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Patterns of sediment reworking and transport over small spatial scales on an intertidal sandflat, Manukau Harbour, New Zealand

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Abstract

Measurements of physical sediment reworking and transport were conducted at 22 experimental sites within a 250 × 500 m study site on a sandflat at Wiroa Island (Manukau Harbour, New Zealand), in order to examine spatial patterns of sediment transport, and its relationship to passive advection of benthic fauna (Turner et al., 1997). Sediment reworking and transport were measured four times during February 1994 as replacement of dyed sand in pans of sediment buried in the intertidal zone, change in total height of the sediment column in the pans, and as deposition in tube traps with openings flush with the bed (bedload traps) and at 15 cm above the bed (water-column traps). Sediment reworking replaced about 2–3 mm of sand per day, with increasing cumulative transport to a depth of 20 mm during the study period. In addition, there were site-specific differences among sampling dates. Spatial structure in sediment reworking was analyzed by trend surface analysis. Depending on date, variance in reworking was influenced by location within the study site, tidal shear stress (model generated), and elevation on the sandflat. Analysis of residuals demonstrated that sediment reworking at times contained inherent spatial structure after accounting for the effects of other explanatory variables. Bedload trap rates in the final sampling period accounted for most of the variance in deposition indicated by sediment height. Sediment reworking and transport are variable over scales of 10^1–10^2 m, as well as over a period of days, such that measurements determined in single point studies cannot necessarily be extrapolated over larger spatial scales. Patterns of sediment reworking and transport patterns provide a template against which to compare patterns of faunal transport. However, the linkage will be most apparent when 1) sediment reworking and transport are substantial in magnitude, 2) there is significant *XY* spatial structure to the pattern of sediment transport at the scale of the study, and 3) the fauna of interest are at least potentially transported as bedload (e.g. shelled forms). © 1997 Elsevier Science B.V.

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1. Introduction

Sediment reworking by waves and tides in coastal marine environments is important in a variety of biological and geochemical processes including oxygen penetration, solute exchange, diagenesis, particulate deposition and resuspension, and the advection of benthic fauna (Grant, 1985; Graf, 1992; Huettel et al., 1996). A topic that has received recent attention is the ability of sediment transport to influence the post-settlement movement of bivalves, gastropods, and other infaunal species (Emerson and Grant, 1991; Armonies, 1994; Roegner et al., 1995; Commito et al., 1995a,b). Although these studies suggest that sediment transport can completely alter the primary larval settlement patterns, extrapolation to patterns at the scale of a sandflat is difficult because direct measurements of sediment transport which span spatial scales are rare (e.g. Anderson et al., 1981). Research efforts have focused on event-driven variation in sediment transport over larger spatial scales, i.e., entire sandflats (Dolphin et al., 1995) or on small-scale patterns such as ripple topography (Hogue and Miller, 1981; Eckman, 1979). Measurements of variables such as grain size and bed morphology have proved to be useful in defining sediment transport pathways (Gao and Collins, 1994). However, measurements of changes in bed level used to determine erosion/deposition patterns have mostly been across larger spatial scales including beach faces and estuarine sediment types (Carling, 1982; Childers et al., 1993; Medina et al., 1994) rather than within single habitats.

It has been shown that macrofaunal distribution and post-settlement dispersal and colonization vary over several spatial scales (cf. Thrush et al., 1997; Turner et al., 1997). Therefore, our emphasis in the present study was on describing the spatial variability in sediment reworking and transport, and identifying the controlling factors over scales of 10^1–10^2 meters, on an intertidal sandflat. To do this we addressed the following questions:

1. How does sediment reworking and transport vary over the study site?
2. Do spatial patterns in sediment reworking and transport vary over periods of days?
3. What environmental factors (e.g. bathymetry, currents and waves) contribute to the observed pattern of sediment reworking and transport?

Spatial variability in sediment reworking and transport was measured over a 250×500 m study site on an intertidal sandflat in the Manukau Harbour, New Zealand. Results from complementary studies of sandflat tidal currents (Bell et al., 1997) and juvenile bivalve transport (Turner et al., 1997) were used to identify the potential consequences of sediment transport for the advection and distribution of macrofauna.

