Physical Controls on Development of Lagoon Sand Deposits and Lagoon Infilling in an Indian Ocean Atoll

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ABSTRACT


Lagoon infill from autochthonous sediment, derived from reef flats, is the dominant constructional processes in coral reef environments once reefs attain a stable elevation with respect to sea-level. Tide- and wave-induced currents were measured and the hydraulic response of bioclastic sediments examined to assess physical controls on development of lagoon sand bodies and infill of the Cocos (Keeling) Islands atoll, Indian Ocean. Results show that the sediment transport system is active during mean energy conditions. Peak wave-induced currents (140 cms-1 east, 97 cms-1 south) entrain 100% and 97% of reef flat sediment respectively. Potential mobility values decrease through shallow passages (100%, 73% east and south) to sand aprons/flats (73%, 11%, east and south) and shallow lagoon (11% PM) reflecting the lagoonward decline in wave-induced current energy. Unidirectional ocean-side reef flat to lagoon currents transport sediment through passages to sand bodies.

This study identifies a hydrodynamic block, generated by opposing passage and lagoon currents at higher tidal stages, preventing the transport of sediment to the shallow lagoon. This is of great significance as it constrains the active sediment transport system between the reef flat and sand bodies and controls the areal expansion of sand bodies.

Measured higher rates of sediment transport on the east and deposition in a spatially limited area are responsible for vertical accretion of sand aprons and the development of the flood delta morphology. Lower rates of transport and deposition in a greater spatial area are responsible for the subtidal nature and low relief of southern sand flats.

Physical constraints on sand body development and lateral extent have several important implications for infilling the Cocos lagoon: 1) sand aprons have reached their lateral progradation limit; 2) lagoon infill will become more dependent on allochthonous supplies of sediment than autochthonous delivery of reef flat produced sediments; 3) lagoon infilling will take much longer than 4000 years as indicated by Guppy (1889).

ADDITIONAL INDEX WORDS: Atoll infilling, carbonate sediments, hydrodynamics, sediment transport, atoll sedimentation.

INTRODUCTION

Lagoonal infill of carbonate sediment is the major constructional process in coral reefs once they attain a stable elevation with respect to sea level (MARSHALL and DAVIES, 1982; TUDHOPE, 1989; TUCKER and WRIGHT, 1990). The primary source of sediment is the productive reef flat (BURN, 1991) and approximately eighty percent of sediment produced in this environment (STODDART, 1969) is available to be transported: down the fore-reef slope (LAND, 1979; HUBBARD et al., 1981); around the reef flat to form islands or cays (GOURLAY, 1988, 1990); or into lagoons (FRITH, 1983; MARSHALL and DAVIES, 1982; HUBBARD, 1986; MACINTYRE et al., 1987). Lagoonal sand wedges or sediment aprons are one of the major morphological products of autochthonous input of reef derived sediments to lagoons (KORNICKER and BOYD, 1962; Hopley, 1982; MACINTYRE et al., 1987; Guilcher, 1988; TUDHOPE, 1989; SMITHERS et al., 1994). Most investigations of these deposits have examined surficial or subsurface sediments to determine the source of sediments or used radiometric dating to determine rates of sedimentation (MARSHALL and DAVIES, 1982; FRITH, 1983; COLBY and BOARDMAN, 1989; SMITHERS et al., 1994). Yet, Despite the suggested importance of these deposits in lagoon infill (Guppy, 1889; WOODROFFE et al., 1994) few studies have examined the physical processes controlling their development and contemporary rates of sediment accumulation.

The objective of this paper is to present findings of the examination of wave- and tide-induced current controls on the development of lagoon sand bodies in the Cocos (Keeling) Islands, Indian Ocean. Differences in sand wedge morphology around the atoll are explained, contemporary rates of sediment accumulation are evaluated and the role of sand wedges in the infill of the atoll discussed in relation to historical-based interpretations of lagoon infill.

