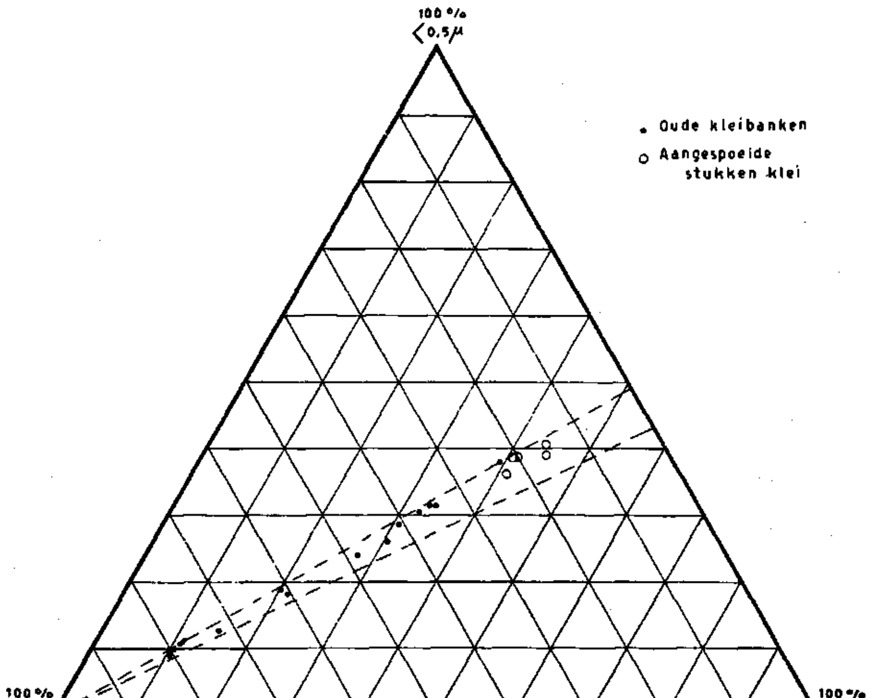

Fig. 9. Samples from old clay banks (.) and drifted clay clods (o)

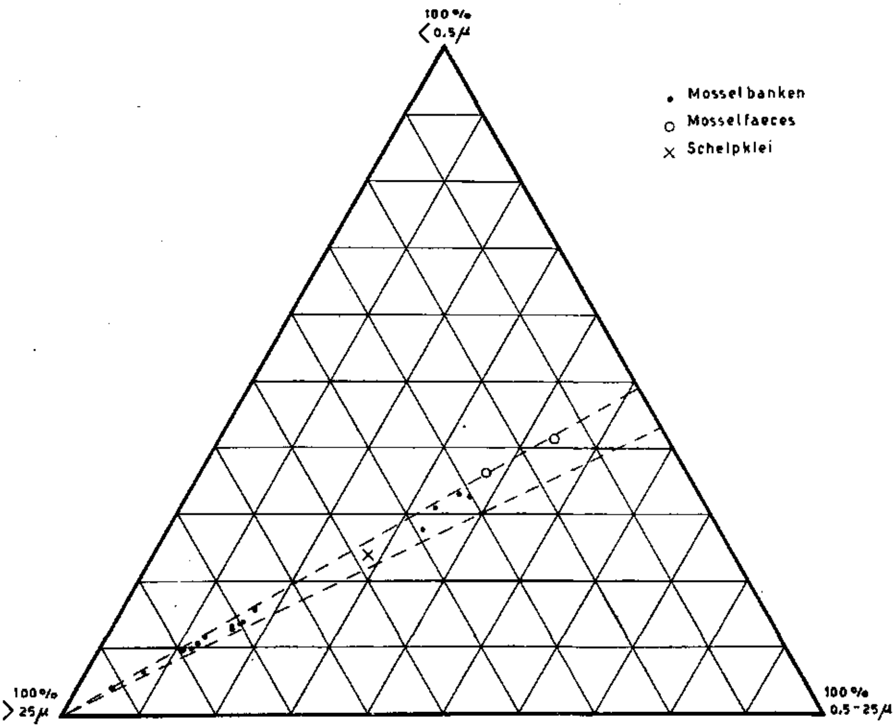

Fig. 10. Mud from mussel banks (.), shell clay (x) and mussel faeces (o)

felspar have shown that the felspar in the „Wadden" samples belongs to the acid plagioclase series.

