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# Analysis of Grain Size Trends, for Defining Sediment Transport Pathways in Marine Environments

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## ABSTRACT

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An approach to grain size trend analysis is developed on the basis of a semi-quantitative filtering technique. Using this technique, grain size trends identified from a grid of surficial sediment samples are transformed into a "residual pattern" representing net sediment transport paths. The method assumes that the grain size trends used for the analysis have a higher frequency of occurrence in sediment transport directions than in the opposite directions, but such dominance does not exist if there is no exchange of material between the sampling sites. The proposed method is applied to the analysis of grain size trends over the Christchurch Bay area, southern England.

Mean grain size, sorting and skewness are used to form eight possible grain size trends; two of these are used to derive a residual pattern. The pattern obtained shows general agreement with transport patterns derived from other sediment dynamics investigations undertaken for the region. Further, a residual pattern similar to that of transport paths on the basis of estimates of longshore transport rates, for the Rhône Delta, is derived. The present investigation indicates that the feasibility of grain size trend analysis depends upon the selection of appropriate grain size trends and the analytical approach.

**ADDITIONAL INDEX WORDS:** *Grain size trends, sediment transport, Christchurch Bay, Rhône Delta.*

## INTRODUCTION

Grain size parameters of surficial sediments vary according to sampling location. Such spatial changes (grain size trends) result from sediment transport processes such as abrasion, selective transport and the mixing of sediments from various sources (RUSSELL, 1939). This observation implies that some distinct patterns of grain size trends are likely to be associated with sediment transport pathways. Hence, many investigators have attempted to relate some of the grain size trends to net sediment transport patterns.

These attempts have been successful only to some extent. For example, mean grain size was considered to become successively finer along transport paths (PETTIJOHN *et al.*, 1972); coarsening trends along the paths, however, have been observed also (MCCAVE, 1978; NORDSTROM, 1989).

Combined grain size trends derived using more than one grain size parameter have been used, in order to overcome this difficulty (MCLAREN and BOWLES, 1985). This approach may fail to identify the transport paths, in some circumstances (*e.g.* MASSELINK, 1992).

Such failures may be caused by: (1) the dominant grain size trends along a transport path being mistakenly defined; or (2) an inappropriate approach being used in the analysis of trends. Until now, the identification of grain size trends related to transport paths has been based upon only some empirical knowledge (*i.e.* their relationship with hydrodynamic conditions are unknown). Further, the procedures for grain size trend analysis need to be improved, to reduce the probability that patterns <u>not</u> associated with net transport paths are interpreted as being representative of such pathways.

It is the purpose of the present contribution to justify, therefore, the use of certain grain size trends on the basis of empirical knowledge; this is to assess an approach proposed previously (GAO and COLLINS, 1991). The Christchurch Bay area (southern England) has been selected for investigation. The Rhône Delta coastline (southern France) is included also in the discussion, for comparison with an earlier method (MASSELINK, 1992).

## THE STUDY AREA

Christchurch Harbour (Figure 1) is located within the southern part of the Hampshire Basin, a sedimentary basin characterised by Tertiary deposits (MELVILLE and FRESHNEY, 1982). From the

