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The leaking bucket of a Maldives atoll: Implications for the understanding of carbonate platform drowning

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ABSTRACT

Seismic and multibeam data, as well as sediment samples were acquired in the South Malé Atoll in the Maldives archipelago in 2011 to unravel the stratigraphy and facies of the lagoonal deposits. Multichannel seismic lines show that the sedimentary succession locally reaches a maximum thickness of 15–20 m above an unconformity interpreted as the emersion surface which developed during the last glacial sea-level lowstand. Such depocenters are located in current-protected areas flanking the reef rim of the atoll or in infillings of karst dolinas. Much of the 50 m deep sea floor in the lagoon interior is current swept, and has no or very minor sediment cover. Erosive current moats line drowned patch reefs, whereas other areas are characterized by nondeposition. Karst sink holes, blue holes and karst valleys occur throughout the lagoon, from its rim to its center. Lagoonal sediments are mostly carbonate rubble and coarse-grained carbonate sands with frequent large benthic foraminifers, *Halimeda* flakes, red algal nodules, mollusks, bioclasts, and intraclasts, some of them glauconitic, as well as very minor ooids. Finer-grained deposits locally are deposited in current-protected areas behind elongated faros, i.e., small atolls which are part of the rim of South Malé Atoll. The South Malé Atoll is a current-flushed atoll, where water and sediment export with the open sea is facilitated by the multiple passes dissecting the atoll rim. With an elevated reef rim and tower-like reefs in the atoll interior it is an example of a leaky bucket atoll which shares characteristics of incipiently drowned carbonate banks or drowning sequences as known from the geological record.

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1. Introduction

Carbonate platform drowning occurs when the sediment accumulation rate is lower than the rate of increase in accommodation space, and the platform top is therefore submerged below the euphotic zone terminating shallow-water carbonate production (Schlager, 1981). Carbonate platforms may drown entirely or partially, when shallow-water carbonate factories punctually continue to accumulate neritic carbonates, forming relic banks growing to sea level. Sediments juxtaposed or overlying the drowned platforms often attest for the occurrence of strong bottom currents. This has been interpreted as a consequence of the acceleration of relatively sluggish ocean tides and currents by the sharp topography of the drowned banks (Schlager, 1998, 1999).

The Maldives carbonate platform provides an example where past bank drowning and onset of currents are probably not two independent processes (Betzler et al., 2009, 2013; Lüdmann et al., 2013). Since the late Miocene, vigorous monsoonal-driven currents and nutrient upwelling force the Maldives atolls into an aggradational to backstepping mode (Betzler et al., 2009). With their 50 to 80 m deep lagoons and the elevated atoll rims, the individual atolls of the Maldives can be classified as empty buckets (Schlager, 1981) or incipiently drowned carbonate banks (Read, 1985) which provide a natural laboratory to test relationships between empty bucket morphology, drowning, and corresponding controlling factors.

This study documents the facies and stratigraphy of such a carbonate bank. The goal of this investigation is to elucidate whether the physical impact of currents in the lagoon of such a carbonate body is a major, previously underestimated or even disregarded controlling factor of tropical carbonate platform evolution. Using seismic, multibeam and sedimentological data acquired in the lagoon of the South Malé Atoll (SMA) it will be shown that bottom currents pervasively control sedimentation in the 50 m deep water body. It is discussed how such currents are a factor that can contribute to carbonate platform drowning.

2. Geological setting

The Maldives archipelago consists of 22 atolls with 1300 islands and faros, which are small ring-shaped reef complexes (Purdy and Bertram, 1993). Water depth of the lagoons ranges between 31 and 82 m. The

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atolls of the Maldives are relicts of a formerly larger platform (Aubert and Droxler, 1992, 1996; Purdy and Bertram, 1993; Belopolsky and Droxler, 2004; Betzler et al., 2009). During the late Miocene and early Pliocene, stepwise disarticulation of a N–S striking megabank occurred, which led to a complex geometry consisting of a western and an eastern strip of neritic carbonates separated by the hemipelagic basin of the Inner Sea.

Starting of the partial platform drowning of the Maldives coincides with the inception of drift sedimentation in the Inner Sea (Betzler et al., 2009). The drowning initiated as passages separating the atolls, and later affected larger bank areas (Aubert and Droxler, 1996). Post-drowning relict banks, which were submerged during these later stages, have elongated outlines indicating current shaping; active atolls of the Maldives have complex growth patterns, with a co-existence of bank margin progradation, aggradation, and backstepping (Betzler et al., 2009, 2013). Progradation is restricted to current sheltered areas, where periplatform drifts (Betzler et al., 2014) accumulate at the atolls flanks. Current-exposed flanks aggrade or step back. The Maldives are affected by a monsoonal triggered seasonal reversing current regime (Schott and McCreary, 2001). The Southwest Monsoon Current (SMC) flows from June to October, and the Northeast Monsoon Current (NMC) from December to April. During the transitions, eastward directed surface jets with velocities of up to 1.3 m/s develop in the open ocean. Monsoonal currents form upwelling cells, producing elevated nutrient values around the reefs (Preu and Engelbrecht, 1991). Location of the upwelling cells is at the downstream sides of the archipelago, and thus seasonally alternates depending on the monsoonal-driven current pattern (Anderson et al., 2011). Betzler et al. (2009) expressed the hypothesis that these monsoon-driven currents and the resulting nutrient injection into the shallow water are a major controlling factor of the Neogene platform evolution.