Differences in the *qualitative mineralogical composition* of the examined samples have been found only in a single case, viz. the mud from the Eems. This contains no montmorillonite and kaolinite is not present in the fraction $<0.5\,\mu$; besides, the illite in this sample is a deviating type in comparison with the other samples. But in general the samples are not sufficiently characterized by their qualitative composition, so this cannot be used for solving the posed problem, i.e. the origin of the fine part of the „Wadden" mud.

Comparing the *quantitative mineralogical composition* of the examined samples it appears that only small variations occur in the compositions of the fraction $<0.5\,\mu$ of the mud from sea-water and from the „Wadden" and that the contents of minerals show great similarity. For quartz the contents vary between 2 and 6%, for kaolinite and montmorillonite between 5 and 10%.

The river-mud differs clearly from these two types of mud by a remarkable low content of montmorillonite and strongly varying contents of quartz and kaolinite; the quartz content of the mud from the Elbe is high, in the mud from the Wezer kaolinite is present only in a small quantity and it is lacking entirely in the mud from the Eems.

Conclusion

The similarity in mineralogical composition between the „Wadden" mud and the mud from sea-water on the one side and the differences with regard to the mud from Eems, Wezer and Elbe on the other side lead to the conclusion that the fine material of the „Wadden" mud is, at least in the main, of marine origin.

In comparison with the mud from sea-water the „Wadden"-mud shows small differences in the contents of minerals, but these differences cannot be due to a mixing with mud originating from Eems, Wezer or Elbe. The differences namely appear in the content of montmorillonite. In the „Wadden" mud it is rather high with regard to the mud from sea-water; mixing with river-mud just should decrease the content of montmorillonite and so it is highly improbable that a more or less direct deposition of river-mud on the „Wadden" takes place. The probable cause of these differences will be discussed later.

The mud from the „Schorren" of Zeeland consists of marine material, not only with regard to the granular composition but also to the mineralogical composition.

CONSIDERATIONS

It has appeared that the constant granular composition of the material below about 25 μ can be considered as a typical characteristic of the examined marine sediments. The observation of Hissink (5), that for sea-clays the ratio between

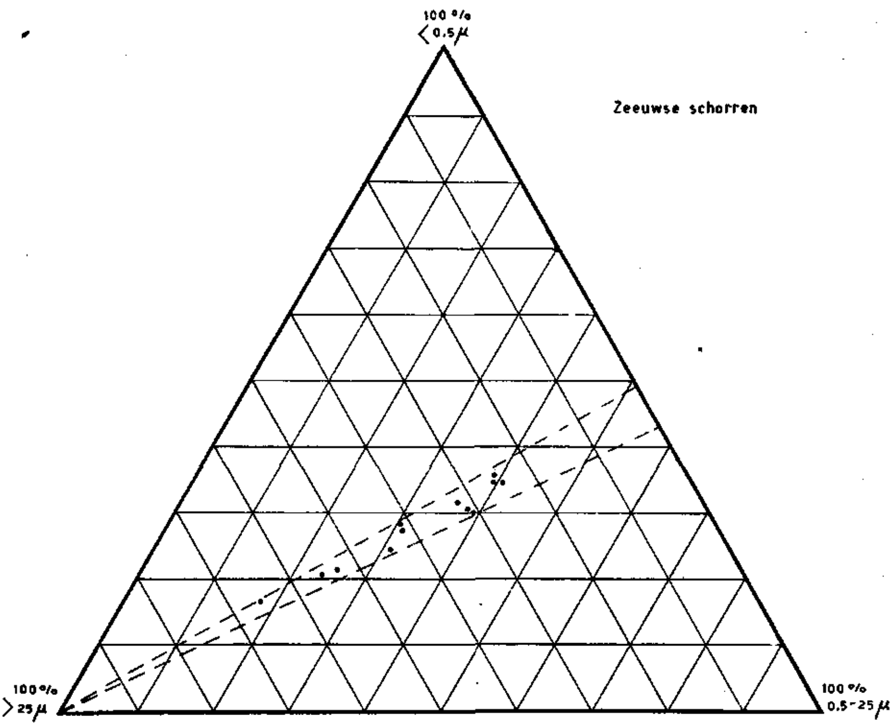

Fig. 11. Mud from the „Schorren" of Zeeland

the percentages of the fractions below 2 μ and 2–16 μ amounts to about 0.4, corresponds with this; ZUUR (6) too points to the constant ratios between the percentages of the subfractions below 16 μ for marine sediments.

