The Triangular Diagram Used for Classification of Estuarine Sediments: A New Approach

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THE TRIANGULAR DIAGRAM USED FOR CLASSIFICATION OF ESTUARINE SEDIMENTS: A NEW APPROACH

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ABSTRACT. Classification of recent estuarine sediments by means of statistical parameters derived from grain size distributions can be troublesome because a large amount of clay in the samples hampers computation. Instead, a triangular diagram based on sand, silt and clay content can be used. However, the diagram most commonly used does not distinguish the different estuarine facies and subfacies satisfactorily. A new diagram is proposed with the triangle divided by lines of constant textural composition of the mud fraction (smaller than 4Ø) and lines representing a constant sand content. Lines of constant textural composition of the mud fraction can be associated with the hydrodynamic conditions during sedimentation. The proposed diagram therefore offers the possibility of both separation and hydrodynamic interpretation of different recent estuarine facies.

INTRODUCTION

Sediments are often classified by statistical parameters computed on the basis of grain size analysis (e.g., Folk & Ward, 1957; Mason & Folk, 1958; Buller & McManus, 1972; Goldbery, 1980). When thus classifying estuarine sediments one often faces the problem that they contain so much clay that only a small part of the textural distribution can be analysed by conventional sieve and pipette methods. This makes computation of the statistical parameters difficult. Other classification methods are often necessary. One such method of classification is the triangular diagram in which the sediment samples are plotted according to their content of sand, silt and clay.

Shepard (1954) summarized most of the triangular diagrams proposed up to that time. The subdivision of the diagrams is either constructed for a specific purpose or it is drawn so that the triangle is divided symmetrically into groups of equal size. The first type suffers from a lack of generality. The second kind is most suitable for classification of sediments with a random textural composition, so that sediments from different facies may plot anywhere in the diagram. However, sediments of this kind rarely exist because the textural composition of a sediment nearly always correlates with the transport processes leading to deposition. McLaren (1981) discussed these general aspects.

The triangular diagram most used for classification of sediments and for distinguishing different depositional facies is that proposed by Shepard (1954, Fig. 1). It was the result of a questionnaire sent to several sedimentologists, which may

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explain why the need for new classification diagrams was hardly apparent in the following years. Not until 1966 was a new one of general application proposed by Link (1966). The major difference between the two diagrams is that the latter contains 15 groups compared to 10 groups in the Shepard diagram. The lines dividing the two diagrams are very similar, and as the divisions between the groups are arbitrary, the increase in groups is of little advantage.

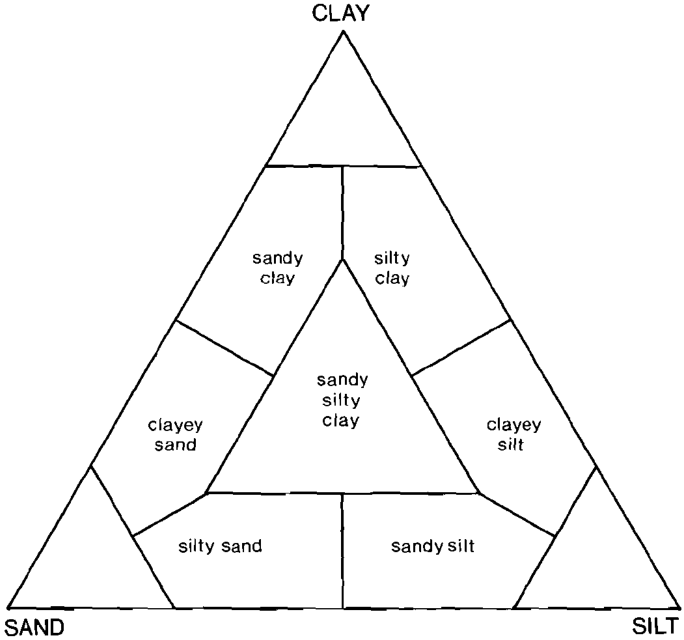


Figure 1. Triangular diagram for classification of different sediment types Shepard (1954).

