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A revised textural classification of gravel-free muddy sediments on the basis of ternary diagrams

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Abstract

A revised textural classification of gravel-free muddy sediments based on the adaptation, modification and expansion of previous schemes using ternary plots is presented. The new approach increases the range of application and the environmental sensitivity of textural sediment classification. In the case of simple two-component sand/mud mixtures, six sediment types based on mud (silt + clay) or sand content are distinguished: sand (<5% mud), slightly muddy sand (5–25% mud), muddy sand (25–50% mud), sandy mud (50–75% mud), slightly sandy mud (75–95% mud), and mud (>95% mud). The class names accurately describe a sediment within defined textural limits, and the scheme can thus be used to divide a depositional environment into textural sub-environments or facies. By diagonally subdividing the two-component system, a more complex three-component classification scheme based on sand/silt/clay ratios has been generated. In this scheme, 25 sediment classes are distinguished, each defined by a generic name and a letter–number code. It not only allows a more detailed textural subdivision of sedimentary environments than the two-component system, but also incorporates a genetic element by distinguishing between different hydrodynamic regimes. Thus, sandier and more silty sediments, reflecting deposition under higher energy conditions, are progressively segregated from muddier and more clayey sediments which reflect deposition under lower energy conditions. This is illustrated with examples from a variety of intertidal and open shelf environments. In addition, the letter–number codes can be used to label sediment facies maps, annotate stratigraphic sections and structure data banks. The two classification schemes are complementary, offering two levels of resolution and fulfilling the basic requirements of practicality, ease of use and global applicability. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Textural classification; Ternary diagram; Sand; Silt; Clay; Mud; Facies

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1. Introduction

Descriptive classifications and nomenclatures in sedimentology allow the distinction of different sedimentary rocks or sediment types on the basis of rational criteria, thereby reducing ambiguity, and aiding communication and discussion of observations and analytical results. In the case of detrital sediments and sedimentary rocks, traditional classification schemes are based on grain size, proportional size classes, or mineral composition (e.g., Udden, 1914; Wentworth, 1922; Rodgers, 1950; Folk, 1954; Shepard, 1954). In the past, simple classifications suitable for field applications (e.g., Robinson, 1949; Folk, 1954) were contrasted with more complex ones used for the presentation of analytically derived laboratory data (Trefethen, 1950; Shepard, 1954).

The profusion of new classification proposals in the late 1940s and early 1950s highlights the rapid expansion of sedimentological research after the 2nd World War and the resulting need of descriptive terminologies (Robinson, 1949; Rodgers, 1950; Trefethen, 1950; Folk, 1954; Shepard, 1954). A variety of classifications were generated to meet the specific demands of different users, e.g., civil and coastal engineers, soil scientists, sedimentologists, and marine geologists (cf. discussion in Shepard, 1954). Unfortunately, the frequent use of identical descriptors for categories sometimes defined by very different class boundaries has produced a regrettable terminological overlap. As a result, the use of a particular nomenclature is meaningless unless the associated classification scheme is revealed, a negative example being contained in Algan et al. (1999). Some recent studies side-step the issue altogether by using ternary diagrams for trend analysis, but avoiding the use of a descriptive terminology (e.g., Lucchi and Kidd, 1998; Wells et al., 1999).

Rodgers (1950) stated that classifications and nomenclatures in sedimentology should ideally be descriptive, objective and precise, rather than genetic. On the other hand, since the interpretation of sedimentary deposits, both modern and ancient, aims at reconstructing depositional processes, environments and facies, it may actually be desirable for classifications to have a genetic basis (cf. Folk et al., 1970). Furthermore, a classification scheme should be practical, easy to use, and of global applicability, while the parameters defining the descriptive categories should be attainable by standard field or laboratory procedures.

An early appeal for greater detail in sediment classification was made by Doeglas (1968). His proposal included statistical information on the shape of grain-size curves, as had previously been done by Niggli (1948). However, the scheme ultimately failed because it became too complicated for practical application. In more recent years, a number of new or modified approaches have been proposed or investigated, e.g., a simplified classification of intertidal Wadden Sea sediments on the basis of sand/mud ratios (Reineck and Siefert, 1980), a hydrodynamically based classification of fine-grained estuarine sediments using sand/silt/clay ratios (Pejrup, 1988), a classification for coarse-grained sediments based on gravel/sand/mud ratios (Blair and McPherson, 1999), or attempts to classify sediments by multivariate analyses, e.g. clustering techniques using three-component mixtures (e.g., Barceló et al., 1999). This apparent need for alternative sediment classification schemes is at least in part due to the increased level of sophistication achieved in the textural analysis of sediments (e.g., automated settling tubes and electronic particle counters; cf. Syvitsky, 1989), this having resulted in higher sampling densities and hence in greater spatial resolution and finer detail in sediment dispersal patterns (e.g., McLaren et al., 1993; Flemming and Ziegler, 1995; Nyandwi and Flemming, 1995; McLaren et al., 1998). On the other hand, most of the new classifications have aggravated rather than alleviated the terminological confusion.