Also the fine material (at least the fraction below 10 μ) of these marine sediments has a uniform mineralogical composition.

In my opinion the explanation of these typical properties can be given as follows:

The granular composition of mud being suspended in water and of mud deposited from water depends on so many factors (to mention only the nature of the material and the current velocity), that no constant ratios can be expected neither in the suspension nor in the sediment, at least if the suspended mud is in suspension entirely as primary particles and if every particle can be effected by those factors independent of the presence of other particles.

If, however, a part of the suspended mud has been coagulated, during the sedimentation the ratio of the quantity of coagulated mud does change with regard to the other fractions present as primary particles, but in the coagulated part itself the ratios between the subfractions do not change. [1])

This is the case with the mud present in sea-water. In consequence of the high content of electrolytes of the sea-water the fine material (below 25 μ) is not in suspension as primary particles, but in coagulated state. The fine material namely consists for the greater part of clay minerals and these are easily coagulated by electrolytes. The coarser material on the contrary (mainly consisting of quartz grains) is present as primary particles.

If a part of the suspended mud settles the ratio between the quantities of fine (coagulated) and coarse material (primary particles) can be changed (both in the settling mud and in the mud remaining in suspension) dependent on the factors determining the settling. In the fine material itself the ratios between the quantities of the subfractions together cannot undergo a change, because this material occurs in the suspension as aggregates and also settles as such. So the granular composition of the fine material is constant both in the suspension and in the deposit.

However, attention must be paid to the fact that the influence of the sea is twofold with regard to the material below 25 μ. In the first place the sea distributes the mud homogeneously, so that the sea acts as a reservoir of material with a definite granular composition, at least in the neighbourhood of the Netherlands coast. In the second place the granular composition of this material remains constant by coagulation in consequence of the content of electrolytes of the sea-water.

For the examined marine samples the variations in the ratios of the fractions 0.5–2, 2–5 and 5–10 μ (with regard to the fraction $<0.5\ \mu$) are small; for the fraction 10–25 μ they are slightly greater and above 25 μ no constant ratios have been found. The limit for the constant composition will also lie between 10 and 25 μ. On this account the well-known 16 μ limit has a real significance for marine sediments.

For river-mud the circumstances are quite different: the content of electrolytes of river-water is low, so that the mud has not been coagulated, at least to a much lower degree than the mud of sea-water (this difference appears

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[1]) ZUUR (l.c.) too assumes in explanation of the constant ratios that in the marine mud the fine clay particles occur as aggregates.

clearly if river-water and sea-water are enabled to deposit their mud: the sea-water is already clear after a short time, which is not the case with river-water, even after weeks). So for river-mud the circumstances during the deposition can effect the entire granular composition of the settling mud and consequently also the entire composition of the mud that remains in suspension. Generally no constant ratios between the quantities of the fractions can be expected.

As the material below about 25 μ of the examined marine sediments has a constant granular composition, we should expect this also of the mineralogical composition. Though this composition (for the fractions below 10 μ) shows a great uniformity, variations occur, especially in the contents of quartz and montmorillonite, which may not be left out of consideration. We have to consider what can be the cause of these variations.

It is understandable that the quartz content shows variations. On the one side small quartz particles will originate from coarser quartz grains in consequence of the dash of the waves, through which the quartz content of the fine fractions increases. On the other side by chemical attack the quartz content of the finest fraction will decrease the most. So we may expect that the quartz content of recent deposits of mud in shallow water is higher (for example Wantij Schiermonnikoog) than in sediments having already passed through a long period of rest (for example the sea-bottom samples). The found quartz contents correspond with this. Naturally the occurring variations will only be perceptible for the fractions $<0.5\ \mu$. Of these the quartz content is low (about 5%); so both increase (in consequence of polishing of coarser grains) and decrease (by chemical attack of quartz particles $<0.5\ \mu$) will effect these contents more than the much larger quartz contents of the coarser fractions (about 30% for the fraction 0.5–2 μ and about 60% for the fraction 2–10 μ).

To explain the variations in the montmorillonite content we can suppose the following possibilities:

1. The higher montmorillonite content is caused by a transmutation of illite into montmorillonite. Though a similar transmutation is surely imaginable it does not explain why high montmorillonite contents (up to 15%) occur very locally.
2. On the „Wadden" the salt content of the water locally can be considerably lower than that of the sea-water in consequence of the supply of fresh water during the sluicing of the canals of Groningen and Friesland. It is possible that this lower salt concentration causes a peptization of montmorillonite, which is coagulated locally where the salt concentration is higher. This effect will mainly occur in the case of montmorillonite, the other clay minerals being deflocculated only at a lower electrolyte content. In our opinion the second possibility is most plausible.