2. Study site

Studies were undertaken in the Manukau Harbour, a large (370 km^2) estuary with extensive intertidal areas, on the west coast of the North Island, New Zealand (37° 02′ S, 174° 41′ E). The study site was on a large intertidal sandflat attached to Wiroa Island (Fig. 1(a)), with homogeneous sediment grain size and topography. The study site has a gentle downshore slope (0.097°), except in the southeastern corner which drops off more steeply (Fig. 2). The sediments are well-sorted fine sands, largely bare of vegetation except for occasional small patches ($<$10 m diam.) of colonizing seagrass (*Zostera*). Distinctive topographic features are small wave and/or current-generated ripples (3–10 cm wavelength, 0.5–1 cm amplitude) and in places ridges and runnels (15 m wavelength, 5–10 cm amplitude; Dolphin et al., 1995). Feeding pits (20–30 cm diameter, 10–15 cm deep) formed by rays (*Myliobatis tenuicaudatus*) are moderately abundant. Tidal currents in the area are generally weak, but waves are generated by local winds with a fetch up to 17 km with a south–west wind at high tide (Dolphin et al., 1995). Further details of the sediments and physical setting are given in Bell et al. (1997). Detailed measurements of sediment reworking and transport were made at 22

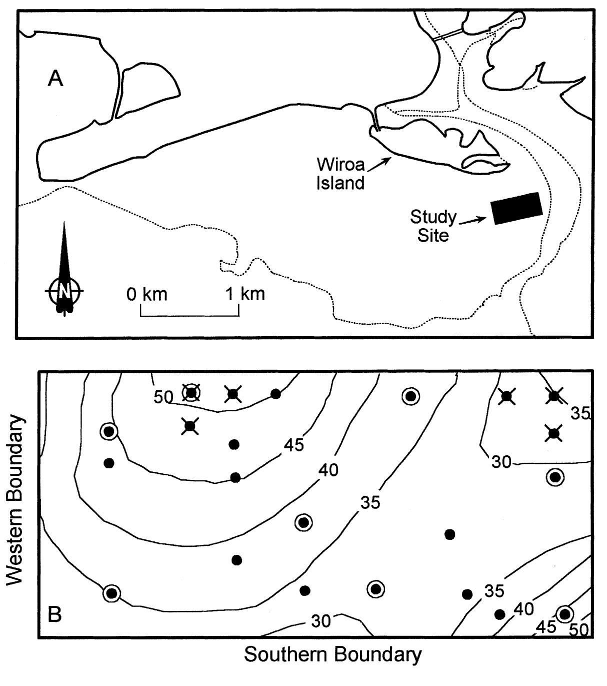

Fig. 1. (a) Map of the Manukau Harbour study site at Wiroa Island. (b) The location of the 22 experimental sites in relation to densities (ind 0.25 m^{-2}) of large ($>$15 mm shell length) *Macomona liliana* within the 250×500 m study site are shown (●). The eight experimental sites where water-column traps were located are also shown (circled). The six experimental sites where the CV's for the bedload trap data were calculated are marked with crosses.

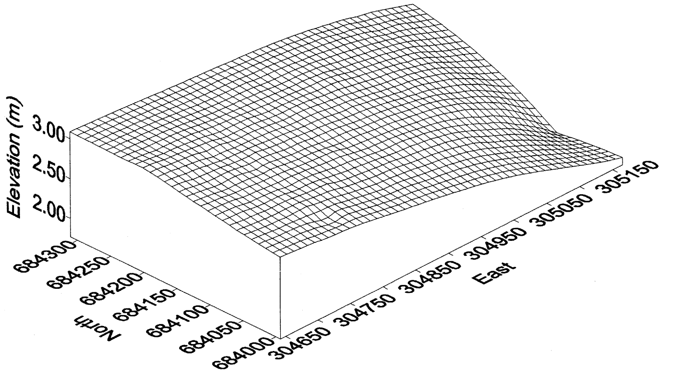

Fig. 2. Map of the surface elevation of the 250×500 m study site, referenced to mean low sea level. North and East units are meters.

experimental sites (Fig. 1(b)) chosen as being representative of a variety of densities of the dominant tellinid bivalve (*Macomona liliana*), a species of primary interest in the faunal dynamics of this flat (Legendre et al., 1997; Thrush et al., 1997; Turner et al., 1997).

3. Materials and methods

3.1. Field measurements of sediment reworking and transport

Sediment reworking was measured by two methods: (1) Dyed sand was placed in buried pans (marker beds) to track reworking by currents and waves, observed as replacement by ambient sand (Grant, 1985). The ''new'' sand height is thus a measure of the depth to which transport or mixing occurred and is relevant to shallow-dwelling infauna that are affected by this mobile layer. This measure is cumulative through time such that with continued transport, the dyed sand will be reworked to ever-increasing depths. (2) Changes in bed level were examined by a variation on a ''buried plate'' method wherein an object is buried in the sediment and measurements of sediment column height above this fixed reference are made as an indication of deposition or erosion (Pickrill, 1979; Grant et al., 1990; Emerson, 1991). As with the dyed sand method, the buried plate technique only detects net changes in the depth to which sediment transport occurs, i.e. it does not record bi-directional events which do not affect overall transport depth or net erosion/deposition. (3) Sediment transport was measured directly by trapping bedload and suspended sediments using sediment traps with the openings set flush with the bed and at 15 cm above the bed respectively (Emerson, 1991; Commito et al., 1995a,b).