Shepard's diagram is frequently used to classify sediments and to distinguish different sedimentary facies from estuarine environments, (e.g., Evans, 1965; Frey & Basan, 1978; Yeo & Risk, 1981). Most often the different facies and subfacies cover two or more groups in the diagram, and this is only partly due to the arbitrariness of the dividing lines. Not all the samples from one sedimentary facies should be expected to plot within a single group because of the arbitrariness of the divisions of a triangular diagram. However, if a specific facies is to be associated with a group in the diagram, most of the samples from this facies must plot within this group. Furthermore, the samples not plotting within this group must in the diagram plot close to the boundary of the group.

Very often samples from the single facies are clustered in an elliptical form in the triangular diagram (cf. Fig. 5A). However, the long axes of the ellipses are not parallel to any of the lines in the Shepard diagram. Therefore this diagram is not well suited for separating the different estuarine depositional facies. Lines drawn from the corner of 100% sand to the opposite side of the triangle would better separate the different facies. Such lines reflect a constant clay content (smaller than 8 Ø) in the mud fraction (smaller than 4 Ø). A constant clay/mud ratio can be explained by different degrees of flocculation of the suspended sediment. Flocculation is strongly influenced by the turbulence of the water, and consequently, lines of constant clay content can be used for a simple description of the hydrodynamic conditions during sedimentation. The only triangular diagram (known to the author) where such divisions are used was proposed by Folk (1954). His diagram was made for the purpose of classifying sedimentary rocks and its applicability for the classification of estuarine sediments was not discussed.

TEXTURAL COMPOSITION OF MUD FRACTION IN ESTUARINE SEDIMENTS

Sediments from estuarine environments very often contain a lot of mud because the processes settling-lag and scour-lag lead to the formation of turbidity maxima. These processes have been described by Postma (1954, 1961, 1967) and van Straaten & Kuenen (1957, 1958). However, the two lag-mechanisms are only efficient for particles from about 7 Ø to about 3 Ø. Therefore, clay and fine silt suspended in the water can only be concentrated in the inner parts of estuaries, provided that they mainly occur in the water as part of flocs.

When looking at the textural composition of the mud fraction of estuarine sediments, it has been shown that the composition of the subfraction less than about 6 Ø varies within rather narrow limits (e.g., Favejee, 1951; van Straaten, 1963; Nota & Loring, 1964; Pejrup, 1981). This constant textural composition of the finest part of the mud fraction can only be explained if these particles are not subject to internal hydraulic sorting. The lack of sorting must be because such fine particles exist in the water as part of sediment flocs. This explanation is supported by field investigations of suspended sediment particle sizes by Syvitski et al. (1985) showing that particles less than about 7 Ø occur as part of sediment flocs. Furthermore, in situ grain size analyses of fine-grained suspended sediment have been carried out in the Danish Wadden Sea. The analyses were done using a Braystoke SK 80 sampler/analyzer, and a detailed description of the procedure is given by Pejrup (1986). Figure 2 shows some results of these analyses from two different sites within the Danish Wadden Sea. Generally there is a poorly sorted coarse fraction (larger than 5 Ø) and a better sorted finer fraction (smaller than 5 Ø). The coarse fraction is the unflocculated part of the grain size distribution, the fine fraction the flocculated part. That the fine fraction really consists of flocculated fine particles resulting in a better sorting can be shown by taking double samples. One sample is analysed in situ and the other is brought to the laboratory. After treatment in an ultrasonic bath for about 15 minutes, it is analysed in the Braystoke SK 80 sampler/analyzer just as the in situ sample. Figure 3 shows such a double analysis. The coarse fractions are identical before and after the sample has been sonified. On the other hand, the flocs making up the fine fraction have been broken up in the ultrasonic bath into their primary constituents.

Flocs are very fragile when suspended in water (Owen, 1971; Krone, 1972, 1978; Gibbs, 1982a, 1982b) and they are easily broken by turbulence. Generally, the more violent the hydrodynamic conditions the more the flocs are broken. Consequently sediments deposited under violent hydrodynamic conditions do not contain much of the fine flocculated grain size population. Because of the constant textural composition of this fine fraction, the clay content in a mud sediment deposited in an estuarine environment can be used to describe the content of the fine flocculated fraction.

