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Grain size trends associated with net sediment transport patterns: An example from the Belgian continental shelf

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Abstract

Grain size trends in relation to net sediment transport pathways are examined, using some commonly-used grain size parameters. The results of the trend analysis (for 15 types of the trends) are compared with a *known* net sediment transport pathways established on the basis of the sandbank hydro- and sediment-dynamics (i.e. general water and sediment movement patterns and bedform asymmetry). It is shown that: (1) the results for grain size trends associated with "a worsening in sorting along the transport pathways" have little similarity to transport pathways; (2) the results for grain size trends associated with "an improvement in sorting along the transport pathways" have relatively high degree of similarity to the identified pathways; and (3) the residual pattern, derived on the basis of a combined grain size trend used elsewhere (Gao and Collins, 1992), appears to be most similar and suitable for defining transport pathways.

1. Introduction

Grain size trends, or spatial changes in grain size parameters of surficial sediments, result from sediment transport processes (Russell, 1939; Swift et al., 1972). Thus, grain size trends may contain information on sediment transport. Many investigators have attempted to use grain size data for identifying sediment transport pathways (e.g. Pettijohn et al., 1972, pp. 77–81; McLaren and Bowles, 1985; Lanckneus et al., 1992).

The term "sediment transport" refers to either net sediment transport rate (including both amplitude and direction) i.e the vector mean of instantaneous transport rates measured at a site, or dispersion of a specific sediment parcel. The purpose of the previous investigations into grain size trends has been to define the direction of net sediment transport (instead of sediment dispersion). In order to achieve this, two problems have to be solved: (1) approaches to grain size trend analysis are required; and (2) the grain size trends which contain information on net transport directions need to be identified.

In terms of the first problem, a "filtering" method has been developed to extract information on net transport directions from the grain size data of a grid of surficial sediment samples (Gao and Collins, 1992). According to this method, any grain size trend which has a significantly higher probability of occurrence in the direction of net transport than in any other directions contains information on net transport directions and can be used to determine the net transport pattern. The identification of such a trend forms the second problem as outlined above.

Since a large number of grain size parameters are required to represent any grain size distribution

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(Blatt et al., 1980), grain size trends which can be generated from these parameters are numerous. Nevertheless, if a small number of parameters are used, then the number of possible trends will be limited. The purpose of the present study is to identify appropriate grain size trends which contain information on net transport pathways, based upon an examination of a group of grain size trends formed using the most-commonly used grain size parameters (i.e. mean grain size, sorting coefficient and skewness).

A grid of seabed sediment samples from a sandbank on the Belgian continental shelf are used for this study. Such a study area was selected because: (1) the sediment dynamics of linear sandbanks are relatively well understood (for a review, see Pattiaratchi and Collins, 1987); and (2) in particular, sediment transport patterns have been established on the basis of bedform surveys and current measurements (Lanckneus et al., 1992).

2. The study area

Offshore of the Belgian coast, a series of NE–SW trending linear sandbanks are developed (Fig. 1). These banks are 10–20 m in height, overlain by water depths of less than 10 m in the shallowest parts. Superimposed upon these banks are NW–SE trending sandwaves and megaripples, with spatially-variable asymmetric patterns. High resolution reflection seismic surveys have shown that the banks lie on an erosional surface of Tertiary strata and consist mainly of Holocene

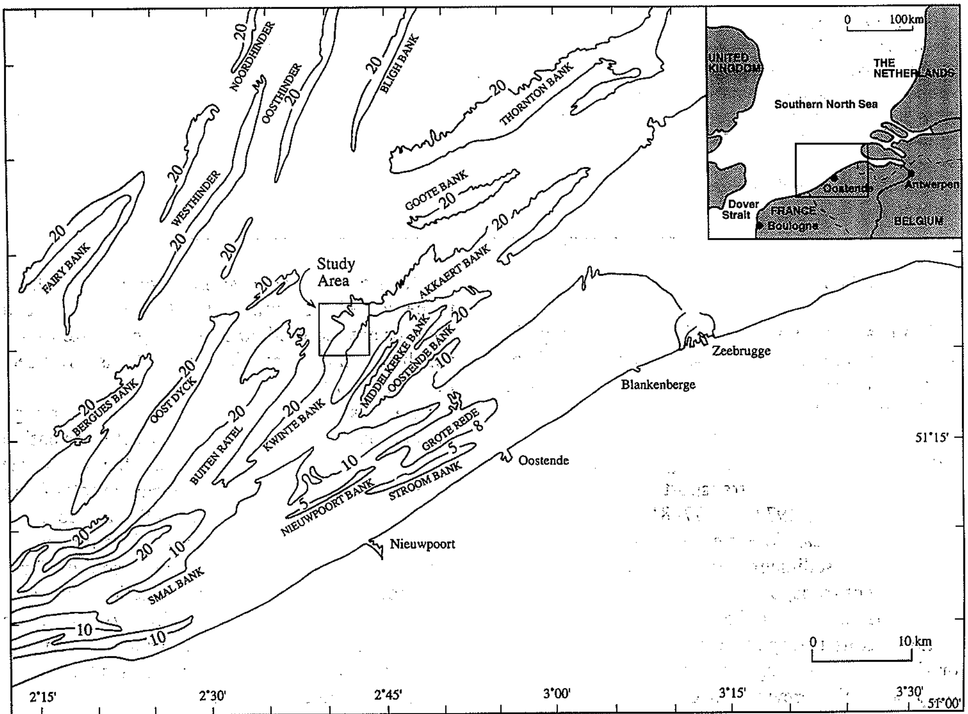


Fig. 1. The linear sandbank system offshore of Belgium and the location for the present study (bathymetry in metres).

deposits (Liu et al., 1992). The erosional surface consists of gravelly material. The gravel layer occurs on the seabed at water depths of around 35 m, where it is exposed occasionally (in this case, the gravels are overgrown with organisms and are immobile) between the sandbanks (Veenstra, 1969). Hence, the sandbanks here have been developed since the Holocene sea-level rise, with the sands supplied by the reworking of Tertiary and/or Pleistocene deposits.