THE COCOS (KEELING) ISLANDS

The Cocos (Keeling) Islands are located in the eastern Indian Ocean (Figure 1). Composed of two atolls, South Keeling atoll (shown in Figure 1, hereafter to referred to as Cocos) is
Figure 1. Location of Cocos (Keeling) Islands. Note distribution of sand aprons and flats, reef edge to shallow lagoon transects showing morphology of eastern sand apron and southern sand flat, and position of current meters for hydrodynamic measurements along each transect (symbols). Boxed areas, a, b, c, are shown in greater detail in Figure 2. Black and grey tone arrows in lagoon depict major flow patterns on the rising and falling tide respectively. Shallow passages exhibit lagoonward flowing currents throughout all tidal cycles.
the focus of this study. It is composed of 26 islands situated on a continuous horseshoe-shaped reef flat that runs from Direction Island to the north of West Island and encloses a lagoon of 102 km². To the north and northwest two deep (15–20 m below MSL) and wide (2 and 5 km) passages provide the only permanent connection between the lagoon and ocean. The lagoon is divided into two broad zones: a shallow southern region (0.0–3.0 m depth below MSL) and a deeper northern section (depths 10–20 m below MSL). A network of deep (20 m) blue holes punctuate the central lagoon and this area connects the shallow and deeper regions. The ocean-side reef flat varies in width from 80 m (east) to 1500 m (south), has an elevation close to mean-low-water mark and is exposed during lower spring tide levels. Continuous Dumpy Level surveys undertaken from Home Island to South Island found the southern reef flat is 0.1 m higher than the east (KENCH, 1994a). Twelve inter-island shallow passages (depths up to 1.5 m below mean sea level (MSL)) connect the reef flat and lagoon on the eastern and southern rim of the atoll. However, as reef flats are exposed at lower tidal levels these passages do not provide a continuous connection to the lagoon.

**Sand Bodies**

Large (up to 1500 m in length) sand bodies extend lagoonward of the passages (Figure 1). The reef edge to shallow lagoon profile (from Dumpy Level surveys) of these deposits resembles tidal deltas on the eastern and southern atoll (Figure 1). On the east the deposits rise in elevation (above the level of the reef flat and MSL) before grading back into the shallow lagoon (Figure 1). Sand aprons are intertidal with apron crests exposed up to 50% of tidal cycles during spring tides. In the south sediment deposits do not exhibit this sand wave form and the surface lies below MSL sloping lagoonward from the passage exit (Figure 1). These deposits are not exposed at any part of the tidal cycle. To reflect differences in morphology the terms sand apron and sand flat are used to refer to the deposits from the east and southern sides of the atoll respectively.

GUPPY (1889) initially referred to these deposits as mud flats, however, SMITHERS (1994) and KENCH (1994a) have shown they are composed of unconsolidated and mobile sand-size sediment. The sediments are predominantly composed of detrital coral particles (>50%) with foraminifera and coralline algae of reef flat origin in subordinate fractions. These sediments are distinct from lagoon deposits which do not possess reef-flat-derived secondary constituents, but are characterised by an increase in *Halimeda* and molluscan particles (SMITHERS, 1994; KENCH, 1994a). The sand aprons and flats are largely devoid of living fauna and flora except for the subtidal lagoonward fringes where sparse seagrass (<5% *Thalassia hemprichii*), *Halimeda* and isolated *Callianassid* burrowing mounds are found. Holothurians are also sparsely distributed on the subtidal areas and massive corals (*Porites sp.*) are found in isolated clusters on southern sand flats.

**Previous Studies**

Evidence of lagoon infill in Cocos was first noted by DARWIN (1842) and later FORBES (1879) in the shallow southern lagoon. GUPPY (1889) was the first to attempt a sediment budget for the atoll based upon rates of coral growth and sediment production across areas of reef flat and lagoon containing coral cover. It was recognised that a component of this budget resulted from the autochthonous delivery of reef-flat-derived sediments to the sand aprons/flats. GUPPY (1889) estimated that 5,000 tons yr⁻¹ of suspended sediment was carried into the lagoon, 80% of which was deposited in the first 700 m. Furthermore, the sand aprons were estimated to be prograding at a rate of 1 m yr⁻¹ (the lagoon was estimated to be vertically infilling at 3 mm yr⁻¹). Using these estimates GUPPY (1889) concluded the lagoon would infill within 4000 years and that the total time from initiation to infill for a particular atoll lagoon would be 15–20,000 years.