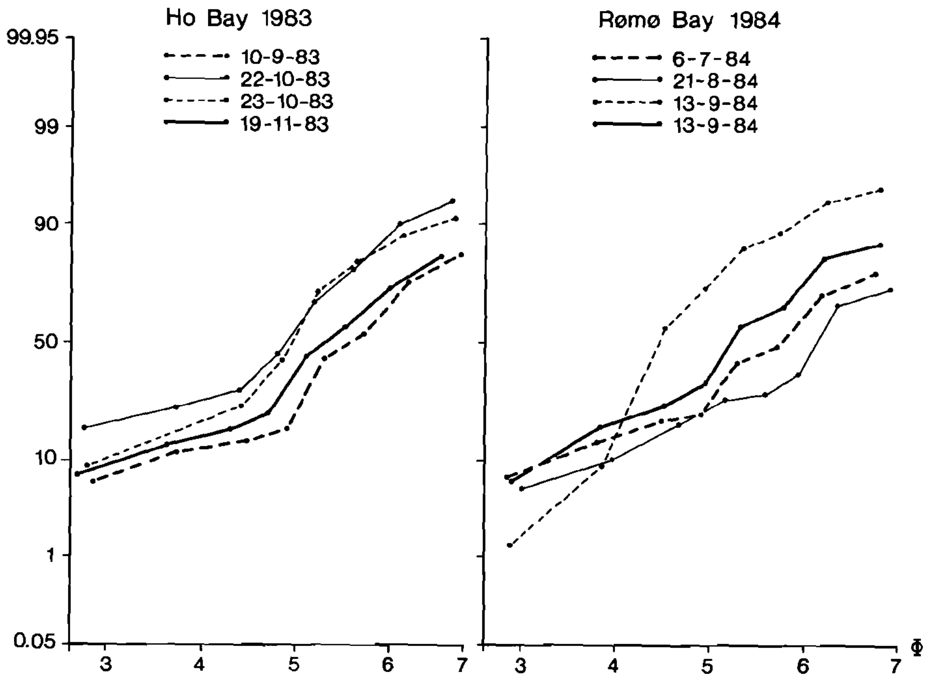


Figure2. Textural composition of fine-grained suspended sediment from two sites within the Danish Wadden Sea. The analyses were made in situ with a Braystoke SK 80 sampler/analyzer. Generally in Ho Bay the samples consist of a coarse unflocculated population greater than 5 Ø, and a better sorted flocculated population smaller than 5 Ø.

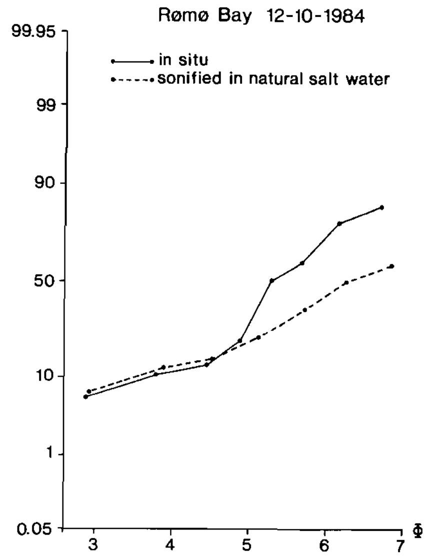
Thus the percentage of clay in the mud fraction of an estuarine sediment can be used as a simple indicator of the hydrodynamic conditions during deposition. Consequently, lines of constant clay content in the mud fraction in the triangular diagram can be used for a simple dynamical classification of different estuarine depositional facies. Hydrodynamic conditions in this connection reflect the total effect of current velocity, wave turbulence and depth, and should not be associated with specific values of Reynold or Froude numbers.

