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EVIDENCE OF RESILIENCE IN LAGOONAL PLATFORM ISLANDS IN RESPONSE TO RISING SEA LEVEL ON HUVADHOO ATOLL, MALDIVES

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Reef islands are at the forefront of concern for future accelerating sea-level rise since their low-lying and isolated nature puts them at higher risk of marine inundation compared to continental coastlines. However, the perceived threat of complete submersion as implied by projected future sea-level rise and current island elevations do not consider the morphologically resilient nature of reef island systems. In particular, the role of sediment supply in the resilience of these islands is still relatively poorly studied. This study presents detailed descriptions of the sedimentary characteristics and stratigraphy of two lagoonal platform islands in Huvadhoo Atoll, Maldives, that formed during periods of Holocene sea-level rise. Island subsurface stratigraphy was reconstructed by analysing the skeletal composition and textural properties of 306 sediment samples from 37 cores extracted across the islands. Island sediments were dominated by coral sands with varied proportions of secondary constituents (molluscs, *Halimeda*, foraminifera, and crustose coralline algae). Downcore variations in composition show that the proportion of coral sands decrease with depth and the proportion of molluscs and *Halimeda* increase with depth (with the exception of cores that terminated on lagoon infill). The increased proportion of *Halimeda* and molluscs in these early island deposits may have resulted from the catch-up growth strategy of the reef during the mid-Holocene highstand as both organisms have high turnover rates and directly contribute to sediment production after death. The sedimentological response of increased *Halimeda* and molluscs highlights the resilient and dynamic nature of reef islands and the ability of reefs to adjust ecologically to changing sea levels.

Keywords: reef islands; sea-level rise; sedimentology

INTRODUCTION

Reef islands are at the forefront of concern for future accelerating sea-level rise since their low-lying and isolated nature puts them at higher risk of marine inundation compared to continental coastlines. However, the perceived threat of complete submersion as implied by projected future sea-level rise and current island elevations do not consider the morphologically resilient nature of reef island systems (East et al., 2018; Kench et al., 2015). Previous studies of medium-term morphological change have found that some reef islands have been morphologically stable or have accreted over timescales of decades to centuries over periods of contemporary sea-level rise (Dawson and Smithers, 2010; Ford and Kench, 2014; Kench et al., 2015; Webb and Kench, 2010). These studies question assertions of island vulnerability, though they only represent case studies from the Pacific and the northern Maldives archipelago. This region has experienced sea level rise for most of the last 8000 years, with a mid-Holocene highstand of approximately 0.5 m reported in the northern archipelago from 4,000 to 2,000 yBP (Kench et al., 2009) and subsequent large oscillations in sea level behavior, including two lowstands (Kench et al., 2020). The existence of islands in the region that have persisted during these periods of sea-level change infer that other factors aside from sea-level history are involved in island formation and building, including sediment supply.

The role of sediment supply in the resilience of these islands is still relatively poorly studied. Investigating downcore sediment characteristics can provide insights into past sediment supply, reef ecology and depositional environments (Yamano et al., 2000). This study presents detailed descriptions of the sedimentary characteristics and stratigraphy of two lagoonal platform islands, Kan'dahalagalaa (KAN) and Kondeymatheelaabadhoo (KOND), in Huvadhoo Atoll, Maldives (Figure 1).

METHODS

Island subsurface stratigraphy was reconstructed by analyzing the skeletal composition and textural properties of 306 sediment samples from 37 cores extracted across the islands. Cores were retrieved using a combination of auger and percussion coring techniques. On KAN, 20 cores were retrieved whereas 17 cores were retrieved from KOND. All cores on KAN and KOND penetrated below mean sea level, up to 2.6 m below msl. Cores were manually extracted in the field and samples (~50 g) were collected along the core wherever a change in sediment characteristics was noted (generally every 25 cm; n = 159 samples for KAN, n = 147 samples for KOND).

