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REPORT

Demise of reef-flat carbonate accumulation with late Holocene sea-level fall: evidence from Molokai, Hawaii

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Abstract Twelve cores from the protected reef-flat of Molokai revealed that carbonate sediment accumulation, ranging from 3 mm year^{-1} to less than 1 mm year^{-1}, ended on average 2,500 years ago. Modern sediment is present as a mobile surface veneer but is not trapped within the reef framework. This finding is consistent with the arrest of deposition at the end of the mid-Holocene highstand, known locally as the "Kapapa Stand of the Sea," ~2 m above the present datum ca. 3,500 years ago in the main Hawaiian Islands. Subsequent erosion, non-deposition, and/or a lack of rigid binding were probable factors leading to the lack of reef-flat accumulation during the late Holocene sea-level fall. Given anticipated climate changes, increased sedimentation of reef-flat environments is to be expected as a consequence of higher sea level.

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Introduction

It is important to understand present-day controls on coral reef development (e.g., Bellwood and Hughes 2001). This knowledge provides input for improving management programs; it is also desirable to understand reef development on longer time scales (100–10,000 years). High energy, short duration events locally impact on reef growth (Dollar 1982), but these are superimposed on long-term cycles of reef accretion and erosion controlled by sea-level change and other global effects (Grigg 1998; Cabioch et al. 1999). With increasing global temperatures, sea-level rise, and changes in storm characteristics, it is important to understand how reef systems will react to these changes. Their late Holocene history provides an important approach to this problem.

In this article we examine the sedimentation history of the reef-flat along the southern shore of Molokai. Sedimentation on the reef-flat is likely to be affected by rising sea level associated with global warming over coming decades. Crucial to projecting reef-flat sediment response to rising water levels is an improved understanding of sediment behavior in recent geological history. The Hawaii Islands offer a special opportunity to investigate environmental controls on the sedimentological framework of the reef-flat under changing sea levels. Sea level was higher in Hawaii during the middle Holocene by approximately 2 m (Fletcher and Jones 1996); hence, its fall over the late Holocene may have left a record of impact on the reef system. Knowledge of the role of falling sea level on back reef sedimentation may inform our understanding of impacts associated with sea-level rise.

Study area

Previous studies of the fringing reef system of Molokai have investigated sedimentation impacts (Calhoun and Field 2002; Ogston et al. 2004; Storlazzi et al. 2005), LIDAR bathymetry (Gibbs et al. 2002; Storlazzi et al. 2003), and Holocene history (Engels et al 2004). This study expands observation of the recent history of the reef system using 12 cores (<5 m in length) aligned across the central reef-flat on four shore-normal transects (Fig. 1). At ~0.5–1.0 km wide and ~53 km long, the Molokai reef-flat functions as a sediment trap and repository of reef history spanning the middle to late Holocene.

Geological framework

The environmental structure of the fringing reef is typical. Water temperatures for the local reef setting vary annually between 19.4 and 31.2 C. Salinity is ~35 PSU and the tidal range is ~1 m (Ogston et al. 2004). Carbonate sand and gravel or terrigenous siliciclastic mud shorelines are locally backed by non-native mangrove stands and fronted by shallow (1–2 m) reef-flats that are largely protected from wave energy by the shallow reef crest.

The reef-flat is a limestone pavement overlain by seaward-thinning carbonate sand and/or gravel. Scattered living coral heads nearshore increase in frequency seaward where they coalesce to form the modern reef crest. The crest is the shallowest region of the reef, commonly exposed at low tide and composed of a combination of living corals, coralline algae, reefal limestone, and turf algae (see Engels et al. 2004 for species and growth form specifics).

Seaward of the reef crest, the fore-reef slope, drops off to large sand fields at depths of ~27 m (Engels et al. 2004). The fore-reef slope comprises of typical spurs-and-grooves, oriented approximately perpendicular to the dominant swell. This is the zone of highest living coral cover and the primary locus of reef accretion, where not limited by high swell (Engels et al. 2004). Four wave regimes characterize the Hawaiian coast (Fig. 2): (1) north swell, (2) storm waves, (3) south swell, and (4) trade wind waves. The north swell has negligible impact on this south-facing reef (Engels et al. 2004). Historically, storm waves have not been significant on Molokai because it is situated in the lee of the island of Lanai from azimuth 147–180. South swell has only limited interaction with the Molokai reef due to shelter from Lanai. Trade wind-generated waves from the northeast are strongest between April and November bringing beneficial increases in circulation and exchange of nutrients to the reef (Grigg 1998).

