

Holocene reef growth in the Maldives: Evidence of a mid-Holocene sea-level highstand in the central Indian Ocean

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ABSTRACT

Radiometrically calibrated ages from three reef cores are used to develop a Holocene reef growth chronostratigraphy and sea-level history in the Maldives, central Indian Ocean. Last interglacial reef (U-series age 122 ± 7 ka) was encountered at 14.1 m below mean sea level. An age of ca. 8100 calibrated (cal) yr B.P. immediately overlying this Pleistocene surface records the initiation of Holocene reef growth. Massive in situ corals occur throughout the cores and the consistency of the three age-depth plots indicate that the reef grew steadily between 8100 and 6500 cal yr B.P., and at a decreasing rate for the next 2 k.y. The position of modern sea level was first achieved ca. 4500 cal yr B.P. and sea level reached at least 0.50 ± 1 m higher from 4000 to 2100 cal yr B.P. before falling to present level. Emergent fossil microatolls provide evidence of this higher sea level. Results are significant to two long-standing issues relating to Maldivian sea-level history. First, the ambiguity of a late Holocene highstand has been resolved with clear evidence of its existence reported here. Second, the uncertainty of the regional pattern of sea-level change in the central Indian Ocean has been clarified, the Maldivian results broadly agreeing with island records in the eastern, rather than western Indian Ocean. Our results provide the first field evidence confirming geophysical model projections of a highstand 4–2 k.y. ago in the central Indian Ocean, though the observed level ($+0.50 \pm 0.1$ m) is lower than that projected.

INTRODUCTION

The Holocene sea-level history of the Maldives has been a source of speculation and scientific debate for more than a century. There have been two major issues: (1) was there a sea-level highstand in the middle to late Holocene in the central Indian Ocean, and (2) is the pattern of relative sea level similar to, or different from, the contrasting sea-level histories of the eastern and western Indian Ocean?

This study presents an 8 k.y. history of reef growth in the central Maldives, resolving aspects of sea-level history in the archipelago and the central Indian Ocean. The Maldives provides an ideal location to examine sea-level change in the Indian Ocean for three reasons. First, the 850-km-long archipelago is located in a tectonically stable mid-ocean setting, midway along the Laccadive-Chagos aseismic submarine ridge (Fig. 1). The atolls are founded on as much as 3 km of limestone overlying Eocene volcanic basement and have been subject to high-amplitude sea-level fluctuations during the Pliocene–Pleistocene with alternate periods of exposure and vertical reef growth (Aubert and Droxler, 1992; Purdy and Bertram, 1993). The Holocene is the latest of these reef growth periods. Second, the Maldives is located in the farfield, where detailed studies of sea-level change are needed to delimit the ice melt history since the Last Glacial Maximum, the equatorial siphoning mechanism (Camoin et al., 2004; Mitrovica and Milne, 2002), and geophysical models that

retrodict local sea-level histories (Peltier, 1999; Lambeck et al., 2000). Finally, understanding the pattern of sea-level change and how Maldivian reefs and islands have responded to past sea-level rise can provide important analogues in assessing the future stability of low-lying atoll islands (Kench et al., 2005a).

Previously published field evidence for a higher Holocene sea level in the Maldives is ambiguous (Woodroffe, 2005). Early interpretations of a highstand were based on the presence of conglomerate rocks (Gardiner, 1903) and subsequently discounted because of their storm-deposited origin (Sewell, 1936; Stoddart et al., 1966). Later, outcrops of lagoonal *Heliopora* reef in Addu atoll were used to suggest that sea level was at or slightly above its present level in the late Holocene (Stoddart et al., 1966; Woodroffe, 1993), although possible moating and uncertain elevation with respect to living coral prevented definitive interpretation (Woodroffe, 2005). Mörner et al. (2004) presented a sea-level curve for the Maldives that included sea level as much as 1.0–1.2 m above present at 3900 yr B.P. However, concerns regarding the nature of the material dated (reworked coral clasts) and poor elevation control on samples have cast serious doubt on the veracity of this curve (Kench et al., 2005b; Woodroffe, 2005). Gischler et al. (2008) found no indication of a higher than present Holocene sea level in their study of Rasdhoo atoll, central Maldives.

