Evidence of the Importance of Deposition and Winnowing of Surficial Sediments at a Continental Shelf Scale

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ABSTRACT

Surficial sediment grain sizes in Bass Strait, southern Australia, vary widely across the Strait. When compared to a calibrated numerical hydrodynamic model of the M2 tidal circulation, this grain size variation was found to correspond with tidal current intensity. In particular, a correspondence between the sediment entrainment threshold velocity and the maximum tidal current was observed. The results highlight the importance of deposition and winnowing at a continental shelf scale while indicating that current strength is the dominant factor determining the nature of the modern sea bed throughout Bass Strait.

ADDITIONAL INDEX WORDS: Sediment dynamics, hydrodynamic model, tidal currents.

INTRODUCTION
In a New Zealand estuary with an abundant supply of modern shell detritus, the location of sandy deposition depended on the residual tidal circulation (BLACK et al., 1989). (The residual is the vector-averaged net current over a tidal cycle at a point in space.) Sandy deposition was found to occur in locations where residual currents were decreasing spatially while shell lags characterised zones where residual currents were increasing. This correspondence was found to be more than qualitative when BLACK and BARNETT (1988) obtained a direct quantitative relationship between the measured shell content of surficial sediments (as a percentage of the surface area) and the measured tidal residual velocities at a series of sites in a New Zealand tidal inlet.

A correspondence with current intensity, rather than residual circulation, has been identified also in estuaries and tidal inlets, and grain size contours are often used to infer much about the hydrodynamics and sediment dynamics (e.g. SWIFT and LUDWICK, 1976; DAHM, 1983). Others have used numerical models to relate tidal currents to bottom sediments (PINGREE and GRIFFITHS, 1979; BOWMAN et al., 1980; PROCTOR and CARTER, 1989) on the continental shelf scale. This paper examines whether similar inferences between tidal currents and grain size can be made on the continental shelf, in Bass Strait, southern Australia.

Several bed sediment sampling programs have been conducted in Bass Strait. For example, JONES and DAVIES (1983) classified the bed at each site as relict or modern, after analysing 365 bed sediment samples from Bass Strait and nearby regions. However, they had no information about the magnitude of the tidal currents, making it difficult for them to hypothesise about the mechanisms causing the differences in bed types. Extending the prior work, BLOM and ALSOP (1988) utilised the numerical hydrodynamic model results of FANDRY et al. (1985) to broadly specify the zones of high and low current intensities. BLOM and ALSOP (1988) found a general correspondence between grain size and current strength, although they did not attempt to relate the grain sizes and sediment entrainment threshold speeds to Bass Strait currents in detail. In this paper the relationship of the surficial sediments to both the modern current strength and current residual is considered.

DESCRIPTION OF THE REGION
Bass Strait (Figure 1) is an approximately rectangular sea some 400 km by 200 km in extent, consisting of a shallow platform mostly about 70 m below sea level. The Strait is flanked by 4–5
Figure 1a. Distribution of mean grain size in Bass Strait (after Morrow and Jones, 1983). The coarse mode was ignored when derived from modern benthos in bimodal and polymodal sediments. The segments marked "?" were not sampled by Morrow and Jones. These locations were later sampled by Blom and Alsop (1988).

Figure 1b. Percentage of gravel in samples collected by Morrow and Jones (1983). The segments marked "?" were not sampled by Morrow and Jones. These locations were later sampled by Blom and Alsop (1988).
km deep ocean to the east and west and by land to the north and south. Measurements indicate strong tidal flows at the entrance cross-sections in the east and west (Hodgkinson et al., 1990). Wind-driven circulation is fast on the shelf at the east of the Strait in east Gippsland (Jones, 1980). Secondary currents are associated with barometric pressure, and ocean circulation driven by temporal differences in level between the two bounding oceans. Coastal trapped waves, evidently entering the Strait from the west and trapped on the northern shoreline by the negative Coriolis force in the southern hemisphere, have been identified (Middleton, personal communication). These have typical periods of about 10 days in response to prevailing weather patterns along the southern Australian coast. The currents they generate however are less than those associated with tides and local wind over much of Bass Strait.