In this paper an attempt is made to merge some commonly used classifications based on ternary plots. In this way a new textural classification and an associated descriptive terminology of fine-grained sediments is achieved in which textural class boundaries are harmonised at different levels of complexity. The classification is restricted to sediments composed entirely of grain sizes <2 mm.

2. Definitions

The textural classification proposed in this paper basically follows the subdivisions introduced by Wentworth (1922). In departure from this scheme, a silt/clay boundary of 9 ϕ or 2 μm is used, as proposed by Friedman and Sanders (1978). The sand/silt boundary is set at 4 ϕ (62.5 μm), the upper limit of sand being defined at -1 ϕ (2 mm).

The term "mud" was initially used in a loose way to designate very fine-grained and mostly cohesive (sticky) sediments (Twenhofel, 1932), but had fallen into disrepute because of its vague definition (cf. Shepard, 1954). In this paper, the now widely accepted textural definition of mud, i.e. all sediments finer than 4 ϕ (i.e. silt + clay) as introduced by Twenhofel (1937) and later reiterated by Folk (1954), is adopted.

3. Some common classification schemes

In addition to the recent classifications mentioned above, a variety of other ternary plots are also in use today. Thus, a modified version of the diagram originally proposed by Trefethen (1950) can be found in Chatenet et al. (1996). The most widely used diagrams are probably those by Shepard (1954) and Folk (1954, 1968). However, besides having 10 subdivisions and sharing 7 names for textural classes of unequal proportions, the two diagrams have little else in common (cf. Figs. 1(A) and (B)). Considering the detail in many modern studies of fine-grained sediments, both schemes are rather crude in that most classes have widely spaced boundaries encompassing sediment mixtures covering fairly large textural ranges. Furthermore, in both classifications the quantitative determination of silt and clay contents is required. In many studies, however, such a distinction is not made, this having been the main reason for the precise textural definition of the term "mud" by Twenhofel (1937) in the first place (see above).

More recently, attempts have been made to classify sediments on the basis of multivariate statistical analyses such as hierarchical clustering (linear discriminant analysis), alr-clustering (additive log-ratio transformation) or BC clustering (Box–Cox transformation) of granulometric data. Barceló et al. (1999) have applied these

