Bottom sediments in Ho Bugt - a wadden sea environment

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Twenty eight samples of bottom sediment from Ho Bugt, located at the west coast of Jutland, have been anlysed, and the variations within the fine and the coarse fractions described in detail. A method for classifying estuarine- and wadden-sea sediments is presented. The classification together with special characteristics found for the coarse fraction is used as a basis for a sediment chart for the northern part of Ho Bugt.

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INTRODUCTION

From August 1975 to July 1978 about 160 samples of the bottom sediment were collected in the northern part of Ho Bugt, located at the west coast of Jutland, cf. fig. 1 A, with the purpose to give a detailed description of the sediment. Analyses of 28 of these samples are presented in this paper, cf. fig. 1 B, and on the basis of the results, a sediment chart of the area has been elaborated. The topography and hydrography of Ho Bugt has been described in details elsewhere, Gry (1942), Bartholdy (1979) and Pejrup (1980) and shall therefore not be repeated here.

Earlier work in the same area was done by Gry, op.cit., who presented a sediment chart of Ho Bugt. Later, specific sediment types were treated by Hansen (1951 and 1952), who also described the share of coarse and fine fractions in the different types of sediment. In 1966, Lüneburg discussed some of the sandy sediments and their transportation by the tidal current.

The work presented in this paper is an attempt to further improve the fairly good knowledge of the bottom sediment, especially in the northern part of Ho Bugt, and to give a classification of the sediment.

METHODS

The samples were taken with a plexiglass drill, and the volume of each wet sample was determined in the field, where also a description of the sediment was made. In the laboratory the wet and the dry bulk density was determined by weighing and drying. The organic content was determined partly by ignition loss at 500°C and partly by ignition at 1650°C of a dry, homogeneous sample and subsequent col-

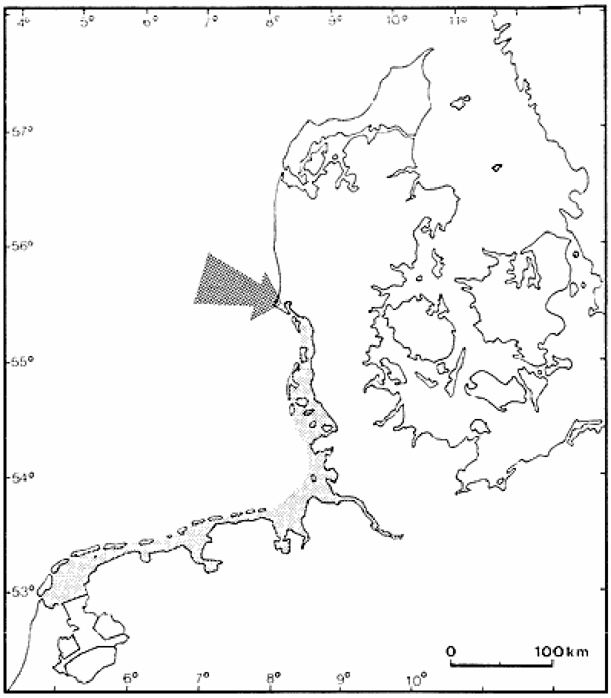

Fig. 1 A: Map showing the extension of the European Wadden Sea. The arrow indicates the location of Ho Bugt.
Fig. 1 A: Kort over Det Europæiske Vadehav. Pilen viser Ho Bugts placering.

lection of the released organic carbon (C). After correction for the content of carbonate, the sampled amount of C can be used to determine the organic content of the sample, assuming that the organic matter has a content of 58% C. The following connection between the two methods was found:

$$\text{Org.\%} = 0.668 \text{ ign. loss \%} - 0.163 \quad r = 0.971 \quad (1)$$

This equation has been used to calculate the organic content. Texture analyses of the sediment were made in the following way: The fine and the coarse fractions were separated by wet-sieving, whereafter the coarse fraction was sieved with 1/4-Φ intervals. The fine fraction (less than 63 μ) was analysed by the pipette method down to a grain size of 2 μ, and the sample peptizised in 0.002 M sodium-hexa-metaphosphate throughout the analysis. The organic content of the coarse fraction was removed before sieving, whereas this was