The western Victorian coastline is commonly subjected to Southern Ocean swell from the southwest quadrant, while on the eastern coastline, waves from the south-eastern quadrant are largest, as Tasmania shelters this zone from the south and south-west. Wave heights vary considerably around the Strait due to changing coastline orientations and the degree of local sheltering. In the exposed regions of eastern and western Bass Strait, significant wave heights of 10 m can occur during storms (Esso, 1990; Reid (CSIRO Hobart), personal communication). Within central Bass Strait, the wave climate varies spatially. The median significant wave heights are about 1–2 m with the smallest waves occurring along the northern Tasmanian coastline.

FIELD PROGRAM

As part of a wider study to investigate wave/current interaction on the continental shelf, a field measurement program was established in east Gippsland, eastern Victoria to measure tides, currents and sea bed characteristics on a shore-normal transect 9 km long. The program included examination of the relationship of the sea bed type to the prevailing tidal currents and wave orbital motions, which is subject of this paper. Parry et al. (1990) simultaneously conducted a bed sediment survey in adjacent regions.

The shore-normal transect extended from near the shoreline in 20 m depth to the 50 m depth contour offshore (Figure 1). InterOcean S4 and Neil Brown vector-averaging current meters were placed at three locations along the transect in 20 m, 40 m and 50 m depths. The current meters take instantaneous readings of current every 0.5 sec in two orthogonal directions, and average the results over a selected time interval, typically 15–30 minutes. The meters are therefore suitable for mixed wave and current environments.

A near-bed and “surface” current meter was placed on the shoreward and offshore moorings and a surface meter only was deployed on the third. (Unfortunately, the near-bed meter at the offshore mooring failed.) The surface meters were all at 10 m below mean sea level, while the near-bed meters were 3 m above the bottom. The meters were suspended from buoyed moorings with at least 120 kg of buoyancy to minimise their movement when surface waves were present. A tilt reading on the instrument indicated that the meters were within 4° of vertical at all times. In “burst mode,” the S4 current meters recorded wave orbital motion at 2 sec intervals for 2 minutes every 30 minutes. The average of these values provided the mean currents.

To specify the nature of the sea bed and to measure bedform wavelength and height, an underwater video camera was lowered to the sea bed at 23 locations along the transect. The camera was placed on a metal frame and oriented perpendicular to a large vane attached to the metal frame which kept the entire system at a constant alignment with the currents. A graduated scale board was suspended from the frame such that it penetrated the sand bottom at right angles to the bedform crests, thereby highlighting the bedform profile for subsequent analysis.

OTHER DATA

Six other data sets were utilised. These were:

1. surficial bed sediment samples of Jones and Davies (1983) (2) bed sediment samples of Blom and Alsop (1988) (3) surficial samples of Parry et al. (1990) as analysed by George and Black (1989) (4) surficial samples of Morrow and Jones (1988) (5) current meter records from Bass Strait after Hodgkinson et al. (1990), as utilised by Fandry et al. (1985) and (vi) tidal amplitudes around Bass Strait taken from the Australian National Tide Tables (1990) and other sources (Hinwood and Wallis, 1991). The first four define the bed sediments in the Strait, while the last two provide for calibration of the numerical hydrodynamic model.
JONES and DAVIES (1983) specified the nature of the sea bed in Bass Strait and along the Tasmanian continental shelf after analysing 365 surface and near-surface sea bed samples primarily recovered by pipe dredging (Figure 1). The sample grain sizes and percentages of gravel were obtained by a combination of sieving for the coarse fraction, settling velocity measurement for the sand fraction and pipette analysis for the muds. In bimodal distributions, the coarser fraction was ignored when it consisted of shell debris from the “existing benthic community.” This introduced an ambiguity into the grain size results so the percentage of gravel contained in each sample is examined in conjunction with the grain size data in this paper. BLOM and ALSOP (1988) completed the survey of JONES and DAVIES by sampling throughout central Bass Strait.

