Lagoonal reef island formation in Huvadhoo atoll, Maldives, highlights marked temporal variations in island building across the archipelago

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ABSTRACT

Coral reef islands provide the only pedestals of human habitation in mid-ocean atoll archipelagoes. Understanding the environmental controls on island formation is critical for evaluating the future response of islands to environmental change and sea-level rise. This study examines the evolution of lagoonal reef islands in Huvadhoo atoll, southern Maldives. Using extensive ground penetrating radar (GPR) imaging of island sediment structure, combined with comprehensive analysis of island morphology, sedimentology, and 49 radiometric dates, detailed reconstructions of the evolution of two lagoonal islands is presented. A four-stage model shows a complex history of island formation across various stages of sea-level change during the late-Holocene: 1) lagoon infill occurring from ~3000-2000 years ago during a period of sea-level fall from the mid-Holocene highstand; 2) emergence of the island core through vertical aggradation during the latter stages of sea-level fall between ~2,000-1,500 yBP; 3) Rapid lateral expansion of the islands between 1,500 and 500 yBP coincident with the availability of sand-size sediments and during a period of sea-level oscillation; and, 4) Subsequent minor expansion and modification of island shorelines through alongshore reworking of island sediments over the past 500 years. Results provide evidence of marked differences in the timing and mode of island formation within Huvadhoo atoll. Significantly, the formation of the lagoonal islands post-dates the formation of islands on the atoll rim by 1,000-2,000 years. Furthermore, the formation of sand islands over infilled shallow lagoons contrasts the formation of most atoll rim islands through the sequential deposition of storm-generated rubble deposited directly across reef surfaces that have reached their vertical growth limit. Results of lagoonal island formation in the southern Maldives provide comparative data for the northern Maldives. While the sequence of island formation

follows the faro infill model identified in the northern archipelago, lagoonal islands in the south appear to have formed 2,000 years after those in the north. This difference is likely to reflect lagged reef growth response from deeper foundations in the southern archipelago.

Key words: Reef islands, coral reefs, sea level, Maldives, sedimentology

1 Introduction

Coral reef islands are small, low-lying landforms, formed mainly from bioclastic sands and gravels during the mid- to late-Holocene (last ~6000 years). The bioclastic sediments comprising islands are commonly derived from the surrounding coral reefs, and consist of the skeletal remains of reef organisms such as coral, coralline algae, molluscs, foraminifera and *Halimeda* (Barry et al., 2007; Dawson et al., 2012; Kench et al., 2005; Woodroffe, 1992; Yamano et al., 2000). Reef islands provide the only habitable land within atoll nations and support more than 540,000 people in the Maldives alone (World Bank population data, 2022). Consequently, the vulnerability of reef islands to projected sea-level rise is of global concern with widespread assertions that islands will be physically destabilized and rendered uninhabitable (Dickinson, 2009; Storlazzi et al., 2018). However, there is considerable debate surrounding the future of reef islands, as future predictions of physical stability are constrained by an incomplete understanding of the environmental controls on island formation and change.

To better resolve the role of sea level as a driver of island formation and change, a number of studies have reconstructed the evolution of islands across millennial timescales and against known variations in sea level. Indeed, sea-level fall has been viewed as a critical driver of island formation, and consequently, sea-level rise has been implicated as a major driver of future island instability (Dickinson, 2004; 2009). Underpinning this model of island formation was that reef growth and platform development at sea level were necessary precursors for island formation. Examples supporting this model are found in the eastern Indian Ocean, Pacific Ocean and Torres Strait where island formation occurred subsequent to the mid-Holocene sea level highstand across emergent reef flats that had attained their vertical growth limit in response to the higher sea level (Woodroffe et al., 1999; Woodroffe and Morrison, 2001; Kench et al., 2012). However, a study from Jabat Island, Marshall Islands, in the southwest Pacific showed that the island formed in the mid-Holocene during the latter stages of sea-level rise, to the mid-Holocene highstand, and has subsequently become emergent due to sea-level fall (Kench et al., 2014b). Of note, islands formed on emergent platforms, as a consequence of relative sea-level fall, are likely disconnected from the active contemporary process regime. Evidence from a number of sand cays from Caribbean reefs and atolls off Belize also indicate that islands have accumulated against the backdrop of incremental rising sea level over the past few millennia (Woodroffe, 2008). Formation of islands during the latter stages of Holocene sea-level rise has also been reported in the Maldivian archipelago (Kench et al., 2005). A critical difference in this setting is that a number of islands have formed across sediment-filled lagoons, that have not reached sea level, and have subsequently persisted across a sea level highstand (Kench et al., 2005; Perry et al., 2013). Still further studies from the southwest Pacific have island formation over the past 1,000-1,500 years, at current sea level and across sea level constrained reef flats (McKoy et al., 2010; Kench, 2014a, Kench

et al., 2018). Collectively these studies from different reef regions challenge the simplistic sea level-driven assumptions of island behaviour, demonstrating that islands have formed in response to varied sea level and reef growth histories (Kench et al., 2020a) with the defining controls being accommodation space, which is governed by relative water depth, modulated by reef growth and sea-level change, and sediment supply.

While the above findings have improved understanding of island formation, it is important to highlight that the number of studies of reef island evolution is small, compared with the number and diversity of reef islands found through the tropical reef regions (Stoddart and Steers, 1977; Perry, 2011). Existing studies have largely focused on individual islands, or a small subset of islands (2-3) from atoll archipelagos or barrier reef systems that typically contain thousands of islands (e.g. Maldives, Marshall Islands, Great Barrier Reef). The extent to which the evolutionary reconstruction of an individual island represents the general formation of all islands in an archipelago is speculative. In this context, recent studies emerging from the Maldivian archipelago are distinctive in that they are beginning to provide improved resolution of along-archipelago variations in timing of the onset and window of island accumulation, and in differences in the substrate conditions supporting island accumulation. Earlier studies on three islands in South Maalhosmadulu atoll, in the northern sector of the Maldives, depicted islands forming as early as 4,500 years ago across sediment filled lagoons, and under rising sea level (Kench, 2005; Perry et al., 2013). Notably these islands were situated on individual reef platforms inside the larger lagoon of the atoll periphery. More recently, East et al. (2018) and Kench et al. (2020a) examined the formation of a number of islands located on the exposed peripheral reef rim of Huvadhoo atoll in the southern Maldives. Their findings indicated that islands formed much later in the Holocene (over the past 2,500 years) across a period of sea level oscillation over the past two millennia (Kench et al., 2020b). Furthermore, East et al. (2018) found islands had formed across sea level constrained reef flats, whereas, Kench et al (2020a) found island formation across the infilled shallow lagoon of the peripheral reef rim.

Collectively these studies highlight marked differences in the timing of island formation (~2,000 years) along the archipelago. Such differences may be related to the relative position of islands within atolls. Rim islands form on reef platforms around atoll perimeters whereas lagoonal reef islands form within the atoll lagoon. Studies from the north focused on lagoonal reef islands deposited on reef platforms that rise from the lagoon floor (Kench, et al., 2005; Perry et al., 2013), whereas examples from the south are rim islands situated on the atoll periphery (East et al., 2018; Kench et al., 2020a). These locational differences have implications for the boundary energetics controlling island accumulation, with lagoonal platforms protected from oceanic wave energy.

This study examines the formation of two reef islands located on lagoonal reef platforms in Huvadhoo atoll in the southern Maldives, based on detailed morpho- and chronostratigraphic analyses and ground penetrating radar. Results show a complex history of island formation during latter stages of the Holocene marine transgression. Results are used to compare island evolutionary history with neighbouring islands on the atoll periphery and similarly located lagoonal islands in the north of the archipelago, and to establish any consistent differences related to island position within atolls or whether spatial gradient exists in formation history. Exploration of differences in the onset and temporal window of island formation within reef provinces is essential to better

resolve the controls on, and timeframes of, formation of these reef-bound island landscapes that are critical to human habitation of archipelagic systems.

