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THE USE OF GRAIN SIZE TRENDS IN MARINE SEDIMENT DYNAMICS: A REVIEW*

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Abstract Spatial changes in grain size parameters (i.e. grain size trends) contain information on sediment transport patterns. An analytical procedure has been proposed to transform the grain size trends into an image of trend vectors, which may represent net sediment transport pathways. A fundamental assumption for such an approach is that the frequency of occurrence of the trend adopted is much higher in the transport direction, than in any of other directions. Preliminary studies show agreement between this assumption and observations. However, further investigations into the physical processes and mechanisms for the formation of grain size trends are required to improve the technique, including flume experiments and numerical modeling. Moreover, attention should be paid to the trends associated with fine-grained sediment, for the method of grain size trend analysis is so far designed for coarse-grained material only. The processes of flocculation during settling and the wash-load property must be considered. Appropriate interpretation of grain size data will improve our understanding of the physics of granular materials.

Key words: Grain size, trend vectors, sediment transport, marine environment

INTRODUCTION

Grain size distribution curves of natural sediments have been used for a long time by sedimentologists to identify the type of depositional environments. It has been found also that, within the same sedimentary environment, the grain size distribution of seabed sediment tends to vary according to sampling locations. The spatial changes in size parameters (i.e. grain size trends) result from a variety of transport processes such as abrasion, selective transport, and mixing of sedimentary material derived from different sources. An inverse problem arises from this observation: can we infer the transport processes on the basis of spatial variations in the grain size data? If the answer is positive, then how can the information on sediment transport be extracted from the grain size data? Solutions to these problems are important for the science of marine sediment dynamics. Patterns of sediment movement and the associated physical processes are complex in marine environments, causing difficulties in verifying the results of sediment transport rate calculations using empirical formulae. Thus, any information on material movement is beneficial to the study of transport processes and to the test of the transport formulae.

In this aspect, McLaren (1981) suggested that some types of grain size trends must be indicative of sediment transport directions. Since then, a number of researchers have undertaken investigations into the feasibility of a technique known as "grain size trend analysis", in order to relate the grain size data to sediment transport patterns. In the present contribution, we intend to review the

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progress in this area and outline some future studies for further improvements of the technique.

DEFINITION OF GRAIN SIZE TRENDS

Grain size analysis

The purpose of grain size analysis is to obtain the size distribution curve for a sediment sample. Traditionally, sediments are divided into fine- and coarse-grained materials, with the boundary being located at the diameter of 0.063 mm. The fine-grained part can be analyzed using the pipette method, the coarse-grained part by the sieving method. The two parts can be merged to produce a unified curve (it should be pointed out that in sedimentology the diameter of a particle is often expressed by a dimensionless quantity, rather than in millimeters, on the basis of the φ transformation). Today, because of the development of new instruments (such as laser particle sizers), the efficiency of grain size analysis has been enhanced enormously.

For any given grain size distribution curve, a series of grain size parameters can be defined. The most frequently used parameters include mean grain size, sorting coefficient and skewness. There are a number of formulae for the calculation of the latter two parameters; statistically, the sorting coefficient is expressed as a function of the second moment and the skewness as a function of the third moment. In the following text, these three parameters will be used to represent grain size characteristics of sediment.

Definition of grain size trends

Grain size trends are referred to as spatial variations in the grain size parameters. In a study area, many types of grain size trends are possible between any two sampling sites A and B. For instance, the sorting coefficient may become larger from Site A to Site B, and the mean grain size may increase. Further, in defining a type of the trend, several grain size parameters can be used at the same time. For example, using three parameters (i.e. mean, sorting coefficient and skewness), 8 types of trends can be formed between Sites A and B, as listed below:

Type 1: $\sigma_A < \sigma_B$, $\mu_A < \mu_B$, $Sk_A > Sk_B$
Type 2: $\sigma_A < \sigma_B$, $\mu_A > \mu_B$, $Sk_A < Sk_B$
Type 3: $\sigma_A < \sigma_B$, $\mu_A < \mu_B$, $Sk_A < Sk_B$
Type 4: $\sigma_A < \sigma_B$, $\mu_A > \mu_B$, $Sk_A > Sk_B$
Type 5: $\sigma_A > \sigma_B$, $\mu_A < \mu_B$, $Sk_A > Sk_B$
Type 6: $\sigma_A > \sigma_B$, $\mu_A > \mu_B$, $Sk_A < Sk_B$
Type 7: $\sigma_A > \sigma_B$, $\mu_A < \mu_B$, $Sk_A < Sk_B$
Type 8: $\sigma_A > \sigma_B$, $\mu_A > \mu_B$, $Sk_A > Sk_B$

where μ is the mean grain size, σ is the sorting coefficient, Sk is the skewness, and the subscripts A and B denote the sampling sites.