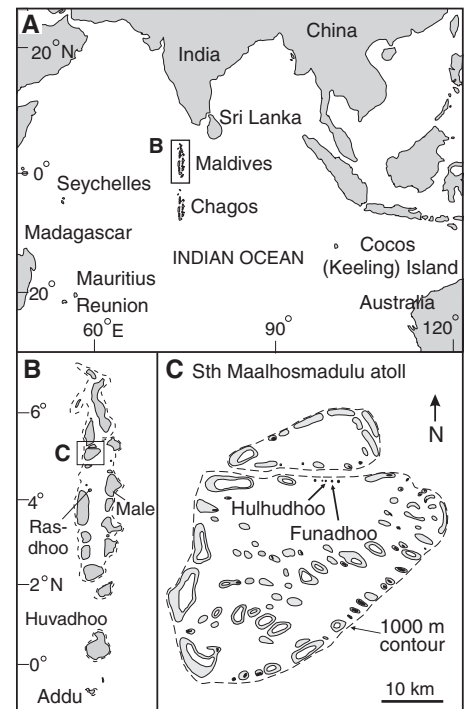


Figure 1. Location of study islands in South Maalhosmadulu Atoll, Maldives, central Indian Ocean.

The second issue relates to the different Holocene sea-level histories established between the western and eastern Indian Ocean. In this context, because of its central position, the Maldivian archipelago is seen as a key site “at which to clarify the regional pattern of Holocene sea-level variation in the central Indian Ocean” (Woodroffe, 2005, p. 134). There is evidence for a higher Holocene sea level to the east. Woodroffe et al. (1990) showed that sea level reached 0.6 ± 0.2 m above present 3300–2500 yr B.P. on the Cocos (Keeling) Islands. In the western Indian Ocean, sea-level history is more equivocal. Camoin et al. (2004) established that sea level rose from its glacial lowstand to stabilize around present level 3 k.y. ago. Their sea-level reconstructions from the granitic Seychelles and the volcanic islands of Reunion, Mauritius, and Comores do not reflect higher stands during the late Holocene. Montaggioni (2005, p. 52) also noted that “emergent in situ reef buildups are missing” on these and other