PARRY et al. (1990) conducted a detailed benthic survey of the east Gippsland continental shelf when 52 samples were collected over a region 83 km (longshore) by 30 km (offshore) (Figure 1). These samples were analysed by GEORGE and BLACK (1989) by a combination of sieving for the sand fraction greater than -2.25 phi (4.76 mm), and settling velocity analysis for the remainder. The muds (> 4 phi or 0.063 mm) were washed out. A prior survey, made by MORROW and JONES (1988) in east Gippsland, provided additional and supportive data.

A number of tide gauge and current meter deployments have been made in Bass Strait (HODGKINSON et al., 1990), initially for the purpose of establishing a numerical hydrodynamic model of the circulation (FANDRY et al., 1985).

NUMERICAL MODELLING

The model code (2DD) applied in Bass Strait has been described in a number of publications and is the same as the code used to investigate the formation of sand banks in New Zealand estuaries (BLACK et al., 1989). An explicit, leap-frog solution is applied to solve the 2-dimensional momentum and conservation equations.

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = - \frac{\partial \xi}{\partial x} - \frac{g(U^2 + V^2)\gamma}{C^2(d + \xi)} + \frac{\rho \gamma |W| W}{\rho(d + \xi)} x + A_m \left( \frac{\partial^4 U}{\partial x^2} - \frac{\partial^4 U}{\partial y^2} \right) \tag{1}
\]

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = - \frac{\partial \xi}{\partial y} - \frac{gV(U^2 + V^2)\gamma}{C^2(d + \xi)} + \frac{\rho \gamma |W| W}{\rho(d + \xi)} y + A_m \left( \frac{\partial^4 V}{\partial x^2} - \frac{\partial^4 V}{\partial y^2} \right) \tag{2}
\]

where \( t \) is the time, \( U, V \) are mean vertically-averaged velocities in the x, y directions respectively, \( g \) the gravitational acceleration, \( \xi \) the sea level above a horizontal datum, \( d \) the water depth below datum, \( f \) the Coriolis parameter, \( \rho \) the water density, \( W \) the wind speed at 10 m above sea level while \( W_x \) and \( W_y \) are the x and y components, \( \gamma \) is the wind drag coefficient, \( \rho_a \) the density of air, \( C \) is Chezy’s C and \( A_m \) the horizontal eddy viscosity coefficient.

The bed friction is quadratic with roughness represented by a Chezy’s C obtained from the roughness length \( z_o \) as,

\[
C = 18 \log_{10}(0.37(d + \xi)/z_o) \tag{4}
\]

The wind was not modelled in the simulations presented.

The new model of the Strait presented in this paper has a finer grid size than the model presented by FANDRY et al. (1985) (10 km rather than 17 km) to improve resolution. The bathymetry was digitised from the detailed surveys undertaken by Australian National Mapping (Canberra). The 10-km grid made it possible to include schematic representations of Port Phillip and Western Port Bays on the Victorian coastline and a more accurate representation of the entrances to Bass Strait on the sections through King and Flinders Island (Figure 1). The extra resolution was also expected to result in a more accurate water current simulation.

A clamped sea level boundary condition was employed at all open boundaries. The tidal amplitudes and phases used at the model boundaries (Figure 2a) were similar to those of FANDRY et al. (1985) but some modifications were found to be required during model calibration. Simulations with the 5 major constituents (\( M_2, S_2, O_1, K_1, N_2 \)) were undertaken but only the dominant \( M_2 \) is presented here.

Sea Bed Roughness Length

During the calibration phase, bed friction was set to \( z_o = 0.005 \) m and eddy viscosity was taken
The open boundary off eastern Tasmania was placed at the location where tidal amplitudes and phases were measured. The inset shows the open boundary sea levels and phases used in the simulation. Boundary levels were linearly interpolated between the referenced positions.

Figure 2a. Vertically-averaged flood currents in Bass Strait. The length of the arrow tails represents the current intensity. The full model grid is shown. The open boundary off eastern Tasmania was placed at the location where tidal amplitudes and phases were measured. The inset shows the open boundary sea levels and phases used in the simulation. Boundary levels were linearly interpolated between the referenced positions.