2 Field Setting and Method

The Maldives archipelago is a chain of 22 atolls that straddle the equator in the central Indian Ocean (Fig. 1A). The archipelago experienced rapid Holocene sea-level rise from 8,000 to 4,000 yBP (Camoin et al., 2004; Gishler et al., 2008) 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 oscillation in sea level by up to 0.9 m over the past two millennia (Kench et al, 2020b). While located outside the zone of cyclogenesis, the archipelago is influenced by marked transitions in monsoons from the southwest (April-November) and northeast (December-March; Kench et al., 2008). This study examines the island sedimentary structure, mode of island building, and depositional chronology of two lagoonal islands in Huvadhoo atoll, in the south of the archipelago (Fig. 1C). Kandahalagalaa (KAN) located in the southern lagoon and Kondeymatheelaabadhoo (KON) located in the east, are similar in size (5.38 ha and 4.58 ha respectively) and both occupy ~20% of their reef platform surface (Fig. 1D, E). Both islands are located less than 5 km inside the atoll rim and have deep and narrow passes through the rim to the SSE and NE. Residual ocean swell is able to propagate through these passes and impact the study islands. While the presence of the atoll rim serves to minimize the lagoon-generating fetch distance on one aspect of each island, their different lagoonal positions indicate the dominant wave-generated fetch length affecting the two islands is from the north on KAN and from the west on KON.

The topography of both islands was surveyed along 12 transects using a laser level. The topographic data were reduced to height relative to mean sea level using water level at survey time and tide tables at Gan (00°41S, 73°09E) accessed through the University of Hawaii Sea Level Center. Island subsurface stratigraphy was reconstructed by analysing the skeletal composition and textural properties of 306 sediment samples from 37 cores extracted across the islands using percussion coring and augering techniques. Sediment texture was determined by dry sieving samples in a sieve shaker (15 minutes per sample) into half-phi size fractions from -2φ to 4φ and the mean grain size was calculated in GRADISTAT (Blott and Pye, 2001). Composition was determined by point-counting 100 grains from each half-phi size fraction between -2.0 and 3.0 φ under a binocular microscope (n=1,100 grains per sample) following the methods of Collen and Garton (2004) and Kench et al. (2014a).

The style of island sedimentation is interpreted from 960 m of ground penetrating radar (GPR) data obtained along surveyed transects. A GSSI (Geophysical Survey Systems Inc.) SIR2000 system with a monostatic 200 MHz shielded antenna was used, which continuously recorded and stacked laterally to create the radar reflection profile. GPR images were processed using RADAN 6.6 software (GSSI) and an experimentally derived dielectric constant of T=9. Stratigraphy was temporally constrained with 49 radiometric ages. *Halimeda* segments (n=41) were dated using AMS radiocarbon techniques at the Waikato Radiocarbon Dating Laboratory, New Zealand. *Halimeda* segments were inspected under a binocular microscope and deemed pristine if the whole segment was intact and there was little evidence of surface abrasion or chemical alteration. In addition, six

bulk sand samples and two *Acropora* coral sticks (also inspected under a microscope for minimal surface abrasion and intact corallites) from basal sections of cores were dated using conventional radiocarbon dating. Radiometric ages discussed are the mid-point of the calibrated age range.

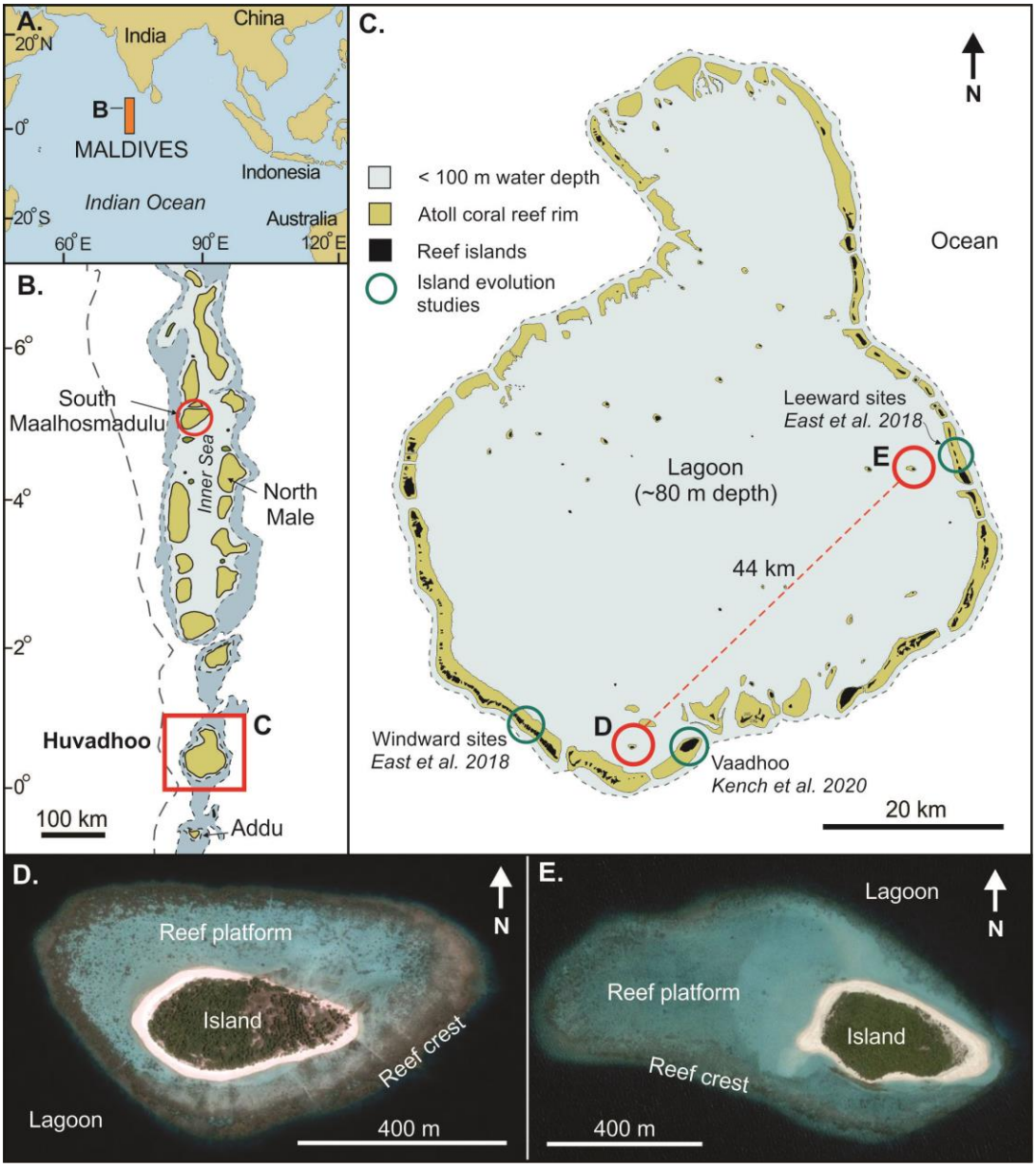

Figure 1. Location of study islands in Huvadhoo atoll lagoon, Maldives. (A) Location of the Maldives archipelago, Indian Ocean. B) Maldives archipelago. C) Huvadhoo atoll showing location of lagoonal study islands. D) Kandahalagalaa (map data: Google, DigitalGlobe), and E) Kondeymatheelaabadhoo (map data: Google, CNES/Astrium), which are 44 km apart.

3 Results

3.1 Morphostratigraphy

Topographic surveys show that KAN has an asymmetric morphology along its west-east axis (Fig. 2B) increasing in elevation from 1.06 m msl at the western ridge to a central platform of 1.43 m msl and rising to a maximum elevation of 1.9 m msl on two narrow ridges on the east (Fig. 2B). The central north-south transect (Fig. 2C) shows a near planar surface comprising a number of low amplitude ridges, with marginal ridges at 1.39 m msl (north) and 1.56 m (south). On KON, two north-south transects show contrasting morphologies. To the west, Transect 2 shows a convex morphology which has its maximum elevation in the centre (2.44 m msl) and reduces in elevation toward both shorelines in a sequence of ridges. The northern beach ridge is 1.34 m msl, while the southern shoreline island ridge is 1.22 m msl and grades into the shallow lagoon (Fig. 3B). Further to the east, Transect 3 shows a marked asymmetric profile, which increases in elevation beyond the northern beach ridge (1.41 m msl) to the southern shoreline at 2.32 m msl. Notably, the highest ridges are located on the east and south of KAN and KON, both orientations align with deeper passages in the atoll rim (Fig. 1B). Both islands have steep beachfaces that intersect the reef platform or shallow lagoon.