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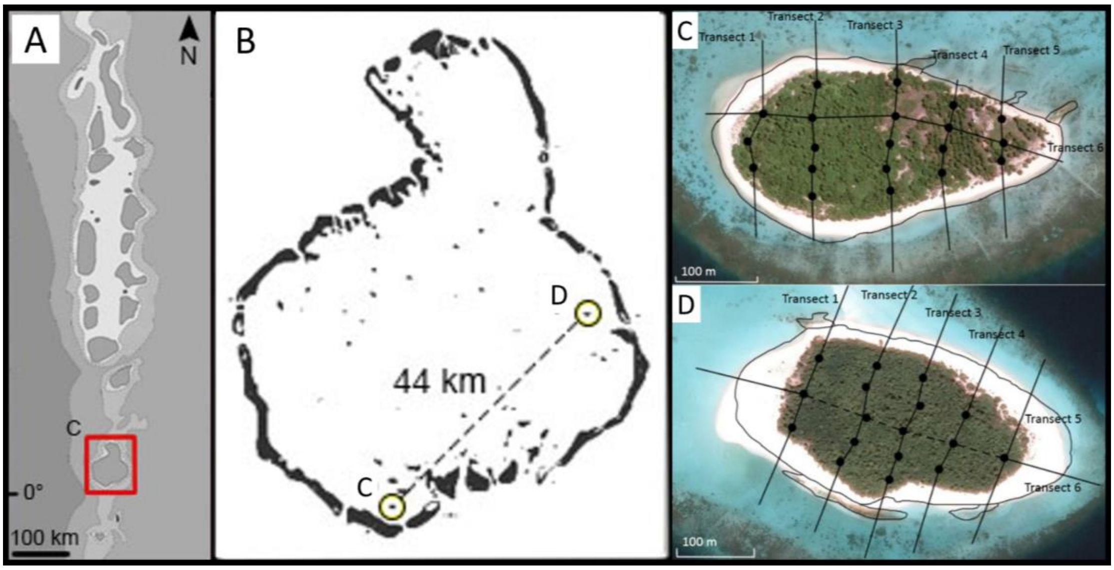

Figure 1. Location of: (A) the Maldives archipelago; (B) Huvadhoo Atoll; and study sites Kan'dahalagalaa (C. 0°13'N 73°12'E) and Kondeymatheelaabadhoo (D. 0°30'N 73°29'E). Transects and cores are shown on study islands. Island outline indicates the toe of beach during the field period (KAN map data: Google, DigitalGlobe; KOND map data: Google, CNES/Astrium).

Sediment texture was determined by dry sieving samples into half-phi size fractions from -2ϕ to 4ϕ and the mean grain size was calculated in GRADISTAT (Blott and Pye, 2001). Sediment composition was quantified by point-counting 100 grains from each half-phi size fraction between -2ϕ to 3ϕ under a binocular microscope (n = 1100 grains per sample; as per the methods of Yamano et al., 2000). Sediments were classified into the following categories: coral, crustose coralline algae (CCA), *Halimeda*, molluscs, foraminifera, and other. The "other" category includes unidentifiable constituents as well as echinoderms (urchin remains), due to low counts. A K-means cluster analysis performed using PAST software (version 2.14; Hammer et al., 2001) was used to examine and arrange the sample set into 4 clusters based on sediment composition.

RESULTS

Sedimentary characteristics and stratigraphy of KAN

Twenty cores were extracted from KAN reaching depths of between 0.1 m below msl to 2.6 m below msl. Downcore depth of penetration ranged from 140 cm to 350 cm. Sediment size throughout the cores varied from medium sands (1.94ϕ) to very coarse sands (-0.93ϕ). Typically, the cores exhibited a fining upcore sequence with a coarse basal layer of the island (coral fragments) ranging from 0.92ϕ to -0.93ϕ while the sands on the island surface ranged from 1.10ϕ to 1.93ϕ. This trend is exemplified in cores from Transect 3 (Figure 2), thus only these core logs will be presented for conciseness as there is little spatial variation between cores of all transects. On Transect 3, the basal layer (lower 50 cm of cores) of C9, C12, C13 comprised coarse to very coarse sediments (0.63ϕ to -0.79ϕ), fining upwards to medium-grained sands (1.83ϕ to 1.55ϕ) towards the island surface (Figure 2).