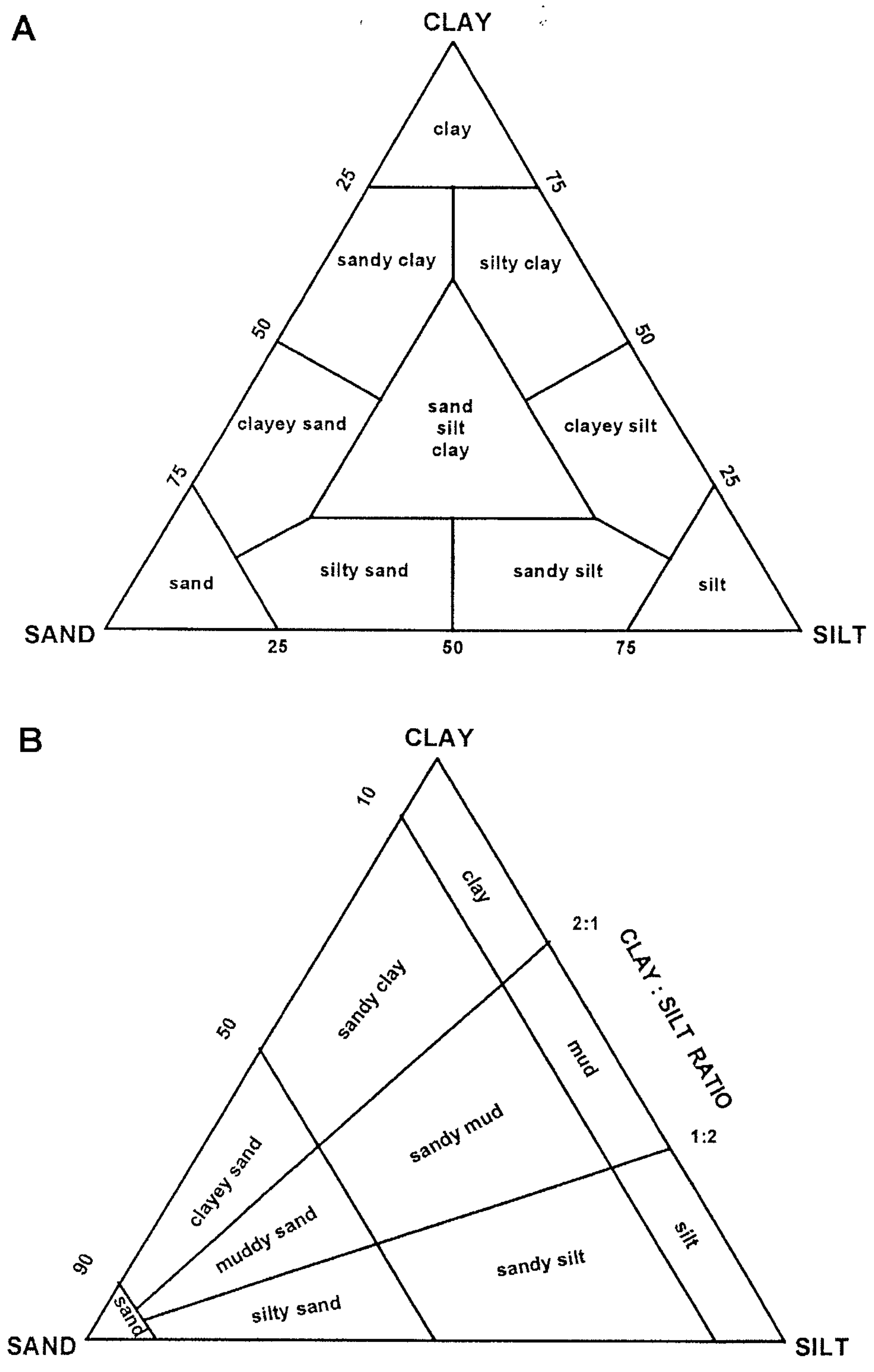

Fig. 1. Ternary diagrams for the textural classification of sediments on the basis of sand/silt/clay ratios. Diagram A: after Shepard (1954). Diagram B: after Folk (1968) and Folk et al. (1970).

statistics to one and the same data set, producing a substantially different spatial pattern in each case. However, besides failing to extract geological meaning from the divergent patterns, the authors also fail to demonstrate what advantage these techniques might have over conventional classification procedures. Nevertheless, the application of multivariate statistical procedures for sediment classification certainly