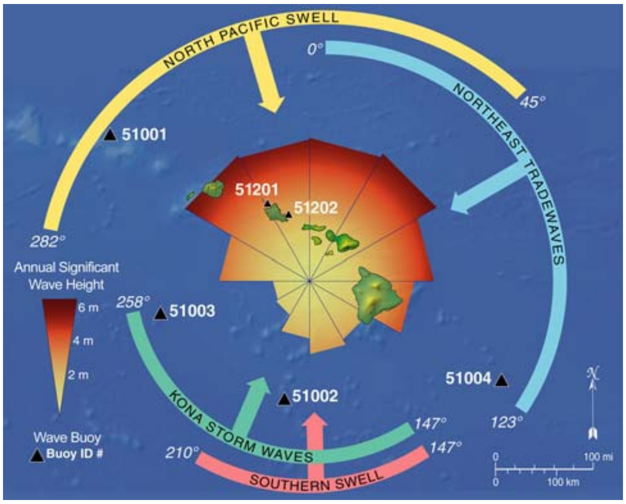

Fig. 2 Long-period swell impacts coral growth on all sides of the Hawaiian Islands. North swell is prevalent in the winter, south swell in the summer. Swell waves from both directions refract around the island to adjacent shorelines. Trade wind swell and local seas occur over 75% of the year and 90% of summer months

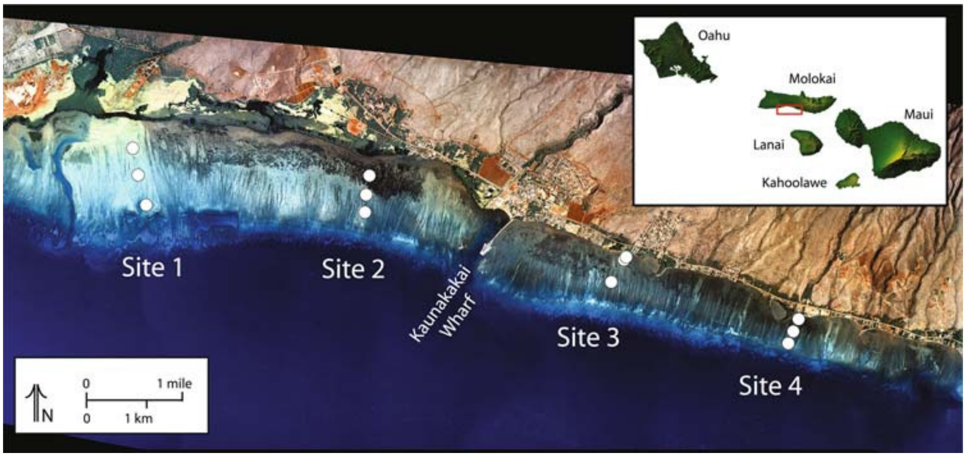

Fig. 1 Overview of study sites. Twelve cores were collected along shore-normal transects at four sites on the reef-flat at Molokai. All cores came from behind the reef crest in water depth of less than 2 m. Satellite photograph (*source*: USGS) of the south shore of Molokai showing the location of sampling sites and cores (white circles). Molokai is in the Hawaiian island chain (see inset)

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Table 1 Carbon 14 accelerator mass spectrometry (AMS) ages and sediment deposition rates