WOODROFFE et al. (1994) show that infill of the Cocos lagoon began approximately 4,000–3,500 years B.P. following mid-Holocene emergence (relative water level fall of 0.9 m). Radiometric dating of vibrocores retrieved from the southern and eastern shallow lagoon identified higher vertical accumulation rates in sand aprons/flats (0.5–1.0 mm yr⁻¹) than island lee sediments (0.25–0.5 mm yr⁻¹). WOODROFFE et al. (1994) concur with GUPPY (1889) that sand aprons represent progradational infill of Cocos lagoon by reef flat sediments. However, WOODROFFE et al. (1994) do not provide an estimate of rates of sand apron progradation.

**Climate and Hydrodynamic Setting**

Southeasterly trade winds, sustained for more than 85% of the year, are a pervasive feature of the Cocos climate (FALKLAND, 1994). Mean daily wind speed peaks in September (8 ms⁻¹) and becomes more variable between November and March, with weakest mean daily wind speeds of 4.6 ms⁻¹ in February (FALKLAND, 1994). Maximum wind velocity of 27.22 ms⁻¹ experienced during the field program was associated with the passage of Tropical Cyclone Graham.

South-southeastery trade wind driven swell produces a mean wave height at the reef crest of approximately 2 m and the reef flats are dominated by wave energy (KENCH, 1994a). Cocos experiences a semi-diurnal microtidal regime with a mean range of 0.5 and 1.1 m for neap and spring tides respectively. The maximum tidal range is 1.3 m. The lagoon is tidally dominated with currents entering the northern passage on rising tides and draining westward through the northwest passage on falling tides (KENCH, 1994b).

**METHOD**

To document the direction and magnitude of currents that control sediment movement onto the sand bodies hydrodynamic measurements were undertaken. First, Inter-Ocean S4 bidirectional electromagnetic currents meters were positioned in seven mid-passages and two positions behind the sand aprons in the shallow lagoon (Figure 1). Sixteen day velocity records were obtained in which current records represent averages of 120 half second samples spaced at 10 minute intervals. These measurements reflect the `mean' tidal current energy. Second, current meters were positioned on transects in the reef flat, mid-passage, sand apron/flat and shallow lagoon (Figure 1). Half second velocities were record-
ed for 20 minute bursts at high, mid and low tides to identify the magnitude of wave-induced currents and change in this energy across the reef flat and onto sand bodies. These experiments were repeated during neap and spring tides.

To determine the hydraulic response of sediment to incident energy 182 sediment samples were retrieved on transects between the reef flat and shallow lagoon through all passages (Figure 2). As sieve grain-size estimates do not reflect the hydraulic characteristics of mixed (size, shape density and component) bioclastic sediments (MAIKLEM, 1968; BRAITHWAITE, 1973; KENCH and MCLEAN, 1996) samples were settled through a McArthur Rapid Sediment Analyser and are described using the settling velocity distribution. Figure 2 shows the summary pattern of settling velocity characteristics for deposits based on the mean settling velocity of samples (in chi units). This pattern shows a decline in settling velocity character of deposits from fast settling (larger) grains on the reef flat to slower settling deposits (smaller size) on sand aprons.

To determine entrainment characteristics for deposits bulk...
samples were divided into fractions with similar settling properties (termed settling fractions). Settling fractions are analogous to size fractions except they contain particles of varied size, shape, density and component mix). Using settling fractions Kench and McLean (1996) derived an experimental sediment settling versus entrainment threshold relationship for bioclastic material (Figure 3). This threshold relationship combined with maximum measured wave-induced currents enables the potential mobility (PM) of deposits within each geomorphic zone to be determined. Expressed as a percentage potential mobility is determined by establishing, on the cumulative settling frequency curve, the percent of a deposit able to be mobilised at a particular velocity.

Sediment trap experiments were undertaken in shallow passages to provide an estimate of sediment volumes transported through shallow passages onto sand bodies. Smith Helley sediment traps (Graf, 1971) were placed adjacent to current meters in shallow passages throughout the sample period. Traps have an opening 10 cm high by 15 cm wide which capture sediment transported in traction, along the sediment surface, and by saltation. The traps operate on an expansion flow principle. As water and sediment pass through the constricted opening the trap expands causing flow to decelerate and sediment to be deposited. Sediment was retained in mesh bags (mesh size of 3 phi). Traps were aligned with dominant flow direction and were emptied at irregular intervals. Sediment trap material was dried, weighed and weight values multiplied by the trap orifice to passage width ratio to provide a total passage transport estimate.