SUMMARY

From the granular composition it has appeared that marine mud is characterized by definite constant ratios between the quantities of the subfractions with grain sizes below about 25 μ, which points to a uniform composition of the fine part of the marine mud. Also the X-ray mineralogical investigation of the mud below 10 μ leads to this conclusion.

On the contrary the mud from river-water has another composition in two respects; there exists no grain area in which the ratios between the quantities

of the subfractions are constant and the mineralogical composition shows (apart from particular differences) a typical difference with that of marine mud, viz. a very low content of montmorillonite.

The „Wadden" mud corresponds completely with the marine mud. This similarity on the one side and the difference from the mud from Eems, Wezer and Elbe on the other side justify the conclusion that the fine part of the „Wadden" mud – at least in the main – is of marine origin.

So this investigation leads to the same conclusion as the investigation of CROMMELIN (2) for the coarser part (above 10 μ) of the „Wadden" mud.

The constant granulometric composition and the uniform mineralogical composition of the finer fractions of marine sediments can be explained by coagulation in consequence of the high electrolyte content of the sea-water.

The small variations in the quartz content are probably due to mechanical and chemical attack of the quartz grains. For montmorillonite such variations might be caused by local differences in the salt concentration of the water on the „Wadden".

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TABLE 1

Survey of the examined samples

	Nature and Nos. of the samples	Sample locality
I	New „Wadden" mud R 125 and 126, 181–186	Reclaiming works before the coast of Groningen (see map, Fig. 1)
II	Mud from sea-water	Inlets between the „wadden" islands N. of Groningen
	R 60	Lauwers
	61	Schild
	62	Eilander Balg
	63	Oude Wester Eems
III	Sea-bottom samples	North Sea
	R 127 and 128	S.E. of Doggersbank
	129	Duitse Bocht
	140, 142, 145 and 150	S. of Doggersbank
IV	Mud from river-water	
	Eems: 277 and 278	Halter Fähre, km 227.8
	id. 279 and 280	Hüntel, km 176.6
	Wezer: 344 and 345	Some km upstream from Bremen
	id. 275 and 276	Nienburg
	Elbe: 346	Hoopte, km 599
	id. 347	Lassrönne, km 595
	id. 348	Tesperhude, km 579
	id. 349	Boizenburg, km 559
	Rhine: 272	Lexkesveer, at high water (8-11-'40)
	330	„ at rising stage (27-1-'41)
	332	„ at rising stage (29-1-'41)
	334	at the highest stage (31-1-'41)
	443	„ at high water (26-3-'42)
V	Mud of old clay banks R 233–248	„Wadden" area of Groningen (see map, Fig. 1)
	Drifted clay clods R 69–73	Ameland
VI	Mud of mussel banks R 250–264	„Wadden" area of Groningen (see map, Fig. 1)
	Shell clay R 212	
	Mussel faeces R 231 and 232	
VII	Samples from the wan-tide Schiermonnikoog R 101–118	see map, Fig. 1
VIII	Samples from the „Schorren" of Zeeland R 312–323	see map, Fig. 2

