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# Late Quaternary reef growth and sea level in the Maldives (Indian Ocean)

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**Abstract**

Based on rotary drilling and radiometric and U-series dating, we present the first comprehensive data on Holocene reef anatomy and sea-level rise as well as nature and age of underlying Pleistocene limestone in the Maldives. Holocene reefs in Rasdhoo Atoll, central Maldives, are composed of four facies including (1) robust-branching coral facies, (2) coralline algal facies, (3) domal coral facies, and (4) detrital sand and rubble facies. Branching coral and coralline algal facies predominate the marginal reefs and domal corals and detrital facies preferentially occur in a lagoon reef. In addition, microbialite crusts are found in lower core sections of marginal reefs. Microbialites formed during the early Holocene in reef cavities. Holocene reef thickness ranges from 14.5 m to >22 m. Reef growth started as early as 8.5 kyr BP. Marginal reefs accreted in the keep-up mode with rates of >15 m/kyr. Rate of sea-level rise significantly slowed down from 7–6 kyr BP and subsequently gradually rose with rates <1 m/kyr. The lagoon reef accreted in the catch-up mode with rates of around 4 m/kyr. Even though no indications of a higher than present sea level were found during this study, it is not entirely clear from the data whether the sea gradually rose to or exceeded present level in the late Holocene. Submarine cementation in Holocene reefs studied is rather weak, presumably as a consequence of high accretion-rates, i.e., short time available for consolidation. Pleistocene coral grainstone was encountered in one core at 14.5 m below present level and three U-series dates indicate deposition during marine isotope stage 5e ca. 135 kyr BP.


*Keywords:* Maldives; reef; sea level; Holocene; Pleistocene

## 1. Introduction

The Maldives archipelago is among the largest modern tropical carbonate areas of the world (Fig. 1). Whereas the Tertiary development of the Maldives is well-known from exploration and ODP drilling and comprehensive seismic surveys (Aubert and Droxler, 1992; Purdy and Bertram, 1993; Aubert and Droxler, 1996; Belopolsky and Droxler, 2003, 2004), the knowledge of the Quaternary history of this major carbonate area is quite limited. Likewise, data on Holocene sea-level rise, which is of fundamental importance to the inhabitants of the Maldives and inhabitants of similar low-lying islands in that past reef and island responses to sea-level rise may be relevant for the near future, is rather fragmentary. Woodroffe (1992) reported on an 18 m long core, which was drilled on the island of Male. Four radiometric dates from corals and five bulk sediment dates were used to draw a Holocene age–depth plot, which shows rapid reef accretion in the catch-up mode from 6–3 kyr BP. Sea level appears to have been stable at present level from 3–0 kyr BP. One coral date from the southern Maldives suggests a slightly higher (0–0.3 m) sea level as compared to today (Woodroffe, 1992). More recently, Woodroffe (2005) mentioned additional drill cores taken in the southern Maldives, which indicate a Holocene reef thickness of 15–20 m above Pleistocene limestone. No radiometric age data are given. Like with the Male record, detailed core descriptions or core logs are not provided. Anderson (1998) described cliffs on outer atoll slopes at depths of around 130 m, found during an echo sounding study, which presumably formed during the lowstand of sea level during the last glacial maximum.

Late Holocene sea-level history of the Maldives is a matter of debate since the early studies more than a century ago. Gardiner (1903, p. 163) and Agassiz (1903, p. 61, 135–136) observed