Such linear sandbanks are formed in an environment associated with strong currents. Over the southern North Sea region, tidal currents through the Strait of Dover provide the hydrodynamic forces required. Here, maximum depth-averaged current speeds on springs (due to the M_2 and S_2 tidal constituents alone) reach up to 1.6 m s^{-1} within the Strait of Dover; they range between 0.9 and 1.2 m s^{-1} offshore of Belgium (Howarth and Proctor, 1992).

The area for the present investigation is a part of one of the Flemish Banks i.e. the Kwintebank (Fig. 1). The study area covers the northern end of the bank. The bank itself has an asymmetric morphology: the crest is located on the western side of the bank. Further, the crest lowers from the southwest towards the northeast. The troughs on both sides of the bank are deeper than 20 m, but the gravel layer is not exposed here. Thus, the sedimentary material consists mainly of well-sorted sands, with a very small gravel fraction (Lanckneus, 1989). Over this area, bedforms such as sandwaves and megaripples are present extensively, with various wavelengths, heights, orientations and asymmetric patterns.

3. Method

3.1. Grain size trend analyses

Any grain size trend used to infer net sediment transport pathways must have a significantly higher frequency of occurrence in the transport directions, than in other or the opposite directions. Because physical aspects of changes in grain size distributions are still not well understood, it is impossible to deduce (on a physical basis) which grain size trends satisfy this requirement. Nevertheless, because only a limited number of the grain size trend types can exist, if no more than three grain size parameters are involved, it is technically feasible to examine each of the grain size trends to identify those of most use. Using N grain size parameters, there will be 2^N types of the possible grain size trends between any two sampling sites. Three groups of such grain size trends are listed in Table 1, using: (1) mean grain size; (2) mean grain size and sorting coefficient; and (3) mean grain size, sorting coefficient and skewness, respectively. A combination of some of these grain size trends, in fact, can form a new grain size trend. For example, grain size trends III-1 and III-2 have been used as a combined grain size trend (Gao and Collins, 1992). Such a combined grain size trend and those listed in Table 1 will be analysed.

The grain size parameters were obtained from the analysis of 84 seabed sediment samples collected over the study area (Fig. 2), during the winter of 1989, using a Van Veen grab sampler. Grain size analyses were carried out using sieving at half ϕ intervals. For each of the samples, mean grain size, sorting coefficient and skewness were calculated on the basis of the Folk and Ward (1957) method. For each of the trends, analysis was undertaken on the basis of the following procedures.

Firstly, for each of the grain size trends, *trend*

Table 1
Possible types of grain size trends, using three grain size parameters (i.e. mean grain size, μ, sorting, σ, and skewness, S_k, in ϕ units). The subscripts A and B denote the sampling sites

Group	Case	Definition
I	I-1	$\sigma_A \geq \sigma_B$
	I-2	$\sigma_A \leq \sigma_B$
II	II-1	$\mu_A \geq \mu_B$ and $\sigma_A \geq \sigma_B$
	II-2	$\mu_A \leq \mu_B$ and $\sigma_A \geq \sigma_B$
	II-3	$\mu_A \geq \mu_B$ and $\sigma_A \leq \sigma_B$
	II-4	$\mu_A \leq \mu_B$ and $\sigma_A \leq \sigma_B$
III	III-1	$\mu_A \geq \mu_B$, $\sigma_A \geq \sigma_B$, and $S_{k,A} \leq S_{k,B}$
	III-2	$\mu_A \leq \mu_B$, $\sigma_A \geq \sigma_B$, and $S_{k,A} \geq S_{k,B}$
	III-3	$\mu_A \geq \mu_B$, $\sigma_A \geq \sigma_B$, and $S_{k,A} \geq S_{k,B}$
	III-4	$\mu_A \leq \mu_B$, $\sigma_A \geq \sigma_B$, and $S_{k,A} \leq S_{k,B}$
	III-5	$\mu_A \geq \mu_B$, $\sigma_A \leq \sigma_B$, and $S_{k,A} \leq S_{k,B}$
	III-6	$\mu_A \leq \mu_B$, $\sigma_A \leq \sigma_B$, and $S_{k,A} \geq S_{k,B}$
	III-7	$\mu_A \geq \mu_B$, $\sigma_A \leq \sigma_B$, and $S_{k,A} \geq S_{k,B}$
	III-8	$\mu_A \leq \mu_B$, $\sigma_A \leq \sigma_B$, and $S_{k,A} \leq S_{k,B}$

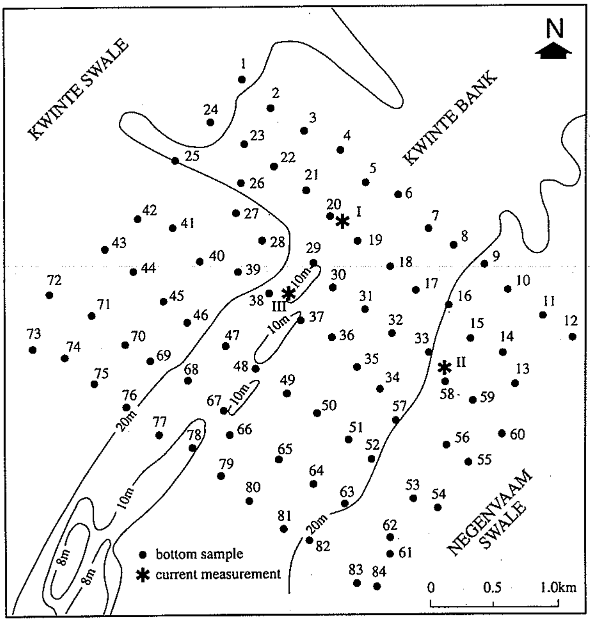


Fig. 2. Seabed sediment sampling sites and stations for current meter observations (bathymetry in metres).