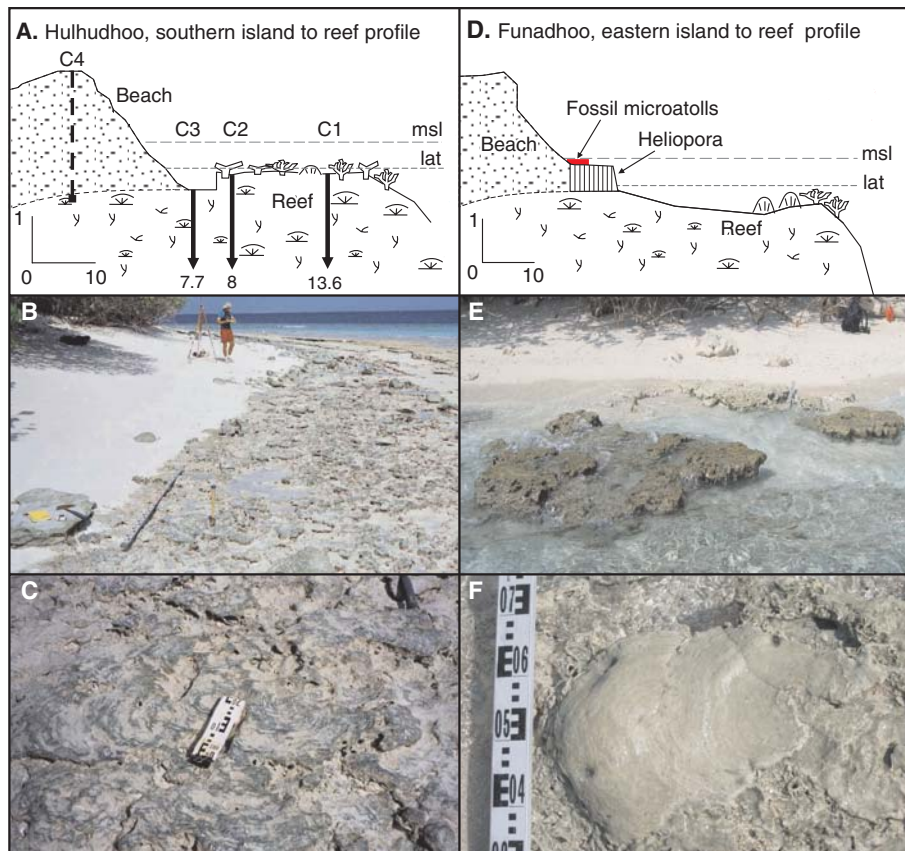


Figure 2. Surveyed sections from island shoreline to reef edge at Hulhudhoo (A) showing location and elevation of drill holes and Funadhoo (D) showing position of fossil microatolls. B, C: Photographs showing emergent fossil microatoll field on northeast shoreline of Hulhudhoo and dated microatoll (C). E: *Heliopora* reef capped by fossil microatolls outcropping on eastern shoreline of Funadhoo. F: Abraded fossil microatoll in growth position above fossil *Heliopora* surface.

oceanic islands in the western and central Indian Ocean, including the Maldives, a view supported by Gischler et al. (2008).

FIELD SETTING AND METHOD

Reef drilling was conducted on Hulhudhoo Island, South Maalhosmadulu atoll, in the central-west of the archipelago (Fig. 1). The atoll is ~40 km wide and the lagoon contains numerous faro formations. The Hulhudhoo reef platform is ~400 m in diameter and is typical of moderate-energy lagoonal reefs in the Maldives.

Three closely spaced rotary drillcores were extracted from the southern Hulhudhoo reef flat over a distance of 20 m (Fig. 2A). Core lengths ranged from 6.2 to 14.6 m with recovery exceeding 70%. An additional core was obtained from the island ridge that overlies the reef surface, 12 m landward of core 3. Cores were supplemented with surveys of in situ fossil microatolls outcropping along the eastern shorelines of Hulhudhoo and Funadhoo (Figs. 1C and 2).

A U/Th date was obtained on the basal core sample (core 1) at the University of Melbourne following the method of Hellstrom (2003). Radiocarbon age determinations were made on

23 coral samples spaced at uniform intervals along cores and three in situ fossil corals from reef surfaces (Table 1). X-ray diffraction analysis indicated that the samples had undergone little diagenetic alteration (aragonite 92%–99%).

The elevation of all cores and surface corals was surveyed using an auto level and reduced to mean sea level (msl) based on water-level recorders (DOBIE pressure sensors) deployed on Hulhudhoo reef and comparison with continuous sea-level records at Male. Detailed surveys of living and fossil microatoll fields were also undertaken. Measurements of 49 living microatolls on Hulhudhoo reef yielded a mean elevation of 0.59 ± 0.1 m below mean sea level (bmsl), which denotes the height of living coral (HLC; Smithers and Woodroffe, 2000).

The possibility of moating of fossil corals was carefully considered, but is discounted on the following bases: (1) the fossil corals were elevated above both the upper HLC and the outer reef surface, which our radiocarbon chronology indicates reached sea level first; (2) the narrow width of reef flats (<50 m); (3) the large areal extent of the fossil coral and microatoll sites; and (4) ponding by geomorphic barriers (e.g.,

gravel deposits) to seaward was not observed at any site. We conclude that the dated emergent corals grew in free-draining situations, at a relative sea level higher than present.