Each of the trend types, as listed above, can be represented by a vector, which is defined such that it is directed from Site A towards Site B, and its magnitude is expressed by a unit (dimensionless) length. Such a vector is referred to as a trend vector (Gao and Collins, 1992). For a sampling grid, if the grain size parameters of every sampling site are compared with those of each of the adjoining sites, then all of the trend vectors within the grid can be identified.

It is worth noting that the definition of the unit length for trend vectors is based upon the assumption that the gradient of spatial changes in the grain size parameter is not related to the transport direction, and that the three parameters are equally important in describing the size characteristics.

In reality, the gradient of spatial changes in the grain size parameter may differ between different parameters and between different directions; such differences may contain information on transport processes. Hence, it is important to determine whether or not the vector length should be defined by taking into account the gradients of all the three parameters. Some researchers proposed that the direction of the trend vector should be determined by the maximum gradient of the grain size parameters (Le Roux, 1994). However, observations have shown that in many cases net sediment transport directions are not consistent with the maximum gradient. Because the data sets available so far are still insufficient to evaluate generally the effect of the gradient, further efforts are needed in the future.

Anisotropy of trend vectors

One of the characteristics of the trend vector is that the frequency of occurrence of the vector varies with the direction within the sampling grid. The trend vectors of a site can be summed to form a single vector. If all the summed vectors at different sites are plotted, then they are likely to form an orderly distribution pattern. Thus, the vectors are associated with some anisotropy, since under an isotropic condition, the lengths of the summed vectors would approach to zero. In natural marine environments, the degree of the anisotropy for the trend vectors may differ from place to place, but its presence has been confirmed by observations.

Basic assumptions for the use of grain size trends in marine sediment dynamics

How can the anisotropy associated with the grain size trend be explained? A hypothesis in sediment dynamics is that it is related to net sediment transport pathways: in the direction of net transport, certain types of the trends have a much higher frequency of occurrence than other trend types (McLaren and Bowles, 1985). A more detailed analysis shows that such a hypothesis should be modified, taking into account the fact that the anisotropy is related to a single type of trends. Hence, a more appropriate expression should be that in the net transport direction, certain types of the trends will occur with a larger probability than in other directions (Gao et al., 1994). If such a hypothesis is valid, then the net transport pathways can be inferred from analysis of the grain size trend anisotropy. To achieve this goal, the analytical technique must consist of the following aspects: (i) identification of the suitable trend types that can be used; (ii) quantitative determination of the trend anisotropy; and (iii) transformation between the anisotropic data and the information on net sediment transport (for details of the analysis, see below).

GRAIN SIZE TREND ANALYSIS

Types of the trends representing sediment movement

In the 8 types of grain size trends listed above, Types 1 and 2 are considered to have a higher frequency of occurrence in the net transport direction than in other directions; this is based upon empirical observations (Gao and Collins, 1992; Gao et al., 1994). Hence, Type 1 is equivalent to the statement that "sediment will become better sorted, finer and more negatively skewed along the transport direction", whilst Type 2 means that "sediment will become better sorted, coarser and more positively skewed along the transport pathway". The problem of how exactly the grain size parameter will change in response to transport processes cannot be solved fully without the establishment of the principles of physics for granular materials. However, whether or not Types 1 and 2 are suitable for the trend analysis can be determined using empirical methods: the patterns of grain size trends can be examined for an environment for which sediment transport pathways are already known. An ideal marine environment for testing the technique of trend analysis is a shallow water tidal ridge. It is known that in the northern hemisphere the crest of a tidal ridge represents a boundary for sediment movement: net transport is in the opposite directions on the two flanks of the ridge; thus, an anti-clockwise circulation of sediments is formed in plan view. Based upon such an observation, seabed sediment samples were collected from a tidal ridge in the southeastern North Sea in Europe; simultaneously, tidal currents were measured and side-scan sonar survey was undertaken (Gao et al., 1994). Subsequently, net sediment transport patterns were plotted using the data of tidal current velocities, morphology of the ridge crest and the asymmetric patterns of bedforms. The anisotropy of the 8 trend types was derived and compared with the known sediment transport patterns. The results show that Types 1 and 2 are indeed associated with a relatively high frequency of occurrence in the transport direction. Further, a combined trend type (associated with the occurrence of either Type 1 or Type 2) results in a better correlation than used individually.