Thirty seven cores penetrated the island sediment sequences, terminating in basal sediments (Fig. 2A, 3A). Sedimentary characteristics are similar between islands, which are dominated by medium-grained (1.06-1.9 ø) moderately sorted sands (Table 1), though cores reveal downcore variations in which coarse to very coarse sand layers are present at depth. The skeletal composition of island sediments is dominated by coral, with subordinate fractions of *Halimeda*, molluscs and foraminifera (Table 1). Cluster analysis of samples determined four sediment types based on texture and composition (Table 1, Fig. 2, 3). Upper island units (clusters 1 and 2) comprise medium sands dominated by coral (67-80%) with secondary constituents such as foraminifera, molluscs and *Halimeda*, in minor proportions (~ ≤10%). Downcore, lower island units become coarser (0.43-0.72 ø) with coral assuming smaller proportions (33-59%) and an increasing presence of *Halimeda* (max. 32%), molluscs (max. 20%) and foraminifera (max. 15%). Underlying the islands sediment is a basal unit comprising coarse sands with inclusions of coral gravels (*Acropora* sticks).

3.2 Signatures of Island Sedimentation

GPR traces from both islands reveal four depositional units (Fig. 2C, 3C). First, near-horizontal stratigraphy at the lower depths, which are interpreted as faro lagoon infill units similar to the underlying *velu* unit of Kench et al. (2005) and Perry et al. (2013). Second, and overlying this basal unit near the centre of each island, is evidence of vertically stacked convex sediment sequences (Fig. 2C, 3C). This unit is interpreted as the initial phase of island formation above sea level as a supratidal sand deposit (*finolhu* of Kench et al., 2005). Third, a lateral progradational sequence extending either side of the island core is evident, which has seaward-dipping clinoforms to the west (0.5-8.2°) and east (2.1-9.2°). Fourth, the progradational sequence terminates at the contemporary beach and beach ridge. The third and fourth progradational sequences are evidenced by contemporary transect topography: transects display a series of low amplitude ridges, which could represent

previous positions of island margin deposition. Further, the slope of the reflectors in these progradational facies are comparable to the slope of the contemporary beach face. While there is evidence of each of these units on both islands, the precise location of the island core is only inferred on KON, bounded by hyperbolic reflectors on either side of the locations at Cores 11 and 12 (Fig. 3C). This style of progradation is consistent with the GPR profile of Kench et al. (2005) for a reef island in the north Maldives, where steeply dipping beds in the facies around the central node of Thiladhoo indicated shoreline progradation and aggradation of the island ridge.

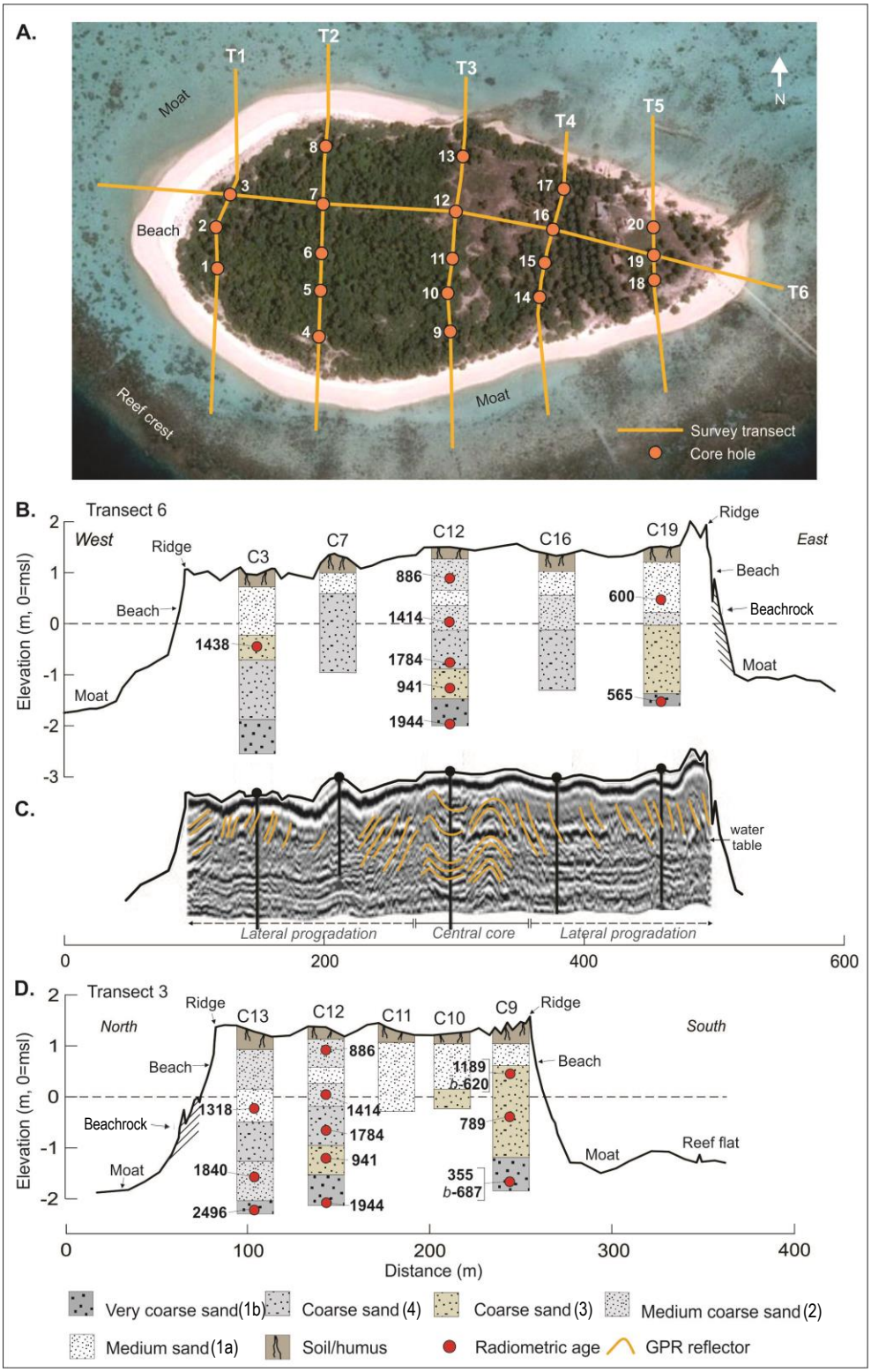

Figure 2. Morphostratigraphy of Kandahalagalaa (KAN), Huvadhoo atoll. A) Location of survey transects and island core holes. B) West-East island profile, stratigraphy and radiometric ages, Transect 6. C) Ground penetrating radar (GPR) records along transect 6 showing horizontal accretion around the central core. Gold lines provide summary of key reflectors. D) North-South island profile, stratigraphy and radiometric ages, Transect 3. Location of island in lagoon shown in Figure 1C. Radiometric ages are the mid-point of the calibrated age range of single constituent *Halimeda* grains. '*b*' denotes bulk sample dated. Corresponding cluster number (Table 1) denoted in brackets in legend.