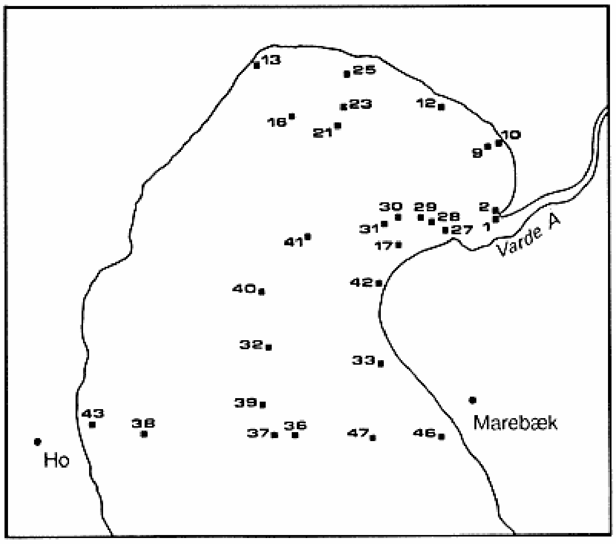

Fig. 1 B: Map of the northern part of Ho Bugt showing the location of the analysed samples.
Fig. 1 B: Kort over den nordlige del af Ho Bugt med de analyserede prøver indtegnet.

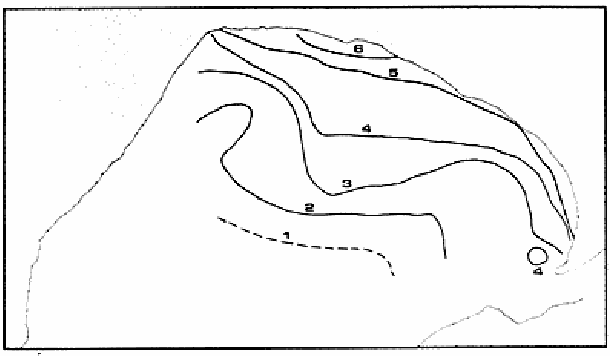

Fig. 2: Map of the northern part of Ho Bugt with isolines indicating the percentage of organic content of the bottom sediment.
Fig. 2: Kort over Ho Bugts nordlige del med indtegnede isolinjer for det procentiske organiske indhold i bundsedimentet.

not done for the fine fraction. The statistical parameters have been calculated according to Folk and Ward (1957).

RESULTS

Organic content and bulk density

The total organic content of the sediment varies relatively little in Ho Bugt, and the variations found reflect primarily differencies in mean grain size. The reason for this is that the organic content of the coarse fraction is about 1% throughout the area and consists primarily of slightly decomposed vegetable matter which has no bearing on the sediment structure. Reversely for the fine fraction, where, with decreasing grain sizes, one finds an increasing content of organic matter, which is well decomposed and integrated in the sediment.

Fig. 2 shows the organic content of the bottom sediment in the northernmost part of the bay, and it is obvious how, from about 6% in the northwestern part, it is decreasing to about 1% in the southern part of the area where the sediment becomes more sandy. From the figure it further appears that the isolines follow the coast due to the decreasing mean grain size in an onshore direction, a problem which will be discussed later. The maximum value of organic matter is generally found 5-10 cm below the sediment surface, but the trend is a decreasing organic content with increasing depth below the surface.

Because of the varying content of sand, silt and clay in the bottom sediment, there is a great variation in the wet bulk density, i.e. from about 1.1 g/cm³ for the very fine-grained surface sediment to about 2.1 g/cm³ for the sandy sediments. The mixed sediments lie somewhere in between, with a typical value of about 1.7 g/cm³. The bulk density increases with increasing depth under the sediment surface, this being most pronounced for the fine-grained sediments.