Method of extracting the transport information

Two representative methods for the extraction of transport information from grain size data have been proposed. The first method is to compare the grain size parameters of every two sampling sites along a sampling line (McLaren and Bowles, 1985). The frequency of occurrence for the trend is then calculated for both directions associated with the line; if the probability for any of the directions is sufficiently large, then the related direction is considered to be the net transport direction. Thus, for a sampling line consisting of sampling sites S_1, S_2, ..., S_n, all the possible combinations of two sites are taken into account (e.g. between S_1 and S_2, S_1 and S_n, S_2 and S_3, etc). One of the problems of this approach is that the spatial scale is confused (for example, the distance between S_1 and S_2 is much smaller than between S_1 and S_n); further, it cannot be guaranteed that the sampling line is parallel to the net transport direction (Gao and Collins, 1991). As a result, the application of this method may lead to errors (Masselink, 1992), though this method may still be useful for some river/estuarine environments (e.g. McLaren et al., 1993; Wu and Shen, 1999).

The second method is to deal with the distribution patterns of the grain size trends as if it is an image containing both useful signals (i.e. information on transport) and noises (Gao and Collins, 1992). Thus, techniques of image processing can be used to extract transport information from the two-dimensional image of trend vectors; after the data processing, the grain size data from a grid of samples are transformed into a vector diagram showing the transport patterns. The first step of the trend analysis is to identify all of the trend vectors for each sampling site by comparing the grain size data of the site with those of its adjoining sites. In order to identify the adjoining sites, a characteristic distance D_{cr}, which is taken as the maximum sampling interval, is used. Any site within the distance of D_{cr} is taken as an adjoining site. The second step of the analysis is to add the trend vectors together for each of the sites, using

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

where n is the total number of the trend vectors relating to the site, $r(x,y)_i$ is a trend vector, and $\vec{R}(x,y)$ is the summed vector.

In order to reduce the noise i.e. high frequency spatial changes of $R(x,y)$, the $R(x,y)$ vectors are smoothed using the following equation:

$$\vec{R}_m(x,y) = \frac{1}{k+1}\left[\vec{R}(x,y) + \sum_{1}^{k} \vec{R}_j\right] \tag{2}$$

where $\vec{R}_j$ is a summed vector of an adjoining site derived from Eq.(1), k is the number of the adjoining sites (these are also judged using the characteristic distance D_{cr}), and $\vec{R}_m(x,y)$ represents the trend vector after smoothing. The image of $\vec{R}_m(x, y)$ now shows the patterns of net sediment transport.

Approach to sampling and result interpretation

The analytical method outlined above has been applied to a number of marine environments, including tidal inlets (Gao and Collins, 1992, 1994), beaches (Gao and Collins, 1994; Pedreros et al., 1996), tidal ridges (Gao et al., 1994) and river/estuary environments (Asselman, 1999). The results obtained show a high degree of agreement with the net transport patterns based upon current velocity measurements, experiments of artificial tracers and observations of sedimentological/geomorphological characteristics. These are positive indications for the applicability of the trend analysis. A Fortran program for the analysis has been published and is available on internet (Gao, 1996).

Nevertheless, several aspects should be noted with regard to the relationship between the trend vector image and the net transport pattern, in association with this particular method. Firstly, although the image provides the directions of transport, the length of the vectors does not represent the intensity of transport. This limitation is due to the nature of the analytical method. The relationship between the trend vectors and the transport intensity is not known and pends further investigations.

Secondly, the image of trend vectors is influenced by the sampling depth (Gao and Collins, 1992). The sampling depth is controlled by the techniques used: for example, a grab sampler may collect a sample within 10 – 30 cm from the seabed. From the point of view of sediment transport, the sample should contain only the material involved in transport processes, or, in other words, the material should be associated with the moving layer (or the depth of disturbance). Studies have shown that the thickness of the moving layer varies if different temporal scales are considered. For instance, within a marine environment, the thickness relating to a tidal cycle (around 12.5 hours) is measured by centimeters, whilst on an annual basis this quantity may reach several dozens of centimeters. Therefore, to some extent the sampling depth reflects the net transport processes on the temporal scale associated with the depth. The temporal scale should be considered when comparing the trend vector image with the results derived from other methods for sediment transport studies.