Dyed sediment was prepared from sand collected from the study site, washed in hydrogen peroxide to remove organic matter, rinsed with freshwater, sieved (500 mm) to remove shell material, dried in the sun, and then dyed with red fluorescent paint chips

(Radiant Red–JS-Rd3035 9484, Magruder Colour Company, California) dissolved in acetone. After air-drying to remove acetone, the red sand was placed into aluminium baking pans ($20 \times 14 \times 4.5$ cm deep) and transported to the field site. The pans were buried flush with the sediment surface at the 22 experimental sites in the in the study site. The sediment in the pans was wetted with seawater and small holes were pierced in the bottom of pans to allow drainage at low tide. At each experimental site, six pans were placed in a line at 1 m intervals, avoiding irregular surface topography features such as ray pits. The long axis of the pans was oriented parallel to the long axis of ripples. At each site there were two replicate pans containing dyed sand and four additional pans used for faunal colonization experiments (Turner et al., 1997). Pans were placed (7 February) so that dyed sand treatments were not adjacent to one another.

Pans were sampled on 8, 11, 14, and 21 February at low tide, using a 1 cm diam. transparent plastic syringe to core the surface of both ripple crests and troughs in each of the two replicate dyed sediment pans at every site. The height of ambient accumulated sediment (‘‘new sediment’’) above the red dyed sand was measured with a ruler along the syringe. This variable is subsequently referred to as ‘‘new sediment height’’ (mm), and is the mean of the two replicates, specific to measurements made on ripple crests or troughs. For the bed level measurement, a thin metal rod was inserted into a crest and a trough in each pan to measure sediment column height above the pan bottom. This variable is subsequently referred to as ‘‘total sediment height’’ (mm) and is specific to measurements made on ripple crests or troughs. Sediment samples obtained for analysis of grain size showed that grain size was uniform throughout the study site (see Bell et al., 1997).

Sediment traps consisted of PVC tubes (4 cm internal diam., 50 cm length) either buried flush with the bed (bedload traps, all 22 sites) or projecting 15 cm above the sediment surface (water-column traps, eight sites; see Fig. 1(b)). Traps were deployed by insertion into permanently buried PVC sleeves (6.5 cm internal diam., 55 cm long), arranged in line with the pans. At low tide on each sampling date, the traps were removed, the contents (water + sediment) emptied into sampling bags, and the traps redeployed. Once the fauna were removed from the sediment (see Turner et al., 1997), sediment transport rates from traps were derived from sediment that had been oven-dried at 60°C for 48 h. Trapping rates were expressed as kg dry mass m^{-2} trap area $(day)^{-1}$. Trap samples from the first two dates were mislabeled and are not reported.

3.2. Hydrodynamic modelling

Tides and currents were measured at the site and used to calibrate a finite element hydrodynamic model (RMA-2) in the study site (Bell et al., 1997). The model was then used to generate peak ebb and flood tide velocities and peak bed shear stress for a mean tide at each node of a 20×20 m grid within the sampling plot. Details of the modelling are described in Bell et al. (1997). Flood and ebb shear stress specific to the 22 experimental sites derived from the latter model output were used as independent variables in statistical analyses of sediment transport. Although wave models have also been generated for the study site (Bell et al., 1997), their output is specific to prevailing wind directions which did not occur during the study period, and were therefore not included in the present analysis.

3.3. Statistical analyses

The null hypothesis in our analysis was that sediment reworking and transport were constant over the study period (no date effect), and similar between experimental sites (no site effect). For dyed sand and bed level measures of reworking, a preliminary analysis of variance was carried out to establish that there were significant temporal and location differences in both variables. For brevity, these ANOVAs are not shown. Paired *t*-tests which maintain site-specific comparisons are reported as *a posteriori* tests to compare sediment transport measures between dates, adjusting the a level for the number of tests. Multiple regression was used to relate sediment reworking and transport to physical variables derived from models (ebb and flood shear stress) and measurements (elevation). Since the pan locations do not form a regular grid, trend surface analysis was used instead of spatial correlograms to detect spatial structures in sediment reworking and physical variables in relation to the *XY* grid. These methods of spatial analysis are described in Legendre and Fortin (1989). Briefly, a multiple regression of variable *Z* is performed as a polynomial function of the *X* and *Y* coordinates of the sampling sites (to allow for a non-planar response surface) to determine the significance of spatial patterns. Specifically, after centring ($X -$ mean X, $Y -$ mean Y), the X and Y coordinates were used to construct a third-order spatial polynomial of the coordinates on a flat map. The terms (monomials) used in the polynomial regression equation are the following: X, Y, X^2, XY, Y^2, X^3, X^2Y, XY^2, Y^3. In all analyses, an overall significance level $\alpha = 0.05$ was used.