vectors are defined for a grid of sampling sites, by comparing each sample with its neighbouring sites. If the grain size trend under consideration is identified to be from one sampling site to another, then a dimensionless *trend vector* is defined for the former site. For the analysis of grain size trend I-1, for example, if this grain size trend occurs between Sites A and B (i.e. $\sigma_A \geqslant \sigma_B$), then the trend vector is defined for Site A and the direction of such a vector is directed towards Site B. The length of the vector is assumed to have a unit length. In order to identify a *neighbouring* site, a characteristic distance (D_{cr}) (which is taken here as the maximum spatial sampling interval) is specified. If the distance between any two sites is smaller than D_{cr}, they are considered as neighbouring sites and their grain size parameters are compared. The purpose of the first step in the analysis is to identify the locations where the grain size trend being considered is present.

Secondly, the trend vectors are summed to produce a single vector, for the sampling sites with more than one trend vector identified from the first step. This transformation is expressed mathematically as follows:

$$\vec{R}(x,y)=\sum_{1}^{n} \vec{r}(x,y)_i \qquad (1)$$

where n is the number of trend vectors identified for the site, $\vec{r}_i(x,y)$ is a trend vector, and $\vec{R}(x,y)$ is the sum of the trend vectors. This step is required to define a single trend vector for each of the sampling sites, so that the next part of the procedure can be undertaken.

Finally, a filtering (or averaging) operation is applied, to remove or reduce any remaining noise (here, *noise* is defined as vectors which are not in agreement with the general pattern). Once again, a neighbouring site is defined on the basis of a characteristic distance (D_{cr}), as defined previously.

The averaging procedure is equivalent to the following mathematical transformation, for the site at which $\vec{R}(x,y)$ is defined:

$$\vec{R}_{av}(x,y)=\frac{1}{k+1}[\vec{R}(x,y)+\sum_{1}^{k}\vec{R}_j] \qquad (2)$$

where $\vec{R}_j$ is a summed trend vector obtained on the basis of Eq. 1 at a neighbouring site, and k is the total number of such sites.

The vectors $\{\vec{R}_{av}(x,y)$ form a *residual* pattern. This represents a pattern of sediment transport pathways, if the trend used is a suitable one.

For the interpretation of the derived residual pattern, some *edge* effects (associated with the filtering operation) should be taken into account. For example, a site on the edge of the sampling grid is not treated in the same way as a site within the central part of the grid, during the filtering operation (as implied by Eq. 2). Such an effect is likely to introduce some distortions. Hence, sampling sites along the edge of the sampling grid should be applied with caution in the final interpretation.

3.2. *Evaluation of the derived residual patterns*

The derived residual patterns, on the basis of various grain size trends, may have various degrees of similarity to the "real" transport patterns. The similarity can be determined on the basis of the difference between the direction of the real transport and that predicted by the trend analysis. Hence, any grain size trend which results in a large difference (i.e. a low similarity to the known transport patterns) is considered to be not suitable for grain size trend analysis. On the other hand, those trends which are associated with small differences have a high similarity and are, therefore, suitable for grain size trend analysis. Thus, such a difference was used as a criterion for the suitability of the various grain size trends.

4. Sandbank dynamics

4.1. *General patterns of sediment movement*

Linear sandbanks are distributed widely in tidally-dominated environments (Off, 1963). A number of unique characteristics, in terms of sediment movement, are associated with linear sandbanks (Fig. 3).

Firstly, because of a combination of the Coriolis effect and seabed friction, sandbanks in the northern hemisphere are orientated anti-clockwise with respect to the rectilinear tidal currents (and clockwise in the southern hemisphere) (Zimmerman, 1981). The angle between the axis of the sandbank and the long axis of a tidal current ellipse reaches up to 20° (Kenyon et al., 1981).

Secondly, as a result of the oblique orientation, there is a component of sediment transport towards the crest of the sandbank, on both sides. Hence, the sandbank grows upwards in response to deposition along the crest.

Thirdly, the component of sediment transport parallel to the sandbank axis, on the two sides, are in opposite directions; this forms a residual sediment circulation around the sandbank (Caston and Stride, 1970; Huthnance, 1982a,b). Towards the ends of the sandbank, such residual circulation

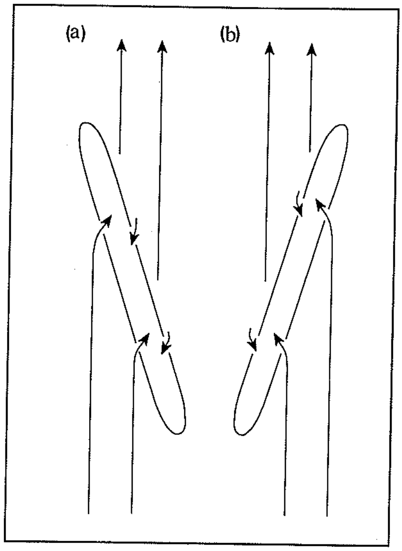


Fig. 3. Flow and sediment transport patterns around a linear sandbank (modified from Kenyon et al., 1981), in the northern (a) and southern (b) hemispheres.

becomes weaker. Nevertheless, reversal in the mean currents still occurs across the bank, with the bedforms being less asymmetric in their morphology (Caston, 1981; McCave and Langhorne, 1982).

Finally, a regional residual transport pattern may be superimposed upon the localised around-bank circulation. Hence, the intensity of the residual transport along one side may be stronger than on the other side (Kenyon et al., 1981).

4.2. Sediment transport on the northern Kwintebank

Transport patterns associated with the Kwintebank can be established on the basis of the general pattern of sediment movement on linear sandbanks, in combination with local information on current speeds and bedform asymmetry characteristics.