Texture Analysis

The texture analysis shows a rather great variation in the textural composition within relatively small distances. From the southern part of the area and northward, the mean grain size tends to increase until the northernmost waddens where it decreases drastically. Another example of textural variations is found along the east-west line from Marebæk to Ho, cf. fig. 1B, such as evidenced by the samples 46, 47, 36, 37, 38, and 43; the statistical parameters for these samples are given in table I.

Table I: Sample no.	Mean grain size μ	Φ	Sorting Φ	Skewness	Kurtosis
E 46	211	2.18	0.59	0.04	1.04
47	196	2.35	0.20	0.20	3.98
36	148	2.76	0.81	0.39	2.25
37	36	4.78	-	-	-
38	19	5.71	-	-	-
W 43	10	6.6	-	-	-

To the east one finds an almost normally distributed sandy sediment with a mean grain size of 211 μ. When moving westward along the line, it is seen that the mean grain size is decreasing because of an increasing content of fine-grained material, which causes the sediment to be positively skewed and badly sorted. Furthermore, the kurtosis values get rather high because of the poor sorting of the material in the fine part of the sediment. The increasing content of fine material to the west may partly be caused by a more calm sedimentary environment due to predominantly westerly and northwesterly winds, and partly by erosion of the materials bordering the bay. These are older salt marshes of holocene age to the west and sand cliffs of miocene age to the east. There seems to be no doubt that the vicinity of these sediment types has a strong bearing on the presented sediments sequence.

Variations in the fine fraction
It has long been known that the textural composition of the fine fractions of estuarine sediments varies within rather narrow limits, and this has been used by several Dutch authors to describe the variations within the fine fraction. The clay content of the fractions smaller that 16 μ (6Φ), 22 μ (5½Φ) and 63 μ (4 Φ) respectively can be expressed as the ratios Φ9/Φ6, Φ9/Φ5½, and Φ9/Φ4; Φ9 being the part of the fine fraction less than 9Φ and so forth. In Dutch literature, the ratio Φ9/Φ6 has often been used as an indication of the sedimentary environment, among others by Zonneveld (1960) and van Straaten (1963). A value of about 0.65 should indicate a marine sedimentary environment, whereas values somewhat lower, say 0.40, should indicate a brackish sedimentary environment. For freshwater environments no constant value for the ratio has been found. The reason for the constant composition of the finest part of the fine fraction is that the smallest particles are found in a flocculated state in the saline water, so that the parameters controlling the sedimentation cannot affect the ratio between the flocculated particles as long as the flocs are not destroyed. The flocs must be of either constant, or of random composition, but still having approximately the same fall velocity. Tidal mixing and high concentrations of flocculated material can serve to homogenize the flocs, so they obtain an almost constant fall velocity.

Table II

Ratio	Mean value	Std. Dev.	Variation Coefficient
Φ9/Φ6	0.65	0.06	8
Φ9/Φ5½	0.59	0.08	13
Φ9/Φ4	0.47	0.11	23

When calculating the above ratios for the samples from Ho Bugt, we get the values shown in table II. From this it can be seen that the variation in the ratios Φ9/Φ6 and Φ9/Φ5½ are relatively small, whereas the ratio Φ9/Φ4 varies much more. This means that the variation in textural composition of the fine fraction is rather small for particles less than 22 μ (5½Φ), and that this is due to different contents of particles larger than 22 μ. This is in accordance with results presented by Kranck (1975) who investigated the sedimentation from a fine-grained flocculated suspension and found that grains smaller than the modal diameter of the suspension settle as part of flocs, whereas grains larger than the modal diameter settle as single grains. This result has been confirmed by in situ measurements by Kranck (1981). As the modal diameter of the fine fraction of the bottom sediment in Ho Bugt has been found to vary within the limits of 19 to 37 μ, it seems likely that the constant textural composition of the finest part of the fine fraction is caused by the tendency of these particles to coagulate in a saline environment.

