New model of reef-island evolution: Maldives, Indian Ocean

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ABSTRACT

A new model of reef-island evolution, based on detailed morphostratigraphic analysis and radiometric dating of three islands in South Maalhosmadulu Atoll, Maldives, is presented. Islands initially formed on a foundation of lagoonal sediments between 5500 and 4500 yr B.P. when the reef surface was as much as 2.5 m below modern sea level. Islands accumulated rapidly during the following 1500 yr, effectively reaching their current dimensions by 4000 yr B.P. Since then the high circum-island peripheral ridge has been subject to seasonal and longer-term shoreline changes, while the outer reef has grown upward, reducing the energy window and confining the islands. This new model has far-reaching implications for island stability during a period of global warming and raised sea level, which will partially reactivate the energy window, although it is not expected to inhibit upward reef growth or compromise island stability.

Keywords: atoll, reef islands, sedimentation, Holocene, coral reefs, sea-level rise.

INTRODUCTION

Coral-reef islands are accumulations of the calcareous sands and gravels that characterize the surface of atolls and other reef platforms. The islands' low elevation, small size, and reliance on locally generated reefal sediments make them particularly vulnerable to the impacts of climate change and sea-level rise. Consequently, the stability of reef islands is of major concern in atoll nations where such islands provide the only habitable land. Improved understanding of the depositional history of reef islands is required to better resolve their future stability.

Bleak prospects for low-lying islands are founded on conventional theory of island formation that requires reef-flat development at sea level as a precondition for island accumulation (Woodroffe et al., 1999). This sequential model has been widely applied in the Indo-Pacific (McLean and Woodroffe, 1994; Richmond, 1994) and implies that island stability is sensitive to water depth over reefs, as controlled by sea level. Consequently, chronic island erosion resulting from increased water depth across reefs is envisaged (Dickinson, 1999) as anthropogenic stress (McCulloch et al., 2003) and global warming (Hoegh-Guldberg, 1999) inhibit future reef growth in response to sea-level rise (Kleypas et al., 1999). Here we present an alternate model of reef-island formation in the Maldives that has significant implications for the physical stability of islands with anticipated sea-level rise.

FIELD SETTING AND METHOD

The 22 atolls that comprise the Maldives archipelago contain >1200 reef islands, the formation of which is poorly understood. The population of the reef islands is ~260,000. Maldivian islands exist in a predominantly storm-free environment in which the process regime is marked by strong seasonal reversals in monsoon winds from the west and northeast that govern short-term changes in island shorelines (Kench et al., 2003). Our study examined the morphology, stratigraphy, chronology, and evolution of three islands in South Maalhosmadulu Atoll, Maldives (Fig. 1).

Topographic surveys of the reef platform and islands were undertaken along 10 traverses covering 4270 m (Fig. 1). Subsurface stratigraphy was identified from 102 cores obtained from piston corer, auger, and diamond drill techniques. A total of 600 m of ground penetrating radar (GPR) trace was obtained along the central axis of the islands. Surveys were reduced to mean sea level from water-level recorders on each reef and comparison with continuous sea-level records at Malé provided by the University of Hawaii Sea Level Center. Morphostratigraphy is temporally constrained by 29 radiometric dates (Table 1).