A thin soil horizon comprised the upper ~0.5 m of sediment cores from KAN, composed of organic material and fine to medium grey-brown colored carbonate sands. Below this, island sediments were dominated by carbonate sands, with coral being the dominant constituent, ranging from 41.1% to 84.7%. The greatest proportion of coral was found near the top and base of cores: for example, coral comprised up to 81.7%, 77.7%, and 84.2% of sediments between 50-100 cm downcore in C9, C10, and C11, respectively and up to 81.8%, 84.7%, and 84.1% of sediments in the lower 20-50 cm of C9, C12, and C13, respectively (Figure 2). Excluding the coral-rich basal layer, the proportion of molluscs and *Halimeda* in sediments generally increased downcore, as shown in C9, C12, and C13 (Figure 2). Mollusc proportions in sediments increased from 9.9%, 14.0%, and 9.9%, in the upper 50 cm of C9, C12, and C13, respectively, to 20.3%, 23.0%, and 20.3%, in the lower 150 cm of C9, C12, and C13, respectively (Figure 2). *Halimeda* in these cores increased from 0.6%, 6.5%, and 3.9%, respectively, in

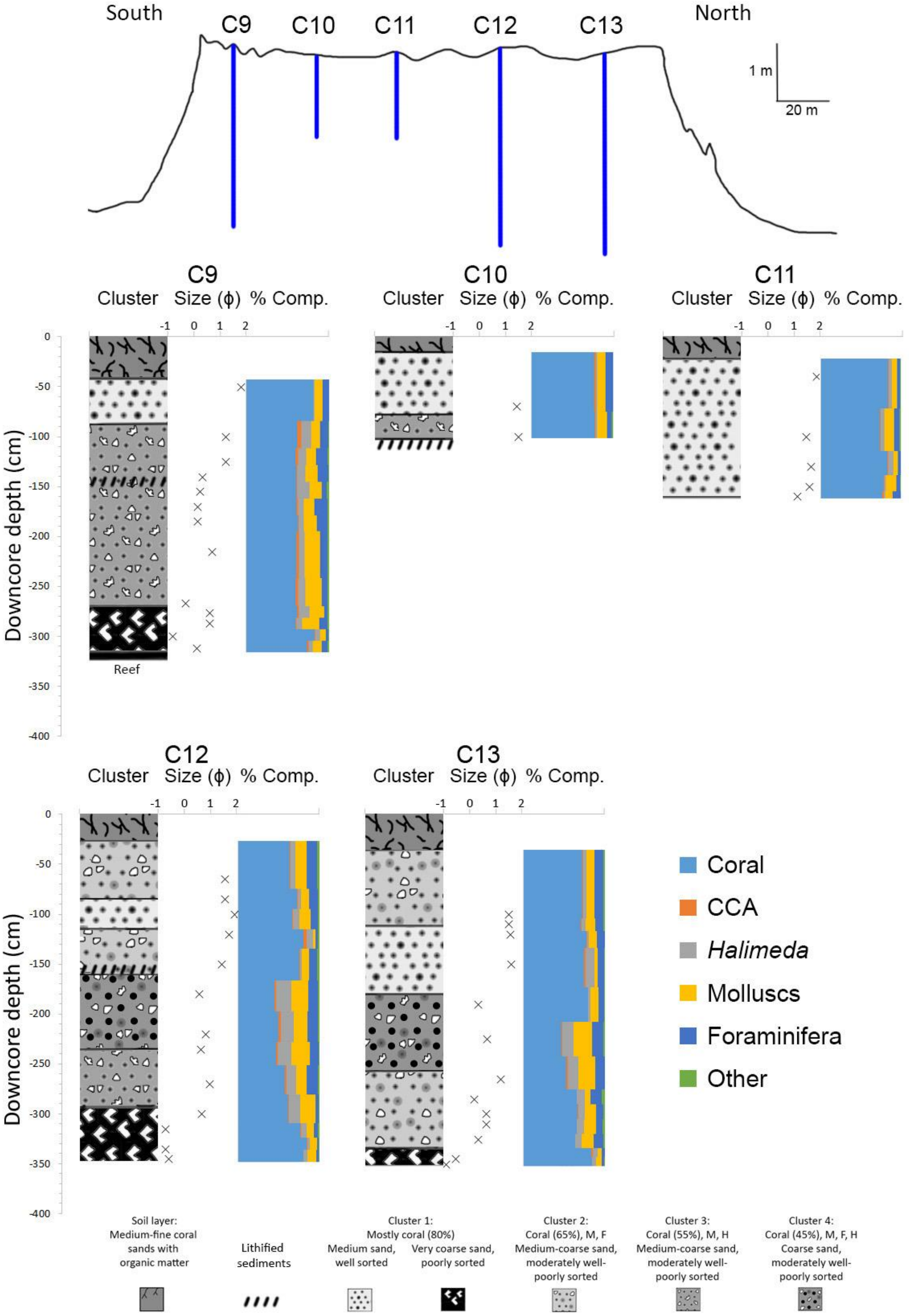

Figure 2. Downcore variations in mean grain size (ϕ), percent composition, and cluster type for cores in the mid-profile (Transect 3) of KAN.

the upper 50 cm of the cores, to 14.6%, 18.9%, and 14.0%, respectively, in the lower 150 cm of the cores (Figure 2). Lithified (cemented) sediments, which can be associated with presence of organic matter (i.e. phosphate rock), were recovered from five cores on KAN, including C9, C10, and C12 (Figure 2). Eleven other cores contained subsurface layers of organic matter but were not associated with lithified sediments.