Following the sediment sampling, a side-scan sonar survey was undertaken. A slant range of 100 m and track spacing of around 140 m were maintained. However, the sonographs obtained cover only the northern part of the sampling area (Fig. 4). Information on the currents over the area for the survey time was not available; thus, current velocity data measured at 3 mooring stations, on April 1991, together with some previous observations (Lanckneus, 1989; Lanckneus et al., 1992), were used. Based upon these observations, characteristics of the bedforms and current velocities have been identified.

Bedforms which contain information on sediment transport include megaripples, sandwaves, sand ribbons and gravel furrows. The asymmetry of sandwaves (wavelength >30 m) and megaripples (wavelength 5–10 m) was recorded during the side-scan sonar survey (Lanckneus et al., 1992), and used to determine sediment transport pathways.

A significant difference in the migration behaviour between a megaripple and a sandwave is that (in a tidally-dominated environment) the latter has more stable asymmetry patterns than the former.

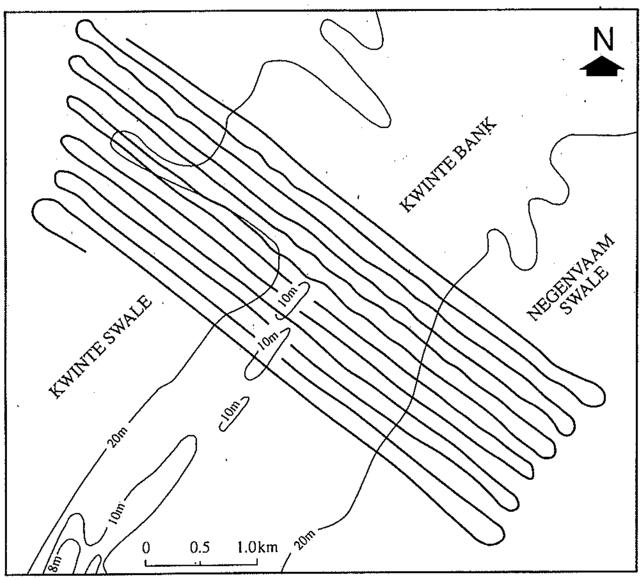


Fig. 4. Tracks of the side-scan sonar survey (undertaken on 28 November, 1989).

The stability of the asymmetry is controlled by the grain size of sediments of which the bedform is composed, the current speeds and the wavelength and height of the bedform. For example, the morphology of a gravel megaripple is more stable than that of a sand megaripple. In places where the current speeds are relatively weak and highly asymmetrical, some megaripples (with wavelength greater than 6 m) cannot reverse their asymmetry patterns in response to the tidal cycle phase (Boothroyd, 1985); on the other hand, if the currents are strong, even sandwaves may change their asymmetry patterns (e.g. Hawkins and Sebbage, 1972). For the study area, previous observations (De Moor, 1985; Lanckneus, 1989; Lanckneus et al., 1992) have shown that the megaripples here are quite stable: measurements during the entire tidal cycle show that they do not change their asymmetry during the cycle.

The distribution of sandwaves and megaripples, on the basis of interpretation of the side-scan sonar images, is shown on Fig. 5. Megaripples have been observed to be superimposed upon the sandwaves fields and, in some places, no sandwaves were present. The steeper slope of these bedforms is directed generally towards the northeast with some being directed towards the southwestern side; towards the south on the eastern side, the degree of megaripple asymmetry is low or cannot be defined, according to the side-scan sonar records. Megaripples may reverse their asymmetric patterns during a tidal or spring-neap cycle if the tidal currents are strong. However, since the side-scan sonar surveys were undertaken in the same time

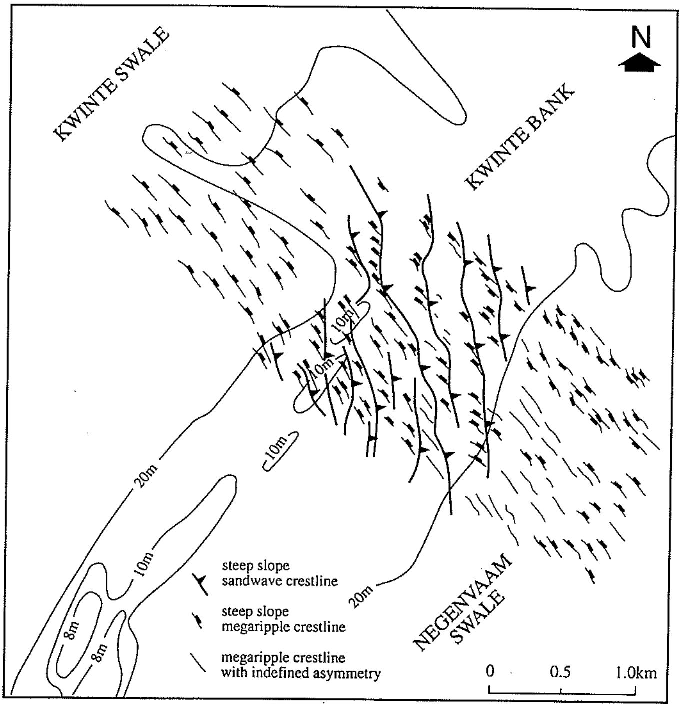


Fig. 5. Distribution of sandwaves and megaripples, on northern Kwintebank, observed using a side-scan sonar.

for both sides of the bank, the difference in the asymmetric patterns indicates that the hydrodynamic conditions are truly different on the two sides. Furthermore, on the Kwintebank, maximum current speeds (at 2 m above the bed) are of the order of 0.6 m s^{-1} on springs, at all of the three current meter stations (Lanckneus et al., 1992) (Fig. 3). The velocity asymmetry is consistent with the asymmetry patterns of the megaripples. In fact, it has been observed elsewhere that on the sandbanks megaripple (or small sandwaves) are probably better indicators of sediment transport (Langhorne, 1977; McCave and Langhorne, 1982). Therefore, the asymmetry patterns of the megaripples are considered as being indicative of net sediment transport, during the study period.