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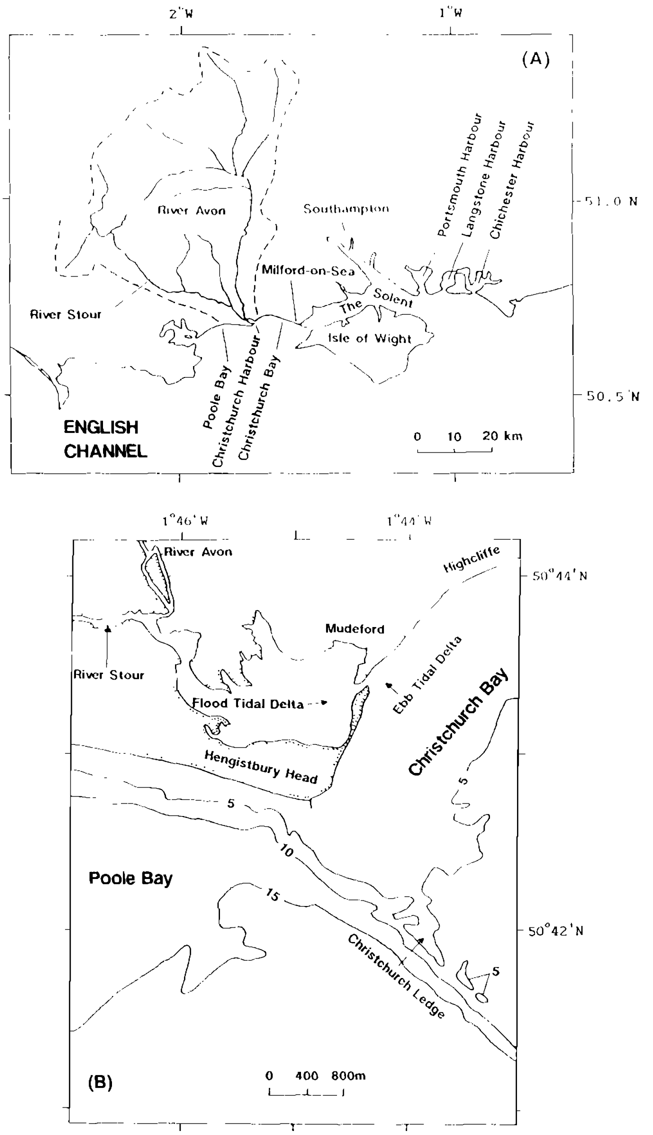

Figure 1. (A) Location of Christchurch Harbour (with the drainage basin area shown by the dashed line); and (B) geomorphological characteristics of the tidal inlet system (bathymetry in metres).

Middle Palaeocene to Lower Oligocene, alternating marine muds and sands interlayered with gravels were deposited. During the Miocene, the area was uplifted, however, and subjected to erosion because of movements associated with Alpine mountain building.

The Pleistocene strata are characterised by (fluvial or marine) gravelly deposits. The sea level rise during the Holocene has caused extensive erosion along the coastlines in Poole and Christchurch Bays. As a result, cliffs of 15 to 35 m in height have been formed here. Sediments eroded from the cliffs around Hengistbury Head and Highcliffe have formed into two spits (Figure 1), which have semi-enclosed Christchurch Harbour to form an estuarine/tidal inlet system. The tidal

Table 1. *Possible cases, using three grain size parameters (i.e. mean grain size, $\mu$, sorting, $\sigma$, and skewness, $S_k$).*

| Case | Definition |
|---|---|
| 1 | $\mu_A > \mu_B$, $\sigma_A < \sigma_B$, and $S_{k,A} < S_{k,B}$ |
| 2 | $\mu_A < \mu_B$, $\sigma_A < \sigma_B$, and $S_{k,A} > S_{k,B}$ |
| 3 | $\mu_A < \mu_B$, $\sigma_A > \sigma_B$, and $S_{k,A} > S_{k,B}$ |
| 4 | $\mu_A > \mu_B$, $\sigma_A > \sigma_B$, and $S_{k,A} < S_{k,B}$ |
| 5 | $\mu_A > \mu_B$, $\sigma_A < \sigma_B$, and $S_{k,A} > S_{k,B}$ |
| 6 | $\mu_A < \mu_B$, $\sigma_A < \sigma_B$, and $S_{k,A} < S_{k,B}$ |
| 7 | $\mu_A < \mu_B$, $\sigma_A > \sigma_B$, and $S_{k,A} < S_{k,B}$ |
| 8 | $\mu_A > \mu_B$, $\sigma_A > \sigma_B$, and $S_{k,A} > S_{k,B}$ |

basin has an area of 1.9 km$^2$ (TOSSWELL, 1978). Within the Harbour, the water is shallow, with extensive intertidal flats and salt marshes (MURRAY, 1966).

Near the entrance to Christchurch Harbour, flood and ebb tidal deltas are present. The ebb tidal delta has been observed to be unstable, in terms of its position and elevation (BURTON, 1931; ROBINSON, 1955).

Christchurch Bay is dominated by southwesterly waves (HYDRAULICS RESEARCH, 1989). In the offshore areas, the most frequently-occurring wave heights are less than 0.6 m, but waves with a significant wave height ($H_s$) of up to 7 m can occur. All the waves with a $H_s$ over 6 m are from SW-SWW directions.