Whereas there is a reasonable understanding of the sedimentology, the stratigraphy and the sequence stratigraphic stacking pattern in the Inner Sea, little is known about the sedimentary dynamics acting in the Maldivian atolls. Observation on sedimentation processes in the lagoons dates back to Darwin (1842) who described how the currents affect the lagoons: “The currents of the sea flow across these atolls, …, with considerable force and drift the sediment from side to side during the monsoons, transporting much of it seaward; yet the currents sweep with greater force round their flanks” (p. 108). In the passages of the atoll rims of the Maldives, monsoon and tidal currents have velocities of up to 1.5–2 m/s (Preu and Engelbrecht, 1991; Owen et al., 2011), triggering winnowing in the passages and in the lagoons where hard bottoms occur (Ciarapica and Passeri, 1993; Gischler, 2006). Bianchi et al. (1997) reported azooxanthellate corals at the slope of the atolls in water depths as shallow as 15 m and in the passes of the atoll rims. In such passes, the depth boundary between zooxanthellate and azooxanthellate corals depends on the current intensity, being shallower in the current-swept passes, which is attributed to strong currents favoring growth of rheophilic forms (Bianchi et al., 1997). Strong currents also erode the outer atoll flanks (Ciarapica and Passeri, 1993). Gischler (2006), Parker and Gischler (2011), Klostermann and Gischler (2014) and Klostermann et al. (2014) analyzed the sedimentary succession in Rasdhoo Atoll (Fig. 1), which is a small atoll enclosed by a reef rim with two passages. The marine postglacial deposits in this atoll which date back to 8 ka BP are little more than 4 m thick in the current protected areas, away from the passages. No data exist for the larger atolls with multiple passages. Naseer (2003), in a comparison of Indian and Pacific Ocean atoll water depths, however, forwarded that Maldivian lagoons are infilling slower than other Indo-Pacific atolls located in the trade wind zone.

The time of main wave action in the Maldives is during the 8 months of summer monsoon with E-directed waves, producing a swell in the lagoons (Kench et al., 2006). The winter monsoon induces a shorter episode of minor, W-directed wave action. Kench and Brandner (2006) and Kench et al. (2009) showed that the islands undergo extreme rates of gross shoreline change between monsoonal seasons and that the beach width varied by up to 53 m. On an annual basis, there is a minimal net shoreline change, indicating a spatially balanced shoreline pattern. For an island with a diameter of less than 200 m, it was calculated that between 9 and 23 × 10^3 m^3 of sediment volume is moved seasonally. Assuming that the sediment input of the reefs onto the islands is an ongoing process, this implies that the sediment dispersal system is open and that a certain amount of material is remobilized and transported into the lagoon. For an island located in North Malé atoll in the eastern atoll string of the Maldives, Morgan and Kench (2014) showed that seasonal varying wave incidence affects sediment transport pathways with high bank and off-reef export to the reef slope and the lagoon.

3. Methods

A research cruise was performed in late November 2011 with the dive safari vessel HOPE CRUISER. Forty five seismic profiles were recorded with a total length of 331.5 km. The seismic equipment used for the survey consisted of a boomer-plate AA301 (Applied Acoustic, U.K.) as acoustic source, which was operated with a power of 300 J/shot, a 24-channel MicroEel analog streamer (Geometrics, U.S.A.), and a global positioning system (Hemisphere, Canada). To maximize the resolution and quality of the seismic data, the source used different shot intervals from 0.533 s to 0.7 s for the lagoon areas and up to 1.2 s for the Inner Sea. The applied recording length was 0.2 s TWT. During the survey the vessel moved at a speed of 3 to 3.5 knots. The processing of the seismic data was performed with the software package SU-SEISMIC UNIX (Colorado School of Mines, U.S.A.). The software Petrel (Schlumberger, U.S.A.) was used for the interpretation and correlation of various seismic profiles.

Sea floor mapping was performed with the mobile multibeam system SwathPlus (S.E.A. Beckington Castle, U.K.) at a sonar frequency of 117 kHz. The swath was stabilized for roll, pitch and yaw. Vertical sound profiles through the water column were recorded at a regular term as a patch test for geometry correction. The data was processed using the software S.E.A. (S.E.A. Beckington Castle, U.K.) and CARIS (CARIS, Fredericton, Canada). For the interpretation of the multibeam data the software Fledermaus (IVS 3D) was used. Multibeam tracks and maps were merged with pansharpened LANDSAT 8 images in ARCGIS (ESRI, Redlands, USA).

Surface sediment samples were taken with a Van-Veen grab-sampler which was handled with a portable electric BuLiteK crane (Hamburg University). The geographical position and the water depth were recorded by GPS and a Humminbird Fishfinder 587ci HD echosounder. A total of 65 samples were taken and texture was characterized with the Dunham classification (Dunham, 1962). A first description of the color, the macroscopic components, and the texture of the samples was performed aboard by using a stereoscopic microscope. In the laboratory, split-samples were freeze-dried and infused with resin to produce thin sections. For grain-size analysis, further split samples were freeze-dried and weighed. Samples were wet sieved (>2 mm, 2 mm–500 μm, 500 μm–250 μm, 250 μm–63 μm, <63 μm). The distinct fractions were dried and weighted to determine the percentage of each grain-size fraction. Sediment composition was analyzed with a binocular for the grain sizes of 0.5–2 mm and larger 2 mm. The nature of the grain size smaller 63 μm was analyzed with a scanning electron microscope. Element mapping in thin section was performed with a LEO 1455 SEM with EDX.

4. Results

4.1. Seismic and hydroacoustic facies

Seismic facies (Figs. 2, 3) are defined by the criteria of the seismic interpretation and stratigraphy introduced by Mitchum et al. (1977).

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