RESULTS

Selected current records (Figure 4) show that velocity in passages increase sharply 1.5–2.0 hours after low tide and peak (50 cm s⁻¹ and 60 cm s⁻¹, east and south) in the 2 hours prior to neap high tide. Whereas the velocity structure in eastern passages is bimodal, southern passages exhibit an asymmetric velocity structure. Shallow lagoon records (Figure 4) also exhibit a bimodal velocity structure with peak

Figure 3. Experimentally derived threshold vs settling velocity relationship for bioclastic sediments. Source Kench and McLean (1996).

Figure 4. Water level records and selected raw velocity records from passages (1, 9) and shallow lagoon (SE and SW).
velocities (21 cms⁻¹, and 30 cms⁻¹ east and south) of higher magnitude and sustained for longer periods on falling spring tides.

Summary vector plots of tide-induced current directions (Figure 5) show that unidirectional ocean to lagoon flows dominate the shallow passages throughout neap tides. This flow is maintained during spring tides in the south but reversals do occur in eastern passages. These reversals are of low magnitude and short duration. Vectors travel greater distances during neap as opposed to spring tides. Currents behind the sand aprons are tidally modulated and penetrate south-southeast through the deep lagoon toward the terminal end of the sand deposits on the rising to mid-falling tides and drain to the northwest during the mid falling to early rising tide.

Figure 6 shows that high frequency current oscillations occur at the periodicity of gravity waves. The asymmetry of the current records indicate net lagoonward transport. Selected 10 minute high frequency current records (Figure 7) show that peak wave-induced velocities are greater in magnitude than tide-induced currents (Figure 4) and there are differences in current magnitude between the eastern and southern transects. Wave-induced currents are greater in magnitude on the east of the atoll (140 cms⁻¹, 97 cms⁻¹, and 38 cms⁻¹, for reef flat, passage and sand apron) than the south (79 cms⁻¹, 48 cm⁻¹, and 30 cm⁻¹) at highest spring tide. Wave-induced current energy is also rapidly dissipated between the reef flat and sand bodies. Examination of all current records show that for each geomorphic zone the magnitude of currents increases with tidal stage.

**Sediment Mobility Analysis**

Table 1 summarises the mean settling velocity of samples, maximum wave-induced current velocity and estimated potential mobility of these samples. Reflecting the magnitude of currents reef flat samples are totally mobile on the east, and up to 95% mobile on the south. Eastern passage deposits display high mobility values whereas southern passage sediments are only 73% mobile. Mean sediment mobility on sand aprons is 65%. In contrast Southern sand flats and shallow lagoon zones have low mobility values (mean of 11%, range between 3 and 20%).

**Sediment Trap Results**

Details of sediment trap deployments (Table 2) show the eastern passages have much greater transportation rates than the south. The passage of Tropical Cyclone Graham produced an increase in transport of more than 350%. However this was only recorded in two traps. An estimate of the annual rate of sediment transport through the passages is determined using results from this study (Table 2) and those of KENCH (1994a) from lower energy 'doldrum' conditions. Low energy transport rates were assumed to operate for three months per year, during the conventional doldrum period. Normal trade-wind driven transport, measured during this study (Table 2), was assumed to operate for the remainder of the year which dominates transport estimates (Table 3). As tropical cyclones infrequently influence Cocos (FALKLAND, 1994), building storm-driven transport into an estimate is difficult. Furthermore, data on storm frequency is unavailable. In order to recognise expected increases in sediment transport associated with high energy the transport rate for Tropical Cyclone Graham was doubled (Table 3). For the three passages in which sediment transport was not measured the ratio of channel width to transport rate (from measured passages, Table 2) was used to infer the transport rate. The re-
Figure 7. Selected ten minute continuous (0.5 second) velocity records. (A) eastern transect, high tide January 9 1993. (B) southern transect, high tide January 11, 1993.

Table 1. Summary of maximum measured wave-induced currents and range of mean settling velocity of samples within each geomorphic zone. Maximum currents refer to the highest magnitude 0.5 second (wave-induced) velocities recorded within a neap-spring tidal cycle respectively. Source Kench (1994a) and this study.