Because the area lies close to an amphidromic point, the tidal range in this area is the lowest within the English Channel. At the mouth of Christchurch Harbour, the mean spring and neap tidal ranges are only 1.4 m and 0.8 m, respectively. Nevertheless, the currents within the entrance channel are strong. Cross-sectional mean current speeds of up to 2.5 m s$^{-1}$ have been observed (GAO, 1993).

The tidal water level shows a distinctive "double high" feature (*i.e.* the high water occurs twice during a tidal cycle, especially during spring tides) (TYHURST, 1978). Thus, the tidal prism (the water volume which is transported into the tidal basin during the flood phases of a tidal cycle) is greater than it would be if the double highs were not present. The total catchment area of rivers discharging into the Harbour is approximately 3,135 km$^2$, with an annual average freshwater discharge of around 30 m$^3$ s$^{-1}$. Seasonal changes in the freshwater discharge are significant. For example, the maximum mean daily freshwater discharge for January in 1991 reached 117 m$^3$ s$^{-1}$, whilst it was only 16 m$^3$ s$^{-1}$ during August. Hence, the observed strong currents within the entrance result from a combination of the "double high" feature of the tidal water level and the freshwater discharges from Rivers Stour and Avon.

Tidal currents, waves and river flows are active in transporting sediments within the tidal inlet system. For example, sediment transport on the beaches here is directed towards the northeast, at a rate of around 5.3 × 10$^4$ m$^3$ yr$^{-1}$ (NICHOLLS and WRIGHT, 1991).

## METHOD

### Theoretical Considerations

Although the relationship between grain size trends and hydrodynamic processes is still not well understood, some transport processes have been shown to be mechanisms which cause changes in grain size parameters (RUSSELL, 1939). For example, along a transport path: abrasion makes sedimentary particles finer; selective transport results in either fining or coarsening of sediments; and mixing of material from various sources may destroy any ordered grain size patterns, produced by other mechanisms of transport.

More importantly, only a very limited number of the grain size trends can exist along the transport path. Using a single grain size parameter, for example, there are only two possible cases: the parameter will either increase or decrease. In general, if N grain size parameters are involved to form combined cases, then the total number of the possible cases of grain size trends (obtained from a comparison of the parameters between sampling sites A and B) will be $2^N$. For example, if the mean grain size, sorting coefficient and skewness are used, then there exist eight possible cases, which are listed in Table 1. Hence, it is feasible technically to examine each of the cases, so that the trends associated with transport paths can be identified.

Because each of the cases listed in Table 1 is likely to occur along the transport path (GAO and COLLINS, 1991), such an examination can only be undertaken if the following conditions are satisfied that: (1) some of these cases have a significantly higher frequency of occurrence in transport directions than in the opposite directions; and (2) such dominance does not exist if there is no relationship of material exchange among the sediment samples involved. If such cases can be identified, then sediment transport paths can be defined on the basis of some analytical procedures (see below).

### Grain Size Trends Used in the Analysis

For the purpose of the grain size trend analysis, it is important to determine which trends to utilise. Two types of hypothetical trends similar to Cases 1 and 2 (*cf.* Table 1) have been used by McLaren and Bowles (1985). An empirical assessment of the hypothesis, through a statistical examination of the published information from previous investigations, shows that observations of grain size trends along the known transport paths do not generally contradict Cases 1 and 2 (Gao and Collins, 1992). Further, the use of such cases for a tidal inlet system has resulted in patterns which appear to represent sediment transport paths identified on the basis of some geomorphological and sedimentological evidence (Gao and Collins, 1992). In the present study, therefore, Cases 1 and 2 are assumed to satisfy the two conditions described previously and are used in the grain size trend analysis.

### Analytical Procedures

The procedures for grain size trend analysis used in the present study are now described. According to the premise of the analysis, the trends used can occur along or against sediment transport paths, but the probability of occurrence of the former is much higher than that of the latter. Thus, the trends against the transport paths are considered as "noise". Such noise can be removed, using a semi-quantitative filtering technique (which is similar to the filtering techniques used in satellite image processing, in order to recover the imagery affected by noise).