Based upon bedform observations, transport patterns for the study area is established (Fig. 6). The bank is dominated by transport towards the northeast, especially along the western side; transport towards the southwest is present over part of the eastern side, although the existence of the bedforms with poorly-defined asymmetry towards the south may imply that such a southwesterly transport is weak. Further, the current meter measurements imply also net transport towards the northeast along the west side and over the crest area of the bank.

5. Results and discussion

5.1. Grain size data

The distribution patterns of mean grain size, sorting coefficient and skewness (Fig. 7) show that the seabed sediments are relatively coarse on top of the bank, with a general fining trend towards

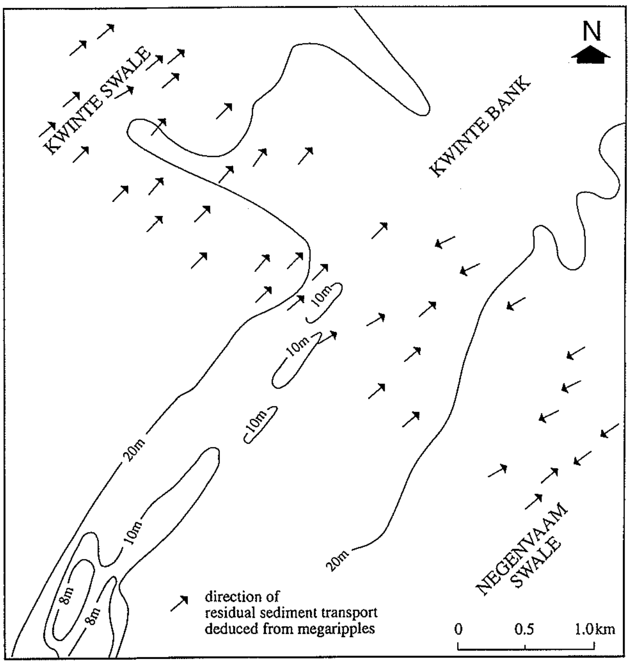


Fig. 6. Sediment transport patterns, on the basis of linear sandbank morphology, current speed data and bedform orientations.

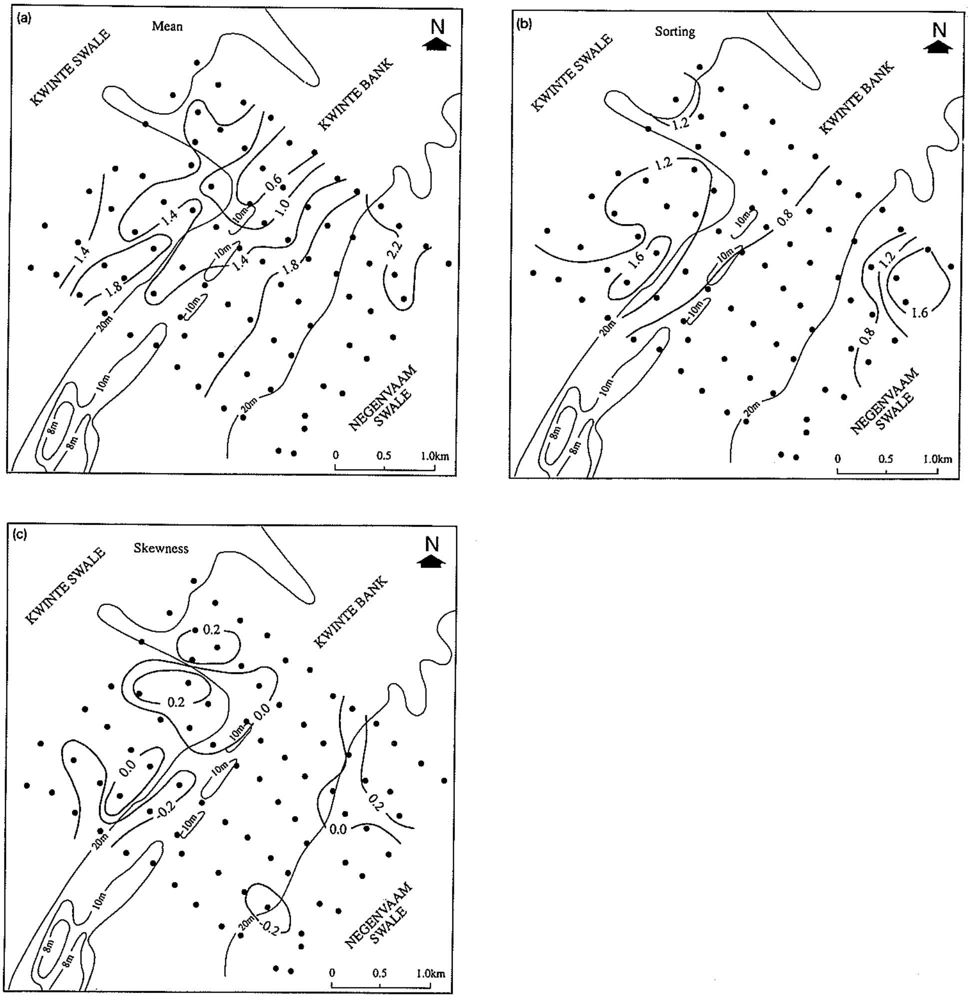


Fig. 7. Distribution of grain size parameters (in ϕ units): (a) mean grain size; (b) sorting coefficient; and (c) skewness.

the southeast (Fig. 7a). The best-sorted sediments are located on the southeastern flank of the bank (Fig. 7b). Except over the eastern part, the sorting improves generally from the northwest to the southeast. The skewness is dominated by negative values in the south (Fig. 7c). Positive skewness values are associated generally with samples of relatively high sorting coefficients (cf. Fig. 7b and c). Thus, a general zonation of sediment distribution is found which can be related to the bank's morphology: (1) the southeastern side of the bank is characterised by relatively fine, well-sorted and

