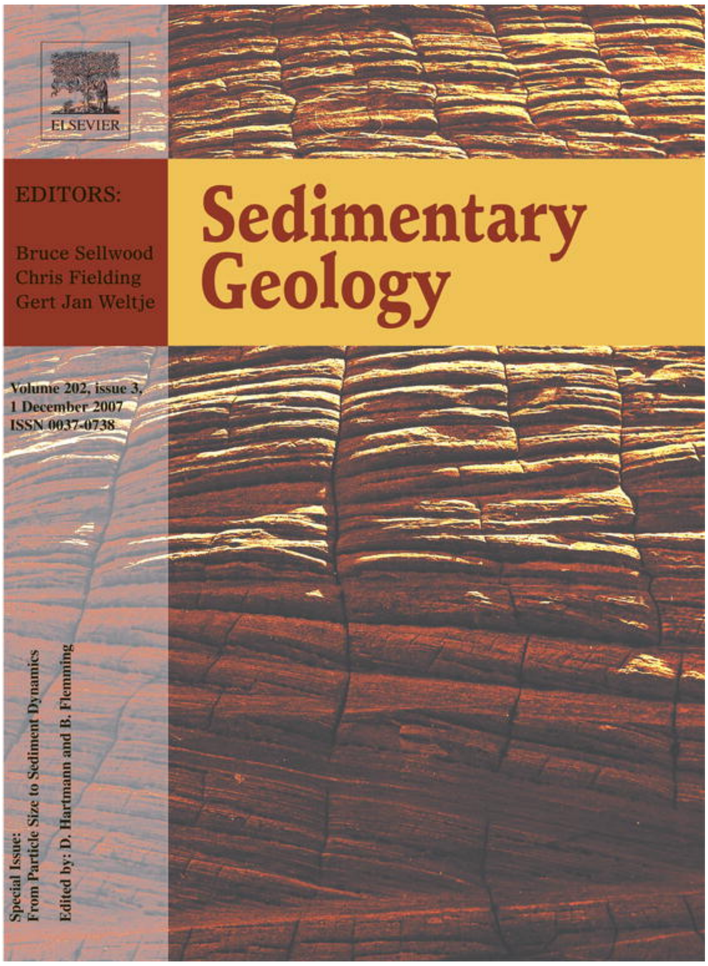
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Deriving transport pathways in a sediment trend analysis (STA)

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Abstract

Sediment trend analysis (STA) is a technique that enables patterns of net sediment transport to be determined by relative changes in grain-size distributions of all naturally occurring sediments. In addition, STA can determine the dynamic behaviour of bottom sediments with respect to erosion, accretion or dynamic equilibrium. The data requirements for STA are the full grain-size distributions taken from sediment grab samples collected at a regular spacing over a particular area of interest. Two types of methods are presently used in the derivation of the transport pathways: a line-by-line approach, in which transport pathways are determined by searching for sample sequences in which the distributions change, in a statistically acceptable manner; and various vector approaches, in which each sample is compared to neighbouring sites from which a vector sum is calculated.

The basic assumption for STA is that the processes that cause sediment transport will affect the statistics of sediment distributions in a predictable way. In reality, this type of analysis is complicated through the inclusion of a number of uncertainties, or noise. The goal of STA is to extract the information (the transport pathways) from the noisy signal (the grain-size distributions), an approach that is made difficult because neither the nature of the information nor the noise is known. Because of this, obtaining results by simply applying its theory in a "black-box" approach may provide poor solutions.

The line-by-line approach to STA draws from communications theory to achieve a solution. In some communications systems, the information from many sources is combined into one signal. The resulting signal is, from a statistical viewpoint, nothing but noise. The extraction of specific information assumes that information is indeed present, and determines if that assumption is consistent with the received signal. For STA, the procedure is to assume a transport direction over an area comprising many sample sites. From this assumption, the predicted sediment trends are compared with the pathways determined by the actual samples. The assumed transport direction is repeatedly modified until the best fit is achieved.

Vector techniques may be very helpful to provide insights and guidance to the line-by-line approach. However, the approach is ultimately necessary to finalize a credible solution as well as providing important further information on the dynamic behaviour of the sediments, and to delineate specific sediment transport environments.