Figure 2b. Vertically-averaged ebb currents in Bass Strait. The length of the arrow tails represents the current intensity. The full model grid is shown. The open boundary off eastern Tasmania was placed at the location where tidal amplitudes and phases were measured.
Table 1. Bedforms observed with underwater video (Parry, personal communication). All bedforms were symmetrical suggesting a wave origin.

<table>
<thead>
<tr>
<th>Site</th>
<th>H (m)</th>
<th>L (m)</th>
<th>( z_o ) (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.03</td>
<td>0.15</td>
<td>0.30</td>
<td>irregular</td>
</tr>
<tr>
<td>16</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>no bedform</td>
</tr>
<tr>
<td>18</td>
<td>0.04</td>
<td>0.22</td>
<td>0.36</td>
<td>regular</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>1.10</td>
<td>0.32</td>
<td>highly regular</td>
</tr>
<tr>
<td>34</td>
<td>0.08</td>
<td>0.06</td>
<td>0.53</td>
<td>regular</td>
</tr>
</tbody>
</table>

as 10 m²/sec⁻¹ at all model cells. A typical value for the roughness length \( z_o \) is 0.0007 m over gravels or undulating sand (Black and Healy, 1982), but over bedforms the roughness length can be much higher and is better estimated (Black and Healy, 1982) using the formula (Lettau, 1969),

\[ z_o = \frac{H^2}{2L} \]  

where \( H \) is the bedform height and \( L \) is the wavelength. Thus, using the bedform heights and lengths observed by Parry (personal communication) (Table 1), the calculated values of \( z_o \) obtained using equation (5) suggest very high frictional retardation. However, measurements during the field program indicated that the tidal currents mostly flow parallel with the coast, while the bedforms were wave generated and therefore aligned more perpendicular to the coast. Thus, the tidal currents generally flow along, rather than across, the bedform crests, so that the bedforms have a lessened influence on the velocity profile in the absence of surface waves (Black and McShane, 1990). Moreover, the relative orientations will vary across Bass Strait and wave action changes with the water depth and surface wave period. Thus, an average value of the roughness length of \( z_o \) = 0.005 m, found to be the most satisfactory value during the calibration phase of the hydrodynamic model, was applied universally. Accordingly, this value was considered to be the most appropriate for calculation of sediment threshold speeds (see below).

Hydrodynamic model calibration results (Figure 3, Table 2) were similar to those of Fandry et al. (1985). This occurred because similar boundary conditions and bed roughness were employed. However, with the finer grid size and some modifications to the open boundaries, a number of minor improvements were achieved (Figure 3a and b), particularly in southern Bass Strait along the Tasmanian coast where the tidal amplitude predicted by the model was formerly too large.

RESULTS

Bed Sediments

The sea bed of Bass Strait is characterised by a wide variety of grain sizes and bed types. The bed sediment surveys indicated coarse sediments and high gravel contents in two sections (1) through King Island on the western side of the Strait and (2) through Flinders Island to the east (Figure 1a and b). In central Bass Strait, however, the bed sediments were fine and muddy. Fine to medium sand occurred along the Gippsland shelf and near the coast between Cape Otway and Port Phillip Bay.

The surveys of Parry et al. (1990) and Morrow and Jones (1988) in eastern Bass Strait identified a cross-shelf variability in bed types. Medium well-sorted sands were found on the beach (George and Black, 1989). The sediments deposited nearshore were coarse sands (medians between 0 and 1 phi). Isolated pockets of very coarse sand to granules (medians between 0 and -2 phi) reflected the higher proportions of large shells and pebbles at these sites. The sediments became progressively finer with distance from the shore and were almost entirely medium sands (medians between 1 and 2 phi), with only one site comprising fine sand (median between 2 and 3 phi).

The detailed underwater video observations on the cross-shore transect confirmed these findings. The sea bed changed from symmetrical wave-generated sandy ripples nearshore, becoming more shelly in the troughs as the depth increased. Further offshore, a change to an irregular bed colonised by marine growth occurred near 35 m depth. The bed was composed of finer sediments with subtle irregularities and an increasing abundance
Figure 3a. M₂ tidal amplitude contours (cm) taken from the hydrodynamic model compared with data. The data was extracted from a number of sources as summarised by Hinwood and Wallis (1991).