THE NEW TRIANGULAR DIAGRAM

Lines of constant clay content of the mud fraction can now be drawn for division of the triangle. Estuarine sediments with a clay content of more than 80% in the mud fraction are rarely found, and the line reflecting this content level has therefore been chosen to divide the triangle. For symmetrical reasons the lines of 20% clay in the mud fraction was chosen, and finally, the line of 50% clay was chosen, thus dividing the middle section of the triangle into two equal sections.

The triangle is now divided into four sections labelled I to IV (Fig. 4). Section I indicates very calm hydrodynamic conditions, rarely found in estuaries, and sections II to IV indicate increasingly violent hydrodynamic conditions.

Figure 3. Comparison of the natural textural composition of a fine-grained suspended sediment sample, and the textural composition of the same sample after it has been sonified in natural salt water. The coarse fractions of the distributions are almost identical whereas the flocs constituting the fine part have broken up during treatment in an ultrasonic bath.



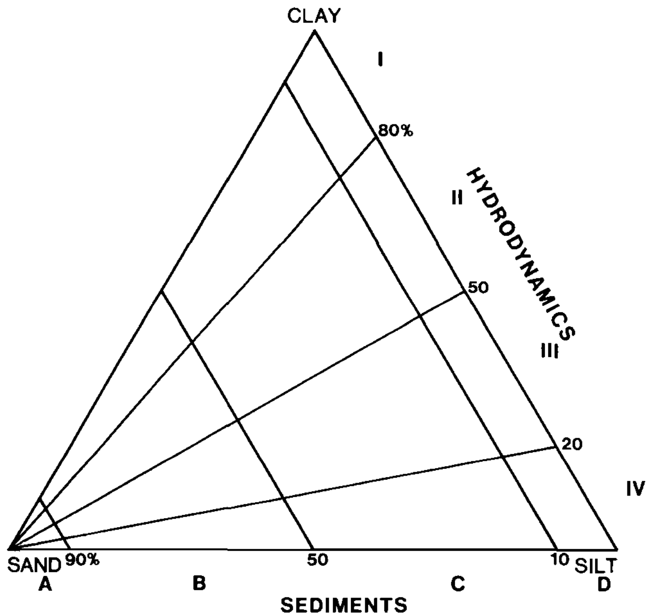


Figure 4. Triangular diagram for classification of estuarine sediments. The hydrodynamic conditions of the depositional environment are described by the percentage of clay in the mud fraction. Sections I to IV reflect increasingly violent hydrodynamic conditions. The sediments are classified according to their sand content into four sections, A to D. Thus the triangle has been divided into 16 groups, each labelled by a letter and a number. E.g. group (C,III) represents sediments containing between 50% and 10% sand deposited under rather violent conditions.

The sand content of an estuarine sediment is not always a good indicator of the depositional environment because sand can be transported both in suspension and along the bottom and also because the sand group covers a wide range of grain sizes. Furthermore, the sand content of a sediment may be very dependent on the distance from the source, which in estuarine environments are often the tidal channels. However, the sand content is well suited for a rough textural classification of the sediment, and therefore lines of constant sand content have been used for further subdivision of the triangle, so that different sediment types can be distinguished. The line of 10% sand was chosen because a sand content of this level is insignificant in a mud sediment, whereas the line of 90% sand was chosen because a sediment loses its cohesive character when the sand content decreases to this level. Finally, the line representing 50% sand was chosen to divide the middle group into two equal sections. Thus the triangle is divided into four sections, labelled A to D (Fig. 4).

The triangle consists of 16 groups, each of which can be named by a letter indicating the type of sediment and a number indicating the hydrodynamic conditions during deposition. The group (B,II) represents sediments containing from 90 to 50% sand deposited under rather quiet hydrodynamic conditions, whereas the group (C,IV) represents sediments containing between 50 and 10% sand deposited under much more violent hydrodynamic conditions. In this way the new triangular diagram offers the possibility of both a textural classification of the sediment based on the content of sand and mud, and a hydrodynamic description of the depositional environment based on the textural composition of the mud fraction. The data input is unsophisticated and will be available from most estuaries where the sedimentology has been investigated.