Keywords: Sediment trend analysis; Sediment transport

1. Introduction

Sediment trend analysis (STA) is a technique that uses the relative changes in grain-size distributions of naturally occurring sediments to establish patterns of net sediment transport. Following publication of the theory describing how grain-size distributions are likely to change from one deposit to the next in the direction of net sediment transport (McLaren, 1981; McLaren and Bowles, 1985), many researchers have applied the concepts of STA to further their understanding of

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sedimentary environments (Haner, 1984; De Maeyer and Wartel, 1988; Prakash and Prithviraj, 1988; McLaren et al., 1993a,b; Ghosh and Chatterjee, 1994; Mohd-Lokman et al., 1998; Asselman, 1999; Wu and Shen, 1999; Mallet et al., 2000a; Delgado et al., 2002; Pascoe et al., 2002; Rios et al., 2002; Donohue et al., 2003; Cheng et al., 2004). A number of authors found their results to agree, either in whole or in part, with a variety of other evidence including direct measurements of processes, bedform orientations, and through the application of numerical modelling (Livingstone, 1989; Lanckneus et al., 1992; Van de Kreeke and Robaczewska, 1993; Gao and Collins, 1994; Gao et al., 1994; Pedreros et al., 1996; Aldridge, 1997; Bergemann et al., 1998; Van Der Wal, 2000; Mallet et al., 2000b; Duck et al., 2001; Shi et al., 2002). Yet, a further body of literature found no agreement between the STA (or various derivatives of the technique) and outside evidence (Flemming, 1988; Masselink, 1992; Guillen and Jimenez, 1995).

Several techniques to carry out STA have been developed, a good summary of which is found in Rios et al. (2003). McLaren and Bowles (1985) presented a one-dimensional approach whereby individual sample sequences are tested for statistical validity (*Z*-score) to determine the preferred transport direction. Gao and Collins (1991, 1992) and Gao (1996) proposed a two-dimensional vector approach to determine trends, some elements of which were revised by Chang et al. (2001). A somewhat different rationale in the vector approach was described by Le Roux (1994) and Le Roux et al. (2002).

The purpose of this paper is not to evaluate the various techniques that are being applied to STA (a study of the above references supply abundant discussions devoted to this subject) but rather to re-examine at a fundamental level the assumptions that are made in the initial theory, to indicate areas where further research could be both interesting and fruitful, and to suggest that considerable caution is still required in attempting to turn STA into a “black-box” technique.

2. STA theory

According to McLaren and Bowles (1985), when two sediment samples (d_1 and d_2) are taken sequentially in a known transport direction (for example, from a river bed where d_1 is the up-current sample and d_2 is the down-current sample), the sediment distribution of d_2 may become finer (case B) or coarser (case C) than d_1; if it becomes finer, the skewness of the distribution must become more negative. (Note: cases A, B and C were developed in the original theory paper of McLaren and Bowles, 1985. Case A was used as part of the proof, and designates the development of a lag as particles are eroded from a bed sediment. As such, case A does not determine a transport pathway, as do cases B and C. The latter two cases are referred to by Gao and Collins (1994) as cases 1 and 2, and as types 1 and 2 by Le Roux et al. (2002)).

Conversely, if d_2 is coarser than d_1, the skewness must become more positive. The sorting will become better (i.e. the value for variance will become less) for both cases B and C. If either of these two trends is observed, sediment transport from d_1 to d_2 can be inferred. If the trend is different from the two acceptable trends (e.g. if d_2 is finer, better sorted and more positively skewed than d_1), the trend is unacceptable and it cannot be supposed that transport between the two samples has taken place. It should be noted that the theory demonstrates that variance may become larger before decreasing when sampling along a transport path; however, because of this possible ambiguity, only a decrease in variance is accepted when testing for transport direction.

Gao and Collins (1991) mathematically described how two more cases might occur – finer, better sorted and more positively skewed; and coarser, better sorted and more negatively skewed – a concept continued in the work of Le Roux et al. (2002). If accepted, then the results of a trend analysis could be undertaken entirely on the basis of sorting, with the other two variables becoming superfluous. Gao and Collins (1991) have shown in their analysis how these two cases could occur for two random samples. In the McLaren and Bowles derivation the samples are not random, and it is shown that d_2 is derived from d_1 by way of a monotonic transport process, thereby eliminating the possibility of either of these two cases occurring.