Figure 3b. M₂ tidal phase contours (°) taken from the hydrodynamic model compared with data. The data was extracted from a number of sources as summarized by Hinwood and Wallis (1991).
of marine flora growing out of the sediments or attached to shell detritus.

Hydrodynamics

The tides flood into both sides of Bass Strait simultaneously (Figure 2a) and then ebb from both sides about 6 hours later (Figure 2b) in response to the dominant M2 tidal constituent. Consequently, the currents are fastest through the sections containing King and Flinders Islands and are slow in central Bass Strait where the opposing flood flows meet and where the ebbing flows separate. The central region can be considered as a velocity node of a standing wave, with the antinodes at the entrance sections.

Root-mean-square (RMS) current intensities averaged over the tidal cycle (Figure 4) show that M2 tidal currents are very fast in the narrow channels between islands and overall in the two sections through King and Flinders Island. RMS speeds in central Bass Strait are only about 0.08 m·sec⁻¹. On the east Gippsland shelf, the currents decrease eastward.

Correspondence Between Grain Size and Currents

While there are some exceptions, the nature of the sea bed (Figure 1a and b) exhibits a clear correspondence to the tidal currents across Bass Strait (Figure 4). First, the north/south transects through King and Flinders Islands in the west and east of Bass Strait respectively are characterised by the coarsest sediments and by the fastest currents. Second, central Bass Strait is characterised by muddy fines and a very slow RMS current speed. Third, the finer sediments along the Gippsland shoreline are reflected by a reduction in current speeds eastward along the shelf. Fourth, the grain size contours and current contours are approximately aligned on the eastern side of Bass Strait.

Deviations within the overall correspondence (e.g. the grain size contours south of Port Phillip Bay which appear to be unrelated to the velocity contours) may be, at least in part, the result of the grain size analysis procedure. The coarse mode in polymodal sediments was ignored when the coarse material was derived from modern benthos (Jones and Davies, 1983). This may be particularly important because the modern detritus is most likely to be correlated with modern current patterns.

The analysis of sediments in East Gippsland by George and Black (1989) at sites adjacent to those sampled by Jones and Davies (1983) indicated grain sizes which were equivalent to the sizes obtained by Morrow and Jones (1988), but were up to 1 phi unit coarser than that found by Jones and Davies. The grain sizes of Jones and Davies (1983) would undoubtedly vary with location, as the percentage of modern sediments changed.

Investigations in estuaries have indicated that the shell or other detritus should be retained if an assessment of the nature of the bed is to be made (Black and Barnett, 1988; Black et al., 1989). For example, in the narrow entrance to Bass Strait between north-eastern Tasmania and the islands below Flinders Island, the model predicts very fast currents (Figure 4) but the sediment grain sizes are unexceptional (Figure 1). The sea bed is often lagged in the entrance gorge of estuaries where currents are fastest, due to the high speed and the spatially increasing residual current as the entrance is approached (Black et al., 1989). While not apparent on their grain size diagram, the tabulated data of Jones and Davies (1983) describes the site under the fastest flows as “basaltic rock fragments,” and no grain size analysis was undertaken. The lack of sand and the presence of basaltic rock forming a lag therefore concurs with the estuarine findings.

Other factors could mask the relationship between grain size and hydrodynamics. Examples are the variability in tidal constituents across the Strait, variations in bed friction and the relative intensity of near-bed wave orbital motion and wind-driven currents.

Wave Influences

A more detailed examination of wave influences is to be undertaken after the establishment of a numerical hydrodynamic and sediment transport model of the Parry survey region. However, for completeness in this paper, it is useful to draw some general implications from the data.