Alternatively, a more detailed classification is possible by distinguishing not only 4 hydrodynamic sections, but by defining a region in the diagram on the basis of the variation in the clay/mud ratio. This approach was studied by Pejrup (1981). However, in the present work a less detailed division was chosen so that the names of the different groups could be associated with well defined limits, thus facilitating comparison of different estuarine environments.

TEST OF THE DIAGRAM

Separation of Facies

Figure 5A shows the original presentation of data from Minas Basin, Bay of Fundy (Yeo & Risk, 1981). This data set was chosen for the test, because it represents a fair number of samples from different estuarine subfacies, and because each sample was plotted in the diagram. Five different facies and subfacies were recognized by Yeo and Risk, but none fall within one single group in the Shepard diagram, except for the sand flats, sand bars and the lag sediments, which all fall within the sand group. Additionally, the samples from the upper mudflat (UM) and the mixed mudflat (MM) are not even placed close to the boundary between the groups in which they plot. Data presented by Evans (1965) from the Wash, U.K., plot in almost the same groups as the data presented here, so it is reasonable to conclude that the Shepard diagram is not well suited for the separation of different estuarine facies.

When using the proposed triangular diagram, the samples from Minas Basin plot as shown in figure 5B. It can be seen that the samples from the salt marsh still fall into 2 different groups. The samples from the upper mudflat mostly fall into group (C,III), and only 4 out of 17 samples plot in other groups fairly close to the boundary of the (C,III) group. The samples from the lower mudflat can be associated with group (B,III) because 10 out of 15 samples fall into this group and the remaining 5 samples plot close to the boundary of the (B,III) group. The samples from the mixed mudflat facies can be associated with group (B,IV), - 10 out of 14 samples plot in this group, while the rest plots close to the boundary of the group. The different sand sediments fall into the groups (A,II), (A,III) and (A,IV) but there is no clear correlation with the composition of the mud fraction.

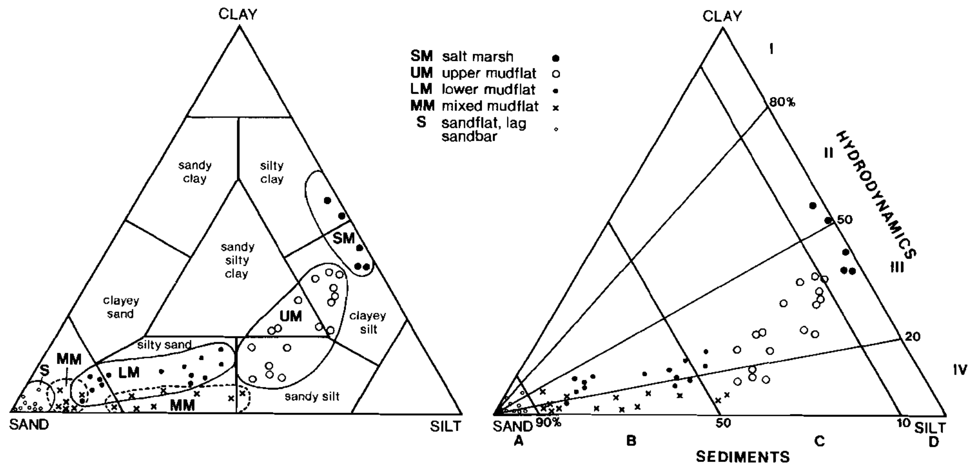


Figure 5. A: Data from Minas Basin, Bay of Fundy (Yeo & Risk, 1981), plotted in a Shepard triangular diagram.
B: The same data replotted in the triangular diagram proposed in this paper. The separation of the different facies and subfacies is best seen in the new diagram.

From this short presentation it is inferred that the new diagram separates the different estuarine facies and subfacies better than the Shepard diagram. The best example is that of the mixed mudflat samples defining 2 separate subfacies in the Shepard diagram, with a third facies in between (lower mudflat facies). In the new diagram they are classified as a single facies. Moreover, the upper mudflat facies and the lower mudflat facies are better defined in the new diagram.