In the above example, where the transport direction is unequivocally known, $d_2(s)$ can be related to $d_1(s)$ by a function $X(s)$ where s is the grain size. The distribution of $X(s)$ may be determined by:

$$X(s) = d_2(s)/d_1(s)$$

$X(s)$ provides the statistical relationship between the two deposits, and its distribution defines the relative probability of each particular grain size being eroded, transported and deposited from d_1 to d_2.

3. Uncertainties

The McLaren and Bowles model requires that the sampled sediments are described in statistical terms (by the moment measures of mean, sorting and skewness) and the basic underlying assumption is that processes causing sediment transport will affect the statistics of the sediments in a predictable way. Following from this assumption, the size frequency distributions of the sediments provide the data with which to search for patterns of net sediment transport.

In reality, perfect sequential changes along a transport path as determined by the model are rarely observed. This is because a variety of uncertainties (i.e. noise) may be introduced at all stages of carrying out STA. These may be summarized as follows.

3.1. Assumptions in the transport model

Whatever method is used to describe sediments, STA requires a model of the sediment transport process. The STA model is based on the assumption that smaller grains are more easily transported than larger grains (i.e. the probability of transport, on a phi scale, monotonically increases as grain size decreases). Under this assumption, it can be shown that transport processes will change the moment measures of sediments in a predictable way. As seen in transfer functions obtained from flume experiments, this assumption is not strictly true. The curves monotonically increase over only a portion of the available grain sizes before returning to zero. Factors such as shielding, whereby the presence of larger grains may impede the transport of smaller grains, increasing cohesion of the finer grains, or the decreasing ability of the eroding process to carry additional fines with increasing load demonstrate that the transport process is a complicated function related to sediment distribution and the strength of the erosion process. Furthermore, the assumption implicitly assumes that the probability of transport of one particular grain size is independent of the transport of other grain sizes.

Thus, we are left with a somewhat unsatisfactory assertion that the probability of transport must increase monotonically over a sufficiently large range of sizes present in the deposits to produce the predicted changes. As Gao and Collins (1994) pointed out, the technique to determine net transport pathways in a wide variety of different marine and coastal environments has been validated through the use of alternative approaches indicating that such an assumption cannot be unreasonable.

3.2. Temporal fluctuations

Sediment samples may comprise the effects of several transport processes. It is assumed that what is sampled is the “average” of all the transport processes affecting the sample site. The “average” transport process may not conform to the transport model developed for a single transport process. The possibility also exists that different samples may result from a different suite of transport events.

In STA, it is assumed that a sample provides a representation of a specific sediment type (or facies). There is no direct time connotation, nor does the depth to which the sample was taken contain any significance provided that the sample does, in fact, accurately represent the facies. For example, d_1 may be a sample of a facies that represents an accumulation over several tidal cycles, and d_2 represents several years of deposition. The trend analysis simply determines if there is a sediment transport relationship between the two facies.

3.3. Sample spacing

The sampling interval (frequency) may be too large to detect relevant transport processes. With increasing distance between sample locations, there is an increasing possibility of collecting sediments unrelated by transport (i.e. different facies). Communications theory (discussed in further detail below) indicates that in order to represent accurately a continuous signal with samples, the signal must be sampled at twice the highest frequency contained in the signal (Shannon, 1948). This would imply that for STA, sample sites placed x km apart could only reliably detect transport processes that occurred over a distance in the order of $2x$ km or more. Transport processes occurring over distances less than $2x$ km would appear as noise or could create spurious transport pathways through the process of “aliasing”.

In practice, selection of a suitable sample spacing must take into account (i) the number of sedimentological environments likely to be affecting the area under specific study; (ii) the desired spatial scale of the sediment trends; and (iii) the geographic shape and extent of the study area.

3.4. Random environmental and measurement uncertainties

All samples will be affected by random errors. These may include unpredictable fluctuations in the depositional environment, the effects of sampling and subsampling a representative sediment population, and random measurement errors.

4. Communications analogy

Our past experience suggests that essentially every set of sediment samples contains a significant noise component. Any technique used for STA must be designed to take into account the assessment of noise and, because of it, statistical techniques used to determine the significance of a postulated transport process must be used with caution. A high degree of significance does not necessarily prove causality.