The east Gippsland data showed that medium sands on the beach become coarser offshore before becoming finer again at greater depths. Patterns similar to this have been previously described by Jago (1981) and Morrow and Jones (1988). Jago's measurements showed that the grain sizes reflected variations in wave height as the waves shoaled across the shelf and changes in tidal currents with offshore distance. A similar explana-
tion can be proposed for eastern Bass Strait. As the waves move into shallower water and their near-bed orbital velocities increase, the bed stresses increase. This results in (1) larger bedforms (Nielsen, 1979) and (2) more potential for winnowing.

Winnowed sediment can be transported away by (1) the longshore currents (wind-driven or tidal) (2) the Stokes’ drift current (Longuet-Higgins, 1953) which acts in the direction of wave propagation under shoaling waves or (3) the shoreward sediment transport resultant under shoaling waves associated with the faster currents under the crest than trough of shoaling waves. Dahm and Healy (1985) evoked the Stoke’s drift phenomenon to explain the grain size patterns on New Zealand’s east coast.

The Gippsland data indicate that fines may have been winnowed out of the sediments in the intermediate depths and transported shorewards. This would explain the presence of coarser sediment offshore than on the beach. Either of the onshore directed mechanisms noted above could be responsible for bringing these fines shoreward. Further offshore in deeper water, wave orbital motion is much reduced and other processes, including longshore transport due to tides and wind-driven flows, are expected to be responsible for the observed bed types as discussed above.

On the cross-shore transect, the transition from a rippled bed into finer sediments colonised by marine growth occurred in about 40 m depth. Jones and Davies (1983) described this transition as a mud depositional limit, which occurred at 45 m off the eastern Tasmanian coast. They note that this compares with 30 m in the North Sea and 73 m in the English Channel (Mccave, 1971) and about 50 m off the Washington and Oregon shelves off the western United States (Smith and Hopkins, 1972). Jones and Davies found the western Tasmanian shelf to be mud free and they suggested that this was due to the higher incidence of long period swells on this coastline exposed to the prevailing westerlies of the Southern Ocean. To quantify the relationship between the hydrodynamics and sediment transport at east Gippsland, an analysis of wave and current measurements and numerical modelling of the region is underway. However, the results of this detailed study are beyond the scope of the present paper.
Table 3. Threshold velocity of quartz grains over a plane and rippled bed ($z_0 = 0.005$ m, $d = 70$ m) and the corresponding equivalent RMS threshold velocity.

<table>
<thead>
<tr>
<th>Grain Size (phi)</th>
<th>Threshold Velocity at 1 m above Bed ($U_{th}$) ($m \cdot s^{-1}$)</th>
<th>RMS Threshold Velocity ($U_{rms}$) ($m \cdot s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.065</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>0.125</td>
<td>0.16</td>
</tr>
<tr>
<td>2</td>
<td>0.250</td>
<td>0.18</td>
</tr>
<tr>
<td>1</td>
<td>0.500</td>
<td>0.23</td>
</tr>
<tr>
<td>0</td>
<td>1.000</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Sediment Threshold Velocity under Tidal Currents

Miller et al. (1977) found that the threshold uni-directional current velocity at 1 m above the bed for quartz-density sands over a plane bed was

$$U_{th} = 0.63D^{0.29}$$ (6)

$D$ is normally taken as the median or mean grain size ($mm$) and $U_{th}$, the threshold velocity at 1 m above the bed, has units $m \cdot sec^{-1}$. Over a rippled bed, Madsen (1976) noted that the threshold velocity was obtainable using the standard Shields’ sediment threshold curve, when the appropriate roughness was applied. The threshold velocity measured at 1 m above the bed is less over bedforms than over plane beds due to the added retardation of the vertical velocity profile near the bed caused by form drag over the ripples. The formula of Miller et al. (1977) therefore provides an upper limit on the entrainment speeds measured at 1 m above the bed.

To account for the bed roughness over bedforms, the method of Black and Healy (1986) was applied with $z_0 = 0.005$ m and $d = 70$ m. The threshold currents predicted for plane and bedformed beds were then compiled in Table 3 for a variety of grain sizes.

Three scale factors are required before the predicted threshold velocities can be compared with the model results.