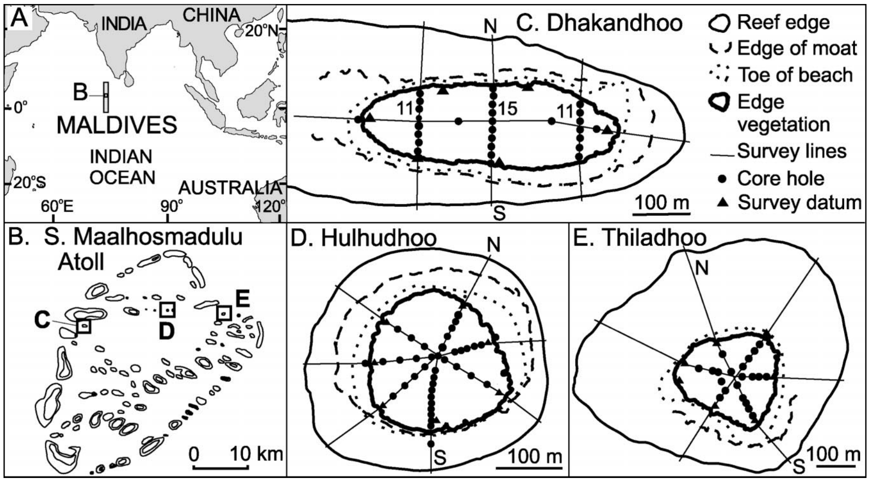

Figure 1. Study islands, transects, and sample locations, South Maalhosmadulu Atoll, Maldives. Ground penetrating radar trace retrieved along N-S transects on each island.

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TABLE 1. RADIOCARBON DATES FROM REEF ISLANDS OF THE SOUTH MAALHOSMADULU ATOLL, MALDIVES

Laboratory code	Facies designation and material	Depth relative to MSL (m)	Conventional age (yr B.P.)	Calibrated age range (95.4% probability) (cal. yr B.P.)
Dhakandhoo Island				
Wk 11293	Velu facies: sand	−0.29	5139 ± 62	5550–5200
Wk 11294	Velu facies: sand	−2.55	5362 ± 63	5730–5440
Wk 11295	Velu facies: sand	−1.58	5032 ± 60	5410–5000
Wk 11296	Finolhu facies: sand	−1.23	5125 ± 61	5530–5130
Wk 11297	Finolhu facies: sand	0.05	4905 ± 51	5230–4860
Wk 12661	Finolhu facies: sand	−0.05	4512 ± 42	4680–4440
Wk 12662	Finolhu facies: sand	−1.18	4352 ± 44	4880–4250
Wk 12660	Dead in situ coral (*Acropora*)	−0.92	105.4 ± 0.5	Modern
Hulhudhoo Island				
Wk 12097	Finolhu facies: sand	0.26	4335 ± 46	4460–4210
Wk 11298	Finolhu facies: sand	−0.29	4234 ± 52	4320–3970
Wk 11299	Finolhu facies: sand	−0.34	4832 ± 59	5140–4790
Wk 11300	Velu facies: sand	−1.29	5168 ± 62	5560–5260
Wk 11301	Finolhu facies: sand	−0.51	3736 ± 57	3640–3350
Wk 11302	In situ reef rock	−1.17	4078 ± 70	4140–3720
Wk 11303	Reefal sand	−1.80	1259 ± 47	780–570
Wk 11304	In situ coral	−2.50	5802 ± 60	6210–5910
Wk 12663	In situ fossil *Porites*	−0.26	3679 ± 40	3550–3340
Wk 12664	Finolhu facies: sand	−0.145	3970 ± 40	3950–3720
Wk 12665	Island-margin facies: sand	−1.13	3954 ± 40	3930–3700
Thiladhoo Island				
Wk 11305	Finolhu facies: sand	−0.79	2677 ± 57	2340–2050
Wk 11306	Velu facies: sand	−1.84	3000 ± 55	2750–2430
Wk 11307	Island-margin facies: sand	0.40	2795 ± 54	2540–2160
Wk 11308	Velu facies: sand	−1.52	5402 ± 54	5750–5480
Wk 11309	Beachrock	0.18	1064 ± 45	630–460
Wk 11310	Beachrock	0.00	1569 ± 44	1100–890
Wk 11311	In situ fossil *Porites*	−1.09	952 ± 46	530–330
Wk 12666	Velu facies: sand	−1.52	5336 ± 43	5680–5460
Wk 12667	Island-margin facies: sand	−0.14	1518 ± 37	1030–840
Wk 12668	Island-margin facies: sand	−0.39	1587 ± 36	1100–920

Note: Radiocarbon dates obtained from the Radiocarbon Dating Laboratory, University of Waikato, New Zealand. Ages calibrated by using OxCal version 3.5 (Bronk Ramsey, 2001) with the marine data set (Stuiver et al., 1998) and Delta-R value of 132 ± 25 as best estimate for the central Indian Ocean reservoir effect (Southon et al., 2002). MSL—mean sea level.