REEF CORES

The cores contain several distinct facies, but are dominated by massive corals (Fig. 3A; Table 1). The longest core penetrated 14.6 m through the outer reef and terminated in highly porous reef rock, with evidence of recrystallization and discoloration, characteristic of Last Interglacial reef limestone (Montaggioni, 2005; Woodroffe, 2005). The upper 13.8 m of core 1 comprised alternating massive corals (predominantly poritids and faviids) and coral rubble (with encrusting coralline algae and little sand matrix).

The central and inner reef flat cores penetrated 6.2 m and 7.2 m, respectively, below the reef surface, terminating in *Halimeda*-rich sand (Fig. 3). Above these basal sediments the cores comprised alternating layers of massive corals (poritids, acroporids, and faviids) and coral rubble and sand (Fig. 3A) comparable to the domal coral skeletal rubble and carbonate sand facies of Montaggioni (2005).

The island ridge core penetrated 1.6 m of unconsolidated, medium-grained sand before encountering layers of cemented sand (beach rock or cay sandstone) overlying in situ coral and reefal sediments.

Two aspects of the massive corals within cores can be noted. First, faviid and acroporid species dominate below a depth of 5 m, and poritid corals above that level as well as on the contemporary reef flat. Second, the structure and orientation of corallites within the massive corals indicate in situ growth, and their thickness (typically 0.2–0.4 m) is comparable to that of living microatolls on reef flats.

CHRONOLOGY OF REEF GROWTH

Dating results are consistent in age and elevation between cores, do not contain age reversals, and reveal a detailed history of Holocene reef growth (Table 1; Fig. 3A). Uranium-series dating of the basal reef sample in core 1 yielded a minimum age of 122 ± 7.0 ka (at 14.12 m bmsl), confirming the limestone as a Last Interglacial reef. An age of ca. 8100 cal yr B.P. immediately overlying this surface records the initiation of Holocene reef growth. This age of initiation is consistent with that from Rasdhoo atoll (Gischler et al., 2008) and other oceanic reefs in the western Indian Ocean (Montaggioni, 2005), but predates the onset of reef accumulation at the Cocos (Keeling) Islands in the eastern Indian Ocean (Woodroffe et al., 1990). Steady vertical reef growth followed from ca. 8100 to 6400 calibrated (cal) yr B.P. (to a water depth of 2.17 m bmsl) at a mean rate of ~7 mm/yr. The rate of

vertical reef accretion then slowed to ~0.8 mm/yr ca. 6400 cal yr B.P., the reef first reaching near its present level ~4000–4500 yr ago (Fig. 2A). Ages of the uppermost poritids from cores 1 and 2 and of in situ fossil *Helioportia* in core 4 have an age range from ca. 3900 to 4600 cal yr B.P., suggesting that the Hulhudhoo reef reached its maximum extent at that time.

Comparison of the age and elevation of dated corals between cores indicates that reef development was dominated by vertical growth from ca. 8000 to 6500 cal yr B.P. with no evidence of lateral extension of the forereef to seaward. Subsequently, the outer section of reef accreted at a faster rate than the inner reef between ~6500 and 4500 yr ago (Fig. 3A; Table 1).

REEF FLAT CORALS

The dated reef flat corals were taken from extensive emergent microatoll fields (Fig. 2). On Hulhudhoo, a *Porites* microatoll outcropping on the northeast shore dated at ca. 3400 cal yr B.P. is at an elevation of 0.25 ± 0.07 m bmsl, or 0.34 m above HLC. Fossil *Porites* microatolls outcropping on the southeast shore of Funadhoo and overlying in situ fossil *Helioportia* (Fig. 2) had a mean elevation of 0.08 ± 0.03 m bmsl ($n = 6$), or 0.51 ± 0.1 m above HLC. Samples from two microatolls from this field were both dated at ca. 2100 cal yr B.P.

The smooth surfaces, thinness (<0.05 m), and locations of the fossil microatolls indicate that they have been abraded by movement of beach sands (Figs. 2C and 2F). Data on the mean thickness of living microatolls (0.25 m, $n = 48$) and of *Porites* corals in cores (0.3–0.4 m) suggest that as much as 0.2 m has been removed by abrasion and that the elevation of the abraded surfaces thus represents a minimum paleo-sea-level position of 0.50 ± 0.1 m above present.