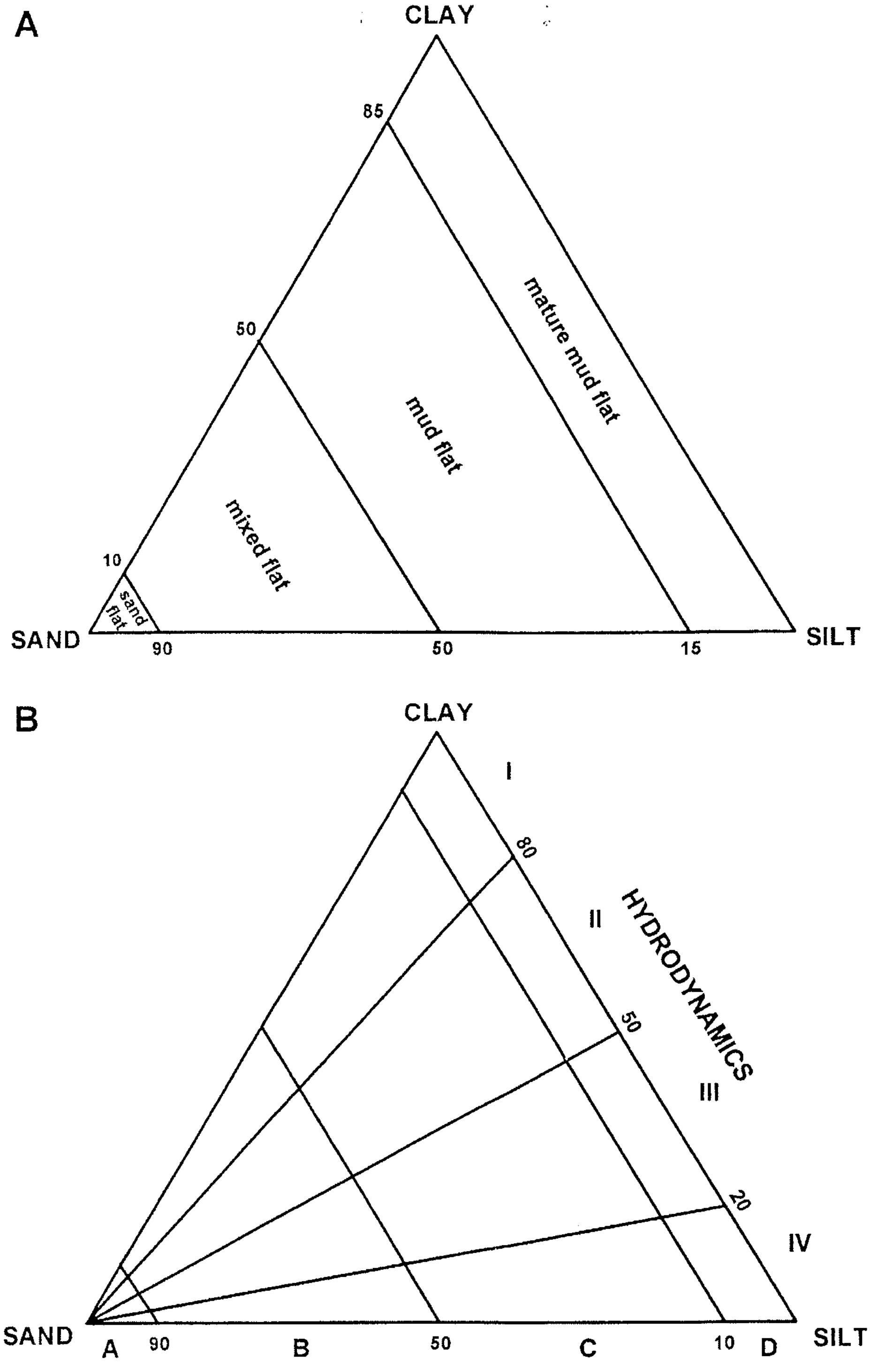

Fig. 2. Ternary diagrams for the textural classification of sediments on the basis of sand/mud ratios. Diagram A: after Reineck and Siefert (1980). Diagram B: after Pejrup (1988).

holds promise for the future, but it cannot be considered a viable alternative at this stage.

Muddy intertidal sediments are commonly subdivided into sand flats, mixed flats and mud flats on the basis of sand or mud contents. A typical example is the two-component triangular plot of Reineck and Siefert (1980) (Fig. 2(A)) which represents a strongly simplified derivative of the subdivision originally developed by

Sindowski (1973) to illustrate sand/silt/mud ratios of Wadden Sea sediments. The textural classes of this latter scheme had numerous irregular and non-symmetrical boundaries, resulting in awkward and sometimes confusing sediment classification patterns. The simplified scheme of Reineck and Siefert (1980) has the advantage of being more general but, with only four subdivisions based on sand content, resulting classifications are rather crude.

In contrast to this, Pejrup (1988) proposed a scheme which modifies and expands the ternary "Folk" diagram on the basis of hydrodynamic considerations (Fig. 2(B)), thus adding a genetic aspect to the classification. By dividing the silt/clay axis into equal parts (50%), and adding partition lines defining silt/clay ratios of 2 : 1 and 1 : 2, he distinguishes four "hydrodynamic" groups (I–IV) between the silt and clay endmembers. The other divisions conform to those of the "Folk" diagram. The lines separating the four hydrodynamic groups are quite arbitrary, being used to highlight the energy gradient from lower (clay-dominated muds) to higher energy levels (silt-dominated muds). In each category the energy also decreases from the sandy endmember to the respective muddy endmember, the sediment zonation being labelled from A to D. In this way 16 textural classes are distinguished, each being identified by a letter–number code. In this scheme, class A–IV designates the highest, class D–I the lowest energy regime. A major shortcoming of the "Pejrup" scheme, however, is its lack of descriptive terminology.

4. Elements of a revised classification scheme

By modifying and expanding the classification schemes of Reineck and Siefert (1980), and Pejrup (1988), two interrelated classification schemes have been generated, a simple one based on sand/mud ratios, and a more complex one based on sand/silt/clay ratios. The simple scheme for two-component data sets is illustrated in Fig. 3. It distinguishes six textural classes on the basis of simple sand/mud mixtures, sand (<5% mud content) and mud (>95% mud content) being the respective endmembers (Table 1). In comparison to previous schemes, it allows a higher spatial resolution of textural trends defined by simple sand/mud ratios, and provides a descriptive classification using familiar terminology. At the same time the scheme forms the basis for a more complex three-component classification of sediments whose sand, silt and clay contents are known.