4. Results

4.1. Temporal changes in new sediment height

Experimental pans equilibrated rapidly with respect to the ambient sediment, and although there was occasional scouring of pan corners, in general the pans assumed the appearance of the surrounding sediment, including the presence of bedforms. Reworking of dyed sand in the experimental pans was apparent on the day following initiation of the experiment, with new sand added to a depth of 1–20 mm below the sediment surface. As expected, there was a deepening of the transport layer during the experiment, a trend observed in both ripple crests and troughs (Fig. 3(a)). On the last sampling date, the new sand replaced the dyed sediment to depths ranging from 3–35 mm. Paired *t*-tests for site–site comparisons between dates ($\alpha = 0.008$ to accommodate six tests) indicated that the depth of newly transported sediment at crests was significantly greater on date 4 (21 February) than any of the other dates ($p < 0.001$) and reworking was significantly greater on date 3 (14 February) than on either 8 (date 1; $p = 0.003$) or 11 February (date 2; $p < 0.001$).

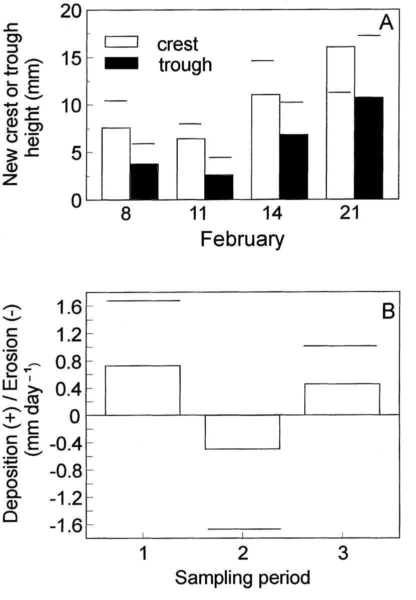

Fig. 3. Means (+SD) of sediment reworking and transport results for the 22 experimental sites. (a) Depth of reworking (thickness of new ambient sediment on top of dyed sediment) derived from sediment pans, measured at both ripple crests and troughs. (b) Mean change (+SD) in total sediment height over the study period expressed as deposition/erosion normalized to time: Sampling period 1=8–11 February, 2=11–14 February, 3=14–21 February.

A comparison of mean crest and trough heights indicates that ripples in the pans developed a height difference similar to the ambient sediment (~1 cm). This aspect was maintained throughout the experiment (Fig. 3(a)). In every case (4 dates), new crest and new trough height within each of two replicate pans on a single date were significantly correlated. Total crest and total trough height (see below) within replicate pans were correlated in seven of eight similar comparisons. These results suggest that for both new and total sediment height, measurements at the ripple crests alone provide adequate representation of the patterns of sediment transport. In the following analysis, we thus refer to new and total sediment height to indicate measurements made on the ripple crests.

4.2. Temporal changes in total sediment height

A second measure of sediment reworking, ripple crest height above a fixed depth (total sediment height, mm), shows that in addition to replacement of dyed sand by sediment from adjacent areas, there were net changes in bed level among the sampling periods. The differences between total sediment height for each site between two time periods provide a measure of deposition (+ values) and erosion (− values), standardized to time, which can be used as a variable in subsequent analyses. Fig. 3(b) shows that the first and last periods were characterized by deposition, while the second period was erosional. Changes in bed level were on average <1 mm day^{-1}, but were in some cases several mm day^{-1}. Paired *t*-tests ($\alpha = 0.017$ for three tests) confirm that deposition was significantly greater in period 1 compared to period 2 ($p = 0.004$) and that deposition was significantly greater in period 3 compared to period 2 ($p = 0.005$).

4.3. Bedload traps

Bedload transport rates were two orders of magnitude greater than water-column trap rates, due to the closer proximity of the bedload traps to the near-bed sand transport layer (Fig. 4). Comparison of bedload and water-column trap data between the second (11–14) and third periods (14–21 February; normalized to daily rates) shows that bedload transport was significantly greater during the latter period (paired *t*-test, $p < 0.001$), but that such increases could not be detected in water-column transport (Wilcoxon signed ranks test due to small sample size; $p = 0.123$). The increased pan deposition which occurred from dates 3 to 4 (period 3, Fig. 3(b)) was reflected in the significant regression equation across sites between bedload trap data and erosion/deposition data ($r^2 = 0.53$, $p < 0.01$, $n = 22$):

$$\text{Total net deposition day}^{-1} = 0.031\ (\text{Bedload deposition day}^{-1}) - 1.048 \qquad (1)$$

Hourly winds recorded at adjacent Auckland Airport during the study period indicated increased wind speed in period 3 (mean = 4.9 ms^{-1} ±2.1 SD compared to periods 1 and 2 (means = 2.9 ms^{-1} ±1.6 SD and 3.2±1.8 SD, respectively). Waves generated by these stronger winds may account for the increased bedload transport during period 3.