First, "trend vectors" are defined for a grid of sampling sites by comparing each sample with its neighbour. In order to identify a "neighbouring" site, a characteristic distance ($D_{cr}$), which is taken as the maximum spatial sampling interval, is specified. If the distance between any two sites is smaller than this characteristic distance, they are considered as neighbouring sites and their grain size parameters are compared. If either a Case 1 or a Case 2 trend is identified between the two sites, then a dimensionless "trend" vector is defined for the site with the higher sorting coefficient. The direction of such a vector runs from the site with the higher sorting coefficient to that with the lower value. Because the mean, sorting and skewness all combine to form a trend, it is difficult to define the length of the vector on the basis of the parameters themselves without any bias towards one of the parameters. Hence, for convenience, the length of the vector is assumed to be unity.

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 as follows:

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

where n is the number of trend vectors identified for the site, $\vec{r}(x, y)$ is a trend vector, and $\vec{R}(x, y)$ is the sum of the trend vectors.

Finally, an averaging operation is applied. Once again, an adjoining site is assessed 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:

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

where $\vec{R}_j$ is a summed trend vector obtained on the basis of Equation 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 pattern can be compared with a real pattern of sediment transport paths. If the two patterns are similar, then Cases 1 and 2 satisfy the assumption of the method and the residual pattern represents net transport paths.

The purpose of the first step is to identify all the Case 1 and 2 trends. The second step is required to specify a probable transport direction for each of the sites. In the final step, the majority of the noise is removed.

It may be noted that the trend vectors should not show any ordered pattern, if there is no material exchange among the sediment sampling sites involved. In such a situation, the residual pattern after the filtering operation will have no orderliness. This condition is possible also, however, for a grid of trends from a real sediment transport environment, because the orderliness of the trends may be destroyed by transport processes such as mixing. Hence, even if the residual pattern does not show any orderliness, it does not imply that there is no net transport taking place within the environment.

Further, a site on the edge of the sampling grid may not be treated in the same way as a site within the central part of the grid, during the filtering operation. For example, for a site at the centre of the grid, trend vectors of nine neighbouring sites may be available for the calculation using Equation 2. For a site on the edge of the grid, however, it is likely that only six are available. This edge effect can be reduced if a large number of sites are used.

### Sediment Sampling and Grain Size Analysis

During May and October of 1989, 152 seabed sediment samples were collected over the Christchurch area (Figure 2). The van Veen grab was used for the subtidal sites, where direct access and sampling were impossible. For grain size analysis, each of the samples was separated into gravel, sand and mud sub-samples, using wet and dry sieving methods. The gravel sub-samples were dry-sieved, at an interval of 0.5 $\phi$. For each of the sub-samples, between 100 and 150 g were analysed using sieves with an interval of 0.5 $\phi$, between $-1$ $\phi$ and 4 $\phi$. The mud sub-samples were analysed on a SediGraph-5100, with the truncated point at 10 $\phi$.

The grain size data from the analyses of sub-samples were then merged together to obtain complete grain size distributions. Based upon these distributions, mean grain size ($\mu$), sorting coefficient ($\sigma$) and skewness ($S_k$) were calculated using the moment formulae (McManus, 1988):

$$\mu = \sum_{1}^{n} P_i s_i \tag{3}$$

$$\sigma = \left[ \sum_{1}^{n} P_i (s_i - \mu)^2 \right]^{1/2} \tag{4}$$

$$S_k = \left[ \sum_{1}^{n} P_i (s_i - \mu)^3 \right]^{1/3} \tag{5}$$

where $P_i$ is the frequency of occurrence of the material represented by the grain size $s_i$ and n is the total number of grain size fractions.

## RESULTS

### Grain Size Data

The mean grain size, sorting and skewness data have been obtained from the grain size analysis. The distribution patterns of the grain size parameters over the area are shown on Figure 3.

Generally, the Harbour and the ebb tidal delta areas are dominated by sandy sediments; gravels are present, however, within the entrance channel to the Harbour and on the beaches (Figure 3A). The sediments from the tidal deltas are the best sorted. Relatively poor sorting is present for the sediments in the bay-head (within the Harbour) and offshore (outside the Harbour) areas (Figure 3B). The sediments within the Harbour are mainly positively skewed, while negative skewness tends to dominate outside the Harbour (Figure 3C).

### Residual Patterns of the Grain Size Trends

Residual patterns based upon the grain size trend analysis for the Christchurch area are shown on Figure 4. If such patterns represent transport paths, then transport within the harbour is directed towards the east along the southern coastline and westwards in the north. Near the entrance, the vectors are directed to landward; while outside the Harbour, they are directed generally towards the north and northwest.