From table II it can be seen that the mean value of the Φ9/Φ6 ratio is 0.65. This value seems to be extremely constant for sediments in marine environments where the sediment concentration is relatively high. Nota and Loring (1964) found a mean value of about 0.64 for the bottom sediment from St. Lawrence Gulf and River, and van Straaten (1963) gives values between 0.65 and 0.70 for marine deposits. In this connection the term, marine sedimentary environment, must mean an environment where the salinity is somewhat higher than 3‰, as most works on flocculation claim that the flocculation of fine-grained material has stopped at salinity values of this size, Whitehouse et al. (1960), Mignoet (1968) and Edzwald and O'Melia (1975).

The fine-grained material in Ho Bugt is primarily of marine or local biological origin. This has been shown by studying the distribution of fluvially supplied mercury to the bay, Pejrup (1980). The fluvial share of the fine-grained material is found to be about 15%.

Variations in the coarse fraction.
When looking at the different sand populations occurring in the bottom sediment from Ho Bugt, one finds that these differ much more than found for the fine populations. If the statistical parameters are calculated for the coarse fraction separately, it is possible to define 4 different groups of sand. This is done in table III. From this it appears that group 1 and 2 are almost identical what sorting and kurtosis values concerns, but the sand populations in group 1 have mean grain sizes smaller than the populations from group 2.

Table III.

Group No.	Mean grain size μ	Φ	Sorting Φ	Skewness	Kurtosis
1	90-120	3.5-3.1	0.37-0.71	-0.65--0.30	1.10-1.80
2	130-175	2.9-2,5	0.40-0.55	0.00-0.15	1.05-1.70
3	200-275	2.3-1.9	0.51-0.69	-0.02-0.12	0.92-1.15
4	283-470	1.8-1.1	0.76-1.08	-0.16-0.13	1.06-1.30

Furthermore, the populations belonging to the last group are almost symmetrical, whereas those from group 1 are negatively skewed. Group 3 and 4 differ from group 1 and 2 in being almost symmetrical and with kurtosis values close to 1.0, thus reflecting an almost normal distribution of the sand populations from group 3 and 4. The reason for not taking group 3 and 4 as one group is the great variation in mean grain size and the fact that the 2 groups are genetically different. The poor sorting of the populations from group 4 is due to the higher value of the mean grain size.

The sand populations from group 1 are found in the sediment making up the waddens in the northernmost and the central part of the bay. The populations belonging to group 2 are found in the sediment in the southwestern part of the area, in a belt from the village of Ho to the central part of the bay extending in a southern direction. Populations from group 3 are only found in the wadden sediment near the cliffs north and south to Marebæk; finally, the sand populations from group 4 are only found in the bottom sediment close to the outlet of the river Varde Å.

The last-mentioned sand populations are of fluvial origin, which seems to be confirmed by a comparison with the bottom-transported sand discharged into the bay from Varde Å, Bartholdy (1980). In the same way the sand populations from group 3 seem to be of local origin, as there is a striking similarity between the textural parameters for the sand waddens near the cliffs bordering Ho Bugt to the east and the sand making up the cliffs.

The sand populations in the bottom sediment from Ho Bugt, belonging to group 1 and 2, have been described by Hansen (1951 and 1952), who defined these populations as wadden sand. Similar sand populations have been described from other parts of the Danish Wadden Sea area, e.g. from the waddens in the southernmost part of the Wadden Sea where Jacobsen (1964) found sand populations described as well-sorted with mean grain sizes of 60 to 100 μ. Finally it can be mentioned that the sand populations in question are very common in the North Sea just outside the Wadden Sea, Nielsen and Nielsen (1978) and Veenstra and Winkelmolen (1971). There seems therefore to be little doubt about the marine origin of sand populations belonging to group 1 and 2.