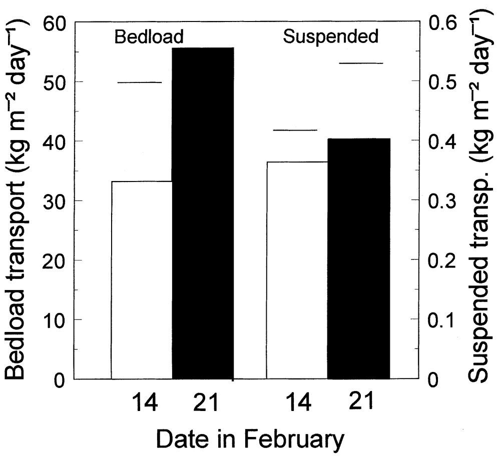

Fig. 4. Results of bedload ($n = 22$; means +SD) and water-column traps ($n = 8$; means +SD) for two collection periods (11–14 February and 14–21 February) on Wiroa Island sandflat.

4.4. Sediment reworking and physical variables

Hydrodynamic model output indicates that tidal currents across the study site are ebb-dominated with significantly greater peak ebb (mean = 0.074 Nm^{-2} ± 0.004 SD) than flood bottom shear stress (0.034 Nm^{-2} ± 0.018 SD; paired *t*-test, $n = 180$, $p < 0.0001$). Surface contour maps show that peak ebb and flood shear stress are generally higher on the northeastern portion of the study site, corresponding to the border of Pukaki Creek (Bell et al., 1997). Based on our median sediment grain size of ~144 mm, we estimate that critical shear stress for erosion would be on the order of 0.1N m^{-2} (Miller et al., 1977). As expected under non-storm conditions, the peak shear stress predicted by the hydrodynamic model is less than the critical stress, especially during flood tide, and therefore sediments are unlikely to be entrained under typical tidal conditions. Bell et al. (1997) report a similar conclusion.

New sediment height was analyzed using models that included shear stress (ebb and flood) and elevation (Table 1). Using simplified multiple regression equations with only the significant terms, (Table 1(a)), or models including all three environmental variables (Table 1(b)), the coefficient of determination (R^2) decreases with time. Thus, the spatial distribution of new sediment height becomes increasingly difficult to explain as a function of available physical variables. On the first two dates, elevation is the best predictor of new sediment height (Table 1(a)). This result underscores the importance of some aspect of topography in controlling sediment transport. On 14 February, causality changes and ebb shear stress becomes the only predictor of new sediment height. On 21 February, elevation becomes significant again in the combined model of Table 1(b), or in a model that includes the almost-significant flood stress variable ($p = 0.053$), but it is not possible to obtain a model with single variables significant at the 0.05 level (Table 1(a)), probably due to lack of power of the data set.

4.5. Spatial variation in sediment reworking measures

Although the multiple regressions with all three environmental variables are able to explain up to 32% of the variance in new sediment height (Table 1(b)), there is still substantial variance that remains unaccounted for. We therefore pose the questions: (a) is there some significant spatial structure remaining in the data, after the effect of the explanatory variables has been controlled for; and (b) is there a change in the spatial pattern of reworking among sampling dates? In order to answer these questions, we computed a partial trend surface analysis, i.e. a partial regression of new sediment height on the *XY* spatial polynomial, controlling for the effect of ebb and flood sheer stress and elevation (Borcard and Legendre, 1994). We then examine whether *XY* monomials remain significant in the residuals.

On 8 February, the spatial term *XY* in the polynomial equation was significant ($p = 0.0453$), indicating that the regression residuals still contained some significant spatial structure. The coefficient of determination (R^2) increased slightly when including the monomial *XY* into the multiple regression model together with the three explanatory variables (Table 1(b)).

Table 1
Multiple regression equations for variable new sediment height

(a) Multiple regression equations: significant terms only

Date	R^2	p	Intercept	Variable	Partial Regr Coefficient
8 February	0.284	0.0002	−17.24	Elevation	9.15***
11 February	0.250	0.0006	−13.61	Elevation	7.38***
14 February	0.205	0.0020	39.17	Ebb stress	−381.21**
21 February				None	

(b) Partitioning of variance

	February 8		February 11		February 14		February 21	
Component of variance	R^2	p	R^2	p	R^2	p	R^2	p
Environmental variables	0.316	0.0015	0.297	0.0026	0.284	0.0036	0.148	0.0962
Environmental variables + spatial polynomial	0.383	0.0007	0.638	0.0001	0.403	0.0004	0.479	0.0023

(a) Ordinary partial regression coefficients are given for significant explanatory variables. Significance levels are indicated by ** = 0.01, *** = 0.001
(b) Multiple regression equations and trend surface analysis for new sediment height to examine the importance of spatial pattern in the residual variance unexplained by the three environmental variables, ebb stress, flood stress and elevation. The R^2 and p-values given for the environmental variables are for models including all three of these variables. The environmental variables + spatial polynomial (trend surface) add the variance due to the significant monomials as given in the text.