Sample ID (site–core–sample)	Type	Sample depth (cm)	$\delta^{13}C$	^{14}C age (years)	^{14}C error (years)	Calibrated ^{14}C age (years)	Calibrated age at 2 s[a] (years)	Accumulation rate (mm $year^{-1}$)
1–A–A	Coral	8	−0.56	3,310	30	3,002	3,062–3,317	–
1–C–B	Coral	134	1.23	970	30	479	513–643	0.86
1–C–C	Coral	421	−0.67	3,980	35	3,828	3,872–4,142	–
2–D–A	Coral	13	0.00	2,980	30	2,619	2,701–2,862	0.93
2–D–B	Coral	275	−0.53	5,190	40	5,432	5,459–5,674	–
2–E–C	Coral	7	−0.18	2,780	30	2,365	2,391–2,690	UTC
2–E–D	Coral	378	1.17	1,140	30	599	639–789	–
3–H–A	Coral	5	0.68	505	25	TYC	TYC	UTC
3–H–B	Coral	198	−0.33	2,740	35	2,308	2,344–2,655	–
4–J–A	Coral	10	0.09	3,850	30	3,663	3,704–3,957	3.22
4–J–B	Coral	597	0.32	5,240	35	5,488	5,539–5,731	–
4–K–C	Coral	5	−0.17	3,580	40	3,346	3,374–3,621	2.62
4–K–D	Coral	229	0.74	4,250	45	4,201	4,222–4,525	–

[a] Age range at 2 sigma

Abbreviations: TYC, to young to calibrate; UTC, unable to calculate

Materials and methods

Cores were drilled along four transects (spaced ~4 km) using a hand-held, hydraulic, un-cased bit and rod system modified after Macintyre (1975) and described in Engels et al. (2004). Cored limestone sections were classified according to the Embry and Klovan (1971) modification of the Dunham (1962) scheme. A total of 13 coral samples were selected for radiocarbon dating (Table 1) and X-ray diffraction (XRD, using a Scintag [Thermo Optek] PAD V Powder diffraction system) determination of percent aragonite. The methods used are described in Engels et al. (2004). Ages are reported calibrated to calendar years before present (cal years BP with standard deviation) using Calib 4.12 (Stuiver and Reimer 1993) and the 1998 INTCAL Calibration dataset (Stuiver et al. 1998). A marine reservoir correction (ΔR) of -21 ± 26 years for regional Hawaiian marine waters is used following Reimer et al. (2004).

Results

Five types of accretion sequences, or lithofacies, were classified in this suite of cores, after usage by Grossman and Fletcher (2004). In order of decreasing structural integrity, they were coral framestone, bindstone, coral rubble, floatstone, and unconsolidated sediment (Fig. 3). The coral framestone lithofacies was composed of coral fragments, commonly from a single colony, and usually sampled in growth position. Massive *Porites lobata* was the most common, with minor branching *Porites compressa*. Bindstone consisted of encrusting *Montipora* sp., *P. lobata*, and coralline algae (*Hydrolithon onkodes* and *Hydrolithon gardineri*) binding coral rubble, algal rhodoliths, and sand-sized particles. This facies was almost always found near the tops of the cores, at the reef-flat surface.

The coral rubble lithofacies was principally composed of *P. compressa* gravel; grains were moderately well rounded with occasional borings, and with limited coralline algal

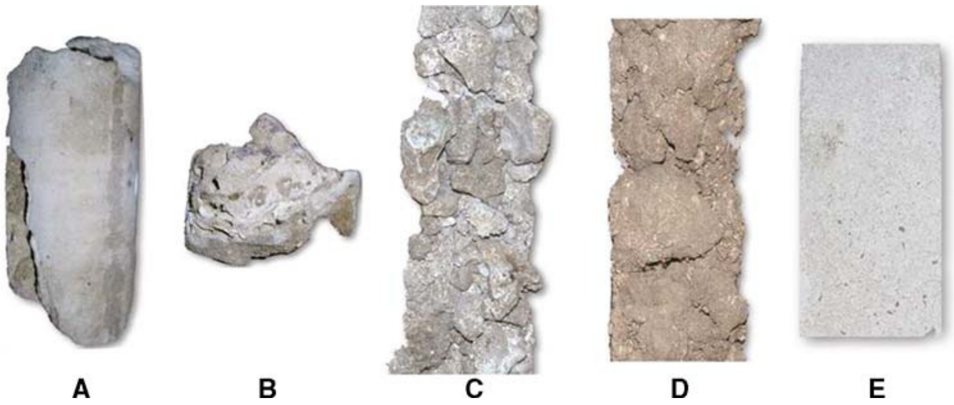

Fig. 3 Drill core lithofacies. In order of decreasing contribution by framebuilders: (**a**) framestone, (**b**) bindstone, (**c**) rubble, (**d**) floatstone, (**e**) unconsolidated sediment. All these lithofacies are present on the reef-flat and represent differing hydrodynamic conditions and sediment sources at the time of deposition and during emplacement