<table>
<thead>
<tr>
<th>Geomorphic Zones</th>
<th>Range of Sample</th>
<th>Mean Settling Velocity Values (cm s⁻¹)</th>
<th>Max Measured Wave-induced Velocity (cm s⁻¹)</th>
<th>Average Potential Mobility (%)</th>
<th>Range of PM Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reef flat</td>
<td></td>
<td>2.0-5.0</td>
<td>140.0</td>
<td>100</td>
<td>100-100</td>
</tr>
<tr>
<td>Passage</td>
<td></td>
<td>2.0-5.0</td>
<td>97.0</td>
<td>100</td>
<td>100-100</td>
</tr>
<tr>
<td>Passage exit</td>
<td></td>
<td>4.1-4.8</td>
<td>48.0</td>
<td>91</td>
<td>79-98</td>
</tr>
<tr>
<td>Sand aprons</td>
<td></td>
<td>4.3-5.4</td>
<td>38.0</td>
<td>65</td>
<td>42-89</td>
</tr>
<tr>
<td>Southern</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reef flat</td>
<td></td>
<td>2.5-4.0</td>
<td>79.0</td>
<td>95</td>
<td>86-100</td>
</tr>
<tr>
<td>Passage</td>
<td></td>
<td>3.0-4.3</td>
<td>48.0</td>
<td>73</td>
<td>54-99</td>
</tr>
<tr>
<td>Passage exit</td>
<td></td>
<td>3.7-4.5</td>
<td>45.0</td>
<td>79</td>
<td>49-98</td>
</tr>
<tr>
<td>Sand flat</td>
<td></td>
<td>3.9-4.5</td>
<td>30.0</td>
<td>11</td>
<td>7-25</td>
</tr>
<tr>
<td>Shallow lagoon</td>
<td></td>
<td>3.1-4.9</td>
<td>30.0</td>
<td>11</td>
<td>3-20</td>
</tr>
</tbody>
</table>

consultant annual estimate for all passages is 1 275.5 m³. The majority of this sediment, 1 142 m³, is transferred through the eastern passages.

### DISCUSSION

Physical processes are responsible for transport of sediment between the reef flats and lagoonward sand deposits. These physical processes are also shown to constrain the expansion of sand bodies and are responsible for morphological differences in sediment bodies. Results indicate that sand aprons may have evolved in a slightly different manner to that previously reported which has implications for the source and rate of infill of the Cocos lagoon.

### Physical Controls

Observed hydrodynamic characteristics are controlled by gross atoll morphology. Lagoon currents penetrate south through the deep northern passage on the rising tide, whereas the interaction of ocean swell with the reef edge drives wave-induced flow across reef flats and through passages.
Reef flat width and roughness also control dissipation of wave and associated current energy across reef flats (Kench, 1994a, b).

Hydrodynamic processes control potential and actual sediment transport between the reef flat and sand bodies on Cocos. Wave-induced currents are the major mechanism entraining sediment on both sides of the atoll. However, as reflected in the high frequency current records (Figure 7), Kench (1994a) shows that 90% of wave energy is dissipated between the eastern reef flat and passage exits. Furthermore, gravity-wave-driven energy is filtered from the energy spectrum across the southern reef flat (Kench, 1994a). Beyond these zones tidal current activity is the dominant hydrodynamic force. Changes in these hydrodynamic forces between the reef flat and sand bodies on the east and south of the atoll are summarised in Figure 8. The major difference between the two sides of the atoll is the higher wave energy on the eastern sand apron (Figure 8).

Once entrained sediment is carried lagoonward by unidirectional ocean to lagoon flows through shallow passages. This flow reverses for small periods during spring tide conditions on the east which is a result of falling water levels exposing the sand apron crest and disconnecting the sand apron ramp and shallow lagoon. Thiscreates a reefward hydraulic gradient and water flows reefward around low tide. The magnitude of these flows is small. Furthermore, sediment is unable to be entrained on the sand apron and passage environments at these low tide stages as wave energy does not propagate across the reef crest at lower tide levels. Kench (1994a) identifies threshold water depths (0.65 m and 0.70 m, east and south) at the reef crest at which wave energy can propagate across the reef flats which correspond to mid to higher tidal stages. This implies that active sediment transport occurs at these mid-higher water elevations and that entrained sediment must be transferred through the shallow passages toward the sand bodies. Higher wave energy conditions on the east also indicate more sediment is transported toward the eastern sand aprons which is in agreement with sediment trap measurements.