Previous investigations have provided other evidence on sediment transport patterns which are consistent with the derived residual patterns. For example, transport towards the north and to landward outside the Harbour is consistent with northerly longshore drift (Lacey, 1985; Nicholls and Wright, 1991) and an offshore area characterised by erosive features (Gao, 1993). Within the Harbour itself, the easterly-directed vectors are associated with a channel, in which river flow predominates and sediment transport is mainly in an easterly direction. Near the entrance, there is a well-developed flood tidal delta; this is indicative of a sand input from a seaward source and convergence of sedimentary material associated with the delta.

The southeastern part of the flood tidal delta is characterised by a series of asymmetrical sandwaves, as shown on a 1989 aerial photograph supplied by Christchurch Borough Council. The bedforms have their wavelengths of around 10 m and their steeper slope faces southwest. Because such flood tidal delta sandwaves do not change their asymmetric patterns during a tidal cycle (Boothroyd, 1985), they represent sediment transport towards the southwest. This direction is in agreement with the patterns derived from grain size trends at the same location.

### Another Example from the Rhône Delta

Along the coastline of the Rhône Delta, 29 beach sediment samples were collected and analysed by Masselink (1992). On the basis of the re-analysis of the grain size data from Masselink's study, the method described above results in a residual pat-

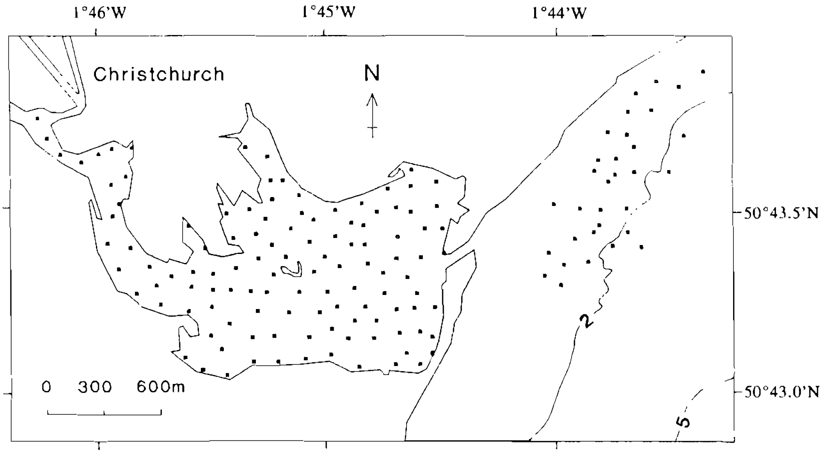

Figure 2. Seabed sediment sampling locations (bathymetry in metres).

tern of the grain size trends (Figure 5). According to this pattern, westerly transport takes place to the east of Beauduc (between sampling sites 1 and 17), southwesterly transport occurs mainly to the west of Beauduc (between sites 25 and 29), and accumulation occurs at Beauduc (between sites 18 and 25). Such a pattern is in general agreement with the observed transport pattern (Masselink, 1992), based upon estimates of longshore transport rates. It is worth noting here that transport on beaches tends to be present in both the longshore and onshore-offshore directions. Hence, it may be more appropriate to use a grid of samples rather than a line of samples, for the purpose of the trend analysis.

For the same location, however, easterly transport along the beach, on the basis of an earlier method for grain size trend analysis (McLaren and Bowles, 1985), is opposed to the observed transport directions (Masselink, 1992).

Such disagreement is likely to be caused by the procedures adopted in the earlier model. For the present model, Cases 1 and 2 are defined only for neighbouring sampling sites; thus, the general residual pattern will not be destroyed if the number of the additional sources are small. In contrast, the McLaren Model defines Case 1 or Case 2 for all the possible coupled sites. In the latter model, for example, a Case 1 trend between two neighbouring sites is considered as being of the same importance as that between two sites with much greater distance between them. This interpretation confuses, however, the space-scale of the analytical approach. For example, the trends defined in this way may reflect some regional variations in grain size parameters and/or the presence of multi-sediment sources, instead of net sediment transport (Gao and Collins, 1991). In fact, erosion along the coastline of the Rhône Delta creates an additional sediment source; hence, any general reduction in the sorting coefficient in an easterly direction (Masselink, 1992) is not correspondingly indicative of transport.