On KAN, a K-means cluster analysis of skeletal composition in subsurface sediments statistically supported results of a downcore increase in *Halimeda* and mollusc proportions (Table 1). All clusters were dominated by coral but varied in proportion of secondary constituents. Downcore variations in sediment clusters were observed, with Cluster 1a and Cluster 2 generally found above msl (upper 100-150 cm of cores) while Clusters 3, 4, and 1b were found below msl or in the lower 150-200 cm of cores. Cluster 1a formed the upper 100-150 cm of 13 out of 20 cores on KAN. Sediments from Cluster 2 formed the upper layers (100-150 cm) of the remaining cores, with the exception of one core. Cluster 1b was only found at lower depths, between 265-350 cm downcore, with five cores on KAN terminating on sediments from this cluster, while the other cores did not reach sufficient depth to terminate on these sediments (assumed to be the basal layer of the island).

Table 1. Summary of clusters of island sediment samples from KAN (n = 159) and KOND (n = 147) based on K-means cluster analysis of skeletal composition. Cluster 1 has been further divided based on mean grain size (m: medium sand; vc: very coarse sand). Average composition (% ± s.d.) for skeletal constituents in each cluster are presented along with mean grain size (μ, ϕ ± s.d.) and sorting (σ, ϕ ± s.d.).

				Skeletal composition				Texture	
Cluster	No.	Coral	CCA	*Halimeda*	Molluscs	Forams	Other	(ϕ)	(ϕ)
KAN									
1a (m)	54	79.8±3.6	1.1±0.9	4.3±2.5	8.3±2.6	5.4±2.3	1.1±0.7	1.61±0.22	0.64±0.13
1b (vc)								-0.55±0.35	1.73±0.36
2	37	66.8±3.8	1.0±1.0	6.8±2.1	11.5±2.3	11.3±2.7	2.5±2.5	1.13±0.38	0.86±0.36
3	41	59.6±2.8	1.8±1.0	10.3±3.5	16.9±3.8	9.7±3.3	1.7±0.6	0.72±0.40	0.65±0.41
4	27	48.5±3.1	1.6±1.1	12.7±4.3	20.4±2.2	15.1±4.6	1.8±0.6	0.70±0.28	0.90±0.20
KON									
1a (m)	61	81.7±4.3	1.9±1.3	3.8±1.8	7.3±2.9	4.5±2.8	0.8±0.8	1.41±0.22	0.57±0.09
1b (vc)								-0.80±0.19	1.68±0.30
2	44	67.5±2.8	2.3±1.5	6.0±2.4	16.2±3.1	6.9±2.3	1.0±0.7	0.80±0.48	0.79±0.19
3	32	55.9±5.5	2.2±0.7	15.1±3.8	17.4±6.4	7.6±2.4	1.8±2.8	0.58±0.33	0.90±0.29
4	10	33.6±4.3	1.2±1.0	32.8±4.5	18.2±3.8	13.8±2.0	1.4±1.1	0.43±0.35	0.90±0.11