CLASSIFICATION

Classification of estuarine sediments on the basis of statistical parameters has often faced the problem that they are difficult to determine because of the high content of clay, which makes reading of the upper fractiles impossible. One is therefore forced to use a conventional triangular diagram where samples are plotted on the basis of their content of sand, silt and clay. Hereafter the diagram can be divided into a number of groups which it has been attempted to relate to different sedimentary environments. Thus, Evans (1965), Frey and Basan (1978) and Yeo and Risk (1981) present sediment data in a triangular diagram with a dividing proposed by Shepard (1954). None of these authors, however, have been able to identify a single sedimentary environment with one single group in the triangular diagram; there seems therfore to be an urgent need for relating the dividing of the diagram to the parameters controlling the sedimentation. In an estuarine environment this is primarily salinity and current velocity (bottom shear stress). As mentioned ealier, the $\Phi 9/\Phi 6$ ratio is rather constant in environments with salinities higher than 3‰, and the variation in the textural composition of the fine fraction is due to different content of particles greater than about 22 μ (5½ Φ). The reason for this difference is that particles of this size occur as single grains and are therefore mechanically sorted during transportation. With the constant $\Phi 9/\Phi 6$ ratio, as can be assumed in estuarine environments with high concentrations of suspended material and current velocities so high that the material is being well mixed, the 3 ratios $\Phi 9/\Phi 4$, $\Phi 6/\Phi 4$, and $\Phi 5½/\Phi 4$ will describe the variation in the sedimentary conditions within an environment. If the ratio $\Phi 9/\Phi 4$ is chosen to describe this variation, and if it is assumed that the variation in the $\Phi 9/\Phi 4$ ratio distributes normally, 95½% of the samples will lie within a $\pm$ 2 standard deviation around the mean value of the ratio. In this case the $\Phi 9/\Phi 4$ ratio has been chosen for the description because constant values of the ratio produce straight lines in a sand/silt/clay triangular diagram. The mean value of the $\Phi 9/\Phi 4$ ratio is drawn in the diagram, thereafter the lines of $\pm$ 2 standard deviations are drawn, thus dividing the diagram into 4 groups where the 2 middle groups will contain 95½% of the samples. The 2 middle groups can be divided further, depending on the sand content of the sediment; the diagram could f.e. be split as shown on fig. 3, where the dividing defines 6 groups, 3 above and 3 below the mean value of the ratio $\Phi 9/\Phi 4$. Samples from the groups above the mean value have a relatively high content of clay in the fine fraction. In an estuarine environment this means that the flocculation has finished and that the hydraulic conditions are fairly calm. The 3 groups below the mean value have a relatively low content of clay in the fine fraction meaning either that the flocculation has not finished yet, or, that the hydraulic conditions are more violent than for the upper 3 groups so that the flocs are destroyed. If the variation within the area of investigation is considerable, the triangular diagram could be divided further by drawing the lines $\pm$ 1 standard deviation and thus get 4 groups to be subdivided on the basis of the sand content.

This way of classifying estuarine and wadden sea sediments has the advantage that the dividing of the diagram is not arbitrarily chosen; on the contrary, it is related to the parameters controlling the sedimentation. Moreover, the system is flexible because the splitting of the diagram has been adjusted to the area of investigation, whereas the criteria remain the same.

Classification of the bottom sediment of Ho Bugt.

If the above described method is used to classify the here investigated bottom samples from Ho Bugt, the result is a dividing of the triangular diagram as shown in fig. 3. In this case it has been chosen to divide the diagram into 6 groups, but as the $\Phi 9/\Phi 4$ ratio does not seem to define any distinct groups, the samples have only been classified into the following 3 groups:

Group I : sand content 100-60% $0.26 < \Phi 9/\Phi 4 < 0.68$
Group II : sand content 60-20% $0.26 < \Phi 9/\Phi 4 < 0.68$
Group III : sand content 20-0 % $0.26 < \Phi 9/\Phi 4 < 0.68$