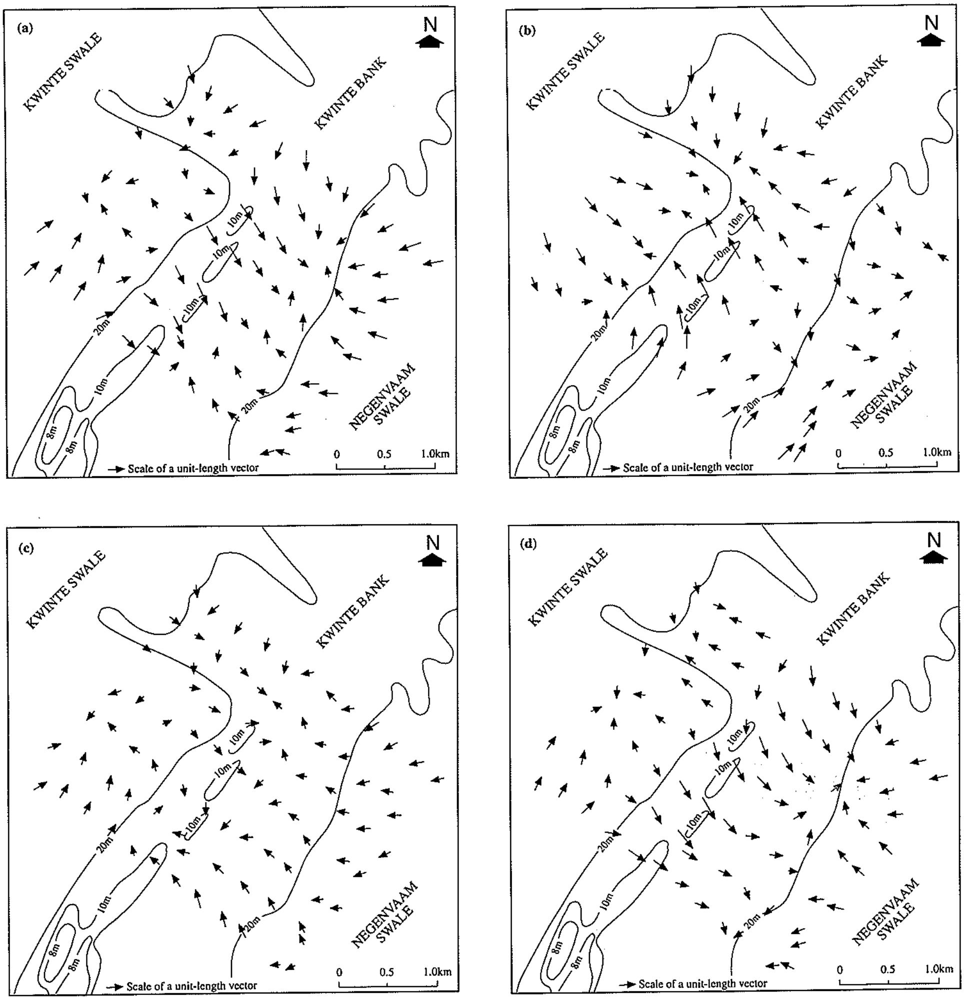
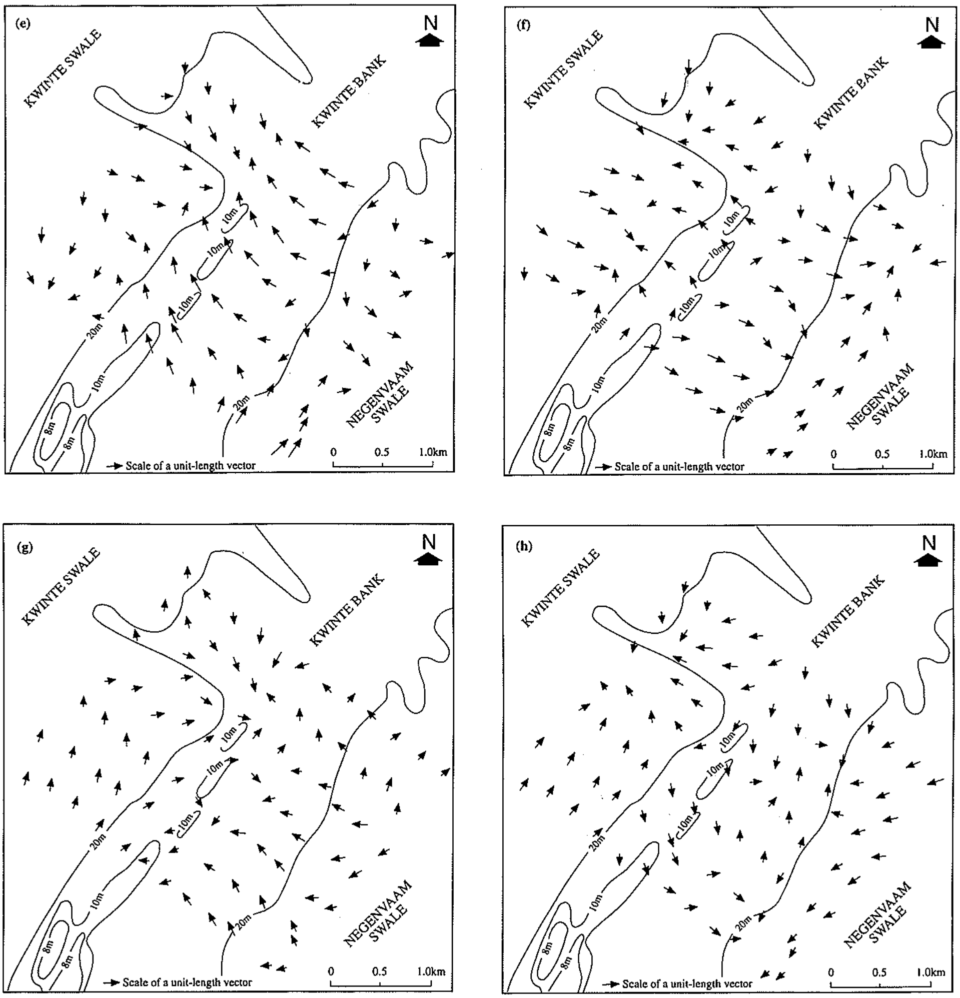