A significant characteristic of circulation in the Cocos lagoon is opposition of unidirectional lagoonward flowing passage currents by south-southeast flowing lagoon currents on the rising to mid-falling tide (Figure 8, and Kench, 1994b).

Table 2. Sediment trap data: deployment location, and estimated transport rates. Rates represent the mean of all deployments over varying timescales. Retained material includes that deposited during Tropical Cyclone Graham.

<table>
<thead>
<tr>
<th>Passage</th>
<th>Mean Weight Retained (kg d (^{-1}))</th>
<th>Mean Channel Width (m)</th>
<th>Daily Rate (kg d (^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.28</td>
<td>429.8</td>
<td>267.3</td>
</tr>
<tr>
<td>1*</td>
<td>5.49</td>
<td>1,814</td>
<td>933.6</td>
</tr>
<tr>
<td>2</td>
<td>0.31</td>
<td>161.2</td>
<td>42.2</td>
</tr>
<tr>
<td>3</td>
<td>0.31</td>
<td>162.4</td>
<td>36.5</td>
</tr>
<tr>
<td>6</td>
<td>0.043</td>
<td>37.5</td>
<td>18.7</td>
</tr>
<tr>
<td>9</td>
<td>0.03</td>
<td>59.0</td>
<td>32.9</td>
</tr>
<tr>
<td>10*</td>
<td>3.089</td>
<td>17,865.6</td>
<td>1,276.1</td>
</tr>
<tr>
<td>12</td>
<td>0.057</td>
<td>31.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

935.8 kg dry weight equals 1 m\(^3\)

Opposition of these flows produces a zone of decelerating currents in which sediment in transport will be deposited. This deposition zone is expected to migrate across the sand bodies depending on relative strengths of passage and lagoon currents. During neap tides stronger passage flows will push this zone across the lagoonward ramp of the sand bodies, whereas, relatively stronger spring tide lagoon currents will push the zone toward passages. During high magnitude storm events in which higher energy waves will propagate through passages and onto sand aprons/flats the deposition zone is expected to migrate into the shallow lagoon. Following mid-falling tide the crests of the intertidal sand aprons are exposed preventing the transfer of sediment to the shallow lagoon.

Table 3. Sediment transport rates and volumes for differing energy regimes. Annual total estimate is also shown.

<table>
<thead>
<tr>
<th>Passage</th>
<th>Doldrum Rate (November-December)</th>
<th>Trade Wind Rate (February-October)</th>
<th>High Energy Rate</th>
<th>Annual Total m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11,477</td>
<td>4,530</td>
<td>27,530</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12,634</td>
<td>70,096</td>
<td>1,394</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12,625</td>
<td>70,068</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5,129</td>
<td>28,460</td>
<td>562</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>41,889</td>
<td>232,468</td>
<td>12,755</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>46,074</td>
<td>261,264</td>
<td>5,175</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2,808</td>
<td>15,582</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>5,215</td>
<td>29,940</td>
<td>572</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8,629</td>
<td>47,888</td>
<td>8,937</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2,808</td>
<td>15,582</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>817</td>
<td>4,530</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

Total 177,062 989,082 27,530 1,275.5

A significant finding of this study is that active sediment transport is constrained within a narrow zone between the reef edge and sand aprons/flats (1.5 km east, 2 km south). There is little opportunity for sediment to be physically transported further lagoonward under mean energy conditions. Predictions of sediment mobility confirm that wave-induced currents are able to entrain sediments between reef flat (97-100% PM) and sand flats/aprons (11-73% PM, Table 1). On both sides of the atoll decreased PM values in passages and on sand bodies reflect the dissipation of wave energy. Reef flats are dominated by entrainment processes, whereas, passages are influenced by entrainment and deposition processes. Due to the low PM values identified on the southern sand flats this zone is dominated by deposition from passages. In contrast the PM of eastern sand apron deposits is relatively high (73%). However, the time asymmetry of hydrodynamic processes blocks movement of this material into the shallow lagoon. The zone of opposing currents is set up during higher tidal stages, when gravity wave-induced currents can mobilise sediment across the sand apron ramp, providing little opportunity for lagoonward transport. Furthermore, as lagoon currents drain to the west the sand apron crest (east) is generally exposed providing a physical barrier to the la-
goonward movement of sediment. As the southern sand flats are not exposed at low tidal stages there is opportunity for further lagoonward transport. However, this transport will be negligible due to the much lower velocities recorded being unable to mobilise grains.