TABLE 2

Quantities of the fractions in per cent of the mineral parts < 200 μ

No. of the sample	<0.5	0.5–2	2–5	5–10	10–25	25–50	50–100	100–200 μ
I New „wadden" mud								
R 125	10.5	3.0	5.3		5.3	6.3	69.7	
126	9.0	2.7	4.1		4.0	4.0	76.3	
181	1.8	0.6	0.7		0.7	1.5	94.8	
182	7.3	2.5	3.3		3.0	4.1	79.8	
183	5.3	1.7	2.4		1.9	3.2	85.5	
184	18.4	6.4	9.0		9.8	11.2	45.3	
185	2.2	0.8	0.8		0.8	2.1	93.3	
186	7.5	2.4	3.3		3.3	3.7	79.7	
II Mud from sea-water								
60	33.8	13.4	17.3		23.1		12.4	
61	39.3	14.7	19.8		19.5		6.7	
62	36.5	12.9	20.1		19.5		11.1	
63	28.6	11.3	14.9		17.5		27.6 [1]	
III Sea-bottom samples								
127	3.5	1.2	2.0		1.0	1.2	91.1	
128	4.1	1.3	2.3		1.4	1.8	89.1	
129	3.7	1.2	2.0		1.4	3.8	87.9	
140	6.2	2.1	3.5		2.2	1.4	84.6	
142	2.8	0.9	1.5		0.8	0.7	93.3	
145	1.6	0.3	0.6		0.3	0.4	96.8	
150	1.4	0.3	0.5		0.2	0.2	97.4	
IV Mud from river-water								
Eems:								
277	44.8	9.2	3.3	3.0	3.8	4.9	27.2	3.8
278	47.6	9.2	3.7	3.6	3.4	4.3	24.6	3.6
279	47.6	8.9	3.0	2.7	2.9	3.1	19.9	12.1
280	49.9	9.5	3.1	3.2	3.2	4.2	17.6	9.2
Wezer:								
344	46.8	14.7	11.3	10.6	11.5	3.6	1.1	0.4
345	46.0	15.0	10.8	11.3	12.3	3.3	1.0	0.4
275	57.7	19.1	11.7	4.1	4.4	2.0	0.8	0.1
276	56.0	18.8	11.2	4.2	4.5	3.1	1.8	0.4
Elbe:								
346	46.0	19.2	10.1	7.7	8.3	4.5	2.7	1.5
347	48.1	18.9	8.7	7.8	9.1	4.6	2.1	0.7
348	54.8	17.6	12.5	7.0	5.7	1.5	0.8	0.2
349	51.6	19.7	12.8	7.4	6.0	1.7	0.7	0.2
Rhine:								
272	35.8	17.7	26.4		10.4	5.5	4.3	
330	35.6	16.9	13.0	9.6	13.9	7.2	3.1	0.7
332	39.1	16.8	12.7	8.8	11.8	5.9	4.0	1.0
334	46.1	18.5	12.7	7.3	8.9	3.4	2.5	0.6
443	47.8	18.9	10.5	8.4	9.8	3.8	0.8	0.1

[1]) During the transport part of the water sample R 63 has been lost; the mud had already settled for the greater part, the content therefore being far too high.

TABLE 2 (*continued*)

No. of the sample	< 0.5	0.5–2	2–5	5–10	10–25	25–50	50–100	100–200 μ
V Mud of old clay banks								
233	9.1	3.0	3.9		3.8	8.9	71.3	
235	18.2	6.2	7.9		7.6	10.9	49.3	
236	9.4	3.0	1.9	1.8	3.7	6.6	68.2	5.4
237	31.4	12.0	14.7		7.6	6.3	28.1	
239	30.7	10.3	7.2	6.0	9.1	10.1	16.3	10.3
240	38.0	13.3	8.5	7.3	10.4	7.8	12.7	1.9
241	9.9	3.0	2.2	1.8	3.5	6.9	50.8	21.8
242	31.3	10.3	6.8	5.9	10.6	10.4	23.7	1.1
243	12.8	4.5	3.0	2.6	5.1	8.3	57.5	6.3
244	11.1	3.9	2.6	2.1	2.6	2.0	9.6	66.1
245	10.8	3.3	2.4	2.0	3.4	3.5	7.1	67.6
246	24.1	8.9	5.7	5.8	7.3	7.7	13.8	26.7
247	28.5	10.2	6.7	5.6	8.5	8.8	28.4	3.3
248	26.0	9.7	6.8	5.6	8.7	9.1	26.0	8.2
Drifted clay clods								
69	39.1	14.0	19.3		11.6	5.2	10.8	
70	40.7	14.3	18.3		11.5	5.2	10.0	
71	38.5	13.9	18.2		8.7	5.8	14.9	
72	38.5	14.2	18.5		8.5	6.3	14.0	
73	36.1	13.4	17.8		9.9	6.1	16.7	
VI Mud of mussel banks								
250	4.0	1.3	0.9	0.8	1.3	1.1	18.1	72.4
251	6.5	2.3	1.5	1.2	2.4	4.3	53.1	28.6
252	31.1	10.9	7.2	5.8	9.6	8.2	25.2	1.9
253	13.1	5.2	3.3	2.6	4.5	5.1	48.2	18.0
254	10.7	4.1	2.5	2.0	3.8	4.4	36.3	36.4
255	13.6	5.2	3.4	2.7	5.2	6.5	54.0	9.4
256	14.0	5.2	3.6	2.8	5.1	6.4	50.2	12.7
257	27.9	10.3	6.6	5.2	11.2	12.9	15.9	9.9
258	9.7	3.6	2.5	1.8	3.1	3.8	53.2	22.4
259	32.6	12.0	8.0	6.1	11.0	10.1	19.7	0.6
260	32.9	11.6	8.2	6.5	9.4	8.1	21.6	1.7
261	9.9	3.7	2.4	1.8	4.1	4.2	23.6	50.4
262	11.9	4.3	3.0	2.4	3.8	3.9	11.5	59.3
263	15.7	5.6	4.1	3.0	4.7	3.6	33.0	30.1
264	12.9	4.7	3.1	2.5	5.6	12.0	54.3	5.0
Shell clay								
212	24.0	8.5	10.9		8.7	10.8	37.2	
Mussel faeces								
231	36.2	13.4	16.4		7.5	2.8	23.7	
232	41.2	17.5	18.9		7.6	3.7	11.2	