MORPHOSTRATIGRAPHY

The three islands exhibit similar morphological characteristics. High peripheral ridges enclose low central depressions (Fig. 2). Significantly, the deepest island cores penetrate below the level of the adjacent reef surface and terminate in unconsolidated sediments, as opposed to a hard nonerodible reef surface, as described in other atoll island settings.

Examination of cores, sediments, and GPR traces indicates that the subsurface stratigraphy can be divided into four discrete facies: reef, ‘‘velu’’ (shallow lagoon), ‘‘finolhu’’ (unvegetated sand bank), and island-margin facies. The peripheral reef facies comprises a layered framework of *Porites* heads and plates, branching *Acropora* corals, and *Heliopora*; medium to coarse coral-algal sand and gravel fill the intercoral voids. The surface of this facies is exposed as the contemporary reef flat and is continuing to accrete. The velu facies occupies the shallow depression occluded by the peripheral reef and provides the foundation for island sediments. It comprises horizontally bedded coarse-grained sand, primarily of unmodified calcified segments of *Halimeda*, with a fine lime mud matrix. Both the unfractured segments and the presence of fines indicate autochthonous production and low-energy sedimentation. Immediately overlying this facies is a convex hummocky stratigraphy (Fig. 2E) characterized by an increase in fractured *Halimeda* and the presence of coral-algal particles, indicative of increased sediment transport and mixing with outer-reef sediments. This finolhu facies represents a change from velu infill to incipient island deposition. Steeply dipping beds (3.8°) extend above and across the finolhu facies and inner reef (Fig. 2F), indicating progradation of the shoreline and aggradation of the island ridge. This island-margin facies comprises a mix of fine to medium abraded coral-algal sands whose provenance is the outer reef. The seaward margin of this facies represents the contemporary beach.

Extensive areas of the subsurface sediments are lithified on the islands. Phosphate rock occupies the central depression on Dhakandhoo and Thiladhoo, and cay sandstone is found in that setting on Hulhudhoo. Shoreline sediments are also lithified as beachrock, and these provide evidence of both present and past island change. Around each island the contemporary beach fluctuates in position on a seasonal basis, in response to reversing monsoons, temporarily burying the beachrock and occupying the shallow moat that encircles the island. The moat surface consists of a coral-algal pavement, devoid of living coral, at a lower elevation (0.2–1.2 m) than the outer reef. An abrupt step marks the boundary between the moat base and outer reef. Differences in reef elevation exist between and within islands, though in all instances there is space to accommodate continued vertical reef growth. Notably, the moat is most clearly developed on Hulhudhoo, where the reef surface is highest (Fig. 2B).

CHRONOLOGY OF ISLAND DEPOSITION

Radiometric dating of skeletal carbonate sediments can be problematic, as a disparity may exist between the time of death of the organism and time of final deposition, which may occur after an undefined period of transport, breakdown, and mixing. In such instances, samples yield the earliest possible time of deposition. However, in the present study the velu and finolhu facies are dominated by unfragmented *Halimeda* grains, reflecting in situ production and accumulation in a lagoonal or backreef setting. In this case we think that the temporal gap between organism death and deposition is minimal. This interpretation, together with the consistent stratigraphic pattern of bulk sample dates and the lack of age inversions (Fig. 2), suggests a realistic chronology of deposition.

Radiometric ages on these autochthonous deposits show that the basal velu sediments, which underlie islands, are oldest and were deposited between 5500 and 5000 yr B.P. Dates on the finolhu and island-margin facies become progressively younger toward the island surface and shore; the youngest dates for these facies are 4352 ± 44 yr B.P. on Dhakandhoo and 3736 ± 57 yr B.P. on Hulhudhoo. Dates, which are consistent between islands, indicate that vertical and lateral accumulation was rapid and that island building was effectively complete by 4000 yr B.P. On Thiladhoo, more recent progradation of the island-margin facies is evident, though the core of the island was clearly present by 4000 yr B.P.