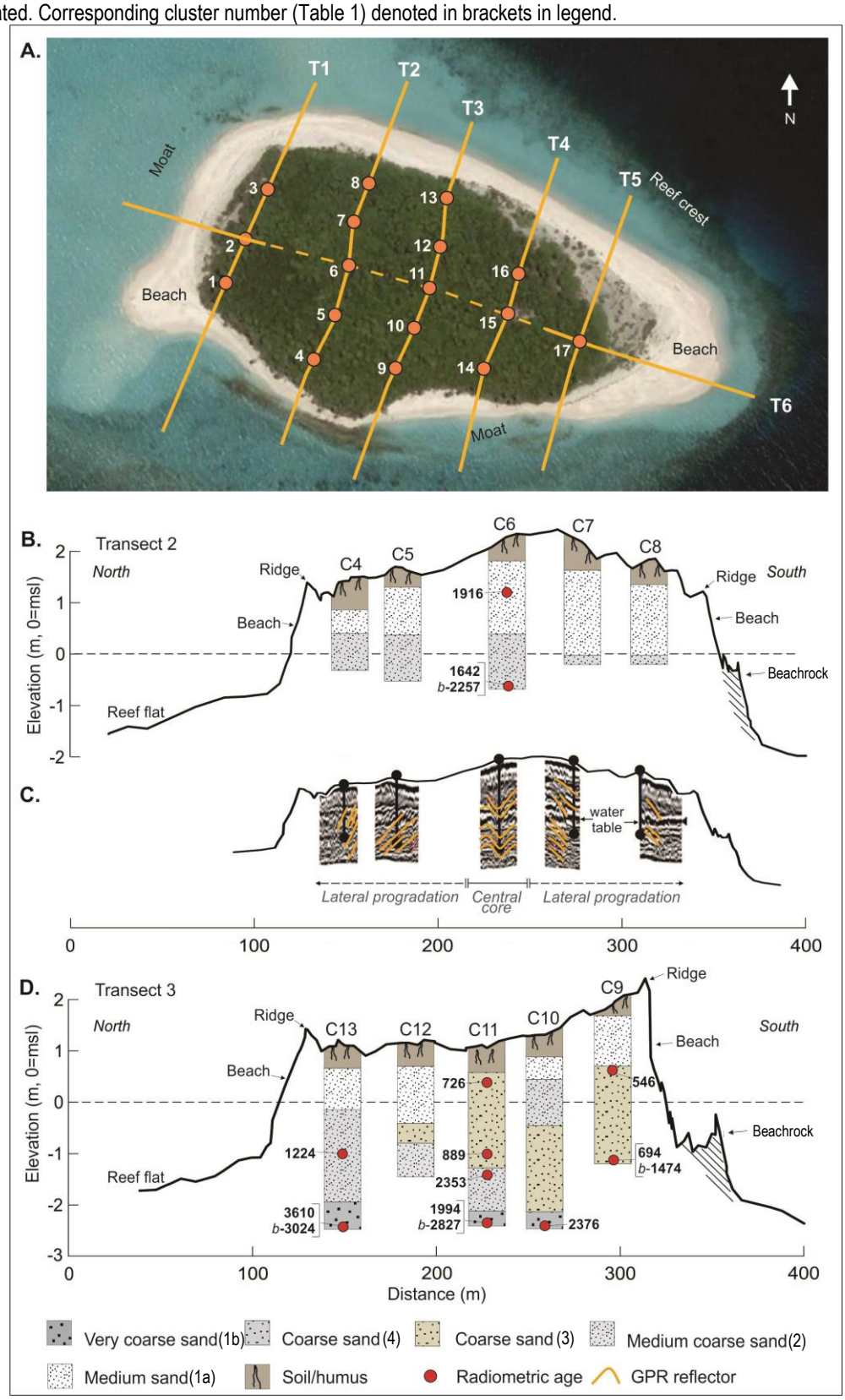

Figure 3. Morphostratigraphy of Kondeymatheelaabadhoo (KON), Huvadhoo atoll. A) Location of survey transects and island core holes. B) North-South island profile, stratigraphy and radiometric ages, Transect 2. C) Ground penetrating radar (GPR) records along Transect 2 showing horizontal accretion around the central core. Gold lines provide summary of key reflectors. D) North-South island profile, stratigraphy and radiometric ages, Transect 3. Location of island in lagoon shown in Figure 1C. Radiometric ages are the mid-point of the calibrated age range of single constituent *Halimeda* grains. '*b*' denotes bulk sample dated. Corresponding cluster number (Table 1) denoted in brackets in legend.

Table 1. Summary of island sediment skeletal composition and texture from Kandahalagalaa (n=159) and Kondeymatheelaabadhoo (n=147) using k-means cluster analysis. Constituents comprising on average >10% of total sample are underlined.

Cluster	n	Skeletal Composition (%)						Texture	
		Coral	CCA	Halimeda	Molluscs	Forams	Other	(φ)	(φ)
Kandahalagalaa									
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
Kondeymatheelaabadhoo									
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. CCA is crustose coralline algae. 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.).

3.3 Radiometric ages of island sediments

The oldest ages on *Halimeda* clasts at Kandahalagalaa are 2,935 and 2,496 cal yBP. An additional date on an *Acropora* stick at the base of core 12 yielded an age of 1,944 cal yBP. These oldest set of dates from basal cores that underlie the island suggest that these sediments constrain the timing of latter stages of lagoonal infill to around 2,000 yBP. The remaining age determinations (n=24) range between 1,840 and 355 cal yBP suggesting a sustained period of sediment generation across this timeframe that contributed to island building. However, it is noticeable that the majority of dates are found in the 1,844 – 500 window (81%) and the highest number of ages were found between 1,500 and 1,000 years ago (40%; Figure 4).

Similar to KAN, the oldest ages on sediments at Kondeymatheelaabadhoo are at the base of cores with seven samples ranging in age from 3,610 to 1,994 cal yBP, which given the depth relative to the contemporary reef surface (Figure 3D), indicates that these sediments also reflect the late stages of shallow lagoon infill. While the age range of remaining samples spans the 2,000 to 350 cal yBP range, providing a broad timeframe for island accumulation, unlike KAN there are fewer ages on island sediments in the 2,000-1,000 year range (n=4, excluding the *Acropora* stick age), with the dominant age of samples in the 1,000-500 cal yBP range (n=9, ~41% of all samples).

Of note, on both islands a number of age inversions, particularly at outer margins of islands, indicate that the islands have not been positionally stable but subject to reworking, indicative of recent island mobility.

Table 2. Radiometric ages on sediments from Kandahalagalaa and Kondeymatheelaabadhoo islands, Huvadhoo atoll, Maldives.