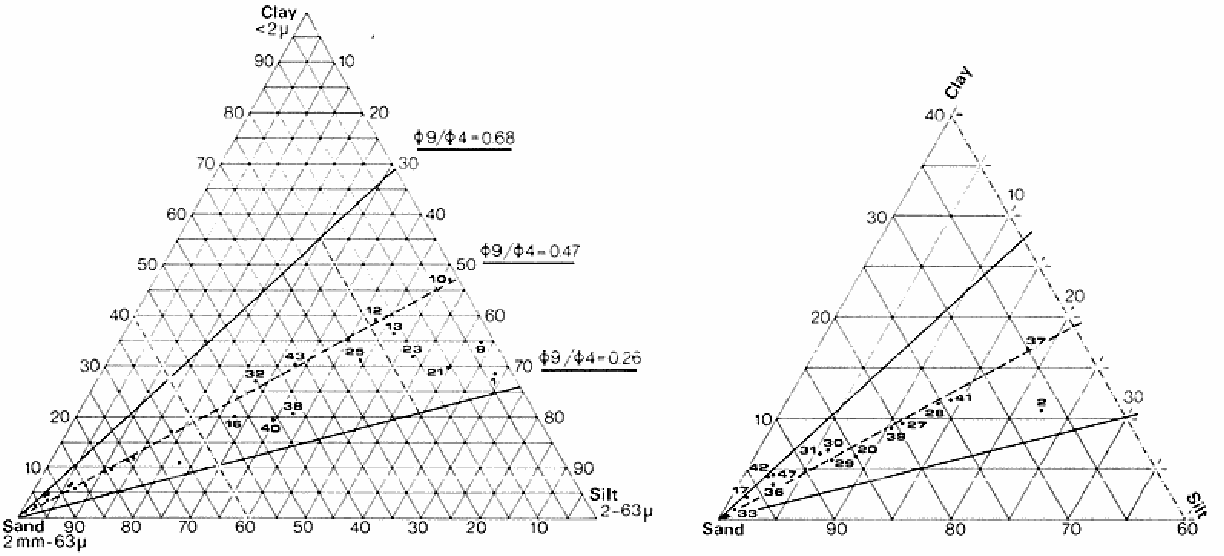

Fig. 3: Triangular diagram with the analysed samples plotted according to their contents of sand, silt, and clay. Full line indicates a constant clay/silt ratio (constant Φ9/Φ4 value), whereas constant content of sand is shown by the dashed lines. To the right an enlargement of the sandy part of the diagram. It appears that all samples lie within ± 2 standard deviations around the mean value of the Φ9/Φ4 ratio.

Fig. 3: Trekantdiagram med de analyserede prøver plottet efter deres indhold af sand, silt og ler. Endvidere er linjer med konstant ler/silt - forhold (konstant Φ9/Φ4-værdi) indtegnet i diagrammet. Linjer for konstant sandindhold er indtegnet med stiplet streg. Til højre ses en forstørrelse af den sandede del af trekantdiagrammet. Det ses, at alle prøver falder inden for ± 2 standardafvigelser omkring middelværdien af Φ9/Φ4 - forholdet.

As mentioned above, the Φ9/Φ4 ratio does not define any distinct groups on the basis of the samples from Ho Bugt. The samples show a clear tendency, however, towards an increasing Φ9/Φ4 ratio in an onshore direction, cf. the samples 1, 9, 10, and 12, 21, 23, 25 in fig. 1B and fig. 3.

In this investigation the sandy sediments have a relatively high Φ9/Φ4 ratio which is contrasting other investigations in the same sedimentary environment. The explanation seems to be that the river Varde Å discharges a lot of very fine-grained suspended material into the Ho Bugt, and as the sandy sediments are situated close to the river outlet, where the fluvially suspended material enters the estuarine environment for the first time, disproportionate amounts of the fluvially suspended clay settle here before a proper mixing is completed.