In the more complex scheme, the subdivision of the two-component sand/mud system has been expanded to differentiate between sand, silt and clay. This is achieved by a lateral subdivision of the two-component system (Fig. 4). In all, six partition lines have been added. These are of unequal lengths but are mirror-imaged along the centre line that divides the mud fraction into equal parts, thus introducing a lateral symmetry into the system without overloading it. As a result, the sand class remains undivided; the slightly muddy sand category is divided into two subclasses to distinguish between a silt-dominated and a clay-dominated mud fraction; the muddy sand category is divided into four subclasses at silt/clay ratios of 3 : 1, 1 : 1 and 1 : 3 to generate two silt-dominated and two clay-dominated subdivisions; and the sandy

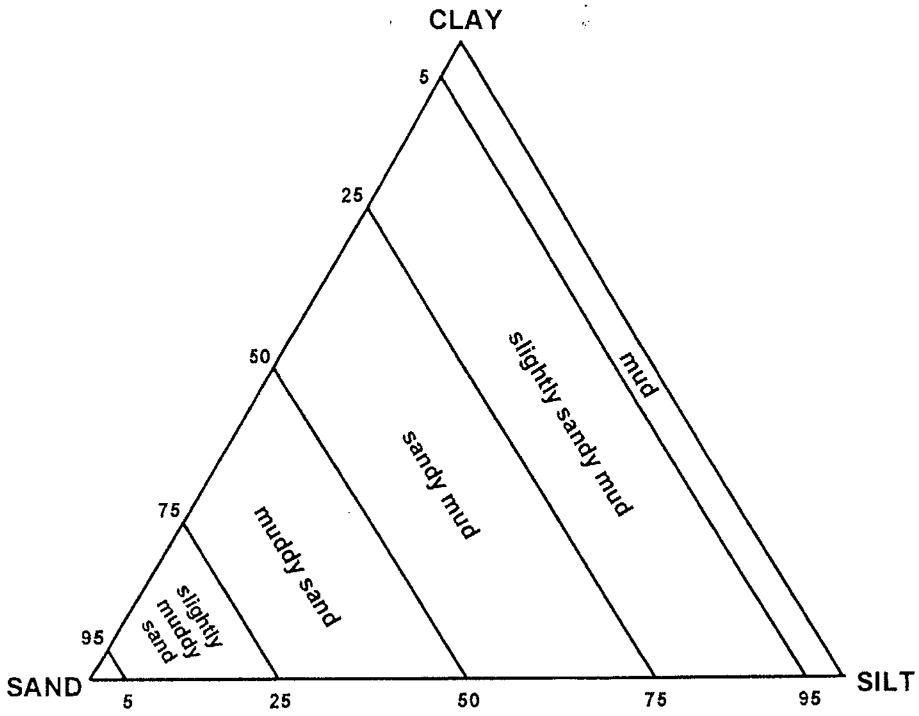

Fig. 3. Ternary diagram for a revised textural classification of sediments on the basis of sand/mud ratios as proposed in this paper.

Table 1
Descriptive terminology for the 6 textural classes based on mud content as defined in Fig. 3

Mud content (%)	Textural class	Mud content (%)	Textural class
<5	Sand	50–75	Sandy mud
5–25	Slightly muddy sand	75–95	Slightly sandy mud
25–50	Muddy sand	>95	Mud

mud, slightly sandy mud and mud categories are each divided into six subclasses at silt/clay ratios of 10 : 1, 3 : 1, 1 : 1, 1 : 3, and 1 : 10, i.e. three silt-dominated and three clay-dominated categories. By this procedure the ternary diagram has been divided into 25 textural classes. Each class has been given a unique generic name which is associated with specified sand/silt/clay ratios. In addition, each class has been labelled by a letter or letter–number code (cf. Fig. 4 and Table 2).

5. Discussion and conclusions

The revised textural classification scheme of gravel-free muddy sediments proposed in this paper harmonises and merges existing schemes that have been slightly modified, thereby allowing applications at increasing levels of complexity as a function of