DISCUSSION AND CONCLUSIONS

The close association between coral growth and sea level is commonly used to develop local histories of relative sea level, recognizing that the reef growth record defines a minimum sea-level position (Blanchon and Shaw, 1995; Toscano and Macintyre, 2003). The presence of massive living poritid and faviid corals, including microatolls, on the contemporary reef flats of South Maalhosmadulu atoll, together with the frequent occurrence of their fossil equivalents throughout the Hulhudhoo cores, is indicative of a comparable paleo-reef setting, suggesting that accretion of the Hulhudhoo reef closely tracked rising sea level. The presence of emergent fossil in situ microatolls provides a higher-resolution late Holocene sea-level indicator, as their upper growth surface is constrained by subaerial exposure during low tides (Smithers and Woodroffe, 2000).

Using these assumptions, the Holocene reef chronostratigraphy from South Maalhosmadulu

TABLE 1. RADIOCARBON AGES FROM REEF CORES AND MICROATOLLS, SOUTH MAALHOSMADULU ATOLL, MALDIVES

Lab code	Island and sample location	Sample material	Depth relative to mean sea level (m)	Conventional age (yr B.P.)	Calibrated age range (95.4% probability) (cal. yr B.P.)
20801	HU C1	<i>Favid sp.</i>	-13.89	7802 ± 53	8302–7970
20802	HU C1	<i>Favid sp.</i>	-13.17	7758 ± 51	8258–7935
20803	HU C1	<i>Favid sp.</i>	-12.17	7732 ± 50	8227–7914
20804	HU C1	<i>Favid sp.</i>	-11.07	7465 ± 50	7940–7646
20805	HU C1	<i>Favid sp.</i>	-8.07	7053 ± 48	7558–7290
20806	HU C1	<i>Favid sp.</i>	-6.07	6864 ± 48	7413–7119
20807	HU C1	<i>Favid sp.</i>	-5.27	6846 ± 48	7404–7083
20808	HU C1	<i>Porites sp.</i>	-4.77	6566 ± 47	7128–6742
20809	HU C1	<i>Favid sp.</i>	-3.72	6292 ± 46	6759–6419
20810	HU C1	<i>Porites sp.</i>	-2.17	6144 ± 46	6599–6280
20811	HU C1	<i>Porites sp.</i>	-1.17	4872 ± 46	5226–4826
20812	HU C1	<i>Porites sp.</i>	-0.87	4548 ± 52	4798–4401
20818	HU C2	<i>Acropora sp.</i>	-6.87	6882 ± 47	7415–7145
20819	HU C2	<i>Acropora sp.</i>	-6.17	6840 ± 57	7406–7056
20820	HU C2	<i>Pocillopora sp.</i>	-5.12	6551 ± 47	7113–6723
20821	HU C2	<i>Porites sp.</i>	-4.17	6614 ± 61	7177–6768
11302	HU C2	<i>Porites sp.</i>	-2.50	5802 ± 60	6210–5910
20813	HU C3	<i>Favid sp.</i>	-7.87	7078 ± 48	7571–7310
20814	HU C3	<i>Favid sp.</i>	-6.72	7052 ± 48	7557–7290
20815	HU C3	<i>Porites sp.</i>	-5.17	6769 ± 57	7322–6954
20816	HU C3	<i>Porites sp.</i>	-2.87	6041 ± 46	6474–6182
20817	HU C3	<i>Porites sp.</i>	-1.36	4404 ± 42	4567–4168
11302	HU C4	Reef rock	-1.17	4078 ± 70	4140–3720
12663	HU RF	<i>Porites</i> FMA	-0.25	3679 ± 45	3550–3340
20797	FU RF	<i>Porites</i> FMA	-0.06	2566 ± 39	2278–1911
20798	FU RF	<i>Porites</i> FMA	-0.06	2578 ± 45	2289–1919