Bioturbing organisms, in particular Callianassid shrimp, have been cited in numerous studies as important mechanisms of biologically induced sediment transport within reef systems (ROBERTS et al., 1981; FRITH, 1983; TUDHOPE and SCOFFIN, 1984; DE VAUGELAS, 1985). As noted earlier, the density of these organisms on the intertidal sand aprons and sand flats is low (less than one m$^{-2}$) with large areas devoid of organisms (intertidal areas) and they are not considered to play an important role in resuspension and subsequent transport of sediment across the Cocos sand aprons/flats.

**The Role of High Energy Events**

The above results and subsequent discussion focus on the role of mean energy events in development of Cocos sand aprons. High energy events are frequently identified as dominant controls on the formation of depositional features in reef environments (TUDHOPE et al., 1985; WARDLAW et al., 1992; SCOFFIN, 1993). While the zone of opposing currents is expected to migrate across the shallow lagoon during high energy episodes, their role in lagoonward progradation of the

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**Figure 8.** Summary of sand apron and sand flat energy processes and transport potential. (A) eastern atoll, (B) southern atoll. Note: zone of opposing currents and decline in potential mobility (PM) of deposits lagoonward.
sand bodies is expected to be limited. Measured transport rates during Tropical Cyclone Graham indicate that daily passage sediment fluxes increase three fold. However, given the infrequent occurrence of extreme high energy events on Cocos (less than one per annum, Falkland, 1994) these events are not considered the most important in formation of the Cocos sand bodies. On an annual basis mean energy processes deliver much larger volumes of sediment to the sand aprons (97.5% of annual total, Table 3). There is little doubt, however, that high energy events would flush sediment from sand bodies into the shallow lagoon. Detailed measurements of transport rates under these conditions have yet to be performed.

Differences in Sand Body Morphology

Hydrodynamic control on aerial extent of sand aprons also accounts for observed differences in morphology of sand aprons and flats. Higher transport rates through eastern shallow passages indicate that greater volumes of sediment have been delivered to the eastern sand aprons. Deposition of this material in the spatially constrained area implies that once sediment has been deposited to the lateral extent possible development of the sand bodies is dominated by vertical sedimentation. Shoaling waves across the sand apron ramp would reinforce apron crest development. In contrast, southern sand flats receive markedly less sediment via passage transport (Table 3). The larger spatial area of this zone coupled with the potential to remove small percentages of slower settling material during the falling tide suggests the sediment receipt to this area has not been saturated as on the east. Thus, the sand flats represent an earlier phase of sand apron development in a zone of lower sediment transport.

CONCLUSIONS

This study shows that physical processes have controlled the aerial extent and development of the Cocos sand aprons/flats limiting their progradation lagoonward. As atoll morphology controls hydrodynamic behaviour the dissipation of wave energy and development of the zone of opposing currents are expected to have operated in a similar fashion since sea-level assumed its present position 3 500 years BP (Woodroffe et al., 1994). The sand bodies have developed by either vertical development across the entire area of the sand aprons, lateral progradation or a combination of the two processes. A unique finding of this study is that, once reaching the zone of opposing currents lateral sand apron progradation has been constrained. Differential transport rates explain differences in morphological development of sand aprons (east) from sand flats (south) with continued deposition in a spatially limited area contributing to continued vertical accretion and development of the apron crest form in the eastern atoll.

Results have several significant implications for the nature and history of lagoon infilling. First, it suggests a rapid slow down and cessation of sand apron/flat progradation and infilling of the Cocos lagoon in contrast to Woodroffe et al. (1994) and Guppy (1889). This is partly supported by a literal interpretation of Guppy's (1889) progradation rates in which the edge of sand aprons should exist a further 2000 m lagoonward than they do at present. Second, it implies that infill of the Cocos lagoon has become increasingly dependent upon allochthonous sediment sources. Third, lagoon infill will take significantly longer than 4000 years as suggested by Guppy (1889).

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LITERATURE CITED