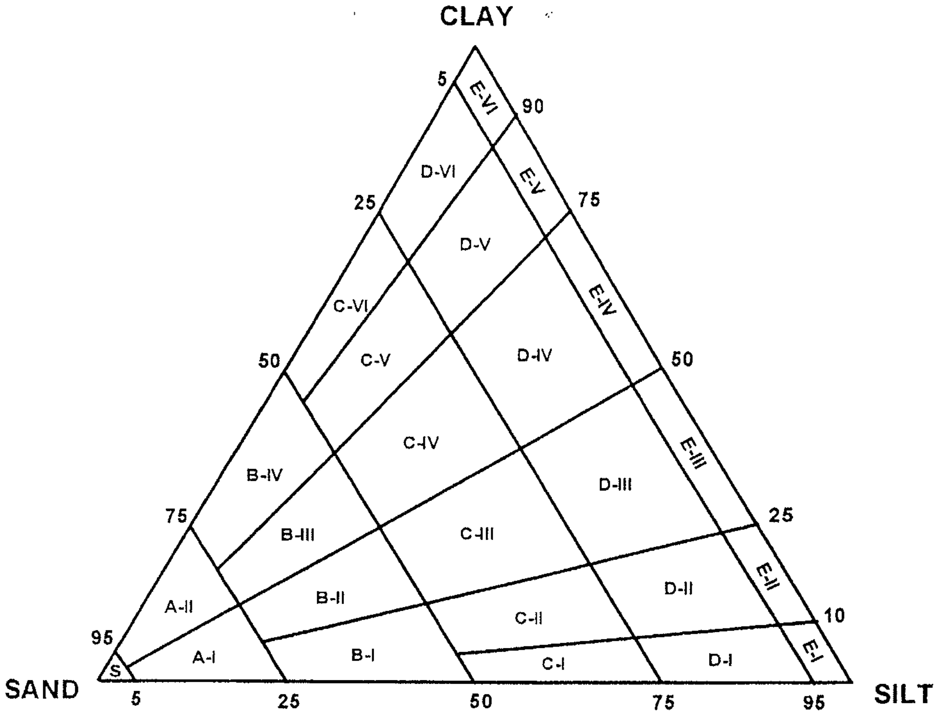

Fig. 4. Ternary diagram for a revised textural classification of hydrodynamic subdivisions on the basis of sand/silt/clay ratios as proposed in this paper.

Table 2
Letter-number codes and descriptive terminology for the 25 textural classes based on sand/silt/clay ratios as defined in Fig. 4

Code	Textural class	Code	Textural class
S	Sand	D–I	Extremely silty slightly sandy mud
A–I	Slightly silty sand	D–II	Very silty slightly sandy mud
A–II	slightly clayey sand	D–III	Silty slightly sandy mud
		D–IV	Clayey slightly sandy mud
B–I	Very silty sand	D–V	Very clayey slightly sandy mud
B–II	Silty sand	D–VI	Extremley clayey slightly sandy mud
B–III	Clayey sand		
B–IV	Very clayey sand	E–I	Silt
		E–II	Slightly clayey silt
C–I	Extremely silty sandy mud	E–III	Clayey silt
C–II	Very silty sandy mud	E–IV	Silty clay
C–III	Silty sandy mud	E–V	Slightly silty clay
C–IV	Clayey sandy mud	E–VI	Clay
C–V	Very clayey sandy mud		
C–VI	Extremely clayey sandy mud		

requirement and available textural information, while using the same basic terminology. The new two-component scheme defines six sediment classes based on simple sand/mud ratios. In each case, the class name (e.g., muddy sand) can also be used to typify a depositional environment or facies on the basis of textural criteria (e.g.,