On 11 February, the spatial monomials X^2, X^3 ($p=0.0008$), X^2Y ($p=0.0002$) and XY^2 ($p=0.0001$) all remained significant after controlling for the effect of the explanatory variables, indicating that the regression residuals retained important spatial structure. The coefficient of determination (R^2) more than doubled when including these spatial terms in the multiple regression model, together with the three explanatory variables (Table 1(b)).

On 14 February the spatial term Y^3 remained significant ($p=0.0082$), showing the extent of significant spatial structure in the regression residuals (Table 1(b)). The amount of variance explained increased from 28 to 40% when including the monomial Y^3 in the multiple regression model, together with the stress and elevation variables.

On 21 February the spatial monomials Y ($p=0.0020$), Y^2 ($p=0.0052$), X^2 ($p=0.0119$), X^2Y ($p=0.0002$) and XY^2 ($p=0.0017$) all remained significant after controlling for the effect of the explanatory variables (Table 1(b)). The increase in R^2 when including these spatial terms in the multiple regression model was more than twice that determined for the three explanatory variables alone. Among the four dates, the changes in the significance of various monomials in the polynomial equations are indicative of change in spatial pattern (i.e. among sites) of sediment reworking in the study site.

A polynomial trend surface analysis of erosion/deposition rates derived from total sediment height data indicates that for 8–11 and 11–14 February, there are no significant trend surface equations, even with the addition of any explanatory variables. In addition, for both periods, the spatial distribution of erosion/deposition values is not significantly related to ebb or flood shear stress or elevation. A three-dimensional spike scatterplot of erosion/deposition indicates that period 1 contains largely spatially uniform values of deposition (Fig. 5). Similarly, the second period contains a number of spatially similar values of erosion. The third period (14–21 February) has an apparently more heterogeneous distribution of sediment transport, and is largely depositional (Figs. 3 and 5). For this period, there was a significant trend surface equation, but a partial trend surface analysis (partial regression of net deposition on the spatial polynomial; Borcard and Legendre, 1994) showed that there is no significant spatial pattern left after controlling for the bedload trap data which accounted for all the significant spatial variation found in the deposition data for 14–21 February (Eq. (1)). These results underline the close correspondence between transport measures during period 3 and the potential importance of wave-induced sediment transport, and/or wave–current interaction during this time of greater wind speeds.

4.6. Summary

The above analyses based on new sediment height show there are (1) temporal changes in sediment reworking and transport which occur over a scale of days, (2) temporal changes in the relative importance of tides and elevation in influencing the pattern of sediment reworking and transport measures, and (3) underlying spatial structure in sediment reworking and transport which is time-dependent and cannot be accounted for by the measured physical variables. In contrast, daily deposition/erosion based on total sediment height measurements contained no spatial structure during the first two periods, but during 14–21 February had the same spatial pattern as bedload