## SUMMARY

(1) An approach to grain size trend analysis has been developed to define net sediment transport paths, on the basis of the assumption that the grain size trends used for the analysis have a higher frequency of occurrence in sediment transport directions than in the opposite directions. Such dominance does not exist if there is no exchange of material between the sediment samples.

(2) If N grain size parameters are involved, then $2^N$ of combined grain size trends are likely to exist along transport paths. In the present study, mean grain size, sorting coefficient and skewness are used to form eight possible cases of the trends. Two of the cases are considered to satisfy the assumption of the method, on the basis of the results from previous investigations.

(3) The analytical procedures are based upon a semi-quantitative filtering technique, to transform the grain size trends into a "residual pattern" representing sediment transport paths. First, a "trend vector" is defined for each Case 1 or Case

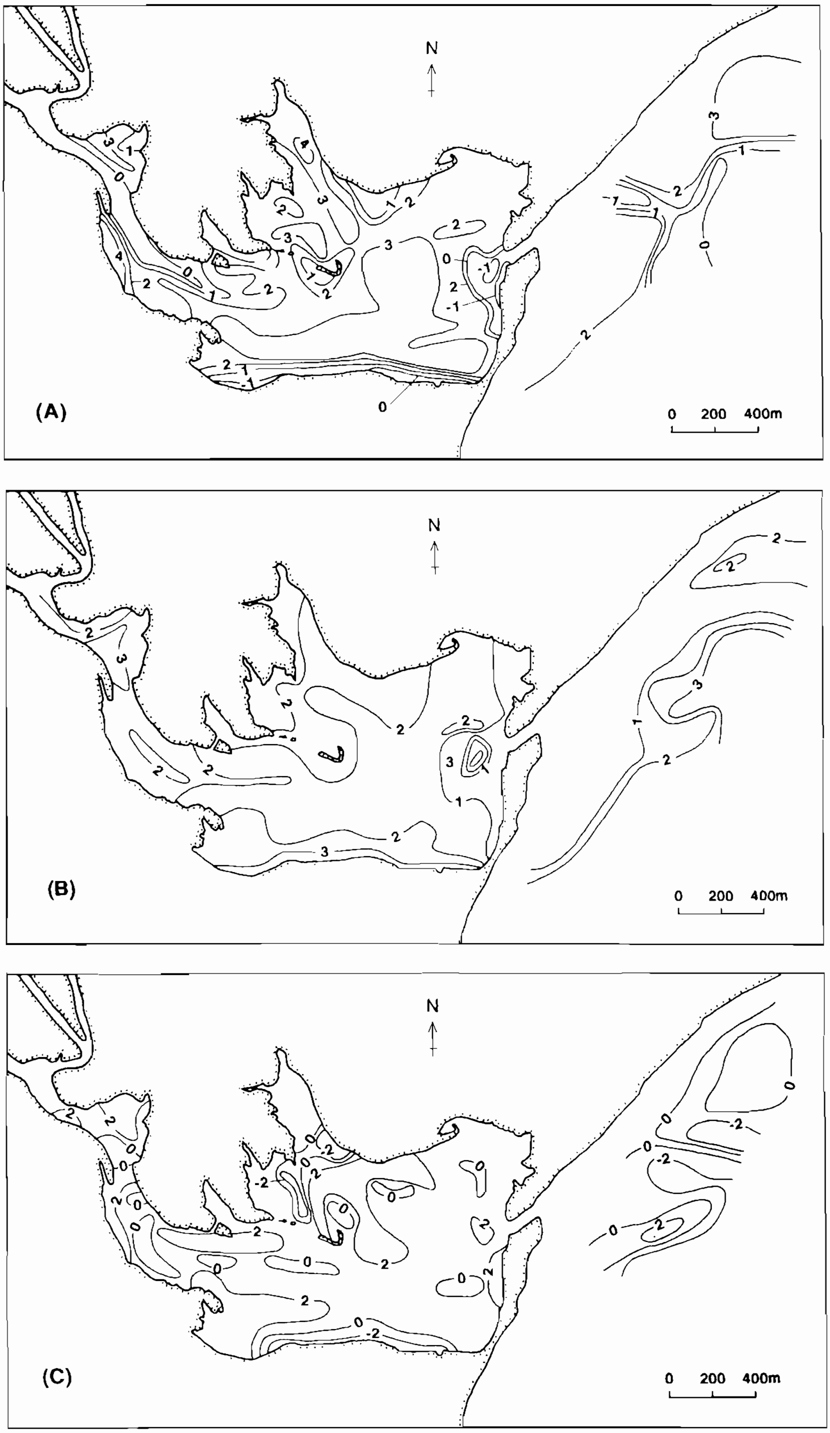

Figure 3. Distribution patterns of (A) mean grain size, (B) sorting coefficient and (C) skewness of surficial sediments (in $\phi$ units) over the Christchurch Harbour/Bay area.