Lab Code	Core location and depth	Depth relative to msl (m)	Material	Conventional age (yBP)	Calibrated age range (95%) (yBP)	Calibrated median age (yBP)
Kandahalagalaa						
Wk40681	C3-140	0.61	*Halimeda*	2,026 ± 20	*1,350-1,525*	1,438
Wk40661	C3-120	-1.19	*Halimeda*	1,849 ± 20	*1,200-1,340*	1,270
Wk40666	C4-45	1.09	*Halimeda*	966 ± 20	*411-521*	466
Wk40664	C4-120	0.34	*Halimeda*	1,732 ± 20	*1,068-1,250*	1,159
Wk40665	C4-200	-0.45	*Halimeda*	3,277 ± 20	*2,825-3,045*	2,935
Wk40667	C6-40	1.25	*Halimeda*	1,134 ± 20	*524-644*	584
Wk40668	C6-130	0.35	*Halimeda*	1,826 ± 20	*1,175-1,310*	1,243
Wk40669	C6-215	-0.5	*Halimeda*	1,975 ± 20	*1,300-1,485*	1,393
Wk40670	C6-320	-1.55	*Halimeda*	1,800 ± 20	*1,161-1,293*	1,227
Wk40671	C8-110	0.17	*Halimeda*	2,347 ± 20	*1,711-1,902*	1,807
Wk40672	C8-165	-0.38	*Halimeda*	1,919 ± 20	*1,265-1,401*	1,333
Wk40673	C-9-100	0.45	*Halimeda*	1,707 ± 20	*1,047-1,231*	1,139
Wk40674	C9-170	-0.25	*Halimeda*	1,369 ± 20	*696-881*	789
Wk40675	C9-312	-1.67	*Halimeda*	838 ± 20	*279-430*	355
Wk40676	C12-45	0.65	*Halimeda*	1,489 ± 20	*797-974*	886
Wk40659	C12-150	-0.2	*Halimeda*	1,994 ± 20	*1,321-1506*	1,414
Wk40677	C12-235	-0.85	*Halimeda*	2,321 ± 20	*1,693-1,874*	1,784
Wk40660	C12-300	-1.65	*Halimeda*	1,516 ± 20	*850-1031*	941
Wk40678	C13-150	-0.23	*Halimeda*	1,897 ± 20	*1,252-1,383*	1,318
Wk40679	C13-300	-1.73	*Halimeda*	2,373 ± 20	*1,742-1,937*	1,840
Wk40680	C13-350	-2.23	*Halimeda*	2,888 ± 20	*2,347-2,644*	2,496
Wk40663	C19-130	0.1	*Halimeda*	1,165 ± 20	*540-660*	600
Wk40662	C19-305	-1.65	*Halimeda*	1,096 ± 20	*504-625*	565
Wk40302	C12-345	-2.08	*Acropora*	2,455 ± 20	*1,846-2,041*	1,944
Wk42999	C6-320B	-1.55	Bulk	1,700 ± 29	*1,026-1,240*	1,133
Wk42997	C9-100B	0.45	Bulk	1,198 ± 31	*545-695*	620
Wk42998	C9-312B	-1.67	Bulk	1,260 ± 20	*628-746*	687
Kondeymatheelaabadhoo						
Wk43017	C2-70	0.09	*Halimeda*	1,154 ± 20	534-655	595
Wk43018	C2-160	-0.81	*Halimeda*	2,604 ± 20	2,017-2,269	2,143
Wk43013	C6-115	1.14	*Halimeda*	2,438 ± 20	1,821-2,011	1,916
Wk43014	C6-300	-0.71	*Halimeda*	2,204 ± 20	1,541-1,743	1,642
Wk43015	C9-130	0.6	*Halimeda*	1,059 ± 20	481-610	546
Wk43016	C9-303	-1.13	*Halimeda*	1,268 ± 20	634-753	694
Wk43007	C10-370	-2.38	*Halimeda*	2,797 ± 20	2,287-2,464	2,376
Wk43003	C11-60	0.46	*Halimeda*	1,315 ± 20	655-797	726
Wk43004	C11-200	-0.94	*Halimeda*	1,492 ± 20	800-978	889
Wk43005	C11-260	-1.54	*Halimeda*	2,778 ± 20	2,250-2,455	2,353
Wk43006	C11-330	-2.24	*Halimeda*	2,497 ± 20	1,891-2,096	1,994
Wk43019	C13-210	-0.97	*Halimeda*	1,796 ± 20	1,157-1,291	1,224
Wk43020	C13-350	-2.37	*Halimeda*	3,830 ± 22	3,503-3,716	3,610
Wk43011	C15-100	0.44	*Halimeda*	1,302 ± 20	653-782	718
Wk43012	C15-222	-0.78	*Halimeda*	1,276 ± 20	639-760	700
Wk43008	C17-140	-0.2	*Halimeda*	813 ± 20	266-416	341
Wk43009	C17-210	-0.9	*Halimeda*	1,368 ± 20	695-880	788
Wk43010	C17-280	-1.6	*Halimeda*	1,434 ± 20	761-921	841
Wk40301	C11-340	-2.34	*Acropora*	3,186 ± 20	2,743-2,827	2,827
Wk43000	C6-300B	-0.71	Bulk	2,740 ± 22	2,155-2,257	2,257
Wk43001	C9-303B	-1.13	Bulk	2,065 ± 20	1,381-1,567	1,474
Wk43002	C13-350B	-2.37	Bulk	3,348 ± 32	2,892-3,155	3,024

Radiocarbon AMS dates shown were obtained from the Radiocarbon Dating Lab, University of Waikato, calibrated using OxCal (Bronk Ramsey, 2001) and a marine reservoir correction of 132 ± 25 was applied (Southon et al., 2002).

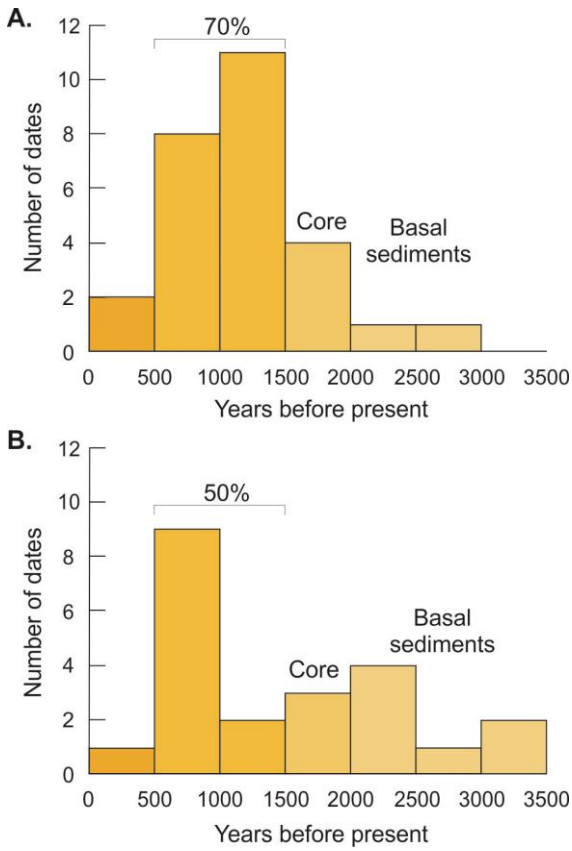

Figure 4. Summary frequency distribution of radiometric ages of sediments in age cohorts for Kandahalagalaa (A) and Kondeymatheelaabadhoo (B), Huvadhoo atoll, Maldives.

4 DISCUSSION

4.1 Model of island formation

The morphostratigraphy, GPR sequences and radiometric dating provide a framework to construct a staged sequence of island formation (Fig. 5) in the context of the established sea level history for the Maldives archipelago (Kench et al., 2020b). Stage one is characterised by terminal infill of the shallow lagoons (*velu*) occupying the central basin of each reef platform, which was near complete by ~2,000 yBP on both islands (Fig. 5A). The *velu* facies are coarser in texture than island sediments and are likely derived from autochthonous contributions from *Acropora* thickets that occupy such shallow lagoonal environments, as also noted by Perry et al. (2013), and *Halimeda*. Formation of the islands across infilled sediment lagoons (*velu*) is a major distinction in the basement structure of these lagoonal islands, compared with most atoll rim islands that are deposited directly on the coral reef platform surface. Of note, the latter stages of *velu* infill occurred during a period of sea-level fall (~0.5 m) from the late-Holocene highstand (Kench et al., 2009), which further implies that water depth and therefore, the wave energy window (Perry, 2011) operating across the reef surface was higher at that time. The wave energy window is also likely to have been enhanced during this period as the reef platform had not yet achieved vertical growth limit, as also observed at other sites in the northern Maldives (Kench et al., 2005). Increased water depth across shallow lagoons has been shown to be conducive to the production of *Halimeda* (Perry et al., 2013) which is prevalent in basal sediments of islands (*velu* and lower *finolhu* facies).