Hydrodynamical Interpretation

Because the samples from the salt marsh have the highest content of clay in the mud fraction, they represent the quietest hydrodynamic conditions shown in the diagram as (D,II) and (D,III). There are too few samples from this facies for further interpretation. The difference between the samples from the upper- and lower mudflats is caused by different sand content and not by different hydrodynamic conditions, because the textural composition of the mud fraction is almost the same in both cases. The different sand content may be caused by the different distances from the source of the sand; this is in fact the case, because the lower mudflat is situated closer to the tidal channel than the upper mudflat, according to the description given by Yeo & Risk (1981). The data plotted in the new diagram indicate a rather diffuse transition between the 2 subfacies. This is confirmed by Yeo & Risk (1981) who separate the 2 subfacies partly on the basis of their sand content and not ultimately on field observations. So, with respect to sediment composition we have 2 different subfacies, caused by their different positions in relation to the tidal channel, whereas the hydrodynamic conditions are fairly uniform.

In contrast, the difference between the lower mudflat and the mixed mudflat is not their textural compositions, but a difference in hydrodynamic conditions. The clay content of the samples from the mixed mudflat is somewhat lower than for the lower mudflat, which indicates more violent wave- and current activity in the subfacies mixed mudflat. This is confirmed by Yeo & Risk (1981), who state that the lower mudflat facies is mainly found on sheltered tidal flats, whereas most of the samples from the mixed mudflat facies are taken from an exposed wave-cut bench.

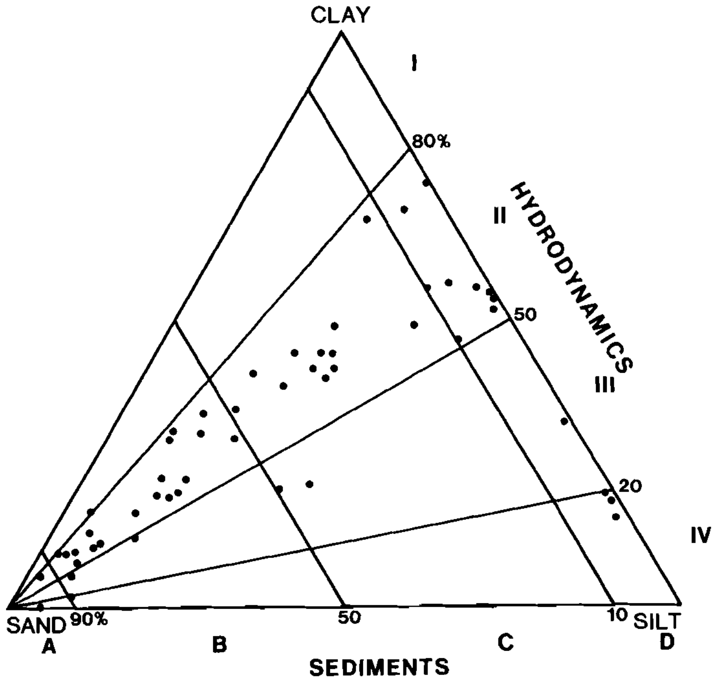


Figure 6. Data from Mugu Lagoon, California after Warme (1971), plotted in the new triangular diagram. Nearly all samples plot in the hydrodynamic section II indicating rather calm hydrodynamic conditions within this estuarine environment.

Comparison of Different Estuarine Environments

The new diagram can also be used for a general characterisation of the depositional conditions within a specific estuary. In figure 6 data from Mugu Lagoon, California (Warme, 1971) are plotted in the diagram.

Nearly all the samples plot in hydrodynamic section II, and thus indicate calm depositional conditions. On comparing these data with the samples from Minas Basin plotted in figure 5B, it can be seen that the Minas Basin samples plot in hydrodynamic sections III and IV indicating much more violent depositional conditions than in Mugu Lagoon. This difference is confirmed by the fact that Mugu Lagoon is a microtidal environment with tidal ranges less than 2 m, whereas Minas Basin is an extreme macrotidal environment with tidal ranges up to 16 meter. The new diagram thus may be used for an overall sedimentological comparison of different estuaries.