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). FMA—fossil microatoll; HU—Hulhudhoo; FU—Funadhoo.

can be divided into four distinct phases (Fig. 3B). Phase 1 is characterized by a steady sea-level rise, flooding the last interglacial surface ca. 8100–6500 cal yr B.P. (~7 mm/yr). After ca. 6500 cal yr B.P., the rate of sea-level rise slowed to <1 mm/yr (phase 2), with sea level first reaching its present level ca. 4500 cal yr B.P. During phase 3 sea level continued to rise to at least 0.5 ± 0.1 m above present until ca. 2100 cal yr B.P., after which it fell to its current position (phase 4).

Results help clarify the pattern of Holocene sea-level change in the Maldives. The elevated microatolls on South Maalhosmadulu provide evidence of a late Holocene sea-level highstand of $+0.50 \pm 0.1$ m ~2–4 k.y. ago, and confirm that emergent reef build-ups are not missing from the central Indian Ocean (Camoin et al., 2004).

Our results also improve understanding of the regional similarities and differences in sea level in the Indian Ocean during the Holocene. The Hulhudhoo curve shows broad agreement with the rapid rise in sea level and reef growth in the period 8000–6500 yr B.P. in both the eastern and western Indian Ocean. However, this rise ended later in the Maldives than in the western Indian Ocean, with the inflection occurring ca. 6500–5500 cal yr B.P. rather than 7500–7000 yr B.P. (Camoin et al., 2004). In both cases the rate of sea-level rise then slowed to ~1 mm/yr. The microatoll evidence of a higher sea level 2000–4000 yr B.P. identified here is, however, at odds

with the record from Rasdhoo atoll as well as from several insular sites in the western Indian Ocean, where evidence of a middle to late Holocene highstand is lacking (Camoin et al., 2004; Gischler et al., 2008). Rather, the Maldivian highstand we report is of similar magnitude and timing to that established at the Cocos (Keeling) Islands in the eastern Indian Ocean (Woodroffe et al., 1990).

It is significant that the discrepancy between our results and those from the western Indian Ocean sheds new light on the reconstruction of regional sea-level changes. The sea-level highstand identified in this study presents the first field evidence confirming geophysical models that predict a middle to late Holocene highstand in the period 2000–4000 yr B.P., and subsequent equatorial siphoning, although our results indicate that the highstand was lower than the 2–3 m predicted (Camoin et al., 2004; Mitrovica and Milne, 2002).

Our results also have important implications for the future of coral reef islands. As suggested by Woodroffe (2005), confirmation of a sea-level highstand allows critical reevaluation of the relationship between sea level, reef growth, and island formation. In the Maldives, islands formed 5500–4500 yr ago (Kench et al., 2005a) and persisted as sea level rose to 0.5 ± 0.1 m above present during the highstand ca. 2000–4000 cal yr B.P. Consequently, Maldivian