TABLE 2 (*continued*)

No. of the sample	<0.5	0.5–2	2–5	5–10	10–25	25–50	50–100	100–200 μ
VII Samples from the wan-tide Schiermonnikoog								
101	6.4	2.3	2.7		2.5	3.6	82.5	
104	22.7	8.9	10.6		5.2	3.8	48.9	
108	0.9	0.4	0.6		0.3	0.8	97.0	
110	1.9	0.5	0.9		0.8	2.1	93.9	
114	4.0	1.3	1.8		1.5	3.9	87.5	
116	3.0	1.0	1.5		1.1	2.0	91.5	
118	0.4	0.2	0.3		0.2	0.2	98.6	
VIII Samples from the „schorren" of Zeeland								
312	35.6	10.9	7.4	7.6	13.2	9.7	8.7	6.8
313	24.3	8.2	5.0	5.4	12.5	17.5	26.6	0.4
314	20.7	6.9	4.4	4.1	8.8	17.0	36.6	1.6
315	16.5	5.1	3.3	3.1	6.7	14.4	48.1	2.9
316	27.3	9.2	5.9	5.3	10.8	15.1	25.9	0.4
317	30.5	10.8	6.8	6.1	14.6	18.6	12.1	0.4
318	21.2	7.3	4.8	4.3	9.4	12.9	27.8	12.3
319	29.9	10.4	7.0	6.7	15.1	19.5	10.3	1.1
320	34.6	11.9	7.8	6.7	14.6	16.5	7.9	0.1
321	31.7	9.8	6.6	6.0	13.9	14.6	14.8	2.6
322	34.6	10.7	7.2	6.7	15.0	15.2	10.2	0.4
323	28.2	9.1	5.9	5.0	10.9	13.5	21.0	6.6

TABLE 3

Ratios of the cumulative fractions with regard to the fraction < 0.5 μ

No. of the sample	<2	<5	<10	<25	<50	<100	<200 μ
I New „wadden" mud							
R 125	1.29	1.55	1.79	2.29	2.90		9.6
126	1.30	1.54	1.75	2.19	2.65		11.2
181	1.33	1.53	1.69	2.05	2.92		55.8
182	1.34	1.58	1.79	2.20	2.76		13.6
183	1.33	1.57	1.77	2.14	2.75		18.9
184	1.34	1.60	1.83	2.37	2.97		5.4
185	1.34	1.54	1.71	2.09	3.07		45.8
186	1.32	1.56	1.77	2.20	2.69		13.3
II Mud from sea-water							
60	1.40	1.68	1.91	2.26	2.59		2.96
61	1.38	1.65	1.88	2.18	2.38		2.55
62	1.35	1.65	1.90	2.24	2.44		2.74
63	1.40	1.68	1.92	2.25	2.53		3.49[1])
III Sea-bottom samples							
127	1.33	1.16	1.89	2.18	2.52		28.2
128	1.32	1.60	1.88	2.21	2.66		24.3
129	1.32	1.60	1.85	2.23	3.26		26.8
140	1.33	1.62	1.89	2.24	2.47		16.0
142	1.32	1.60	1.86	2.16	2.41		36.0
145	1.21	1.41	1.60	1.76	2.02		62.7
150	1.25	1.45	1.61	1.73	1.90		71.0
IV Mud from river-water							
Eems:							
277	1.20	1.28	1.35	1.43	1.54	2.15	2.23
278	1.19	1.27	1.35	1.42	1.51	2.03	2.10
279	1.19	1.25	1.30	1.37	1.43	1.85	2.10
280	1.19	1.25	1.32	1.38	1.47	1.82	2.00
Wezer:							
344	1.31	1.56	1.78	2.03	2.10	2.13	2.14
345	1.33	1.56	1.81	2.08	2.15	2.17	2.18
275	1.33	1.53	1.61	1.68	1.72	1.73	1.73
276	1.34	1.54	1.61	1.69	1.75	1.78	1.79
Elbe:							
346	1.42	1.64	1.81	1.99	2.08	2.14	2.17
347	1.39	1.57	1.74	1.93	2.02	2.07	2.08
348	1.32	1.55	1.68	1.78	1.81	1.82	1.82
349	1.38	1.63	1.77	1.89	1.92	1.94	1.94
Rhine:							
272	1.50	1.88	2.23	2.52	2.68		2.80
330	1.48	1.84	2.11	2.50	2.70	2.79	2.80
332	1.43	1.75	1.98	2.28	2.43	2.53	2.54
334	1.40	1.68	1.84	2.03	2.10	2.16	2.17
443	1.40	1.62	1.79	1.99	2.07	2.09	2.09