The style of island development is one of rapid accumulation around a central node represented by the finolhu facies and controlled by wave convergence across reef platforms (Woodroffe et al., 1999). As the islands extended laterally, across the inner reef surface and toward the higher-energy reef edge, shoreline depositional processes became more energetic and swash runup reached higher levels, promoting vertical accretion and producing the high ridge of the island margins.

Collectively, these results indicate that the major phase of island building in the Maldives took place 1000–1500 yr earlier than reported

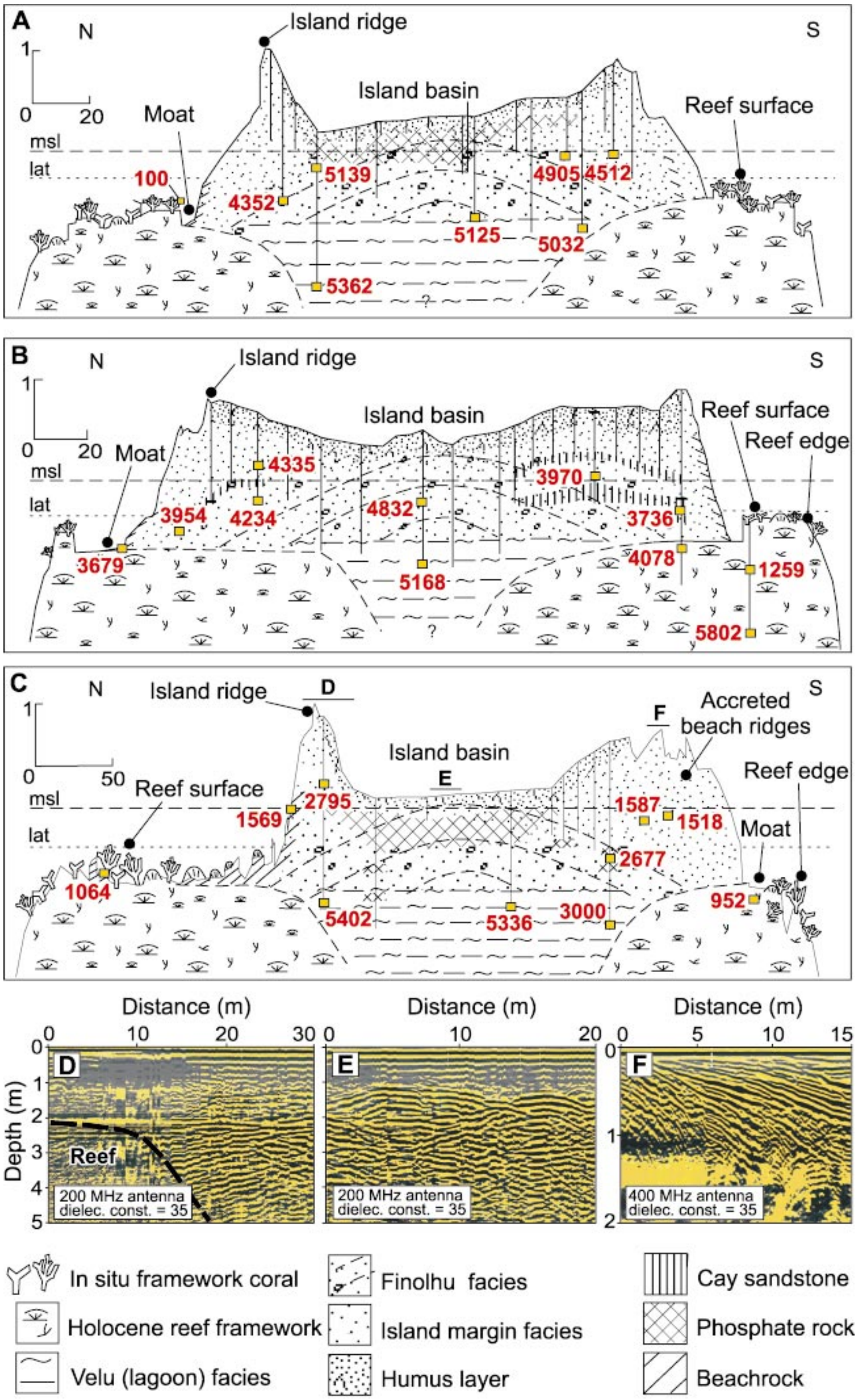

Figure 2. Morphostratigraphy of reef and island cross sections, South Maalhosmadulu Atoll. Locations of transects are shown in Figure 1 (N-S). A: Dhakandhoo. B: Hulhudhoo. C: Thiladhoo. Conventional radiocarbon ages shown in red are in correct stratigraphic position (see Table 1 for error terms). D–F: Ground penetrating radar (GPR) traces from Thiladhoo. D: Reef surface dipping beneath island ridge. E: Horizontal velu facies overlain by hummocky finolhu facies. F: Steeply dipping island-margin facies. GPR data collected by using GSSI SIR2000 system with 200 and 400 mHz antennae, processed by using RADAN software. Water-table depth varies from 8 to 12 m beneath island surfaces; msl—mean sea level; lat—lowest astronomical tide.