N.B. Constituents comprising on average >10% of total sample are underlined.

Sedimentary characteristics and stratigraphy of KOND

Seventeen cores were retrieved from KOND, ranging in depth of penetration from 0.6 m below msl to 2.6 m below msl. Downcore depth of penetration varied from 130 cm to 370 cm. Island sediments ranged in size from medium sands (1.90ϕ) to very fine gravel (-1.08ϕ), and typically, the cores exhibited a fining upcore sequence. This is due to the basal layer of the island being comprised of coarse sediments with coral sticks (0.93ϕ to -1.00ϕ), while the island surface was much finer (1.06ϕ to 1.90ϕ). The upcore fining of sediments is well-documented in the cores of Transect 3 on KOND (Figure 3), although the trend is evident in cores of all transects, thus only Transect 3 will be described in detail in this section for conciseness. In cores C9, C10, and C11, the lower 50 cm of cores comprised coarse to very coarse sands (0.17ϕ to -1.06ϕ), fining upward to medium sands (1.67ϕ to 1.09ϕ), towards the island surface (Figure 3).

The soil layer of KOND occupied the upper ~0.5 m of cores and was composed of organic material with fine to medium grey-brown colored carbonate sands. Below this, island sediments were dominated by carbonate sands, with coral being the dominant constituent, ranging from 44.8% to 91.8%. The highest percent coral in sediments was found near the top and base of cores: for example, coral comprised up to 80.6% and 87.9% of sediments between 50-125 cm downcore in C10 and C13, respectively and up to 82.8% and 80.6% of sediments in the lower 25 cm of C10 and C13, respectively (Figure 3). The proportion of molluscs generally increased downcore, as shown in C9, C10, and C12, increasing from 8.8%, 6.7%, and 7.8%, respectively in the upper 100 cm to 27.6%, 25.0%, and 24.5%, respectively, in the lower 100 cm (Figure 3). *Halimeda* was generally found lower downcore, as shown