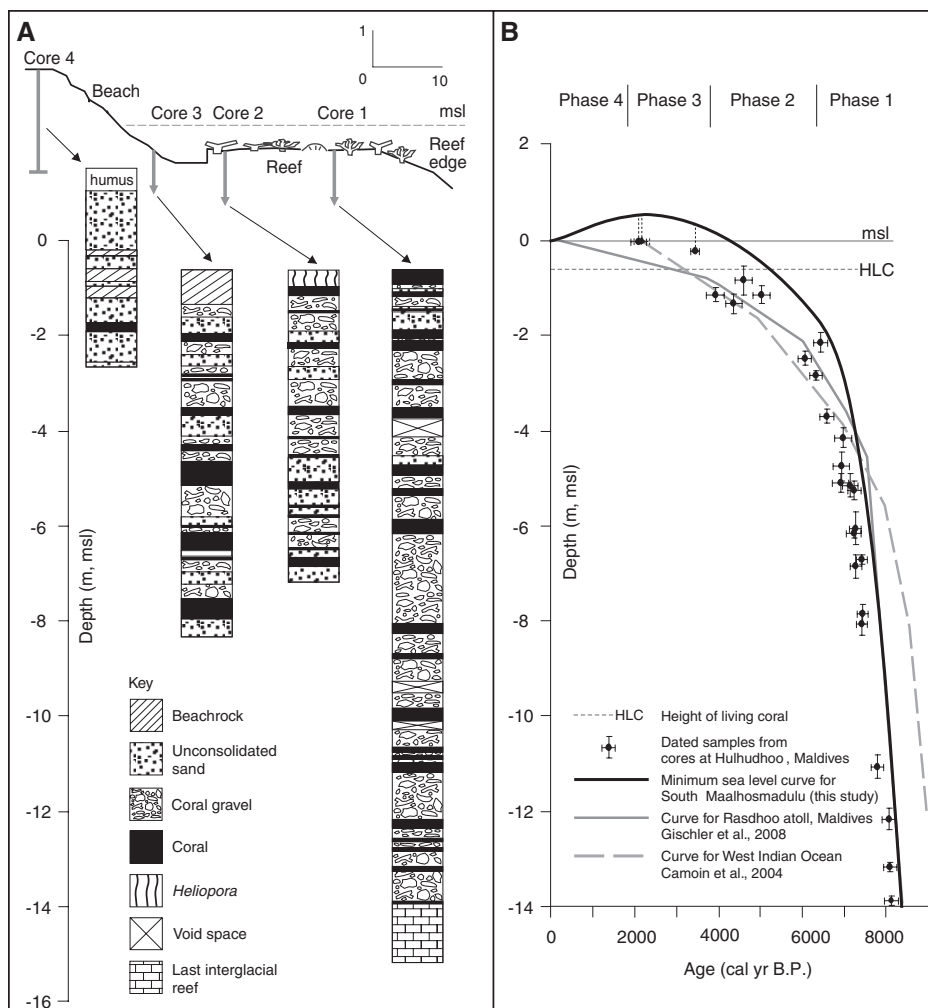


Figure 3. A: Reef drillcores on southern Hulhudhoo reef flat, South Maalhosmadulu Atoll, Maldives. Topography of island margin and reef flat shown at top. **B:** Age-depth plot of coral core and fossil microatoll samples. Black line is inferred minimum sea-level history. Horizontal bars represent 2 σ calibrated age range (Table 1) and vertical bars define uncertainties in vertical elevation of coral and depth of samples.

islands provide the first geological analogue that demonstrates that reef islands are capable of accommodating rising sea level comparable to that projected for the next century.

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REFERENCES CITED

Aubert, O., and Droxler, A., 1992, General Cenozoic evolution of the Maldives carbonate system (Equatorial Indian Ocean): *Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine*, v. 16, p. 113–136.

Blanchon, P., and Shaw, J., 1995, Reef-drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse: *Geology*, v. 23, p. 4–8, doi: 10.1130/0091-7613(1995)023<0004:RDDTLD>2.3.CO;2.

Bronk Ramsey, C., 2001, Development of the radiocarbon program OxCal: *Radiocarbon*, v. 43, p. 355–363.

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, p. 119–146, doi: 10.1016/j.margeo.2004.02.003.

Gardiner, J.S., 1903, The fauna and geography of the Maldiv and Laccadive Archipelagoes: Being the account of the work carried on and of the collections made by an expedition during the years 1899 and 1900, Volume 1: Cambridge, Cambridge University Press, 471 p.

Gischler, E., Hudson, J.H., and Piser, A., 2008, Late Quaternary reef growth and sea level in the Maldives (Indian Ocean): *Marine Geology*, v. 250, p. 104–113, doi: 10.1016/j.margeo.2008.01.004.

Hellstrom, J.C., 2003, Rapid and accurate U/Th dating using parallel ion-counting multi-collector ICP-MS: *Journal of Analytical Atomic Spectrometry*, v. 18, p. 1346–1351, doi: 10.1039/b308781f.