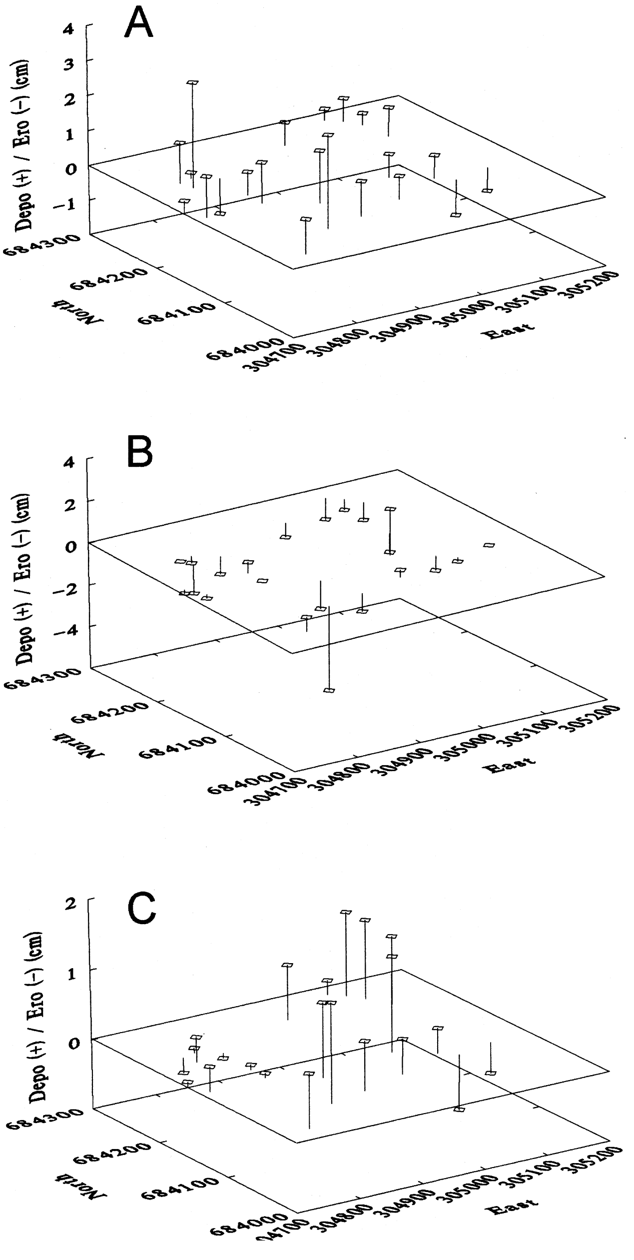

Fig. 5. Three-dimensional spike scatterplot of erosion/deposition (measured at ripple crests, normalized to daily rates) between sampling dates. Locations correspond to the 22 experimental sites shown in Fig. 1. Positive values (above zero *XY* plane, symbols up) indicate deposition and negative values (below zero *XY* plane, symbols down) indicate erosion. (a) Period 1 (8–11 February); (b) Period 2 (11–14 February); and (c) Period 3 (14–21 February). North and East units are meters.

transport measured by the traps. The interpretation of these data relative to faunal distribution rests on comparisons of the various indicators of sediment reworking and transport and their suitability as spatial indicators of passive transport processes.

5. Discussion

5.1. Comparison with previous work

Spatial scales of intertidal sediment reworking and transport have been described as varying from centimetres to kilometres with most attention focused on the extremes. For example, small-scale (cm) patterns of flow, sediment saltation and resuspension associated with ripple crests and troughs have been documented in both flume and modelling studies (Davies, 1979; Baas, 1994; Oost and Baas, 1994). Over larger spatial scales (10^2–10^3 m) there are a number of estuary-wide studies of sediment dynamics based on either survey techniques (Collins et al., 1981) or fixed rods to measure changes in sediment height (Pickrill, 1979; Carling, 1982). In a mesoscale study of a 150×600 m area of intertidal mudflat, Anderson et al. (1981) found that some regions of the study site were erosional while others were concurrently depositional. Similarly, Carling (1982) observed adjacent areas of deposition and erosion on sandflats bordering a salt marsh in South Wales. During periods of deposition, rates of ~0.34 mm day^{-1} were measured, comparable to the mean of 0.56 mm day^{-1} measured at Wiroa Island between periods 3 and 4 (Fig. 3(b)).

Although our study site appears homogeneous in elevation, grain size, and ripple morphology, the measures of sediment reworking and transport that we utilized exhibit variability in sediment movement even over scales of tens of metres. The variability that occurs over this scale may be assessed by comparing adjacent sites. If we consider the two places in our study site where there are contiguous groups of three experimental sites (Fig. 1(b)) and use date 4 as an example, bedload traps displayed coefficients of variation (CV) of 6% (in the NW end of the study site) and 32% (in NE end of the study site), with a range of 29% over the whole study site (22 experimental sites). In comparison, Emerson (1991) found that bedload trap rates had a CV=20–30% in a 10×30 m intertidal area. Commito et al. (1995a), (1995b) found low variability (CV<10%) in bedload measurements using identical traps to ours in an area (~40 m scale) just east of the grid.

5.2. Spatial structure in sediment reworking and transport

Our studies at Wiroa Island comprise the first analysis of the spatial distribution of sediment reworking and transport in the marine environment. Trend surface analysis shows that the depth of reworking indicated by marker beds of dyed sand contained significant structure related to the *XY* grid, explaining as much or more variance than the tidal stress and elevation variables (11 and 21 February; Table 1). This residual variance suggests that some topographic aspect of the flat may regulate the pattern of sediment reworking. For example, mesoscale changes in slope of the flat and their interaction with tidal height will alter local wave energy (Makino, 1994), and therefore sediment reworking and transport, an effect seen locally in the southeastern corner of our study site (Bell et al., 1997). Xiankun et al. (1994) suggested that shear stress on tidal flats of the Wash is increased by local topography, stating that ''the creeks/gullies . . . constitute in themselves a large-scale bedform'' (p. 709; see also Bauer et al., 1995). The addition of form drag due to berms or other features (<100 cm relief) to total friction in the benthic boundary layer would increase shear stress and sediment transport (Grant et al., 1993; Wheatcroft, 1994). On the sandflats adjacent to the study site, there are also low relief ridges, runnels, and drainage channels that may influence sediment reworking and transport in the study site.