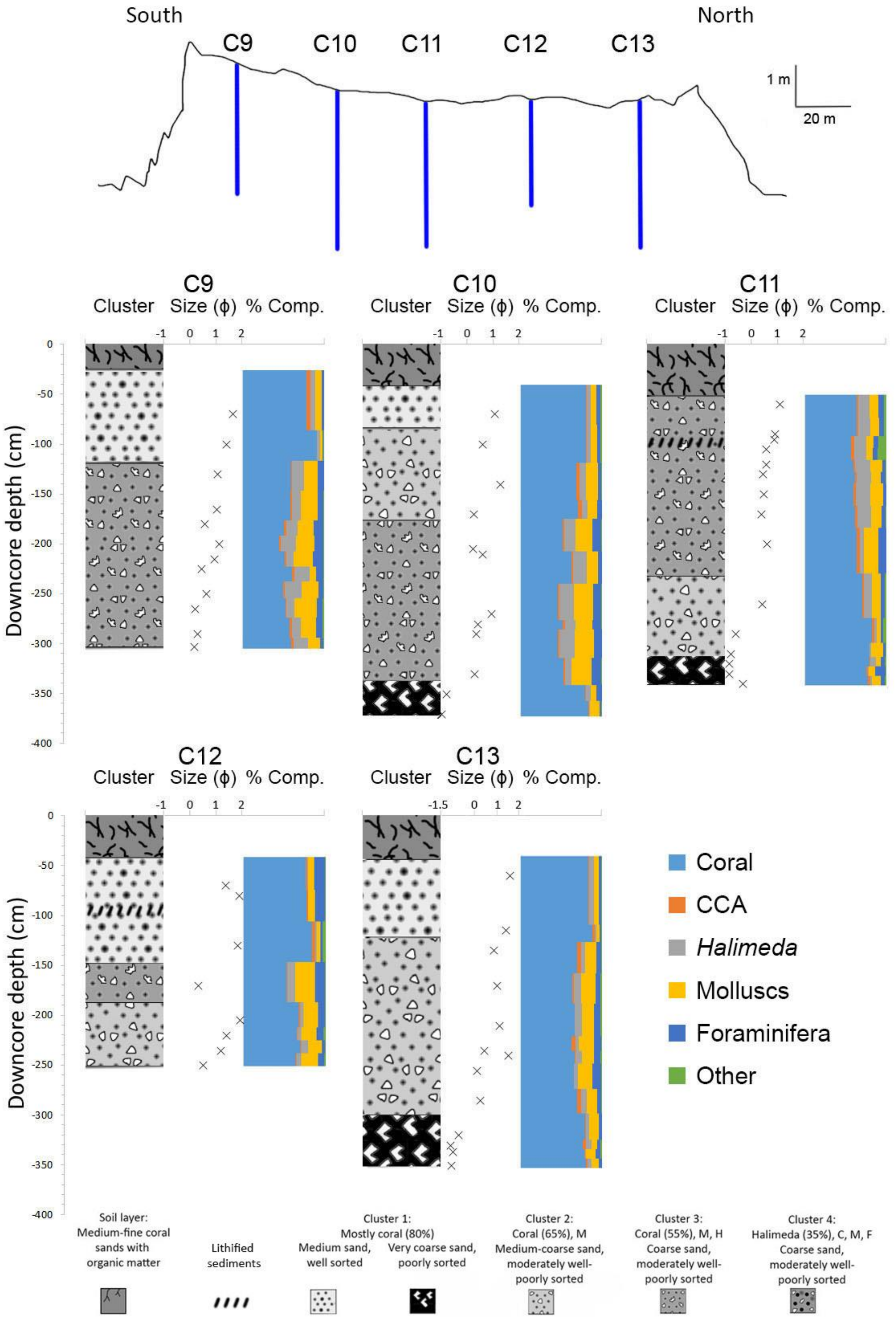

Figure 3. Downcore variations in mean grain size (ϕ), percent composition, and cluster type for cores in the mid-profile (Transect 3) of KOND.

in C9, C10, and C13, increasing from 5.9%, 5.6%, and 5.5%, respectively, in the upper 100 cm to 21.4%, 18.2%, and 8.7%, respectively, in the lower 100 cm (Figure 3). Lithified sediments were recovered in over half of the cores on KOND (10 of the 17 cores) and five other cores contained subsurface layers of organic matter that were not associated with lithified sediments.

On KOND, four clusters were generated from a K-means cluster analysis of skeletal composition of subsurface sediments (Table 1). Similar to KAN, the analysis statistically supports downcore variations in sediment clusters, namely the increase of *Halimeda* and mollusc composition with depth (Table 1). Cluster 1a was the only sediment cluster on KOND that was found above mean sea level (upper 100-150 cm of cores), while Clusters 2-4 and 1b were found below 150 cm downcore. Cluster 1a formed the upper layer (50-150 cm) of all cores on KOND, with the exception of two cores. As on KAN, Cluster 1b on KOND was found at lower depths, between 280-370 cm downcore. Four cores terminated on sediments from Cluster 1b, including C10, C11, and C13 (Figure 3).