Thirdly, the quality of trend vector images is influenced by the spatial interval for seabed sediment sampling (Gao and Collins, 1992). Because grain size parameters may be related to the type of sedimentary environments, samples from different environments may not be related to each other in terms of transport processes. Thus, if the sampling interval is too large, then it is likely that samples from different environments are compared, causing noise in the trend vectors. Therefore, the sampling interval should be small compared with the dimension of the sedimentary environment. On the other hand, if the interval is too small, then errors introduced by grain size analysis may exceed the real spatial variations in the size parameters; thus, the interval cannot be too small. The sampling interval can be reduced if the techniques of grain size analysis are sufficiently advanced; even so there will be a limit for the interval. For some areas these conditions may not be satisfied at the same time (e.g. Wu and Shen, 1999). In this case, the level of noise in the image must be relatively high. If the noise level reaches a critical value, then the orderliness (or anisotropy) of the trend vectors is destroyed. Such a situation is like a degenerated image which contains too much noise: the restoration of the image becomes difficult. A statistical procedure has been used to evaluate the significance level of the anisotropic patterns of the trend vector image (Gao and Collins, 1992).

Finally, the result of the trend analysis is affected by an edge effect. A site within the sampling grid may have 8 adjoining sites, whilst those on the edge may have fewer than 5 adjoining sites. As a result, the trend vectors on the edge may be distorted; hence, ideally, the use of the vectors on the edge should be avoided when interpreting the vector image.

FUTURE RESEARCHES

The technique of grain size trend analysis has been applied mainly for coarse-grained sediments. Since the marine environment is often dominated by fine-grained sediments, the applicability of the trend analysis to these environments should be examined. A problem for such an extension is that fine-grained materials have different hydrodynamic behaviors. For example, fine sediments may respond differently from sands to the processes of selective transport. Furthermore, fine-grained materials are influenced by flocculation / deflocculation processes and a part of the materials may be transported as wash-load. Some experiments and observations are required for the use of the trend analysis for marine environments associated with fine-grained deposits.

So far the interpretation of grain size trends has been based upon empirical observations. However, in order to solve fully the problem about the theory and applicability of the trend analysis, the relationship between sediment movement and the formation of grain size trends must be studied in terms of processes and mechanisms. In addition to field measurements, such investigations can be undertaken by flume experiments and mathematical modeling. In a flume, the flow can be controlled artificially and wave motions can be simulated. Therefore, a number of hydrodynamic conditions can be provided in the flume, including tidal currents and combined tidally- and wave-induced currents. Sedimentary materials with known grain size characteristics at an initial time can be deployed in the flume; subsequent changes in the grain size parameters in response to transport can be determined by sampling and analysis. Based upon the data collected, a relationship between the grain size trends and transport processes may be established.

The formation of grain size trends may also be simulated using a numerical model, on the basis of equations describing changes in grain size due to abrasion, selective transport and mixing. The input data for the model include the hydrodynamic conditions (flows, waves, etc.), the spatial distribution patterns of sediments and grain size distribution curves at the initial time. During the simulation, different hydrodynamic conditions may be involved such as tidal currents, waves, or combined action of uni-directional currents and waves. The sediment at the initial time may be a product of weathering or materials that have subjected to many times of transport processes in a sedimentary environment. The sedimentary material may be derived from a single source, or it may be from multi-sources with different spatial distributions. Finally, because a variety of the equations for the simulation exist, decisions must be made for selecting an appropriate transport equation. Hence, a lot of computing effort is required for modeling the formation of grain size trends under the various combinations of the conditions. Although an attempt had been made to simulate grain size changes during transport (Swift et al., 1972), this research area had not been fully developed in the past due to the limitation in computing capacity and a lack of understanding of transport mechanisms. Today, thanks to the advancement of the computer techniques and the progress in marine sediment dynamics, such investigations become possible. The work in this area will improve the technique of grain size trend analysis and, eventually, help with the establishment of the physics of granular materials.

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