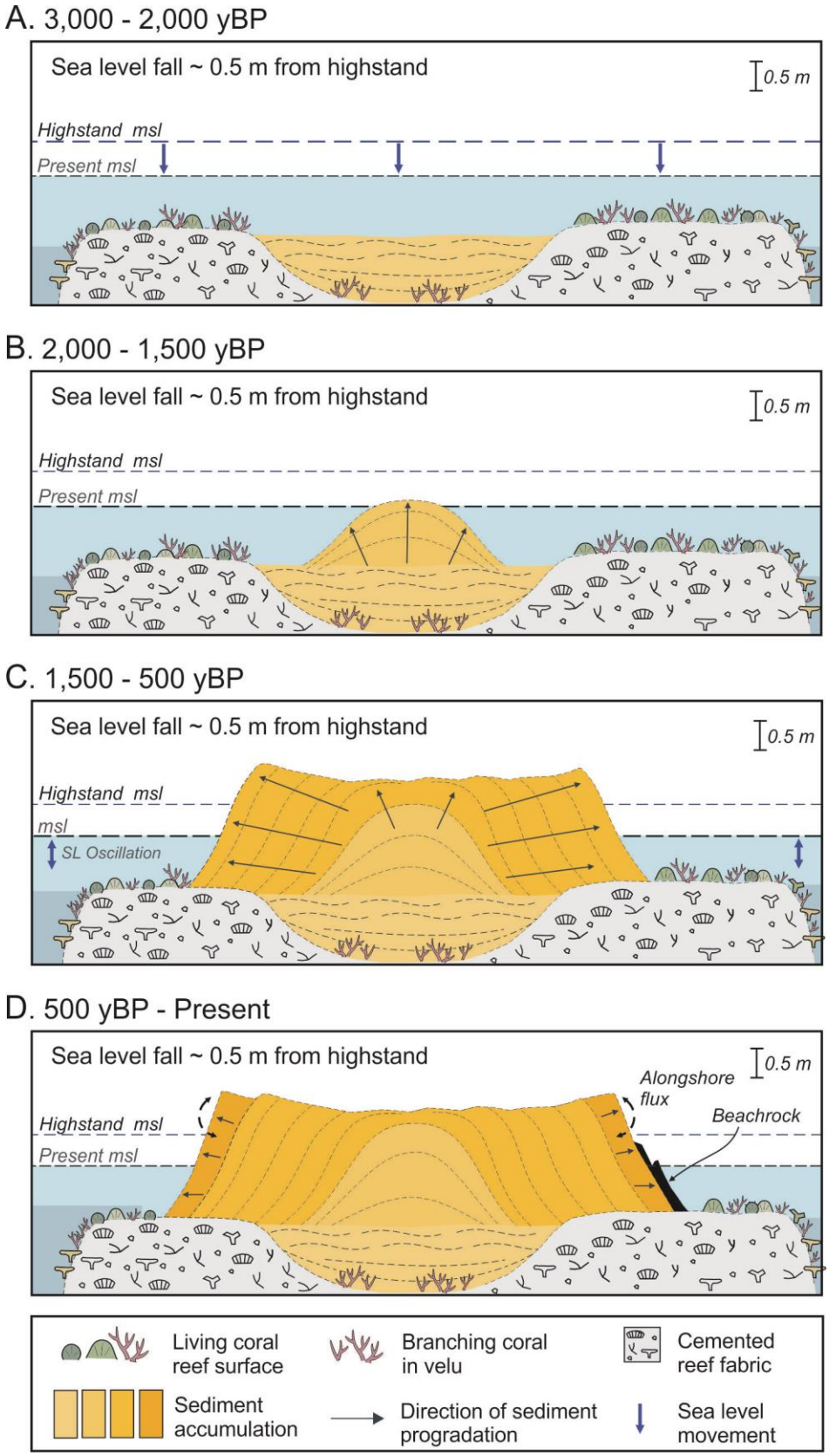

Figure 5. Staged model of the formation of Kandahalagalaa and Kondeymatheelaabadhoo, Huvadhoo atoll, over the past 3,000 years.

Stage two denotes formation of the initial island core as a sand cay (*finolhu*) across a 500-year window (Fig. 5B, 2,000-1,500 yBP). Significantly, this phase was characterised by vertical accretion of the central node of the island in the period when sea level had stabilised at its near present level. The near convex stratigraphy shown in the GPR records supports this island core model (Fig. 2C, 3C). Notably this phase of vertical island accumulation is also coincident with a transition in sediment composition to coral-dominated sands, likely sourced from the surrounding reef flat. Post-highstand sea-level fall would result in reef platforms that no longer need to keep -up or catch -up with an ecological shift to rapidly growing reef organisms (Neumann and Macintyre, 1985; Kennedy and Woodroffe, 2002), resulting in a return to sediments composed predominately of coral. The reduced water depth across the reef surface at this time (following sea-level fall) may have changed ecological reef response and hydrodynamic processes on the reef flat to transfer reef-derived sediment to the island core. Based on the number of samples, it is likely that the accumulation of the island core occurred more rapidly on Kandahalagalaa (Figure 4).

Significant lateral progradation of the islands, and emergence above mean sea level, characterises the third stage of island evolution, which established the majority of the island footprint and reflects the significant increase in generation of sediment for island building in the period 1,500 – 500 yBP (Fig. 5C). Such progradation is confirmed through the GPR traces depicting steeply sloping paleoshorelines (Fig. 2C, 3C). However, the timing of this lateral expansion differed between islands. On Kandahalagalaa, lateral progradation occurred across a 1,000-year window (1,500 – 500 yBP). The eastern side of the island is younger, with dates of 565 and 600 yBP (Fig. 2), indicating that lateral island growth of this margin occurred more recently, though the higher frequency of dates (from both transects) suggests that the most rapid expansion occurred between 1,500 and 1,000 yBP (Fig. 4). In contrast, dating evidence suggests Kondeymatheelaabadhoo underwent its active lateral progradation phase 500 years later, between 1,000 and 500 yBP. The composition of the sediments comprising the upper units of the island are dominated by coral and reflects the reef flat as the dominant source of sediment. Of note, the different timeframes of island expansion occurred during a period of sea-level oscillation in the Maldives with sea level undergoing a fluctuation of 0.8 m fall (1,716 – 1,345 yBP) aligned with the Late Antique Little Ice Age (LALIA; Kench et al., 2020b). This period has been characterised by lateral progradation of the island away from the central core toward the edge of the reef platform (Fig. 3B).

The final stage of island development has occurred over the past 500 years. Geomorphic change appears more subtle than the rapid progradation stage as a consequence of a reduction in sediment availability, as indicated by the significantly reduced number of radiometric ages (Figure 4, Table 2). The key geomorphic development of the island is further, though limited, progradation of the island margins. The more limited progradation is likely a function of the reduction in sediment supply in this period. Consequently, it is likely that further development of the island, or its readjustment on platform surfaces will have occurred using the existing reservoir of island sediment. There is evidence to suggest that this period has been characterised by island migration. Date inversions, particularly in cores on the lateral margins of islands, is indicative of such reworking of island sediments through the alongshore flux and recirculation of sedimentary materials. The increase in

island ridge elevation during this period is likely a response to shorelines moving into a higher energy setting closer to the reef edge (Kench et al., 2009). In addition, beachrock formation along sectors of the island shorelines, denotes sufficient periods of stability (decades) required for their formation (Vousdoukas et al., 2007). In this period the surrounding outer reef platform surface may also have continued to accrete, as reported elsewhere in the Maldives (Kench et al., 2005). Such a process would further reduce wave energy reaching island shorelines.

4.2 Island building and sea-level change

The model of lagoonal island formation from Huvadhoo atoll provides new insights into the mode of accumulation of reef islands and relationship between sediment accumulation and sea-level change. Significantly, GPR evidence has assisted in resolving distinct depositional phases. Firstly, vertical accumulation of the island core, which is coincident with the period of sea-level fall from the late-Holocene highstand. Secondly, lateral progradation away from the island core has characterised the period of small oscillations in sea level of ±0.8m over a 1,000 year period between 1,500 and 500 yBP (Fig. 3B, C). Of note, the transition from coarser lagoonal *Halimeda* rich and coral stick (autochthonous) sediment facies of the basal sediments and lower island core (derived from relative submergence of the central platform and shallow lagoon at higher sea level), to coral-dominated facies of the progradational sequence further supports the depositional model as coral sediments from the reef edge become the major source of sediment once the lagoon has filled and the footprint of the island occupies the central reef platform. Significantly, the GPR and sediment facies data provides evidence of the central core mode of island progradation in island evolution proposed by Woodroffe et al. (1999).