STA is, in many ways, analogous to communications systems. In these systems, information is transmitted to a distant location where a signal is received that includes both the desired information as well as noise. The receiver must be capable of extracting the information from the noisy signal. In sedimentary systems, the information is the transport direction and the received signal is the sediment samples. The goal of STA is to extract the information from the noisy signal. In theory, the information can be recovered by simply subtracting the noise from the signal, an approach that works well in communications systems because the nature of the information and the noise are both well known. This approach will, however, be very difficult in STA because neither the nature of the information nor the noise is well understood.

A large body of analytical techniques has been developed to extract signals in communications systems. These techniques generally fall into two categories: signal coding and noise reduction. For example, in FM radio transmission, the signal is coded as a time-varying frequency about a carrier frequency. At the receiver, rejecting all frequencies other than the carrier frequency reduces noise. The receiver then looks for the time-varying frequency component to extract the original signal. Reducing the noise increases the level of the signal-to-noise ratio, enabling the signal to be detected. Coding the signal simply makes it easier to find because of prior knowledge of the information. It is important to note that knowing what is being looked for is of critical importance in communications systems: merely analyzing the incoming signal would not be sufficient to interpret the signal correctly.

In STA, with no opportunity to code the signal, other aspects of communications theory (noise reduction) might have applications pertinent to the technique. Typically, noise in communications systems is reduced with the use of filters that selectively reduce the signal level for frequencies outside the frequency range of the signal. If these frequency components contain parts of the signal, the filter, too, will reduce them. Knowing the nature of the noise and the signal, filters can be designed that optimally increase the signal-to-noise ratio. The situation in STA is not as straightforward because the noise is not well understood and the nature of the signal is only partly known. In this situation, noise reduction by filtering can be problematic because the filtering can remove significant signal components; however, some statistical communications techniques might be applicable to improve the situation.

In a sedimentary system, noise can be considered in terms of two categories: sample noise and spatial noise.

4.1. Sample noise

Even in a "uniform" sediment deposit, individual samples will likely be corrupted by noise. One way to address this noise would be to take an average of many samples in close proximity to each other. Another method that implicitly attempts to reduce this noise is curve fitting. For example, there has been considerable research on utilizing a log-hyperbolic curve to describe sediments, as it appears to provide a good fit to many naturally occurring deposits (Barndorff-Nielsen, 1977; Bagnold and Barndorff-Nielsen, 1980). Similar to the concepts of STA, it has been shown that parameters of the log-hyperbolic distribution should change in deterministic ways under the influence of erosion or deposition (Barndorff-Nielsen and Christiansen, 1988). Barndorff-Nielsen et al. (1991) and Hartmann and Christiansen (1992) proposed that erosion and deposition cause the location-shape invariant parameters of the log-hyperbolic distribution to vary in particular ways when plotted on the "shape triangle" of the log-hyperbolic distribution. Not all researchers, however, have been convinced that log-hyperbolic distributions provide superior information (e.g. Wyrwoll and Smyth, 1988; Hill and McLaren, 2001).

Curve fitting analysis, whether log-normal or log-hyperbolic, is based on the assumption that sediments follow specific distributions. By fitting a curve to the sedimentary data, it is assumed that points that do not fall on the curve are noise and these are removed. In theory, this works if in fact sediments do conform to the proposed curve. If they do not, then the curve fitting process removes signal as well as noise and, accordingly, there may be more noise in the fitted curve than in the original sample. In the present line-by-line approach of STA, the pitfalls of curve fitting are avoided, as only the raw data of each sediment distribution are used from which the log moments are calculated.

4.2. Spatial noise

As sediment is transported over a distance, noise may also be introduced. To reduce this noise, average values taken from groups of samples could be used. Many of the techniques proposed by researchers are, in reality, efforts to reduce noise in this manner (cf. the one dimensional *Z*-score of McLaren and Bowles (1985), or the vector approaches of Gao (1996), and Le Roux (1994)). The averaging of samples used in such procedures may not be strictly valid when the nature of the noise and the information are not known. Averaging of samples can reduce the information content more than it reduces the noise levels. (An exception is the averaging of a number of samples from the same local environment to generate a better single distribution to represent that environment because the random noise would be reduced.) In STA, the assumption is that noise is randomly distributed and therefore averages to zero, leaving the true trend as the residual after averaging. While these techniques may in fact reduce noise, signal-processing techniques may provide more refined and controllable methods.