elsewhere in the Indo-Pacific (McLean and Hosking, 1991; Woodroffe et al., 1999). Moreover, following the major phase of accretion, the Maldivian islands appear to have undergone little further modification apart from seasonal shifts in beach position and lithification of sediments. The formation of phosphate rock and cay sandstone beneath islands and beachrock at the lateral margin has served to stabilize island cores.

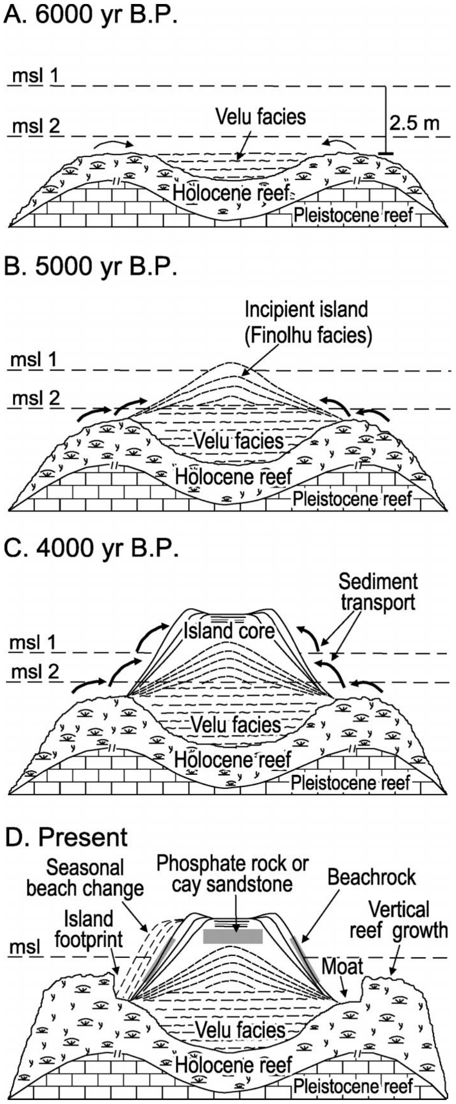

Figure 3. Model of Maldivian reef-island formation and development in middle Holocene to late Holocene. Contrasting sea-level histories—mean sea level (msl) 1 (6000 yr B.P. stillstand) and msl 2 (late Holocene sea-level stabilization at 2000 yr B.P.)—reflect range of possible sea-level positions relative to reef surface at time of island initiation. See text for details.

RELATIONSHIP BETWEEN ISLAND DEPOSITION AND REEF GROWTH

A new model of reef-island development that accounts for the three principal morphological units (reef surface, moat, and island) and their temporal development is depicted in Figure 3. Functionality of the model is dependent on the morphological co-adjustment between reef growth and island sedimentation; each process dominated construction in discrete and alternating phases during the middle to late Holocene.