In figure 7, 26 samples from Ho Bay in the northern part of the Danish Wadden Sea are plotted. The samples plot close to the boundary between hydrodynamic sections II and III. So the depositional conditions in Ho Bay are more violent than in Mugu Lagoon, although Ho Bay too is a microtidal environment with tidal ranges of about 1.3 m. However, the more violent hydrodynamic conditions inferred from the diagram can be explained by the greater wave turbulence in Ho Bay, which is directly exposed to prevailing westerly winds from the North Sea.

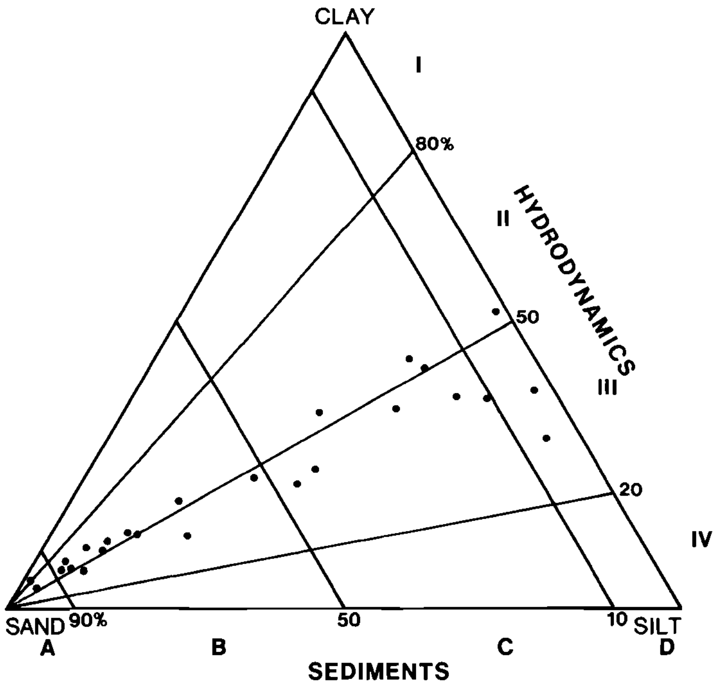


Figure 7. Data from the northern part of the Danish Wadden Sea plotted in the new triangular diagram. Nearly all samples plot along the boundary of hydrodynamic sections I and II.

CONCLUSIONS

The finest part (smaller than 6 Ø) of the mud fraction (smaller than 4 Ø) of estuarine sediments very often has a constant textural composition, because these small grain sizes occur in the water as part of sediment flocs. Therefore they cannot be subject to internal hydraulic sorting. Such sediment flocs are fragile and are easily broken by water turbulence. The percentage of this flocculated grain size population in the mud fraction of an estuarine sediment can therefore be used as a simple indicator of the hydrodynamic conditions under which deposition took place. The greater the percentage of the flocculated population, the less the flocs have been broken and the calmer the hydrodynamic conditions. Because of the constant textural composition of the finest part of the mud fraction, its percentage of the mud fraction can be described by the percentage of clay in the same sediment.

Therefore, lines of constant clay content of the mud fraction separate different facies characterized by differences in hydrodynamic conditions and they have been used to subdivide the triangle.

The triangle is divided into four hydrodynamic sections, I to IV indicating increasingly violent conditions.

Furthermore, lines of constant sand content have been used for division because the sand content of a sediment is well suited for a textural classification. In this way the triangle is divided into four textural classes, A to D, indicating decreasing sand content in the sediment.

The triangle has now been divided into 16 groups, each labelled by a letter (A, B, C, or D) indicating the sand content of the sediment and a number (I, II, III, or IV) indicating the hydrodynamic conditions of the depositional environment.

The new diagram has proved to be useful in the interpretation of sediment samples from Minas Basin. Furthermore, it was shown that the diagram can be used for an overall comparison between different present-day estuarine environments.

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