In communications theory, it is often convenient to transform the signal from the time domain (i.e. a signal that varies over time) to the frequency domain that shows the frequency spectrum of the signal (i.e. the amount of the signal that is carried by all of the individual frequency components). Mathematically, this is performed using a Fourier transform, which converts the signal into its frequency components. After removing the undesirable (noise) components, an inverse transform is performed to transform the signal back to the time domain. In sediment analysis, the signal varies across distance, rather than time, but exactly the same analysis can be performed. In this case, the data (the sediment samples) can be represented as a sum of distance-varying sinusoids using a two-dimensional Fourier transform. What the transform produces is a characterization of the sedimentary deposits that shows how they vary over different distance scales. For example, one component would indicate the intensity of changes over a 100-m range, another over a 1-km range. The sample spacing, as discussed above, will set limits as to what distance ranges can be considered. Having the signal in this form allows the unwanted components to be removed. However, how is it known what is undesirable? In communications systems, the information is known (if it were not, it would be difficult, if not impossible, to find anything). By analogy, in performing a simple analysis of sedimentary data (e.g. mapping the variation in mean grain size), it is highly unlikely that a transport direction would be discovered. To extract the relevant signal, it is necessary to make an assumption as to what is being looked for. It is then possible to filter the data to highlight this and to detect if, in fact, a signal corresponding to the assumption is actually present. For example, assume a transport process that would produce the fining of sediments over a 5-km distance. To extract this process, a two-dimensional Fourier transform can be calculated and all frequency components associated with variations of less than 5 km could be removed. An inverse transform of the data would then highlight variations over the proposed distance scale.

The important feature of this approach (which, in fact, approximates the line-by-line approach of McLaren and Bowles (1985)) is the use of many sample sites to detect a transport direction. This effectively reduces the level of noise. The problem, however, is that it is difficult to mechanize because the number of possible transport directions in a given area can be much too large to try them all. The choosing of a trial transport direction cannot be easily analytically codified and can be reduced to a manageable level only through experience and information from other sources (e.g. bathymetric data, coastal morphology, etc.).

In using the *Z*-score statistic incorporated in the line-by-line approach, a transport trend can be determined whereby all possible pairs in a sample sequence are compared with each other. When either a case B or case C trend exceeds random probability within the chosen sample sequence, the direction of net sediment transport can be inferred. As suggested above, the grid spacing must be compatible with the area under study and take into account the number of sedimentological environments likely to be involved, the geographic shape of the study area, and the desired statistical certainty of the pathways. For practical purposes, it has been found that, for regional studies in open ocean environments, sample spacing should not exceed 1 km; in estuaries, spacing can be reduced to 500 m. For site-specific studies (e.g. to determine the transport regime for a single marina), sample spacing will be reduced so that a minimum number of samples can be taken to ensure adequate coverage. Experience has also shown that extra samples should be taken over sites of specific interest (e.g. dredge-material disposal sites) and in those areas in which the regular grid is insufficient to accommodate specific bathymetric features (e.g. bars and channels).

At present, the line-by-line approach is undertaken as follows:

1. Assume the direction of transport over an area comprising many sample sites;
2. From this assumption, predict the sediment trends that should appear at the sample sites;
3. Compare the prediction with the *Z*-score statistic obtained from the grain-size distributions of the samples; and

4. Modify the assumed direction and repeat the comparison until the best fit is achieved.

Following from the communications analogy, when a final and coherent pattern of transport pathways is obtained that encompasses all, or nearly all, of the samples, the assumption that information (the transport pathways) is contained in the signal (the grain-size distributions) has been verified, despite the inability to define accurately all the uncertainties that might be present.

It must be emphasized that STA cannot identify the actual processes responsible for the transport of particles along the derived pathways. They might in one environment be breaking waves in a littoral drift system; in another, the residual tidal currents; and in yet another, the incorporated effects of bioturbation. Nevertheless, one of the great values in obtaining the transport patterns is to assess the probable processes that are likely taking place to achieve such patterns.

5. Interpretation of the *X*-distribution

In the McLaren and Bowles (1985) paper, no attempt was made to interpret the significance of $X(s)$. It was only considered that the shape of $X(s)$ and its use in the interpretation of a trend could be significant. Although discussed and used in several later papers (McLaren et al., 1993b; Pascoe et al., 2002), there has been little or no further academic research on this aspect of STA. The first author of this paper has made extensive use of the *X*-distribution in about 100 consulting reports and, based on empirical observation from a very large number of environments, it is suggested that interpretation of the *X*-distribution based on its shape relative to the deposits can be summarized as follows (Fig. 1).

