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A new model evaluating Holocene sediment dynamics: Insights from a mixed carbonate–siliciclastic lagoon (Bora Bora, Society Islands, French Polynesia, South Pacific)

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ABSTRACT

Mixed carbonate–siliciclastic lagoons of barrier reefs provide great potential as sedimentary archives focusing on paleoenvironmental and paleoclimatic changes as well as on event deposition. Sediment sources include lagoonal carbonate production, the marginal reef and the volcanic hinterland. Mixed carbonate–siliciclastic continent-attached coastal lagoons have been intensively studied, however, their isolated oceanic counterparts have been widely disregarded. Here, we present a new model of Holocene sediment dynamics in the barrier–reef lagoon of Bora Bora based on sedimentological, paleontological, geochronological and geochemical data. The lagoonal succession started with a Pleistocene soil representing the Lowstand Systems Tract. As the rising Holocene sea inundated the carbonate platform, peat accumulated locally ~10,650–9400 years BP. Mixed carbonate–siliciclastic sedimentation started ca. 8700–5500 years BP and represents the Transgressive Systems Tract. During that time, sediments were characterized by relatively coarse grain size and contained high amounts of terrestrial material from the volcanic hinterland as well as carbonate sediments mainly produced within the lagoon. Siliciclastic content decreases throughout the Holocene. After the rising sea had reached its modern level, sand aprons formed between reef crest and lagoon creating transport pathways for reef-derived material leading to carbonate-dominated sedimentation ca. 6000–3000 years BP during the Highstand Systems Tract. However, mainly fine material was transported and accumulated in the lagoon while coarser grains were retained on the prograding sand apron. From ca. 4500–500 years BP, significant variations in grain-size, total organic carbon as indicator for primary productivity, Ca and Cl element intensities as qualitative indicators for carbonate availability and lagoonal salinity are seen. Such patterns could indicate event (re-)deposition and correlate with contemporaneous event deposits found in the lagoon of nearby Tahaa, which are supposed to be induced by elevated cyclone activity. Correspondingly, enhanced erosion and run-off from the volcanic hinterland as well as lower lagoonal salinity would be associated with intense rainfall during repeated cyclone landfall. Increased amounts of coarse-grained sediment from marginal reef areas would be transported into the lagoon. However, Ti/Ca and Fe/Ca ratios as proxies for terrigenous sediment delivery have incessantly declined since the mid-Holocene. Also, benthic foraminiferal faunas do not validate reef-to-lagoon transport of sediment. Alternatively, the apparent onset of higher hydrodynamic energy conditions can be explained by more permanent southeast trade winds and higher-than-present sea level, which are supposed for the mid-late Holocene in the south Pacific. Sustained winds would have flushed higher amounts of open ocean water into the lagoon enhancing primary productivity and the amount of pelagic organisms within the lagoon while lowering lagoonal salinity. We propose the shift towards coarser-grained sedimentation patterns during the mid-late Holocene to reflect sediment-load shedding of sand aprons due to oversteepening of slopes at sand apron/lagoon edges during times of stronger trades and higher-than-present sea level of the Highstand Systems Tract, which led to redeposition of sediment even within the lagoon center. Modern conditions including a sea-level fall to modern level were reached ca. 1000 years BP, and lagoonal infill has been determined to a large part by fine-grained carbonate-dominated sediments produced within the lagoon and derived from the marignal reef. Infill of lagoonal accommodation space via sand aprons is estimated to be up to six times higher than infill by lagoonal background sedimentation and emphasizes the

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importance of the progradation of sand aprons. Contrary to the commonly supposed assumption that coarse-grained sediment layers within fine-grained lagoonal successions represent overwash events induced by storms or periods of higher storm activity, we postulate a new model of long-term lagoonal sediment dynamics including sea level, climatic change and geomorphological variation of the barrier reef lagoon.

1. Introduction

The potential of coral reef systems as key recorders for paleoenvironmental changes has been known for a long time and applied to fossil and modern carbonate platforms worldwide (e.g., Camoin and Webster, 2015, and references therein). While most of the studies focused on the investigation of the corals and the coral-reef record, back-reef lagoons have rarely been used as sedimentary archives for paleoenvironmental changes and event deposition.

Variations in distribution of sediment texture reflect variations in the hydrodynamic energy system of reefs and carbonate platforms, shown for example by Gischler (2011) at the study site, in the Great Barrier Reef, Pacific Ocean (Frith, 1983), in Cocos (Keeling) Islands Atoll, Indian Ocean (Kench, 1998a) and in the Florida Reef Tract, western Atlantic Ocean (Ginsburg, 1956). Storms or tsunamis are important sporadic high-energy events that lead to significant sediment transport and sorting in distal areas of back-reef lagoons and can therefore not be excluded in sediment studies (Harris et al., 2015; Kench et al., 2008; Scoffin, 1992).

In general, back-reef lagoons act as sediment traps; i.e., carbonate sediment mainly produced on the reef flat undergoes subsequent and continuous transport across the reef flat and sand apron before it finally accumulates in the lagoon (Kench, 2011; Stoddart, 1969; Scoffin and Tudhope, 1988). Hence, sedimentation patterns should result in lagoonward fining of sediments. Even if lagoonal carbonate production occurs, it is predicted to be less significant than allochthonous transport and accumulation of sand apron sediments (e.g., Woodroffe et al., 2004). For those reasons, back-reef lagoons provide not only information of variations of sedimentation and ecology of sediment-producing organisms in the platform interior, but also detect variations and changes of the coral reef and reef-associated organisms from the reef crest and immediate back-reef areas.