Fig. 8. Residual patterns of grain size trends, for the grain size trends listed in Table 1: (a) I-1; (b) I-2; (c) II-1; (d) II-2; (e) II-3; (f) II-4; (g) III-1; (h) III-2; (i) III-3; (j) III-4; (k) III-5; (l) III-6; (m) III-7; and (n) III-8.

negatively-skewed sediments; (2) on the upper part of the bank, the sediments are relatively coarse, with poorer sorting and positive skewness; and (3) the northwestern side of the bank contains coarser, less well-sorted sediments than the other side.

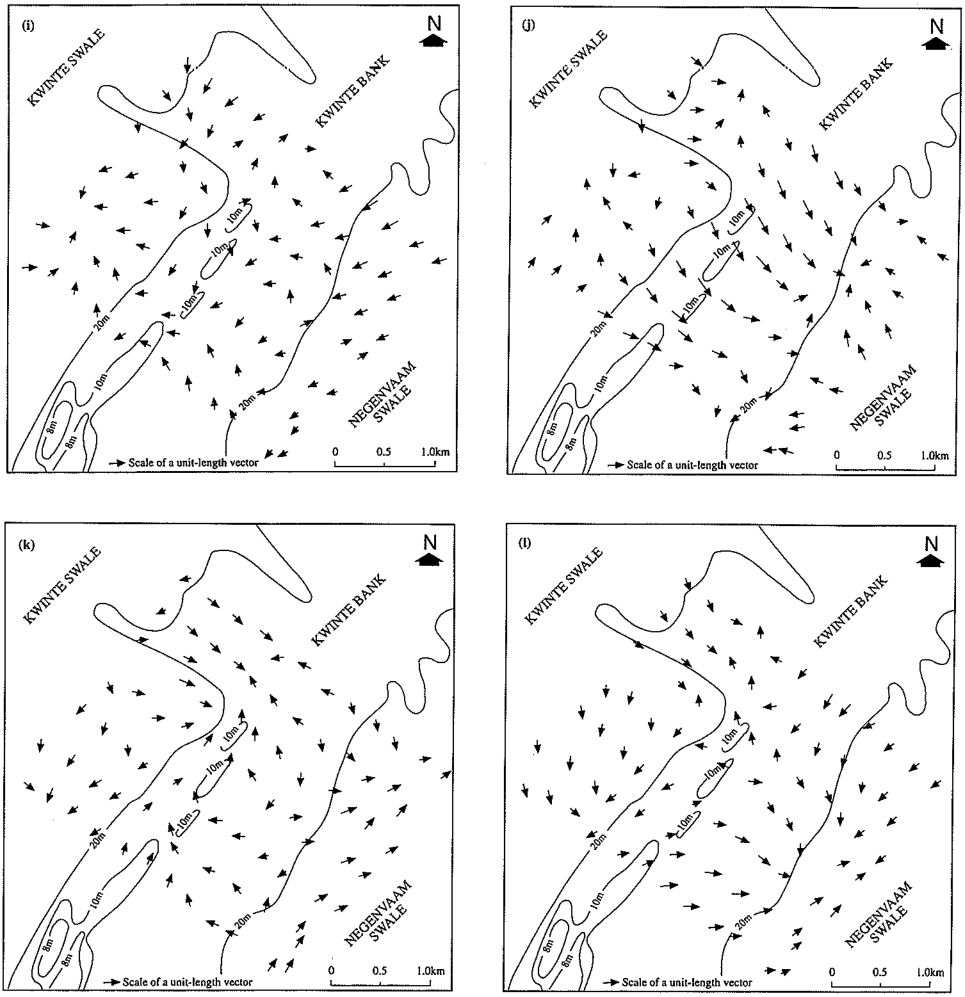
5.2. Residual patterns for various grain size trends

Residual patterns based upon the grain size trend analysis, using the grain size trends listed in Table 1, are shown on Figs. 8 and 9. These patterns



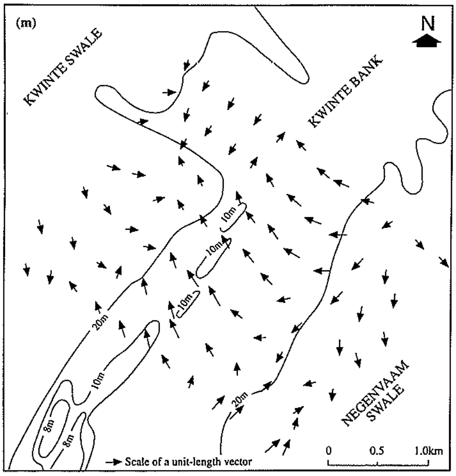
are now compared with the established transport pattern.