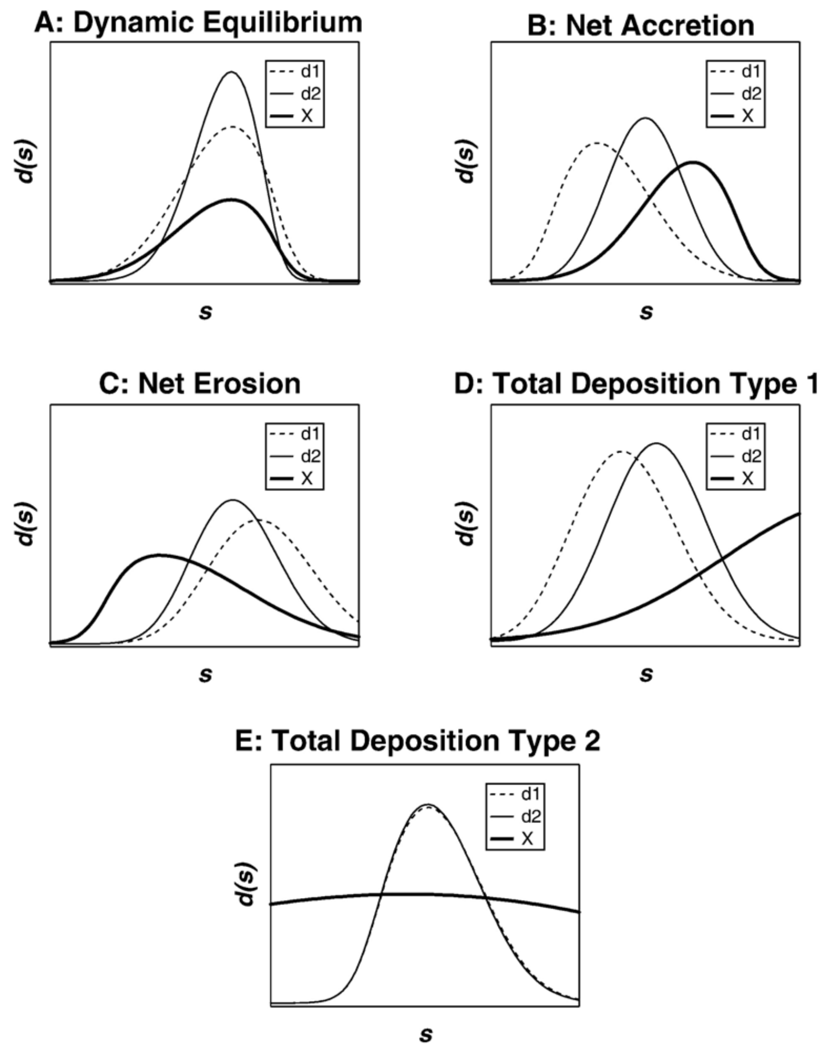

Fig. 1. Summary of the interpretations given to the shapes of *X* distributions relative to the d_1 and d_2 deposits. As described in the STA theory, $X(s)$ is derived by the distribution of a "down-current" sample divided by the distribution of an "up-current" sample, and represents the relative probability of a specific-sized particle being eroded from d_1 and becoming deposited in d_2.

1. The shape of the X-distribution closely resembles the d_1 and d_2 distributions (the modes of the three distributions are more or less the same; Fig. 1A). The similarity of X with d_1 and d_2 suggests that the probability of finding a particular grain in the deposit is equal to the probability of its transport and re-deposition (i.e. there is a grain-by-grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in *dynamic equilibrium*.
2. The mode of X is finer than the modes of d_1 and d_2 (Fig. 1B). Deposits are fining in the direction of transport; however, more grains are deposited than eroded. The bed, though mobile, is accreting (*net accretion*).
3. The mode of X is coarser than the d_1 and d_2 modes (Fig. 1C). Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing *net erosion*.
4. The X-distribution more or less increases monotonically over the complete size range of the deposits (Fig. 1D). Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a "rain" of sediment that fines with distance from source. Once deposited, there is no further transport (total deposition type 1).
5. The X-distribution is essentially horizontal (Fig. 1E). This type of X-distribution is found only in extremely fine sediments when the mean grain size is very fine silt or clay. Such sediments are usually found "far" from their source (compared with total deposition-type 1 sediments in which size sorting of the fine particles is taking place, and therefore the source is relatively "close"). The horizontal nature of the X-distribution suggests that sediment deposition is no longer related strictly to size sorting. In other words, there is now an equal probability of all remaining sizes being deposited (total deposition type 2).