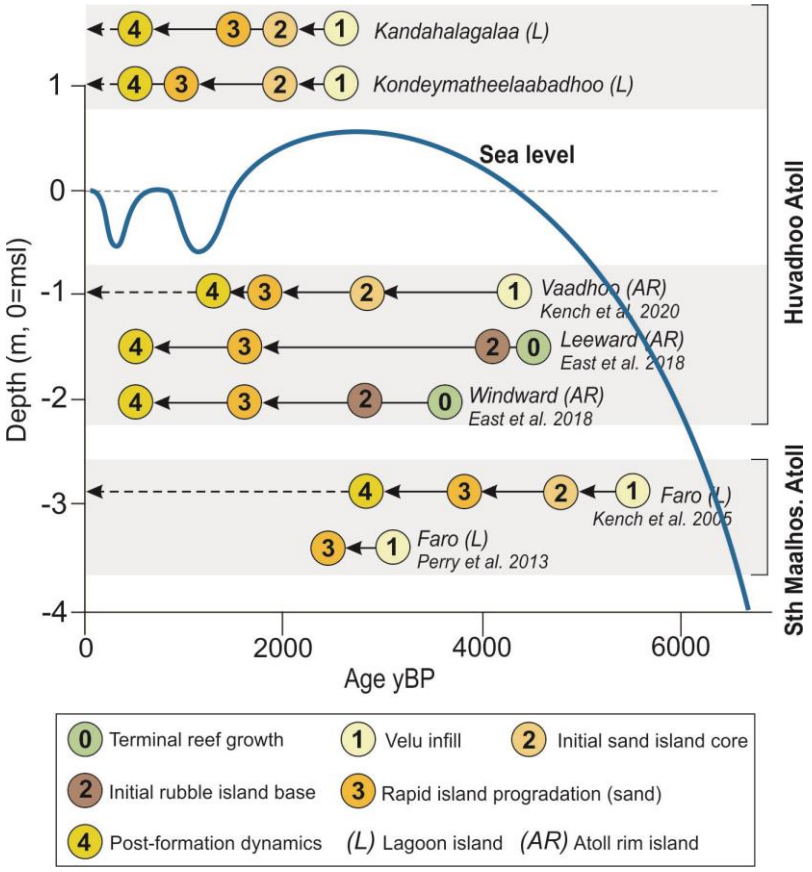

Figure 6. Comparison of the stages of island evolution of the lagoonal study islands of Huvadhoo atoll and South Maalhosmadulu atoll. Stages of island formation are shown in the context of the Holocene sea level history for the Maldives (Kench et al., 2009; 2020b). *L*, denotes lagoonal platform island. *AR* denotes atoll rim island.

Results from these lagoonal platform islands also highlight a different chronology and mode of formation to islands recently studied on the Huvadhoo atoll reef rim (East et al., 2018; Kench et al., 2020a; Figure 6). Significantly, both lagoonal islands began forming 1,000-2,000 years after the islands on the adjacent atoll rim. This temporal lag is likely due to lagging development of lagoonal reef platforms in the mid- to late-Holocene and reduced efficacy of the process regime in the lagoonal environment to fill the shallow lagoon. Reconstruction of the very large Vaadhoo island (180 ha) on the southern atoll rim (Figure 1C), was also found to be deposited over a shallow lagoon (Kench et al., 2020a). The reef rim at this location is impacted by ocean swell energy, which is considered to have been active in transferring sediment across the broad reef platform to fill the lagoon by 3,000 yBP, approximately 1,000 years before the lagoon islands. East et al. (2018) examined the formation of smaller reef rim islands on the windward and leeward sides of Huvadhoo atoll (Figure 1C). Their study found islands formed across reef platforms that had accreted to near their present maximum elevations by ~4,000 yBP (Figure 6). Overlying this reef substrate are rubble/gravel sheets that form the basement and initial core of islands and were deposited starting ~4,200 yBP on the eastern rim, and ~3,000 yBP on the south-western rim, by successive high-energy swell events. Consequently, the mode of island formation of the lagoonal islands differs from most rim islands (East et al., 2018) as they initially accumulated across shallow lagoon (*velu*) infill deposits, and are composed of sand-size materials, as opposed to forming across reef surfaces that had

attained their vertical growth limit, and which have storm-generated rubble material at their core. Examination of the temporal development of the different islands in Huvadhoo indicates that despite different establishment substrates (stages 1 and 0 in Figure 6), varied times of initial island accumulation (stage 2, Figure 6) and differences in sedimentary materials that formed initial island building (sand or gravel), all islands appear to have benefitted from island expansion through the availability of sand-size materials across a 1,500 year window from ~2,000-500 yBP (Figure 6). This synchronous phase of island building activity represents a more atoll-wide period of island development. The temporal pulse in sediment availability is coincident with final stages of sea-level fall and oscillations in sea level across a 1,000-1,500 year period in which water depth across reef surfaces reduced. The fall in water level could result in stronger shear stress at the reef bed and may have enhanced wave abrasion as a process of sediment generation and transfer. The generation of sediment from enhanced physical breakdown of the reef structure at this time was likely coupled with active sediment generation by bioeroders (Morgan and Kench, 2016; Perry et al., 2015).

4.3 Inter-atoll differences in island evolution

Our results also provide a comparison to island formation reported elsewhere along the Maldivian archipelago. Our findings and sequence of island formation over infilled lagoonal reef platforms (faro) is similar to the faro-infill model first described by Kench et al. (2005) and later confirmed by Perry et al. (2013). In their model, island formation post-dates lagoonal infill with trajectories of infill and island formation scaling with reef platform size. Specifically, islands on smaller reef platforms (<0.5 km^2) in South Maaalhosmadulu formed 5,000-4,000 yBP, whereas islands on larger platform sizes (>0.5-1.0 km^2) formed considerably later 3,500-1,500 yBP. Both reef platforms examined in this study (KAN and KON) are less than 0.5 km^2 in area and formed over the last 2,000 years making them considerably younger (by ~3,000-4,000 years) than islands on comparable sized platforms in the northern Maldives (Fig. 4) and indicating lagoonal reef island formation was not synchronous along the archipelago. One possible explanation for this temporal lag in island formation between the northern and southern sites in the archipelago is delayed reef platform development to near sea level, from deeper interglacial foundations. A north to south increasing depth gradient has been identified along the Maldivian archipelago with deeper interglacial reef foundations implicated by Woodroffe (1992) and Purdy and Bertram (1991). A lagged reef growth response from deeper interglacial foundations would account for delayed timing for the onset of island accumulation as also hypothesised by Perry et al. (2013).

4.4 Comparison to previous models of reef island evolution

The model of lagoonal island formation from Huvadhoo atoll presents Maldivian reef island response to a spectrum of sea-level changes. As previously stated, reef islands can form during varying stages of sea-level change (Kench et al., 2005; 2012; 2014a; 2014b). In most Indo-Pacific models, island formation tends to occur over a discrete phase of sea-level change: during Holocene sea-level rise (as in north Maldivian islands; Kench et al., 2005), during the sea level highstand (Cocos Islands, Indian Ocean, in Woodroffe et al., 1999; Bewick Island, GBR, in Kench et al., 2012), during sea-level fall (Warraber Island, Torres Strait, in Woodroffe et al., 2007), at contemporary sea level (Tepuka Island, Tuvalu, in Kench et al., 2014a), or post-sea-level fall (Dickinson, 1999; 2004; Schofield, 1977; Yamano et al., 2000; 2014; Yasukochi et al., 2014). The model of

evolution for Kandahalagalaa and Kondeymatheelaabadhoo, along with rim islands of Huvadhoo atoll (East et al., 2018) and Raa atoll (Kench et al., 2020a), differs from these Indo-Pacific models in that several phases of sea-level change are implicated in island development. Such a finding is similar to Jabat, Marshall Islands, that presents a three-phase model of development over the course of rising sea level, during the highstand, and as sea level fell to present position (4800-2500 cal yr BP; Kench et al., 2014b).

5 CONCLUSIONS

Results highlight that the faro infill model of island formation is similar to that in the north, and the timing of island formation within the Maldives exhibit significant intra and inter-atoll variations along the archipelago. Atoll-scale differences highlight that reef island evolution is complex and site-specific, and is dependent on local factors such as the interaction of reef growth and sea level, antecedent topography, currents and wave exposure, as well as available sediment supply. Resolving such intra-reef differences in the mode, onset and duration of island formation is essential to evaluate spatial differences in susceptibility to sea level and environmental change, to underpin improved vulnerability assessments, but also to inform improved predictions of physical island trajectories to global environmental change.

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References

Barry, S. J., Cowell, P. J., and Woodroffe, C. D., 2007, A morphodynamic model of reef-island development on atolls: Sedimentary Geology, v. 197, no. 1, p. 47-63.