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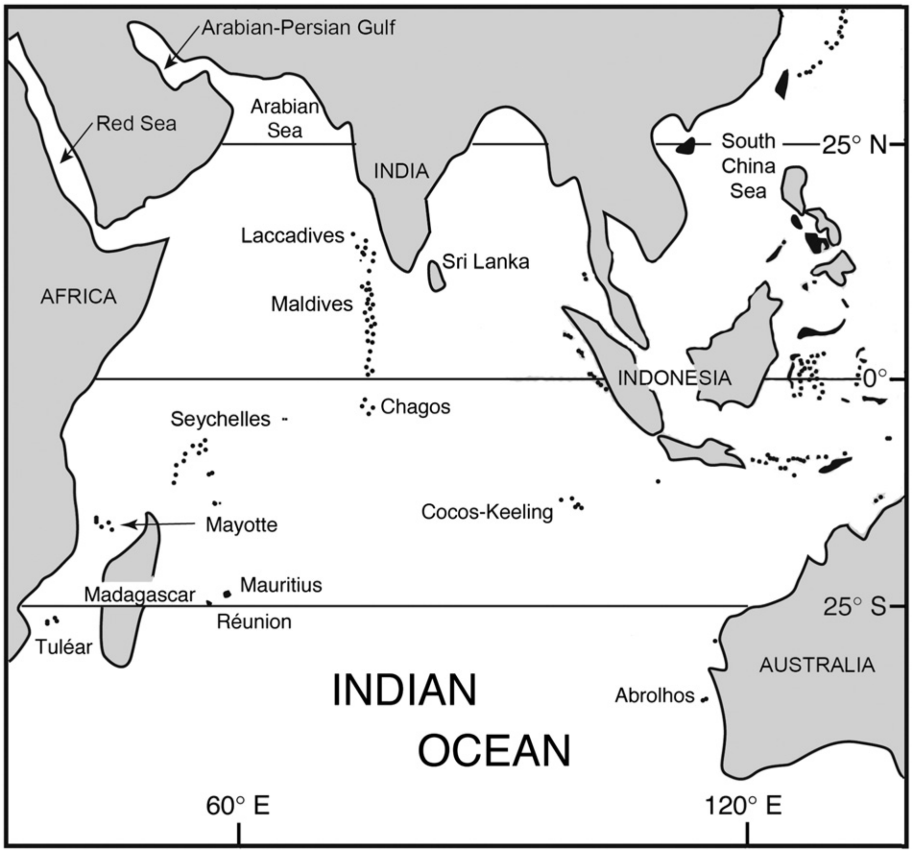


Fig. 1. Simplified map of the Indian Ocean including the location of the Maldives and other reef areas mentioned in the text (after Montaggioni, 2005; modified).

reef rock up to several feet above sea level on reef islands in several Maldivian atolls. Sewell (1936, p. 85) interpreted some of these outcrops as results of a fall of sea level. Likewise, Stoddart (1966, p. 40) speculated about a negative eustatic shift to explain elevated reef rocks on Addu Atoll. Recently, Mörner (2004), Mörner et al. (2004), and Mörner and Tooley (2005) proposed sea levels higher by 30–60 cm during the past 1000 yr and a sea-level fall of 30 cm during the past three decades, based on slightly elevated beachrock, terraces, and beaches. Kench et al. (2005a), Woodroffe (2005), and Woodworth (2005) have raised serious concerns regarding Mörner's interpretations. Woodworth (2005) also concluded that a recent fall of sea level in the Maldives is implausible based on meteorological and oceanographic data. These data rather indicate a recent rise in sea level in the area of the Maldives. Earlier studies by Singh et al. (2001) and Khan et al. (2002) also support a recent trend of sea-level rise in the Maldives. The vulnerability of the Maldive islands was proven in April 1987 when long period swells flooded the island of Male (Harangozo, 1992) and in December 2004 when a tsunami inundated numerous islands in the archipelago (Kench et al., 2006; Gischler and Kikinger, 2006). Kench et al. (2005b) presented a model of Maldive island evolution. They argue that islands formed 5.5–4.5 kyr BP and reached their current dimensions by 4 kyr BP, based on radiometric dating of bulk sediment and corals in cores.

It becomes clear from the foregoing that Holocene sea-level data from the Maldives are rather fragmentary and also controversial. Knowledge of late Quaternary reef development is preliminary at best. Therefore, this study was designed in order to produce a continuous Holocene sea-level data set for the area, to detail reef anatomy and development in the central Maldives, and to determine nature and age of the Holocene reef substrate. Also, the Maldives are probably better suited to obtain sea-level data as compared to larger islands and continental margins, because the small sand islands are less affected by crustal rebound processes.

## 2. Setting

The Republic of Maldives is known as the lowest country on Earth. A double chain of 22 major atolls covers more than 100,000 km$^2$ with some 1200 islands (Fig. 2a), which have a maximum elevation of 5 m above sea level (Naseer and Hatcher, 2004). Rasdhoo is a relatively small circular atoll in the central western part of the Maldives and covers 62 km$^2$ (Fig. 2b). The almost-continuous surface-breaking marginal reef rim has two channels connecting the 40 m deep lagoon with the open ocean. The lagoon contains about 40 coral patch reefs. There are five sand cays on the southern and eastern reef margin. Outside the marginal reef, narrow fore reef slopes grade into an almost vertical fore reef wall. Modern sedimentary facies of the atoll include coral grainstones on reefs as well as mollusk wackestones–packstones and mudstones in the lagoon (Gischler, 2006). Channels and lagoonal areas adjacent to channels are characterized by hardgrounds.