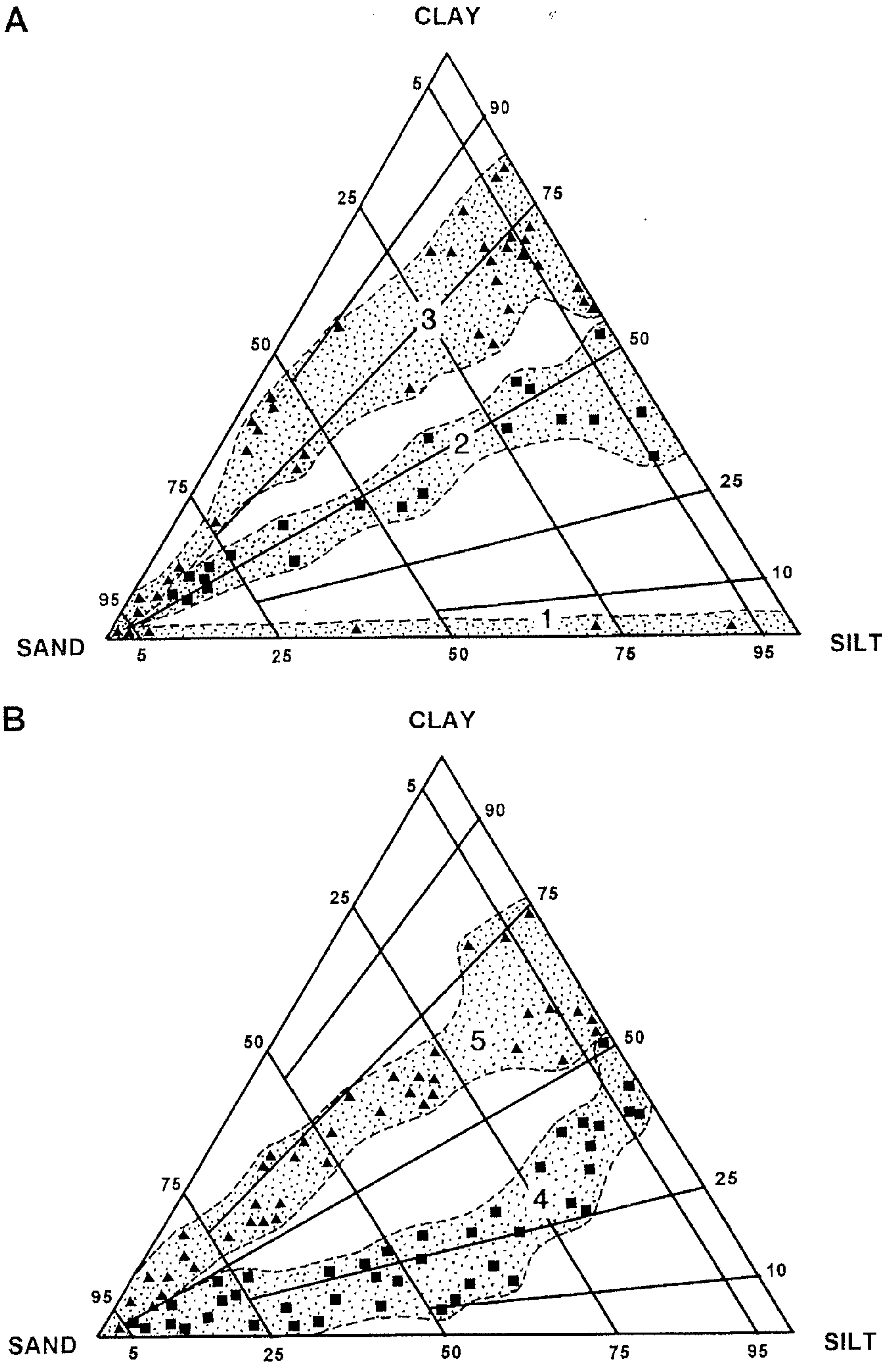

Fig. 5. Ternary diagrams on the basis of sand/silt/clay ratios illustrating textural trends observed in a variety of intertidal environments. Diagram A: macrotidal flats, Kiangsu Province, China (band 1); Danish Wadden Sea (band 2); Dyfi estuary, Wales, UK (band 3). Diagram B: Minas Basin, Bay of Fundy, Canada (band 4); Mugu Lagoon, California, USA (band 5).

a muddy intertidal sand flat or facies). The advantage of this scheme over previous ones is a better spatial resolution of textural provinces, and a sharper delimitation of the sand and mud endmembers by restricting reciprocal contamination to $<5\%$ in each case. This restriction is considered necessary in order to better differentiate sedimentary environments consisting of pure sands or muds.

This basic two-component scheme has been expanded into a new three-component scheme based on sand/silt/clay ratios. In comparison with Pejrup (1988), the number of textural classes has been increased from 16 to 25, thus not only providing a better spatial resolution of textural provinces but also labelling each textural class by a unique generic name and letter-number code. Again the class names (e.g., very silty sand) can be used to describe a depositional environment or facies on the basis of sediment texture (e.g., a very silty sand flat or facies), in this case providing more information about the textural composition of the sediment than the two-component scheme. In addition, the letter–number code can be used to label sediment facies maps, annotate stratigraphic sections, or structure data banks.

The functionality and global applicability of the scheme can be illustrated by the textural trends recorded in different environments and geographic locations. In Figs. 5(A) and (B) the trends for a number of intertidal environments are contrasted, i.e. the Mugu Lagoon in California, USA (Warme, 1971), the Minas Basin in the Bay of Fundy, Canada (Yeo and Risk, 1981), the Danish Wadden Sea (Pejrup, 1988), the Dyfi estuary in Wales, UK (Shi, 1992), and the macrotidal flats along the coast of Kiangsu Province north of Shanghai, China (Flemming, unpublished). In all cases the textural data plot in irregular but clearly defined bands between the sandy and muddy endmembers, encompassing 6–10 textural classes. In terms of the hydrodynamic model of Pejrup (1988), the location of a data set within the ternary diagram reflects specific hydrodynamic energy conditions. The closer such a set is located to the silt endmember, the higher is the energy level; the closer it is to the clay endmenber, the lower is the energy. In this comparison the macrotidal flats of China (band 1, Fig. 5(A)) clearly represent the most energetic environment. It is followed by the Bay of Fundy (band 2, Fig. 5(B)), the Danish Wadden Sea (band 3, Fig. 5(A)), the Mugu Lagoon (band 4, Fig. 5(B)), and the Dyfi estuary (band 5, Fig. 5(B)). In four of the five cases the data points define diagonal bands which gradually widen towards the silt–clay axis. In the case of the Minas Basin, however, the textural gradient shows a marked change at a mud content of about 70%, the progressive shift towards higher clay contents indicating a more rapidly decreasing energy gradient in this part of the basin. The affinity of such plots to specific hydrodynamic energy conditions can, in fact, be demonstrated by splitting up individual data sets into discrete clusters and identifying the origin of the associated samples in the study area. Thus, Vilas et al. (1999) were able to show that each successive cluster within their data band corresponded to a particular depositional zone along a shore-normal transect of the subantarctic macrotidal flats of San Sebastian Bay, Argentina.