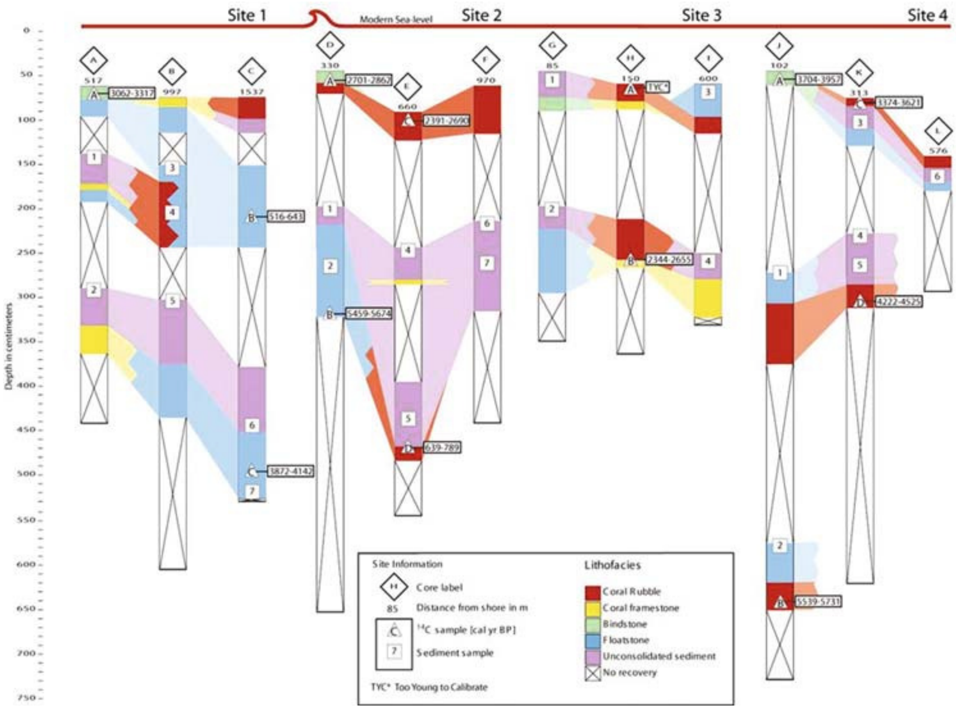

Fig. 4 Drill core lithology, dates and sediment sample locations. Color bands between cores represent projected lateral extent of lithofacies. The majority of surface samples date from the early late Holocene. Only at site 3, core H is there a modern date at the surface

accretion and minor to negligible amounts of other sediment. The floatstone lithofacies was similar in composition to the coral rubble except that clasts are suspended in an unconsolidated sediment matrix. The matrix at site 1 (Fig. 4) was composed of fine sand (grain-size ~0.21 mm) with abundant *Halimeda* sp. fragments (39–60%), whereas at site 4 the matrix was medium sand (grain-size ~0.31 mm) with very few *Halimeda* sp. grains (1–5%). Unconsolidated sediment lithofacies was composed of loose sediments. Grain sizes and compositions varied throughout cores, as did sorting. In some cores, sediment tended to fine upward. This is likely an artifact of drilling as sediments within the core may be rotated at high speeds, preferentially keeping smaller grains in suspension. In order of average compositional abundance, coralline algae (29.8%), crystalline carbonate fragments (21.1%), *Halimeda* sp. flakes (12.7%), coral (12.4%), and other shells (9.1%) accounted for ~80% of total grains in the majority of unconsolidated sediment samples. Other grain types (other (7.3%), molluscs (3.5%), siliciclastic (2.8%), echinoderms (0.8%), and foraminifera (0.6%)), while not contributing significantly to overall grain total, could be locally important. Grain size, sorting, and composition varied throughout the cores.