1. The numerical model provides a vertically-averaged velocity $U$. If a logarithmic boundary layer profile is present then $U_{th}$, the vertically-averaged threshold velocity, is related to $U_{th}$ as

$$U_{th}/U_{rms} = \log_{10}(0.37d/z_0)/\log_{10}(1/z_0)$$ (7)

Entering equation (7) with $d = 70$ m and $z_0 = 0.005$ m for average conditions, indicates that the ratio $U_{th}/U_{rms}$ is 1.61.

2. The RMS velocity of the tidal cycle $U_{rms}$ is related to the maximum velocity during the tidal cycle $U_{max}$ as $U_{rms}/U_{max} = 1/\sqrt{2}$, when the tidal cycle velocities are sinusoidal. This occurs over much of Bass Strait because bathymetric influences, such as sheltering by headlands which cause an asymmetry in the tidal cycle velocities, are mostly unimportant. This was confirmed by calculating the Eulerian residual currents over the Strait and these were nearly always very close to zero.

3. During peak spring tides when the 5 major tidal constituents are in phase, the maximum total current $U_{all}$ is approximately $U_{all} = 1.6U_{M2}$, where $U_{M2}$ refers to the $M_2$ constituent only (Hodgkinson et al., 1990).

By applying these factors, the RMS threshold (vertically-averaged) velocity for comparison with the RMS velocities from the model simulation is $U_{rms} = U_{th}/1.41$. Values of these threshold speeds are compiled in Table 3.

When these values are compared with the measured grain sizes (Figures 1a and 4) there is a remarkable general correspondence, even though the relative orientations of the grain size and RMS velocity contours vary. The 3–4 phi material in central Bass Strait which has a threshold of 0.14 m·sec$^{-1}$ lies within the 0.14 m·sec$^{-1}$ RMS contours. The 1–2 phi sands ($U_{rms} = 0.21$ m·sec$^{-1}$) are bisected by the 0.2–0.24 m·sec$^{-1}$ contours on both sides of the Strait. Most remarkable is the narrow band of 1–2 phi sand stretching southeast from Wilson’s Promontory which coincides almost exactly with the 0.2–0.24 m·sec$^{-1}$ RMS velocity contours, even to the point of turning west near Flinders Island.

Although the tidal currents should not be considered in isolation of the wave orbital motion in nearshore cases, the 2–3 phi and 3–4 phi bands near Lakes Entrance ($U_{rms} = 0.14–0.17$) occur where the currents are diminishing to the east from about 0.24 to 0.12 m·sec$^{-1}$.

In the coarsest regions on the transects through King and Flinders Islands, the grain sizes are finer than expected. That is, the currents are greater than the threshold velocity for beds coarser than 0 phi, but the mean grain sizes are mostly in the range 0–1 phi. As the percentage gravel in these regions is very high, the removal of modern coarse material from the samples prior to the grain size analysis could explain this discrepancy.
over, the gravel lag sometimes forms a thin veneer protecting underlying sands, either of relict origin or trapped by falling between the gravels, perhaps at slack tide. In these cases, care needs to be exercised with the grain sampling technique to ensure that only surficial sediments are sampled.

Winnowing and Spatial Current Variability

Jones and Davies (1983) suggested that the sands of the rises flanking central Bass Strait basin are modern and more or less in equilibrium with present conditions. They also considered the muddy sediments of central Bass Strait to be mainly modern deposits but beds at some locations on the north/south transects through King and Flinders Islands were thought to be relict.

The correlation of grain sizes with current intensity identified in this paper suggests that the bed throughout much of Bass Strait has come into equilibrium with the modern hydrodynamic environment. This suggests that the sediment population of the Bass Strait region has been subdivided into grain size classes by natural processes which are grain size selective, such as winnowing or deposition. As such, the bed is more likely to be relict in the eroding regions (with no local supply of sediment) and modern in zones of deposition if new material is being added to the Bass Strait continental shelf. However, the nature of the bed is related to the modern environment in all cases. The palimpsest sediments in the eroding areas are responding to modern currents.