To demonstrate that the above patterns are not features unique to intertidal environments, some corresponding data from two open shelf environments are illustrated in Fig. 6 (after Sharma, 1979). The sand/silt/clay ratios in band 1 represent the textural signature observed on the Central Gulf of Alaska Shelf, whereas those in band 2 are from the Bering Shelf which is situated further north off Alaska. Clearly, the patterns produced by the two data sets follow the same general trend observed in intertidal environments. In this case the Bering Shelf would be the more energetic

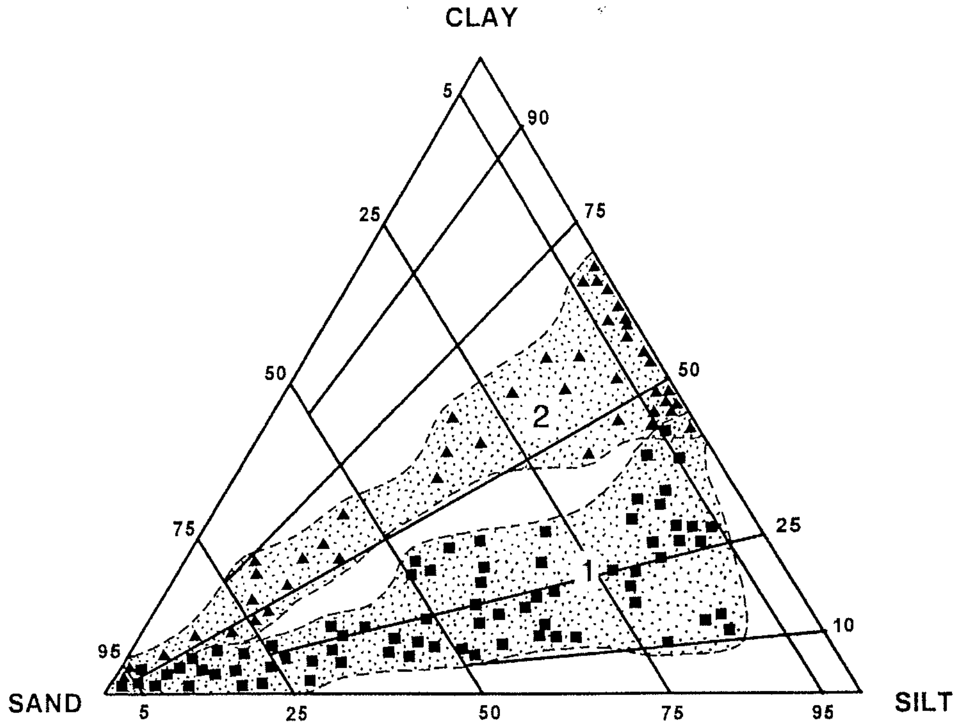

Fig. 6. Ternary diagram on the basis of sand/silt/clay ratios illustrating textural trends observed in open shelf environments (after Sharma, 1979). Band 1: Bering Shelf. Band 2: Central Gulf of Alaska Shelf.

environment, an observation supported by the fact that the Bering Shelf sediments attain a sand/mud ratio of 1 : 1 (50% mud content) at a significantly greater average water depth (55 m) than do the sediments of the Central Gulf of Alaska Shelf (35 m).

It might be argued that the composition of a sediment simply reflects source-related features. While this holds true for the mineralogical and textural composition of many sediments, it is equally true that any source-controlled grain-size spectra would still be subjected to size-sorting in the course of hydraulic transport, which would hence result in selective deposition along an energy gradient (cf. Bagnold, 1968). The macrotidal flats along the coast of Kiangsu Province in China are a case in point. The fine-grained sediments contains almost no clay, thus pointing to the vast inland loess deposits as a major source. However, since the sediment is characterised by progressive fining from fine sands in the offshore to coarse silts in the nearshore, the depositional pattern can only be explained by invoking a size-sorting mechanism associated with the local hydrodynamic energy gradient.

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