[1]) See foot-note Table 2.

TABLE 3 (*continued*)

No. of the sample	<2	<5	<10	<25	<50	<100	<200 μ
V MUD OF OLD CLAY BANKS							
233	1.33	1.56	1.76	2.17	3.15		11.0
235	1.34	1.57	1.77	2.19	2.78		5.49
236	1.32	1.51	1.71	2.10	2.80	10.1	10.6
237	1.38	1.64	1.85	2.09	2.29		3.19
239	1.33	1.57	1.77	2.06	2.39	2.92	3.26
240	1.35	1.57	1.77	2.04	2.24	2.58	2.63
241	1.31	1.53	1.71	2.07	2.76	7.90	10.1
242	1.33	1.54	1.73	2.07	2.40	3.16	3.19
243	1.35	1.58	1.78	2.18	2.83	7.33	7.82
244	1.35	1.58	1.77	2.01	2.19	3.05	9.00
245	1.30	1.53	1.72	2.04	2.36	3.02	9.30
246	1.37	1.61	1.85	2.15	2.47	3.04	4.15
247	1.36	1.59	1.79	2.09	2.40	3.40	3.51
248	1.37	1.63	1.85	2.18	2.53	3.54	3.85
Drifted clay clods							
69	1.36	1.60	1.85	2.15	2.28		2.56
70	1.35	1.59	1.80	2.09	2.21		2.46
71	1.36	1.60	1.83	2.06	2.21		2.60
72	1.37	1.61	1.85	2.07	2.23		2.60
73	1.37	1.62	1.86	2.14	2.30		2.77
VI MUD OF MUSSEL BANKS							
250	1.32	1.55	1.73	2.07	2.35	6.86	24.9
251	1.36	1.59	1.78	2.14	2.80	10.9	15.3
252	1.35	1.58	1.77	2.08	2.34	3.15	3.21
253	1.40	1.65	1.84	2.19	2.57	6.24	7.61
254	1.38	1.62	1.81	2.16	2.57	5.97	9.39
255	1.38	1.63	1.83	2.22	2.70	6.67	7.35
256	1.37	1.62	1.83	2.19	2.65	6.23	7.13
257	1.37	1.61	1.79	2.19	2.66	3.23	3.58
258	1.38	1.63	1.82	2.14	2.53	8.03	10.3
259	1.37	1.62	1.80	2.14	2.45	3.05	3.07
260	1.35	1.60	1.80	2.08	2.33	2.99	3.04
261	1.37	1.61	1.80	2.22	2.64	5.03	10.2
262	1.36	1.61	1.81	2.13	2.45	3.42	8.40
263	1.36	1.62	1.81	2.11	2.34	4.44	6.36
264	1.36	1.60	1.80	2.23	3.16	7.37	7.76
Shell clay							
212	1.35	1.60	1.81	2.17	2.62		4.17
Mussel faeces							
231	1.37	1.62	1.82	2.03	2.11		2.76
232	1.42	1.68	1.88	2.07	2.16		2.43

TABLE 3 (*continued*)