On the basis of the 3 defined groups and the variation of the coarse fraction, cf. table III, the sediment in the northern part of Ho Bugt can be divided into 3 major groups, as mentioned above. Group I is the sandy sediments, group II mixed sediments, and group III the very fine-grained sediments with a low content of fine-grained sand. Group I can be further divided into 3 subgroups on the basis of the variation of the coarse fraction:

- Group I a: containing a very coarse sand population of fluvial origin.
- Group I b: containing a medium coarse sand population of local origin (cliff erosion).
- Group I c: containing a more fine-grained sand population of marine origin.

Typical examples of the textural composition of the samples belonging to the 5 groups are shown in fig. 4. Having divided the bottom sediment into the 5 groups a sediment chart of the northern part of the bay can be made as shown in fig. 5. The chart is in good accordance with the sediment chart presented by Gry (1942), although the classification proposed in this paper is more detailed. Furthermore, the sediment chart presented here is based not only on textural composition of the sediment, but the classification is related to the

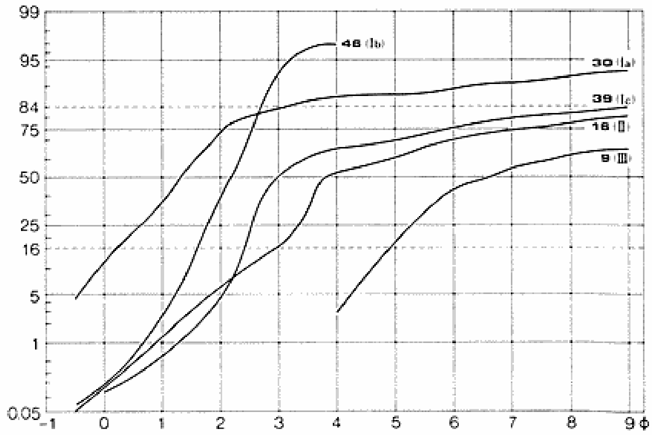

Fig. 4: Texture analyses of 5 samples representing the 5 different sediment types of the bottom sediment in the northern part of Ho Bugt.

Fig. 4: Texturanalyser af 5 prøver repræsenterende de 5 forskellige bundsedimenttyper i den nordlige del af Ho Bugt.

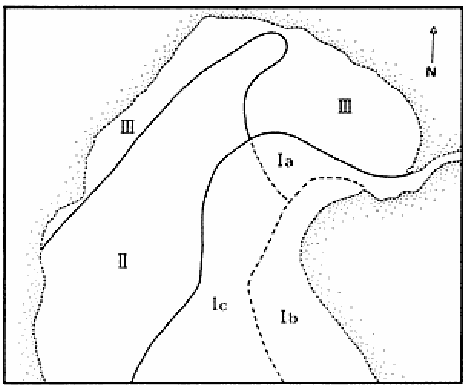

Fig. 5: Sediment chart drawn on the basis of the analysed samples, cf. fig. 1 B. The numbers refer to the description of the sediments in the text.

Fig. 5: Sedimentkort over den nordlige del af Ho Bugt udtegnet på grundlag af de på fig. 1 B viste prøver. Tallene på kortet refererer til sedimentbeskrivelsen i teksten.

parameters controlling the sedimentation as well as the origin of the different sand populations.

RESUME

I perioden august 1975 til juli 1978 er der indsamlet ca. 160 prøver af bundsedimentet i Ho Bugt. 28 af disse prøver er blevet analyseret og beskrevet m.h.t. organisk indhold, rumvægt og texturel sammensætning, se fig. 1 A og 1 B, og resultaterne er præsenteret i den her foreliggende artikel.

Som det fremgår af fig. 2, varierer det organiske indhold af bundsedimentet fra 1 til ca. 6%. Denne variation afspejler først og fremmest sedimentets texturelle sammensætning, da sandfraktionen har et ret konstant organisk indhold på ca. 1 %, medens den fine fraktion (fraktionen $< 63\ \mu$) har et stigende organisk indhold med faldende kornstørrelse. Texturanalyserne viser endvidere, at der inden for ret små afstande er store forskelle i de statistiske parametre. Endelig fremgår det, at den fine fraktions variation skyldes varierende indhold af partikler $>22\ \mu$ (5½Φ), og at forholdet mellem ler og silt for fraktionen $<22\ \mu$ er næsten konstant, hvilket skyldes at denne fraktion optræder i flokkuleret tilstand i det saline vand.