Blott, S. J., and Pye, K., 2001, GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments: Earth surface processes and Landforms, v. 26, no. 11, p. 1237-1248.

Bronk Ramsey, C., 2001, Development of the radiocarbon calibration program: Radiocarbon, v. 43, no. 2; PART A, p. 355-364.

Camoin, G. F., Montaggioni, L. F., and Braithwaite, C. J. R., 2004, Late glacial to post glacial sea levels in the Western Indian Ocean: Marine Geology, v. 206, no. 1, p. 119-146.

Collen, J. D., and Garton, D. W., 2004, Larger foraminifera and sedimentation around Fongafale Island, Funafuti atoll, Tuvalu: Coral Reefs, v. 23, no. 3, p. 445-454.

Dawson, J. L., Hua, Q., and Smithers, S. G., 2012, Benthic foraminifera: their importance to future reef island resilience, *in* Proceedings, Twelfth International Coral Reef Symposium, Cairns, July 9-13 2012, Volume 1A: Reef and reef island geomorphology.

Dickinson, W. R., 1999, Holocene sea-level record on Funafuti and potential impact of global warming on central Pacific atolls: Quaternary Research, v. 51, no. 2, p. 124-132.

Dickinson, W. R., 2004, Impacts of eustasy and hydro-isostasy on the evolution and landforms of Pacific atolls: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 213, no. 3, p. 251-269.

Dickinson, W.R., 2009, Pacific atoll living: How long already and until when: GSA today, v. 19, no. 3, p. 4-10.

East, H.K., Perry, C.T., Kench, P.S., Liang, Y. and Gulliver, P., 2018, Coral reef island initiation and development under higher than present sea levels: Geophysical Research Letters, v. 45, no. 20, p.11-265.

Kench, P. S., Chan, J., Owen, S. D., and McLean, R. F., 2014a, The geomorphology, development and temporal dynamics of Tepuka Island, Funafuti atoll, Tuvalu: Geomorphology, v. 222, p. 46-58.

Kench, P. S., McLean, R. F., and Nichol, S. L., 2005, New model of reef-island evolution: Maldives, Indian Ocean: Geology, v. 33, no. 2, p. 145-148.

Kench, P.S., McLean, R.F., Owen, S.D., Ryan, E., Morgan, K.M., Ke, L., Wang, X. and Roy, K., 2020b, Climate-forced sea-level lowstands in the Indian Ocean during the last two millennia: Nature Geoscience, v. 13, no. 1, pp.61-64.

Kench, P.S., McLean, R.F., Owen, S.D., Tuck, M. and Ford, M.R., 2018, Storm-deposited coral blocks: A mechanism of island genesis, Tutaga island, Funafuti atoll, Tuvalu: Geology, v. 46, no. 10, p. 915-918.

Kench, P. S., Nichol, S. L., Smithers, S. G., McLean, R. F., and Brander, R. W., 2008, Tsunami as agents of geomorphic change in mid ocean reef islands: Geomorphology, v. 95, p. 361-383.

Kench, P.S., Owen, S.D., Beetham, E.P., Mann, T., McLean, R.F. and Ashton, A., 2020a, Holocene sea level dynamics drive formation of a large atoll island in the central Indian Ocean. Global and Planetary Change, v. 195, p.103354.

Kench, P. S., Owen, S. D., and Ford, M. R., 2014b, Evidence for coral island formation during rising sea level in the central Pacific Ocean: Geophysical Research Letters, v. 41, no. 3, p. 820-827.

Kench, P. S., Perry, C.T., and Spencer, T., 2009, Coral Reefs, *in* Slaymaker, O., Spencer, T., and Embleton-Hamann, C., eds., Geomorphology and global environmental change: Cambridge, New York, Cambridge University Press, p. 182-213.

Kench, P. S., Smithers, S. G., and McLean, R. F., 2012, Rapid reef island formation and stability over an emerging reef flat: Bewick Cay, northern Great Barrier Reef, Australia: Geology, v. 40, no. 4, p. 347-350.

Kennedy, D. M., and Woodroffe, C. D., 2002, Fringing reef growth and morphology: a review: Earth-Science Reviews, v. 57, no. 3, p. 255-277.

McKoy, H., Kennedy, D. M., and Kench, P. S., 2010, Sand cay evolution on reef platforms, Mamanuca Islands, Fiji: Marine Geology, v. 269, no. 1, p. 61-73.

Morgan, K.M., and Kench P.S., 2016, Parrotfish erosion underpins reef growth, sand talus development and island-building in the Maldives: Sedimentary Geology, v. 341, p. 50-57.

Neumann, A. C., and MacIntyre, I., 1985, Reef response to sea level rise: keep-up, catch-up or give-up: Proc. Fifth Intern. Coral Reef Congr. Tahiti, v. 3, p. 105-110.

Perry, C.T., 2011, Holocene High Energy Window, *in* Hopley, D. ed., Encyclopedia of Modern Coral Reefs. Structure, form and process: Dordrecht, The Netherlands, Springer, p. 558-560.

Perry, C.T., Kench, P.S., O'Leary, M.J., Morgan, K.M. and Januchowski-Hartley, F., 2015, Linking reef ecology to island building: Parrotfish identified as major producers of island-building sediment in the Maldives: Geology, v. 43, no. 6, p. 503-506.

Perry, C. T., Kench, P. S., Smithers, S. G., Yamano, H., O'Leary, M., and Gulliver, P., 2013, Time scales and modes of reef lagoon infilling in the Maldives and controls on the onset of reef island formation: Geology, v. 41, no. 10, p. 1111-1114.

Purdy, E. G., and Bertram, G. T., 1991, Atoll and carbonate platform development in the Maldives, Indian Ocean: AAPG Studies in Geology, v. 34, p. 1– 56.

Schofield, J. C., 1977, Effect of Late Holocene sea-level fall on atoll development: New Zealand Journal of Geology and Geophysics, v. 20, no. 3, p. 531-536.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., and Yim, W. W., 2002, Marine reservoir corrections for the Indian Ocean and Southeast Asia: Radiocarbon, v. 44, no. 1, p. 167-180.

Stoddart, D.R. and Steers, J.A., 1977. The nature and origin of coral reef islands. Biology and geology of coral reefs, 4, pp.59-105.

Storlazzi, C. D., Gingerich, S. B., van Dongeren, A., Cheriton, O. M., Swarzenski, P. W., Quataert, E., ... and McCall, R., 2018, Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding: Science advances, v. 4, no. 4, eaap9741.

Vousdoukas, M.I., Velegrakis, A.F., Polmaritis, T.A., 2007. Beachrock occurrence, characteristics, formation mechanisms and impacts: Earth Science Reviews, v. 85, p. 23-46.

Woodroffe, C. D., 1992, Morphology and evolution of reef islands in the Maldives, *in* Proceedings, Seventh International Coral Reef Symposium, Volume 2, p. 1217-1226.

Woodroffe, C. D., 2008, Reef-island topography and the vulnerability of atolls to sea-level rise: Global and Planetary Change, v. 62, no. 1, p. 77-96.

Woodroffe, C. D., McLean, R. F., Smithers, S. G., and Lawson, E. M., 1999, Atoll reef-island formation and response to sea-level change: West Island, Cocos (Keeling) Islands: Marine Geology, v. 160, no. 1, p. 85-104.

Woodroffe, C. D., and Morrison, R. J., 2001, Reef-island accretion and soil development on Makin, Kiribati, central Pacific: Catena, v. 44, no. 4, p. 245-261.

Yamano, H., Cabioch, G., Chevillon, C., and Join, J. L., 2014, Late Holocene sea-level change and reef-island evolution in New Caledonia: Geomorphology, v. 222, p. 39-45.

Yamano, H., Miyajima, T., and Koike, I., 2000, Importance of foraminifera for the formation and maintenance of a coral sand cay: Green Island, Australia: Coral Reefs, v. 19, no. 1, p. 51-58.

Yasukochi, T., Kayanne, H., Yamaguchi, T., and Yamano, H., 2014, Sedimentary facies and Holocene depositional processes of Laura Island, Majuro Atoll: Geomorphology, v. 222, p. 59-67.