No. of the sample	< 2	< 5	< 10	< 25	< 50	< 100	< 200 μ
VII SAMPLES FROM THE WANTIDE SCHIERMONNIKOOG							
101	1.36	1.61	1.82	2.17	2.73		15.6
104	1.39	1.65	1.86	2.09	2.25		4.40
108	1.39	1.78	2.08	2.39	3.30		110
110	1.29	1.54	1.75	2.18	3.29		53.8
114	1.33	1.58	1.79	2.15	3.11		24.8
116	1.33	1.60	1.82	2.19	2.84		33.3
118	1.40	1.81	2.16	2.65	3.14		225
VIII SAMPLES FROM THE „SCHORREN" OF ZEELAND							
312	1.31	1.51	1.73	2.10	2.37	2.62	2.81
313	1.34	1.54	1.77	2.28	3.00	4.09	4.11
314	1.33	1.54	1.74	2.17	2.99	4.76	4.83
315	1.31	1.51	1.69	2.10	2.97	5.88	6.05
316	1.34	1.55	1.75	2.14	2.70	3.64	3.66
317	1.36	1.58	1.78	2.26	2.86	3.26	3.27
318	1.34	1.57	1.77	2.21	2.82	4.13	4.71
319	1.35	1.58	1.80	2.31	2.96	3.31	3.34
320	1.34	1.57	1.76	2.18	2.66	2.89	2.89
321	1.31	1.52	1.71	2.15	2.61	3.07	3.16
322	1.31	1.52	1.71	2.15	2.59	2.88	2.89
323	1.32	1.53	1.70	2.09	2.57	3.31	3.54

TABLE 4

Mineralogical composition of the subfractions < 10 μ of the different kinds of mud

	Fraction < 0.5 μ				Fraction 0.5–2 μ				Fraction 2–10 μ				
	illite	kaolinite	montmor.	quartz	illite + musc.	kaolinite	montmor.	quartz	illite + musc.	kaolinite	montmor.	quartz	felspar
I New „Wadden" mud	± 80	5–10	± 10	± 4	50–60	5–10	5–10	± 30					
II Mud from sea-water	80–90	5–10	± 5	4–6	± 60	5–10	± 5	± 30	20–30	± 5	± 3	± 60	5–10
III Sea-bottom samples	80–90	5–10	3–5	± 2	± 50	± 15	5–10	± 30	± 20	± 10	± 5	± 50	± 10
IV Mud from river-water									Fraction 2–5 μ				
Eems	very much	–	< 3	very little	much	very little	< 3	rather much	rather much	very little	< 3	much	very little
Wezer	± 90	3–5	< 3	± 5	± 50	± 5	± 5	30–40	± 30	3–5	< 3	± 60	± 5
Elbe	70–80	5–10	< 3	± 15									
Rhine	80–90	± 10	< 3	± 5	40–50	± 10	± 5	± 40					
									Fraction 2–10 μ				
V Old clay banks	± 80	5–10	5–10	± 4	± 60	5–10	± 5	± 25	± 30	5–10	± 5	± 50	5–10
VI Mussel banks	80–90	5–10	± 5	± 4									
Shell clay	80–90	± 5	5–10	2–4	50–60	± 10	5–10	25–30	± 30	± 5	± 5	50–60	± 5
Mussel faeces	80–90	± 5	3–5	± 6	± 60	± 5	± 5	± 30					
VII Wan-tide Schiermonnikoog	± 80	5–10	5–10	± 6	± 60	5–10	± 5	± 30					
VIII „Schorren" of Zeeland	80–90	± 5	5–10	2–4	± 60	± 10	5–10	± 25					

TABLE 5

Quantities of the minerals in the fractions

	$<0.5\,\mu$	0.5–$2\,\mu$	2–$10\,\mu$
Illite	80–90%	about 60%; for a small part muscovite	20–30%; for a greater part muscovite
Kaolinite	usually 5–10%; lacking in Eems mud	usually about 10%; very little in Eems mud, rather much in sea-bottom samples (± 15%)	usually 5% or less, very little in Eems mud, rather much in sea-bottom samples (10–15%)
Montmorillonite	varies from less than 3% (river-mud) to 15% (wan-tide S.)	from less than 3% to 10%	5% or less
Quartz	usually not more than 5% (the mud from the wan-tide S. and the Elbe excepted)	about 30%	about 60%
Muscovite	very rarely; small quantity in Rhine mud	small quantities	is an important part of the micas
Felspar	absent	very rarely and not more than 5%	usually 5–10%