Sandpopulationerne repræsenteret i bundsedimentet kan opdeles i 4 grupper på grundlag af variationen i de statistiske parametre udregnet for sandpopulationerne alene. To af disse grupper er af marin oprindelse, en er af fluvial oprindelse, medens den sidste stammer fra erosion af tilgrænsende sedimenter.

De analyserede prøver er blevet plottet i et trekantdiagram, der er opdelt i 3 sedimentgrupper på basis af den fine fraktions sammensætning (ler/silt - forholdet) og sedimentets sandindhold, se fig. 3. Den sandede sedimentgruppe kan yderligere opdeles i 3 undergrupper på grundlag af variationen af sandpopulationerne indeholdt i sedimentet. På basis af de resulterende 5 sedimenttyper er der fremstillet et sedimentkort over den nordlige del af Ho Bugt, se fig. 4. Typiske texturelle fordelinger for hver af de 5 sedimenttyper er vist på fig. 5.

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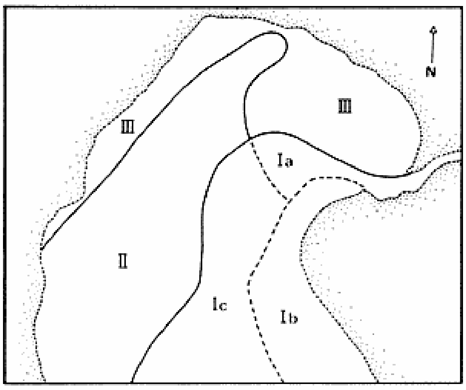

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RESUME

I perioden august 1975 til juli 1978 er der indsamlet ca. 160 prøver af bundsedimentet i Ho Bugt. 28 af disse prøver er blevet analyseret og beskrevet m.h.t. organisk indhold, rumvægt og texturel sammensætning, se fig. 1 A og 1 B, og resultaterne er præsenteret i den her foreliggende artikel.

Som det fremgår af fig. 2, varierer det organiske indhold af bundsedimentet fra 1 til ca. 6%. Denne variation afspejler først og fremmest sedimentets texturelle sammensætning, da sandfraktionen har et ret konstant organisk indhold på ca. 1 %, medens den fine fraktion (fraktionen $< 63\ \mu$) har et stigende organisk indhold med faldende kornstørrelse. Texturanalyserne viser endvidere, at der inden for ret små afstande er store forskelle i de statistiske parametre. Endelig fremgår det, at den fine fraktions variation skyldes varierende indhold af partikler $> 22\ \mu$ (5½Φ), og at forholdet mellem ler og silt for fraktionen $< 22\ \mu$ er næsten konstant, hvilket skyldes at denne fraktion optræder i flokkuleret tilstand i det saline vand.

Sandpopulationerne repræsenteret i bundsedimentet kan opdeles i 4 grupper på grundlag af variationen i de statistiske parametre udregnet for sandpopulationerne alene. To af disse grupper er af marin oprindelse, en er af fluvial oprindelse, medens den sidste stammer fra erosion af tilgrænsende sedimenter.

De analyserede prøver er blevet plottet i et trekantdiagram, der er opdelt i 3 sedimentgrupper på basis af den fine fraktions sammensætning (ler/silt - forholdet) og sedimentets sandindhold, se fig. 3. Den sandede sedimentgruppe kan yderligere opdeles i 3 undergrupper på grundlag af variationen af sandpopulationerne indeholdt i sedimentet. På basis af de resulterende 5 sedimenttyper er der fremstillet et sedimentkort over den nordlige del af Ho Bugt, se fig. 4. Typiske texturelle fordelinger for hver af de 5 sedimenttyper er vist på fig. 5.

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