Kench, P.S., McLean, R.F., and Nichol, S.L., 2005a, New model of reef-island evolution: Maldives, Indian Ocean: *Geology*, v. 33, p. 145–148, doi: 10.1130/G21066.1.

Kench, P.S., Nichol, S.L., and McLean, R.F., 2005b, New perspectives for the future of the Maldives:

Comment: *Global and Planetary Change*, v. 47, p. 67–69, doi: 10.1016/j.gloplacha.2004.12.001.

Lambeck, K., Yokoyama, Y., Johnston, P., and Purcell, A., 2000, Global ice volumes at the Last Glacial Maximum and early late glacial: *Earth and Planetary Science Letters*, v. 181, p. 513–527, doi: 10.1016/S0012-821X(00)00223-5.

Mitrovica, J.X., and Milne, G.A., 2002, On the origin of late Holocene sea-level highstands within equatorial basins: *Quaternary Science Reviews*, v. 21, p. 2179–2190, doi: 10.1016/S0277-3791(02)00080-X.

Montaggioni, L.F., 2005, History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors: *Earth-Science Reviews*, v. 71, p. 1–75, doi: 10.1016/j.earscirev.2005.01.002.

Mörner, N.-A., Tooley, M., and Possnert, G., 2004, New perspectives for the future of the Maldives: *Global and Planetary Change*, v. 40, p. 177–182, doi: 10.1016/S0921-8181(03)00108-5.

Peltier, W.R., 1999, Global sea level rise and glacial isostatic adjustment: *Global and Planetary Change*, v. 20, p. 93–123, doi: 10.1016/S0921-8181(98)00066-6.

Purdy, E.G., and Bertram, G.T., 1993, Carbonate concepts from the Maldives, Indian Ocean: *American Association of Petroleum Geologists Studies in Geology* 34, 56 p.

Sewell, R.B.S., 1936, An account of Horsburgh or Goifurfendhu Atoll, in *Scientific reports of the John Murray expedition to the Indian Ocean, 1933–1934, Volume 1*: London, British Museum of Natural History, p. 109–125.

Smithers, S.G., and Woodroffe, C.D., 2000, Microatolls as sea level indicators on a mid-ocean atoll: *Marine Geology*, v. 168, p. 61–78, doi: 10.1016/S0025-3227(00)00043-8.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., and Yim, W., 2002, Marine reservoir corrections for the Indian Ocean and Southeast Asia: *Radiocarbon*, v. 44, p. 167–180.

Stoddart, D.R., Davies, P.S., and Keith, A., 1966, Geomorphology of Addu Atoll, in Stoddart, D.R., ed., *Reef studies at Addu Atoll, Maldiv Islands: Atoll Research Bulletin* 116, p. 13–41.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., and Purk, M., 1998, INT-CAL98 radiocarbon age calibration, 24,000–0 cal BP: *Radiocarbon*, v. 40, p. 1041–1083.

Toscano, M.A., and Macintyre, I.G., 2003, Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ¹⁴C dates from *Acropora palmata* framework and intertidal mangrove peat: *Coral Reefs*, v. 22, p. 257–270, doi: 10.1007/s00338-003-0315-4.

Woodroffe, C.D., 1993, Morphology and evolution of reef islands in the Maldives: *Proceedings, 7th International Coral Reef Symposium*, v. 2, p. 1217–1226.

Woodroffe, C.D., 2005, Late Quaternary sea-level highstands in the central and eastern Indian Ocean: A review: *Global and Planetary Change*, v. 49, p. 121–138, doi: 10.1016/j.gloplacha.2005.06.002.

Woodroffe, C.D., McLean, R.F., Polach, H., and Wal-lensky, E., 1990, Sea level and coral atolls: Late Holocene emergence in the Indian Ocean: *Geology*, v. 18, p. 62–66, doi: 10.1130/0091-7613(1990)018<0062:SLACAL>2.3.CO;2.

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