Cores reveal a general absence of coral framestone lithofacies and a dominance of unconsolidated sediment, floatstone, and coral rubble. Site 1 cores were collected from ~500 to ~1,500 m offshore in 0.61–0.76 m water depth. Core length ranged from 3.8 to 5.3 m and recovery averaged 51%. Radiocarbon ages increased with depth below the reef surface (Table 1) and varied from 513–643 to 3,872–4,142 cal years BP. The surface of core A was bindstone dated 3,062–3,317 cal years BP. Cores from site 2 were between ~330 and ~970 m offshore in water depths ranging 0.46–0.91 m. Core length ranged from 3.8 to 6.1 m with recovery averaging 32%. Radiocarbon ages increased with depth and ranged from 639–789 to 5,459–5,674 cal years BP. The surface of core D was bindstone dated 2,701–2,862 cal years BP, and in core E surface lithology was coral rubble dated 2,391–2,690 cal years BP. Core E had an age reversal at depth, attributable to contamination by younger surface material during drilling.

Site 3 cores were obtained from ~85 m to ~600 m offshore. Water depth ranged from 0.46 to 0.61 m. Hard reef substrate consisting of reefal limestone was buried by 0.5–0.75 m of terrigenous silt. Cores ranged in length from 2.28 to 3.42 m with an average recovery of 38%. Age increased with depth and ranges from modern to 2,344–2,655 cal years BP. At site 4, cores ranged from 1.52 to 6.84 m long and recovery averaged 25%. Water depth above core locations ranged from 0.46 m nearshore to 1.4 m offshore. Samples in these cores were the oldest obtained by this study and follow the pattern of age increasing with depth, 3,374–3,621 to 5,539–5,731 cal years BP. Surface lithology of core J was bindstone dated 3,704–3,957 cal years BP, and at core K surface lithology was coral rubble dated 3,374–3,621 cal years BP. Carbonate sediment accumulation ended on average 2,500 cal years BP and consisted of a mix of lithology including coral rubble, bindstone, floatstone, coral framestone, and unconsolidated sediment.

Discussion

The uppermost cored samples were largely of late to middle Holocene age (topmost dates in cores A, D, E, H, J, K average ca. 2,500 cal years BP) and consisted of mixed lithofacies including principally bindstone and coral rubble. Although the reef surface at core H was modern, this was due to the presence of coral heads and solitary colonies on the reef-flat. These, however, live on an antecedent (fossil) surface and are not a result of continuous accretion. The reef-flat is a fossil surface that has not experienced carbonate accumulation for over two millennia. This finding is consistent with studies by Easton and Olson (1976) in Hanauma Bay (Oahu), Grossman and Fletcher (2004) in Kailua Bay (Oahu), Rooney et al. (2004) on reefs exposed to north swell, and Grossman et al. (2006) on the south shore of Oahu.

Rooney et al. (2004) found a uniform end to coral framestone accretion at ca. 4,500–5,000 cal years BP on fringing reefs exposed to damaging north swell. They attributed this to occasional seasons of particularly large north swell associated with strong El Niño years that have only occurred since ca. 5,000 years BP. Grossman and Fletcher (2004) and Grossman et al. (2006) found that whereas Holocene coral framestone accretion terminated on the outer Kailua shelf exposed to north swell at ca. 5,000 years ago (consistent with Rooney et al. 2004), it was maintained until 3,000–2,400 years ago on the southern shelf of Oahu and at Hanauma Bay. Both Grossman and Fletcher (2004) and Grossman et al. (2006) speculated that the lack of continued vertical framestone accretion in wave-protected areas reflects a decrease in accommodation space related to falling sea level at the end of the mid-Holocene highstand, locally referred to as the “Kapapa Stand of the Sea” (Stearns 1974; Fletcher and Jones 1996).

The reef-flats at Hanauma Bay and on Molokai are covered by <2 m of water and are beyond the reach of the north swell. Both sites ceased accretion ca. 2,500 years ago, suggesting that sea-level fall rather than north swell activity was the principle limitation on accretion. Hence, shallow fringing reefs in Hawaii have been exposed to at least two major factors that effectively suppress modern accretion, wave stress, and sea-level fall.

Unlike the Kailua Bay and Hanauma Bay reefs, both of which are well lithified by precipitated carbonates, the Molokai reef-flat has remained predominately unconsolidated rubble and loose sediment. Cabioch et al. (1999) suggest that areas with gently sloping surfaces and moderate wave energy are more likely to develop sediment-dominated reefs. Rasser and Riegl (2002) indicate that deposition of reef rubble is usually associated with gentle slopes and/or shallow waters on a wide reef-flat. The Molokai reef-flat fits both these conditions.