The above interpretations have proven to be highly significant in assessing the fate and behaviour of particle-associated contaminants (Little and McLaren, 1989; Pascoe et al., 2002). It is also suggested that the X-distribution might be a more useful distribution to utilize in numerical models as opposed to the characteristics of the sediments themselves. The former takes into account the probabilities of any sized particle being eroded, transported and deposited, whereas a grain-size distribution of the actual sediment reflects only the probability of each size being deposited.

The type of X-distribution also appears to be closely related to the availability of sediment. In environments where large amounts of sediment are in transport, the probability of net accretion increases. With decreasing availability of sediment in transport, the probability of dynamic equilibrium and net erosion increases. In this way, STA frequently identifies environments that are sediment starved and, together with the sources identified by the pathways, the reasons for a declining sediment source may become apparent.

6. Things to consider

The present techniques to carry out STA fall essentially into two categories: the line-by-line approach of McLaren and Bowles (1985), and a number of vector analyses (Gao, 1996; Chang et al., 2001; Le Roux et al., 2002). Based on the experience of numerous consulting projects, we frequently use a vector technique as a first way to discern possible trends. It can be helpful for providing an indication of probable sources and sinks. It is also possible that the results are not correct, or are extremely misleading, and it is our contention that, at their present stage of development, vectors should only be a preliminary first stage that then must be followed by a far more rigorous line-by-line analysis. Used on their own, any of the vector approaches are unable to account for any or all of the possible sources of noise that might be included in the distributions. Important factors that should be considered in carrying out STA include the following.

6.1. Data familiarity

Prior to either a vector or line-by-line examination of trends, GIS techniques should be used to map sediment attributes superimposed on bathymetry. These should include various criteria based on the distributions, such as mean grain sizes, sedimentary facies, percent mud, sand and gravel, etc. Sometimes a cluster analysis on all the distributions is helpful to understand the number and types of facies that have been sampled. For example, are the facies mutually exclusive or are they gradational? Should individual facies be analyzed for trends separately or can the whole dataset be justifiably considered as a single facies? Mud and sand, particularly in estuaries, may move in separate transport regimes. Are the distributions bimodal, in which case can the coarse fraction be used separately from the fine fraction in the trend analysis? Such familiarity with the data is essential in assessing the findings of the STA.

6.2. Analytical technique

How have the samples been analyzed? A mix of techniques in achieving a full grain-size distribution (e.g. a merge of two distributions produced by sieving for sands and a Sedigraph analysis for mud) is unlikely to produce satisfactory distributions for STA. Closure of both the fine and coarse tails of the distributions to less than 1% is also important. If closure of the distributions has not been achieved, particularly at the fine end, STA should not be attempted. Laser particle size analyzers can provide the fullest range of sizes while using only one sizing technique.

6.3. Examination of distributions used in a trend

A single erroneous distribution contained in a trend line can produce an incorrect interpretation. For this reason, all distributions used in a line of samples should be superimposed on each other and examined. In the event that one or more samples are clearly anomalous, they should be discarded.

6.4. Assessing the tails of the distributions

Significant sample noise is most likely to be contained in the tails of the distribution. Both vector and line-by-line techniques must be able to progressively remove successive size fractions found in the tails (skewness is a third-order moment and very small changes in the tails result in large changes in value). In altering the fine and coarse limits of the distributions, the robustness of the trends can be established. If incrementally small changes in the tails of the distributions result in widely different pathway directions, the trends cannot be accepted. On the other hand, if the trends remain much the same with a change in the cutoff value of the tail, the results are robust and have a greater acceptability.