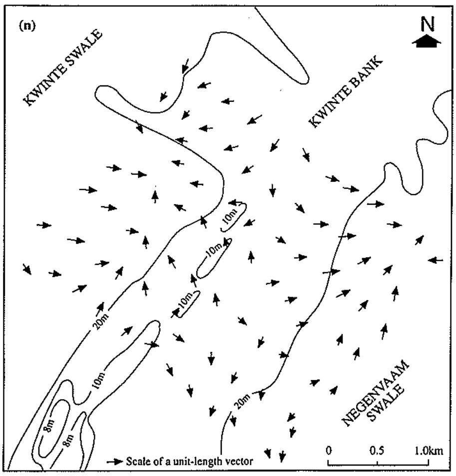
For the sampling sites in the northeast which are covered by the side-scan sonar survey, the *real* transport directions are defined using interpolation of the directions shown on Fig. 6. These directions are compared then with the residual patterns to obtain the difference between the two directions (α_D) for each of the sampling sites. In order to avoid the edge effect, only the sites within the grid were used. The difference data were grouped according to: (1) $\alpha_D < 45°$; (2) $45° \leqslant \alpha_D \leqslant 90°$; and



(3) $\alpha_D > 90°$. Finally, the frequency of occurrence of these three groups of the difference data are calculated. The calculated frequency of occurrence data are listed in Table 2.

Apparently, a low frequency of occurrence for $\alpha_D < 45°$ represents a low similarity between the direction of transport and that predicted by the trends. Thus, if any frequency of occurrence (for $\alpha_D < 45°$) is smaller than 20%, then the related grain size trends are not considered to contain net transport information. On this basis, 5 types of grain size trends are rejected because of their low





similarity. These types are I-2 (Fig. 8b), II-3 (Fig. 8e), II-4 (Fig. 8f), III-6 (Fig. 8l), and III-7 (Fig. 8m), respectively.

Furthermore, if the southwestern part of the residual patterns is taken into account, then the similarity for the trend types III-5 (Fig. 8k) and III-8 (Fig. 8n) is reduced significantly. Hence,

Table 2
Frequency of occurrence (P) of the difference between the observed sediment transport direction and the direction derived from grain size trends

Case	P (%) <45°	45°–90°	>90°
I-1	23	34	43
I-2	7	63	30
II-1	27	43	30
II-2	20	50	30
II-3	7	66	27
II-4	13	53	34
III-1	30	37	33
III-2	27	27	46
III-3	20	27	53
III-4	27	40	33
III-5	23	54	23
III-6	13	47	40
III-7	17	43	40
III-8	23	44	33
III-1 and 2	43	34	23

although their similarity degrees are not very low (i.e. 23% for $\alpha_D < 45°$) over a part of the sampling area, this observation is not valid for the whole of the area. Therefore, these two types of trends should be also rejected. In contrast, the inclusion of the southwestern part enhances the degree of similarity for the other types [i.e. I-1 (Fig. 8a), II-1 (Fig. 8c), II-2 (Fig. 8d), III-1 (Fig. 8g), III-2 (Fig. 8h), III-3 (Fig. 8i), III-4 (Fig. 8j), and the combined type of III-1 and III-2 (Fig. 9)].

It is worth noting here that all patterns associated with an increase in sorting coefficient along the transport pathways differ from the *real* transport patterns, whilst those patterns associated with a decrease in sorting coefficient have a relatively high degree of similarity. Consequently, the trends for defining sediment transport pathways can be selected only from the latter types. Moreover, there appears to be a tendency that the similarity is enhanced using the trends formed by multi-parameters, compared with those using a single grain size parameter.

It is also significant, from Table 2, that the combined grain size trend using III-1 and III-2 results in a residual pattern (Fig. 9) which has the highest degree of similarity. In addition, its fre-

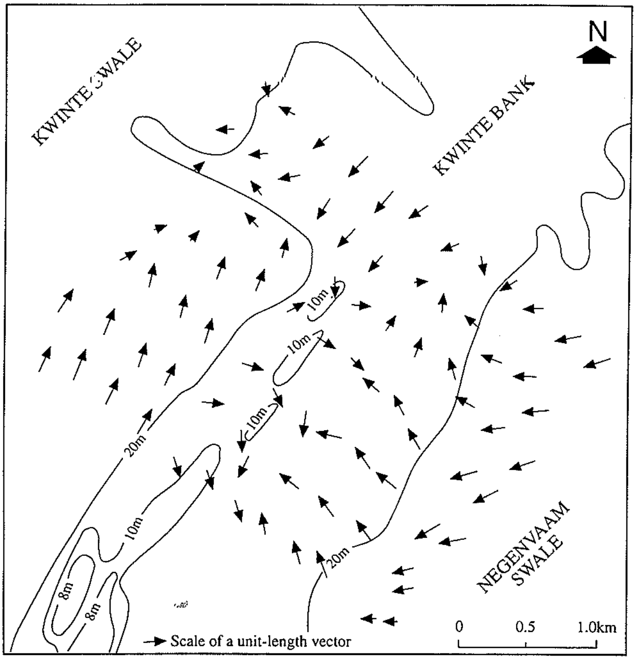


Fig. 9. Patterns of grain size trends, using the combined grain size trend using III-1 and III-2.

quency of occurrence for $\alpha_D > 90°$ is the smallest. This is as expected. If grain size trends III-1 and III-2 both satisfy the premise that a grain size trend which can be used for the identification of transport pathways has a much higher frequency of occurrence in the transport directions than in any other directions (these both have a relatively high degree of similarity, as implied by the data listed in Table 2), then the combined grain size trend must satisfy also the premise. Furthermore, the number of the vectors which defined using the combined grain size trend is greater than the number which can be defined using either III-1 or III-2, singly. The residual pattern can be defined, therefore, more clearly. For these reasons, it would appear that such a combined grain size trend is that most suitable for use in sediment transport investigations.

6. Summary

Various grain size trends exist for any sedimentary environment; only some of these can be used to define net sediment transport paths. Three groups of grain size trends, formed using commonly-used grain size parameters, have been examined in the present study.

Among the 15 types of representative grain size trends examined, 7 types which are associated with "an increase in sorting coefficient along the transport pathways" result in a residual pattern of little similarity to the sediment transport pattern. Therefore, these trends are rejected.

The other types (including a "combined" type), associated with "a decrease in sorting coefficient along the transport pathways", have relatively high degree of similarity to the identified transport patterns. In particular, the residual pattern derived on the basis of the combined type is most similar and can be used for grain size trend analysis.

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