Another distinctive characteristic of the Molokai reef-flat is the lack of lithification and binding since the middle Holocene. Rasser and Riegl (2002) indicate that ideal conditions for rigid rubble binding are low hydrodynamic energy, shallow depositional position, low background sedimentation, high water flux, long disturbance-free periods, conditions favorable for diagenetic cementation, high preliminary biological stabilization, large presence of potential binding agents, and metabolic activity favoring diagenetic cementation. The Molokai reef-flat fits most of these conditions except that portions of the environment experienced high background sedimentation due to soil erosion in adjoining watersheds. This terrigenous mud was mixed with carbonate sand and rubble throughout the reef-flat (Roberts 2001; Ogston et al. 2004; Storlazzi et al. 2005). Rasser and Riegl (2002) speculate that “low abundance of diagenetic cementation could be caused by a low water flux, an interpretation that reflects its relative scarcity in some protected reef-flat and back-reef sediments.” Protected from the brunt of swell energy, the Molokai back reef likely experiences little flushing within the reef structure. Significant loading of the reef-flat by terrigenous mud and low water flux across the back-reef likely precludes the occurrence of significant lithification.

Carbonate erosion during the late Holocene sea-level fall has been suggested by Grigg (1998) as the reason why the Hanauma Bay reef-flat is ca. 2,500 years old. Evidence for an earlier highstand is recorded on Molokai. A wave cut notch at 2–3 m above modern sea level in a middle Holocene (4,750 ± 70 and 5,730 ± 80 cal years BP, means ± SD) calcarenite dune corresponds with both the height and timing of the Kapapa Stand. Given the similarities in age of materials cored in the reef-flats at Hanauma and Molokai and the evidence from both islands of a sea-level highstand (Fletcher and Jones 1996; Fletcher et al. 2005), it is reasonable to expect that a similar mechanism is responsible for the antecedent surfaces in both areas. A second explanation may be related to water depth and wave stress. Storm frequency and wave energy intensity in Hawaii have not diminished since the middle Holocene (Rooney et al. 2004), indicating that rubble accumulation in the reef-flats should have been continuous and not have ceased ca. 2500 years ago. It seems probable that at higher sea-levels carbonate rubble accumulation on the reef-flat would have remained sufficiently steady to allow for preliminary stabilization and some degree of cementation and binding. However, it is likely that the falling sea level of the late Holocene and reductions in water depth across the reef-flat precluded the stabilization of rubble and sediments because of low water flux (see Rasser and Riegl 2002), leading to only temporary storage of sediment prior to advection offshore, as is seen today (Ogston et al. 2004; Storlazzi et al. 2005). Whether late Holocene carbonate sediment has been eroded or was simply unable to accumulate, given water depth and wave conditions, there appears to be no significant carbonate accretion in the reef-flat environment today.

These findings indicate that trends in reef-flat sedimentation can be regional in extent and may not be solely tied to local processes. They also reveal that the reef-flat environment is sensitive to even small changes in sea-level position. The fall of ~2 m over recent millennia has created a surface of nondeposition, or potentially of erosion, which will be regional in extent. The discovery of such surfaces in other high resolution records of carbonate sedimentation suggests the possibility that sea-level variability is the causal mechanism. If projections of accelerated sea-level rise over this century turn out to be accurate; this study suggests that we can expect to see increased sedimentation in reef-flat environments as a reversal of the observed pattern.

The depositional history of the Molokai reef-flat is consistent with the histories of other Hawaiian Islands. The reef-flat is antecedent and ceased to accrete sediment ca. 2,500 cal years BP. Possible reasons for this include reef-flat non-deposition and/or erosion under falling sea levels but may also include falling sea levels that precluded preliminary stabilization and rigid binding of the sediment. In either case, falling sea level at the end of the “Kapapa Stand” led to the demise of reef-flat accumulation on Molokai. Modern carbonate sediments are a mobile surface veneer and are not being trapped within the reef structure. In places they are dominated by terrigenous mud. In the coming decades, under conditions of higher sea level, higher wave energy on the reef-flat is likely to increase the delivery of sands and gravels from seaward sources. Mud accumulation along the shoreline is likely to be mobilized. Increased sediment flux from landward and seaward sources is likely therefore to stimulate increased sediment accumulation on reef-flats. Increased water flux may also lead to increased cementation.

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