In central Bass Strait, tidal currents are unable to transport medium sands and with depths of about 70–80 m wave action will have only a small effect. For example, the maximum bottom orbital velocity of a 2 m wave with a 12 sec period in 70 m water depth is approximately 0.14 m·sec⁻¹. Only waves with heights greater than 5 m have orbital velocities exceeding 0.35 m·sec⁻¹. Thus, only fine sands and muds can reach the central region of the Strait in most conditions. In general, the grain sizes of a depositional bed reflect the maximum carrying capacity of the local currents, i.e. only the sub-population of grains finer than the carrying capacity of the current can reach the bed in question.

The presence of the finer sediments and greater predominance of mud in Central Bass Strait, compared with the coarse sediments elsewhere, therefore suggests deposition. This is in accordance with analyses referred to by Jones and Davies (1983) which found modern pollen in the bed sediments, indicating a modern depositional environment. The fines may overlie sediments reworked during the Pleistocene and Holocene as suggested by Jones and Davies (1983), particularly as the depths in Bass Strait indicate that the western and eastern entrance transects were partly or totally sub-aerial when sea levels were lower than their present level (Blom, 1988).

The regions of fastest flow in the Strait correspond with high gravel content, indicative of a winnowed bed. The converse of the principles governing the depositional bed operates in this case. The gravels are too coarse to be transported through adjacent regions and are therefore expected to be relict, or produced by local shellfish. If the modern detritus is eliminated from the samples, the results of Jones and Davies (1983) are in accordance with the hydrodynamic evidence, although the coarsest of these relict sediments may be larger than the grain size which is in equilibrium with the modern flow.

The residual circulation in Bass Strait is close to zero as there is negligible topographic influence over much of the Strait. The tidal orbits are approximately closed at most locations. Thus, a correlation with residual circulation is not expected to occur in Bass Strait. However, deposition in central Bass Strait occurs where the tidal currents approaching the region of deposition are decreasing spatially and the lagged gravel beds occur in the zone where the approaching currents are increasing spatially.

On the Gippsland shelf, wind-driven circulation causes fast currents to occur temporarily. A general correspondence of grain size to tidal currents alone is therefore not expected, as wave and wind-driven processes have to be considered also.

CONCLUSIONS

The surficial sediment grain sizes and percentages of gravel in Bass Strait are indicative of the present day tidal current intensities. In central Bass Strait, tidal currents are slow and finer modern deposits predominate. In the faster current flows such as the cross-sections through King and Flinders Islands, the finer material evidently has been winnowed out of the bed sediments leaving a relatively coarse detritus. The hydrodynamics suggest that the bed in these cross-sections is likely to be relict, with the exception of modern shell detritus. The grain sizes in the present environment are quantitatively indicative of modern current strengths. Residual tidal circulation in Bass

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Strait is mostly small due to the lack of significant topographic influences. Thus the deposition is not related to the residual tidal circulation but is occurring in regions where the tidal currents decrease spatially as they approach the deposition, while relict beds are exposed in locations where approaching tidal currents increase spatially.

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La taille des sédiments de surface des fonds du détroit de Bass (Australie du Sud) varie beaucoup. Comparée à un modèle numérique hydrodynamique calibré de la circulation tidale M2, la variation de la taille des grains est fonction de l'intensité du courant de marée. En particulier, on a observé une correspondance entre la vitesse critique d’entraînement du sédiment et le courant de marée maximal. Les résultats soulignent l’importance du vannage et du dépôt à l’échelle du plateau continental et montrent que la force du courant est le facteur dominant qui détermine la nature du fond de la mer moderne à travers le détroit de Bass.

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La granulometria de los sedimentos superficiales en el Estrecho de Bass, en el sur de Australia, varían al través del Estrecho. Comparadas las variaciones en la granulometría con un modelo numérico hidrodinámico calibrado, de la onda M2, se halló que se correspondían con la intensidad de la corriente de marea. En particular, se observó una correspondencia entre la velocidad de iniciación de arrastre del sedimento y la máxima corriente de marea. Los resultados resaltan la importancia de la deposición y de la remoción a la escala de la plataforma continental, indicando que la fuerza de la corriente es el factor dominante, determinando la naturaleza del fondo moderno del mar al través del Estrecho de Bass.

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