DISCUSSION

The same main constituents were present in all reef and beach samples, which infers island beach connectivity with the reef and suggests that material comprising island sediments are still being produced on the reef (Liang et al., 2016). These main constituents are present in island subsurface sediments as well, revealing that the main reef building organisms on the contemporary reef were present during island building. However, the proportion of these reef builders has not remained consistent over time. On KAN and KOND, downcore variations in composition show that the proportion of coral sands decrease with depth (with the exception of cores that terminated on coarse sands with coral branches) and the proportion of *Halimeda* and molluscs increase with depth (Figures 2, 3).

The overrepresented proportion of molluscs as compared to their abundance on the contemporary reef (Liang et al., 2016) is likely due to their high durability, which translates to their persistence in reef and island sediments. However, the low durability of *Halimeda* means that these grains are easily abraded in the littoral zone (Morgan and Kench, 2016). Thus, the proportion of *Halimeda* in island sediments may be underrepresented compared to *Halimeda* generation on the reef. Using inverse modelling and coefficient of decay derived from tumbling barrel experiments, Ford (2009) determined that the sediment generation rate of *Halimeda* needs to be 120 times that of coral and molluscs in order to produce similar volumes. Thus, small changes in proportion of *Halimeda* in island subsurface sediments may reflect much bigger ecological shifts on the reef. Shifts in reef ecology can be attributed to a variety of biotic and abiotic factors, and over longer timescales, sea-level change can be a critical factor (Hewins and Perry, 2006; Yamano et al., 2000).

In the north Maldives on Baa Atoll, *Halimeda* sediments accumulated rapidly as the reefs accreted to sea level and once this had occurred, sediment supply shifted from *Halimeda* to coral and coralline algae (Kench et al., 2005). Perry et al. (2011) predicted that the sedimentary response of reefs to a 0.5 m rise in sea level would result in increased production of *Halimeda*, followed by production of coral after an initial lag. The rapid response of *Halimeda* growth is related to the high turnover rate of its calcified segments (Hillis-Colinvaux, 1968), and its direct contribution to sediment production after death as opposed to coral, which must first undergo breakdown processes (Perry et al., 2011). This growth strategy of the reef platform in response to sea-level rise can be described as either: 1) keep-up, where reefs grow at a rate approximating sea-level rise, or 2) catch-up, where reefs lag behind sea level but catch up when sea level stabilizes (Neumann and Macintyre, 1985). Keep-up and catch-up growth would require reefs to accrete vertically at faster rates, which could result in an ecological shift to rapidly growing reef organisms. Thus, the increases in *Halimeda* between 0.41-0.47 m below msl on KAN and 0.29-0.41 m below msl on KOND could be a sedimentological response to rising sea levels or other changes in environmental conditions. In addition, sea-level lowstands could exacerbate coral mortality (as seen in contemporary ENSO rapid sea-level fall; Ampou et al., 2017), which could represent an alternative mechanism for increased proportions of other constituents found in island sediments such as *Halimeda*. Regardless of mechanisms involved in reef ecological response, it is clear that the sediment production regimes change over the course of island building, which likely reflects changes in reef ecology.

With current sea-level trajectory at Huvadhoo Atoll projected as a rise of 4.24 mm per year (Kench et al., 2020), reefs will need to continue to employ a keep-up or catch-up strategy. Although this study presents optimistic results for past island ecological responses to sea-level rise, modern reef islands and their surrounding reefs must contend with additional barriers such as rising sea surface temperatures, ocean acidification, and coastal infrastructure inhibiting sediment transport.

CONCLUSIONS

This study provides the first detailed investigation of lagoonal reef island subsurface morphology on a south Maldivian atoll. The islands were mostly comprised of medium-grained sands dominated by coral constituents. Downcore variations in sediment texture and composition were also observed; most notably, higher proportions of *Halimeda* and molluscs were found at increased depths along cores, which could correspond to higher reef generation rates or hydrodynamic conditions that favored the transport and deposition of these organisms. The sedimentological response of increased *Halimeda* and molluscs highlights the resilient and dynamic nature of reef islands. These islands are not only able to adjust morphologically, this research shows that their reefs are able to adjust ecologically to rising sea levels.

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