In situ coral collected from 2.5 m below modern sea level on the southern Hulhudhoo reef and dated as 5802 ± 60 yr B.P. indicates that vertical reef growth dominated construction in the middle Holocene (before 6000 yr B.P.). By 5500 yr B.P. and for the following 1500 yr, sedimentation became the dominant construction process. Reef growth became constrained by sedimentation on the central reef platform, but was supplanted by rapid vertical and lateral island building (5200–4000 yr B.P.), initially as an unvegetated sand bank (finolhu) and finally as a vegetated island. A further reef date of 4078 ± 70 yr B.P., from a sample collected >1 m below modern sea level underlying the southern ridge on Hulhudhoo, suggests that during the period of velu sedimentation and island accumulation, the reef surface was between 2.0 m and 0.5 m below the present reef surface.

The past 4000 yr have been characterized by cessation of island accumulation; stabilization of the island core through lithification of island sediments both internally and peripherally; and continued upward growth of the outer reef surface. The onset of island formation impeded growth of the inner reef surface, and seasonal fluctuations in beach position resulted in a planated coral-algal moat surface. This surface is a remnant of the paleoreef, and its boundary demarcates the ''island footprint.'' Beyond the island footprint, continued vertical reef growth has produced the marked morphological step above the paleoreef surface, which forms a barrier to further island extension and is critical for island containment.

This interpretation differs from the conventional Indo-Pacific model in that island initiation occurred on unconsolidated velu sediments when reefs were 2.5 m–1.0 m below modern sea level; island development preceded reef-flat formation rather than following it; and the post-island reef flat accreted vertically rather than laterally.

DISCUSSION AND CONCLUSIONS

Of significance for future island stability is the relationship between island and reef formation and Holocene sea-level change. The pattern of Holocene sea-level change in the central Indian Ocean and in particular the Maldives is poorly resolved (Woodroffe, 1994). Notwithstanding current debate about reef-growth strategies, keep-up and catch-up modes, as they relate to sea-level change, are used here to highlight implications for our island-evolution model, the critical difference being the position of sea level at the onset of island formation. Our evolutionary model shows that during the period of island formation, reef elevation was 2.5–1.0 m below present sea level. Reef material dated at these depths must imply either that the reef surface kept pace with sea-level rise, which stabilized by 2000 yr B.P. as proposed by Camoin et al. (1997) for the western Indian Ocean, or that the reef developed in catch-up growth mode prior to and since the 6000 yr B.P. stillstand, as modeled by Clark et al. (1978).

A keep-up growth response implies that the islands formed at lower sea level between 5500 and 4000 yr B.P. and maintained their presence on reef platforms, with little modification, in the face of a further 2.5 m rise in sea level. In contrast, a catch-up reef-growth strategy, as also favored by Woodroffe (1994) in the Maldives, implies that the islands formed over submerged reefs. As reefs reached effective wave base 2.0–2.5 m below mean sea level, sediment was transferred to and accumulated in the velu to trigger island formation. Once the island core developed and established its spatial footprint, upward growth of the surrounding reef flat moderated the at-shore energy regime that controls island change.

Both scenarios suggest that the midrange projection of 0.48 m of sea-level rise by the year 2100 (Church and Gregory, 2001) is unlikely to physically destabilize the reef islands studied. First, if islands formed at lower sea level, they have persisted on reefs despite a 2.5 m increase in sea level in the middle to late Holocene. Second, if islands accumulated on submerged reefs, they must have been subject to much greater water depths across reefs during their formation and higher at-shoreline energy than currently exists. Upward growth of the outer reef progressively closed down this Holocene high-energy window, indicating that the islands are primarily relict deposits, now contained by the surrounding reef. Forecast changes in water depth and wave energy across reefs are well within the depth and energy conditions in existence during island formation in the Maldives and are likely to promote minor readjustment of the island margins. Extensive lithification of island and beach sediments will continue to stabilize islands.

Contrary to most established commentaries on the precarious nature of atoll islands, our data and model present an optimistic view for the Maldivian islands. They have existed for >5000 yr, are morphologically resilient rather than fragile systems, and are expected to persist under current scenarios of future climate change and sea-level rise.

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