Given that the mesoscale topography of the flat (ridge–runnel) changes on much longer time scales than those of the study period (Dolphin et al., 1995; Bell et al., 1997), how can we explain the short-term temporal variability observed in sediment reworking and transport measures within our study site? A variety of studies have documented the relationship between resuspension, sediment transport and wave and tidal action (Carling, 1981; Miller and Sternberg, 1988; Emerson, 1991; Jago et al., 1993; Vincent and Downing, 1994). These studies confirm the notion of Carling (1982) that transport occurs under unsettled rather than average conditions such as those derived from our model output. Changes in the neap–spring tidal cycles influence the interaction of static topography with the flow field, and thus the spatial structure of sediment reworking. This is apparent from the multiple regression of new sediment height (Table 1) where both elevation and current variables may be significant. Moreover, even local changes in ripple size and morphology (cm relief) will affect form drag (Grant et al., 1993; Wheatcroft, 1994; Xu and Wright, 1995). The model grid used to generate shear stress, while sufficiently detailed, would not contain all of the complex spatial and time-dependent interactions (tide, immersion, ripple morphology) that occur within the study site and contribute to the spatial and temporal distribution of sediment reworking and transport. Due to these interactions, observed patterns of sediment transport could not necessarily be extrapolated to more energetic conditions. Moreover, it is highly likely that wind, waves, and wave–tide interactions are important in sediment reworking and transport at the study site (Commito et al., 1995b; Bell et al., 1997).

The depth of reworking indicated by replacement of dyed sand may be a more sensitive indicator of sediment transport than change in total sediment height, since localized transport events (horizontal scales of 10^0–10^1 m) will be recorded. In contrast, tides and waves sufficient to cause a net change in total sediment height are likely the result of flat-wide deposition/erosion. Consequently, new sediment height displays local variation reflected in significant *XY* structure (Table 1). These local reworking effects are also variable between dates. In contrast, change in total sediment height, although significant in magnitude (Fig. 3(b) Fig. 5), has no spatial structure in the first two sampling periods. This finding supports the notion of a uniform and flat-wide response rather than a local response of sediment erosion/deposition. During the period of increasing deposition (period 3, 14–21 February, Fig. 5(c)), change in total sediment height contains significant spatial structure but it is explained by bedload transport (Eq. (1)).

5.3. Sediment reworking and faunal transport

If sediment reworking as measured by new sediment height and total sediment height are assumed to equate with disturbance and resuspension of juvenile bivalves from neighbourhood surface sediments (e.g. Roegner et al., 1995), then they may provide a ''template'' for predicting the distribution and relative abundance of these fauna within the study site. Results from the first three study dates may be more difficult to assess since they displayed less concurrence among transport measures and generally lower levels of sediment transport. The most energetic periods are those most likely to transport juvenile bivalves (Emerson and Grant, 1991; Roegner et al., 1995). Our results predict that if these fauna have passive behaviour similar to sand grains (Butman, 1987), then during study period 4, the distribution of colonizing fauna should correspond to the erosion–deposition pattern seen in Fig. 5(c). Depending on the mechanisms of faunal dispersal (saltation, byssal drifting, swimming; Cummings et al., 1993; Roegner et al., 1995), the water-column traps may provide another pattern of deposition, however their small sample size in our study precluded an analysis similar to bedload traps.

Commito et al. (1995b) utilized the same bedload traps in a small area of the Wiroa Island flat, east of the present study site. During their study, wind speeds were much higher, and corresponding trapping rates were an order of magnitude greater than our values. They suggested that sediment transport would erase small scale heterogeneity in faunal distribution/abundance caused by biotic interactions and similar disturbance. This is likely true on the scale of their measurements (~40 m). However, our results show that deposition/erosion has significant spatial structure on the flat over scales of 10^1–10^2 meters, and at times this pattern is correlated with spatial structure in sediment transport as measured by bedload traps. Therefore, it is less desirable to simply measure sediment reworking and transport at one or two sites on the sandflat in order to explain spatial structure in faunal transport and colonization processes. Besides knowing that animals are transported by physical processes, a spatial component allows elaboration on how transport impacts population structure of juvenile size classes, potentially answering questions about the fate of transported animals. Legendre et al. (1997) point out that the effects of physical variables on observed faunal distribution are both size and species dependent. Colonization experiments (Thrush et al., 1997; Turner et al., 1997) extend these sampling observations by allowing an assessment of how faunal patterns evolve in response to physical forcing.

5.4. Conclusions

In conclusion, this study has demonstrated that sediment reworking and transport are variable over scales of 10^1–10^2 m, as well as over a period of days to weeks. Measurements of sediment reworking and transport made with three methods indicate that results determined in single point studies cannot necessarily be extrapolated over larger spatial scales. Moreover, the forcing mechanisms appear to be a complex interaction between topography, tidal currents, and wind waves, which further complicates both the prediction and spatial extrapolation of transport. In terms of faunal transport, sediment reworking and transport patterns provide a template against which to compare animal distribution. However, the linkage will be most apparent when 1) sediment reworking and transport are substantial in magnitude, 2) there is significant *XY* spatial structure to the pattern of sediment reworking and transport, and 3) the fauna of interest is at least potentially transported as bedload (e.g. shelled forms). The companion paper by Turner et al. in this volume examines faunal colonization in adjacent sediment pans to test these assertions.

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