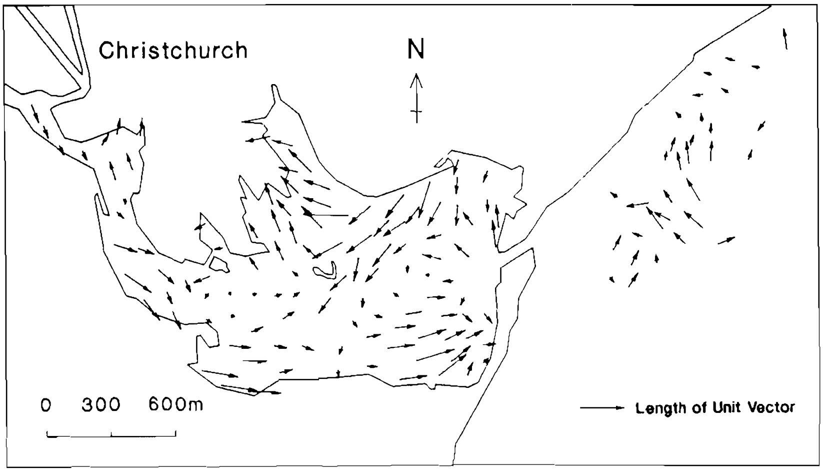

Figure 4. Residual patterns in grain size trends over the Christchurch Harbour/Bay area.

2 trend. Secondly, the trend vectors (if there is more than one) are summed to produce a single vector for each of the sites. Finally, an averaging operation is applied to obtain the "residual pattern".

(4) The method has been applied to the analysis of grain size trends over the Christchurch Bay and Rhône Delta areas. The derived residual patterns of the grain size trends are shown to be similar to the sediment transport patterns identified by other sediment dynamics investigations.

(5) To enhance the applicability of the technique, a grid of sediment sampling sites is required. The sampling interval should be small compared with the dimension of the sedimentary environments under investigation. Further, the technique could be unsuccessful to identify transport paths, as orderliness in the grain size trends

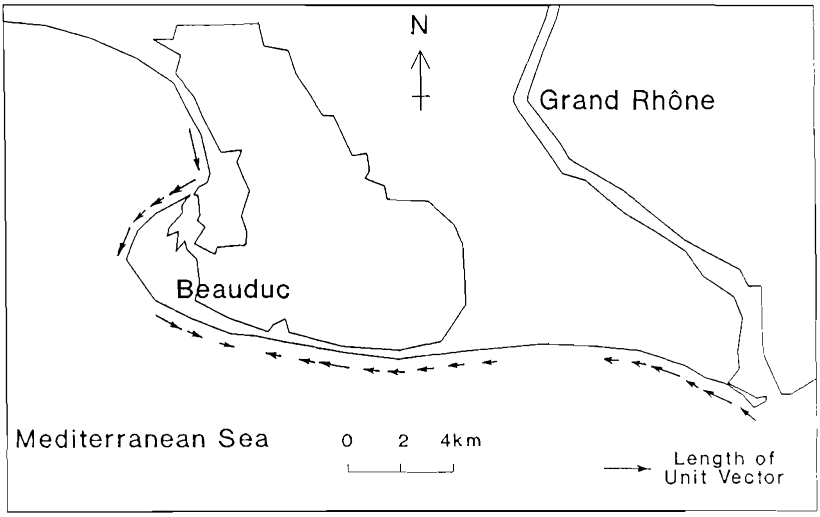

Figure 5. Residual patterns in grain size trends along the coastline of the Rhône Delta.

may be destroyed by the mixing of the material from various sources.

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