6.5. Use of R^2

In addition to the Z-score, a further statistic (the linear correlation coefficient, R^2) provides an additional tool in determining the validity of any transport line. R^2 is defined as:

$$R^2 = \frac{\sum_i (\hat{y}_i - \bar{y})^2}{\sum_i (y_i - \bar{y})^2} \quad \text{where } \hat{y} = f(x_1, x_2, \ldots)$$

$$\text{and } \bar{y} = \frac{1}{N} \sum_i y_i$$

The value of R^2 can range from 0 to 1. The definition of R^2 is based on the use of a model to relate a dependent parameter y to one or more independent parameters (x_1,x_2,...). In our case, the model used is a linear one, which can be written as:

$$\hat{y} = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2$$

The data (y, x_1, x_2) are grain-size distribution statistics, and the parameters (a_0,a_1,a_2) are estimated from the data using a least-squares criterion. The dependent parameter, y, is defined as the skewness and the independent parameters are the mean size, x_1, and the sorting, x_2. An implicit assumption is made that grain-size samples making up a transport line, if plotted in skewness/sorting/mean space, would tend to be clustered along a straight line. The slopes of the straight line, which are the fitted parameters, would depend on the type of transport (fining or coarsening). While there is no theoretical reason to expect a linear relationship among the three descriptors, there is also no theory predicting any other kind of relationship. Using the principle of Occam's Razor, the simplest available relationship was chosen for the model. (Occam's Razor: Entities ought not to be multiplied except from necessity. Occam was a 14th century philosopher who died in 1349.) High values of R^2 (0.8 or greater) together with a significantly high value of the Z-score provide confidence in the validity of the transport line.

A low R^2 may occur even when a trend is statistically acceptable, for the following reasons: (i) sediments on an assumed transport path are, in reality, from different facies and valid trend statistics occurred accidentally; (ii) the sediments are from a single facies but the chosen sequence is only a poor approximation of the actual transport path; and (iii) extraneous sediments have been introduced into the natural transport regime, as in the case of dredge-material disposal. R^2, therefore, is assessed qualitatively and, when low, statistically acceptable trends must be treated with caution.

6.6. Examination of the X-distribution

With every trend examined, the X-distribution should also be assessed. Does it follow one of the shapes found in Fig. 1? If not, it is unlikely that the trend is valid.

6.7. Concept of trunk lines

In many STA analyses using the line-by-line approach, a trunk line of samples is discovered. A trunk line forms a root line of a number of lines that bifurcate from it. In estuaries, for example, a trunk line may follow a main channel with lines bifurcating onto bars or tidal flats. A vector analysis on its own will fail to discover trunk lines, as the vectors tend to point at 90° to such a line.

6.8. Delineation of transport environments

In the line-by-line approach, sample sequences can be extended until an ambiguity occurs, or the trend breaks down altogether. This will happen particularly when a new source of sediment may be entering the transport regime, or the dynamic behaviour changes and a new sample sequence must begin. In this way, the end result can define individual transport environments, each of which has a unique source and/or dynamic behaviour. Transport lines cannot cross such boundaries.

6.9. Derivation of a mutually self-supporting pattern of transport

At present, the selection of trial directions in the line-by-line approach is undertaken initially at random, although the term "random" is used loosely in that it is not strictly possible to remove the element of human decision-making entirely. For example, a first look at the possible transport pathways may encompass all north-south or all east-west directions. As familiarity with the data increases together with the results of a vector approach, exploration for trends becomes less and less random. The number of trial trends becomes reduced to a manageable level through both experience and the use of additional information (usually the bathymetry and morphology of the area under study). As described above, the most important aim is to obtain a final and coherent pattern of transport pathways that can account for all, or nearly all of the samples. Once accomplished, the assumption that there is information (the transport pathways) contained in the signal (the grain-size distributions) has, as described in the communication analogy, been verified.

7. Conclusions

The present techniques to carry out STA fall into two types: a line-by-line analysis and a vector approach. Because of uncertainties (noise) that are present at all stages of the assumptions made in the theory, sampling procedure and analytical techniques, a "black-box" approach to achieving the patterns of transport may result in incorrect solutions. For this reason, it is suggested that vector approaches should be used only as a helpful guide to a more detailed line-by-line method. The rationale for the line-by-line method draws on communication theory, the goal being to retrieve information on transport direction and dynamic behaviour from the signal provided by the grain-size distributions of the sediments. When a coherent and justifiable pattern of transport that accounts for all, or nearly all of the samples is achieved, it is reasonable to accept that the received information is likely to be correct.

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