Oceanic (Darwinian) barrier–reef lagoons represent mixed carbonate–siliciclastic systems, which also receive weathered materials from the volcanic hinterland and are therefore well suited for the application of different proxies to detect environmental variations and changes in sea level and climate. Still, studies investigating oceanic barrier–reef lagoons are rare. Zinke et al. (2005, 2003a, 2000) investigated sediment facies and faunal composition associated with the Holocene transgression in sediment cores from the mixed carbonate–siliciclastic barrier reef lagoon of Mayotte, Indian Ocean. Furthermore, Zinke et al. (2003b, 2001) interpreted lagoonal successions in terms of sequence stratigraphy and delineated lowstand, transgressive and highstand deposits based on seismic and core data. In Tahaa, French Polynesia, South Pacific, Toomey et al. (2013) used grain-size variability in sediment cores from the barrier–reef lagoon to identify high-energy event deposits induced by tropical cyclones during the last 5000 years.

The number of studies focusing on oceanic barrier–reef lagoon systems is limited; therefore we also consulted investigations of atoll lagoons for comparison. For the reconstruction of paleo-storm and tsunami history over the past 4000 years, Yu et al. (2009) dated several sedimentary events in atoll lagoon cores from Yungshu Reef, south China Sea, based on a study of redeposited coral blocks and grain-size variability. However, these authors could not distinguish between storm and tsunami deposits. Klostermann and Gischler (2015) used vibrocores to detail Holocene sedimentary facies and evolution of a Maldivian atoll lagoon (Indian Ocean) with regard to sequence stratigraphy. In addition, Klostermann et al. (2014) identified six sedimentary events induced by tsunamis using grain-size variability and the presence of shallow-water organisms such as corals, coralline algae and reef-associated foraminifera deposited within the lagoon. Because of the close position to the equator, the authors were able to exclude storms as trigger for event deposition.

Modern and innovative methods such as non-destructive x-ray fluorescence (XRF) core scanning provide a quick, inexpensive and accurate high-resolution record, which helps to identify sedimentological and environmental changes (Röhl and Abrams, 2000). Gregory et al. (2015) combined benthic foraminiferal and high-resolution XRF analyses in two coastal lagoon cores from Cuba to examine climatic variability. The authors found decreasing Ti/Ca ratios over the past 4000 years and interpreted this observation to be a consequence of declined precipitation and the onset of a long-term dry period in the Caribbean region. In shallow marine sediment cores of Charlotte Harbor, southwest Florida, van Soelen et al. (2012) used XRF core scanning and biomarker analysis to identify periods with increased runoff and primary productivity during the mid-late Holocene supposing that these were induced by long-term hydrodynamic and atmospheric changes involving shifts of the Intertropical Convergence Zone (ITCZ), the Bermuda-Azores High and the Polar Front. Coarser-grained layers consisting of quartz sands and shell debris are present throughout the core record, but are very common during the late Holocene, which might result from an increase in tropical cyclone activity in the Gulf of Mexico.

In order to add to the limited knowledge on oceanic barrier–reef lagoon development in general, we investigated sediment cores from the lagoon of Bora Bora to unravel sediment dynamics during the evolution of the barrier–reef complex in response to the early Holocene sea-level transgression and subsequent fluctuations during the mid-late Holocene as well as Holocene climate variability. Our multi-proxy approach includes sedimentological, paleontological, geochemical and geochronological data to evaluate factors controlling sedimentary patterns (short-term event deposition vs. long-term sedimentary processes) and driving mechanisms of sediment dynamics through the Holocene in a mixed carbonate–siliciclastic lagoon system.

2. Study area

The oceanic barrier–reef system of Bora Bora is located in the northwestern part of the Society archipelago in the South Pacific Ocean (Fig. 1). The Society islands and nearby Austral, Gambier, Tuamotu and Marquesas islands belong to the overseas territory of French Polynesia. Increasing ages of volcanic islands from southwest (Mehetia; 0.3 Ma) to northwest (Bellingshausen; 4.3 Ma) suggest a plate movement of 11 cm/year over the Society hotspot (Blais et al., 2000; Guillou et al., 2005). According to radiometric (K/Ar) dating of basalts, the volcanic island of Bora Bora and nearby island of Toopua formed 3.45–3.10 Ma ago. These edifices consist of alkali basalt, rare hawaiites, intrusive gabbros, and volcanic breccia (Blais et al., 2000; Uto et al., 2007). The Bay the Povai between the two volcanic islands is supposed to outline the caldera.

The volcanic island of Bora Bora is densely wooded and covers an area of about 30 km^2 with the highest point Mount Otemanu rising up to 727 m above sea level. The irregular coastline forms peninsulas and six extensive bays: Baie Faanui, Baie Tamoo, Baie Haamaire, Baie Aponapu, Baie Faapore and Baie de Povai (clockwise, beginning in the west; Fig. 2). The lagoon floor has a high relief and is up to 45 m deep