Current and sea level control the demise of shallow carbonate production on a tropical bank (Saya de Malha Bank, Indian Ocean)

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ABSTRACT
Carbonate platforms are built mainly by corals living in shallow light-saturated tropical waters. The Saya de Malha Bank (Indian Ocean), one of the world’s largest carbonate platforms, lies in the path of the South Equatorial Current. Its reefs do not reach sea level, and all carbonate production is mesophotic to oligophotic. New geological and oceanographic data unravel the evolution and environment of the bank, elucidating the factors determining this exceptional state. There are no nutrient-related limitations for coral growth. A switch from a rimmed atoll to a current-exposed system with only mesophotic coral growth is proposed to have followed the South Equatorial Current development during the late Neogene. Combined current activity and sea-level fluctuations are likely controlling factors of modern platform configuration.

INTRODUCTION
Carbonate platforms are edifices kilometers high and hundreds of kilometers wide produced mostly by shallow-water organisms, such as reef-building zooxanthellate corals, and by their detritus. Platforms thrive for millions of years in the tropical belt of the oceans, many isolated from continental areas. Coral reefs reach sea level, mainly along the platform rims, such as, e.g., in the Indo-Pacific biogeographic region. Light availability as well as water temperature, turbidity, salinity, nutrients, and current velocity determine the depths at which corals and their photosynthetic symbionts thrive (Schlager, 2005). Coral reefs, amongst the most productive marine ecosystems, flourish in oligotrophic waters.

Sea-level change exerts a fundamental control on reef development at geological time scales (Webster et al., 2018). Reefs migrate sea-ward and platform-ward following falling or rising sea level, whereas a sea-level rise outpacing reef growth interrupts reef development. In the Indo-Pacific biogeographic region, reefs that are now submerged and do not reach sea level are typically structures of Pleistocene age with a thin coralgal cover deposited during a brief episode of recolonization in deglacial time (Montaggioni, 2005). Apart from sites subject to tectonic uplift, incipient builds that formed before 19 kyr B.P. were drowned. Some reefs were able to keep up with deglacial sea-level rise, but others, for reasons that are not fully understood, were not (Montaggioni, 2005; Woodroffe and Webster, 2014; Webster et al., 2018). The latter are today the sites of many mesophotic coral ecosystems.

The Saya de Malha Bank in the Indian Ocean lies in the window of optimal conditions for shallow-water reef development, but the carbonate platform today is mostly populated by mesophotic coral ecosystems. Using geophysical, oceanographical, and sedimentological data, we studied how ocean currents shape this platform and how—along with sea-level changes—they impede shallow-water reef growth. This has implications for other cases of carbonate platforms in the geological record where reefs do or did not grow to sea level, i.e., those that are fully or partially drowned.

GEOLICAL AND OCEANOGRAPHICAL SETTING
Indian Ocean Cenozoic isolated carbonate platforms grow on volcanic ridges generated by Indian and African plate drift over the Réunion hotspot (Purdy and Bertram, 1993). The Indian plate platforms are the Maldives, the Laccadive Islands, and the Chagos Archipelago. On the African plate, the Mascarene Plateau, with the Saya de Malha Bank and Nazareth Bank, is located between 4°S and 20°S (Fig. 1A). Saya de Malha Bank covers an area of 40,000 km² and consists of the smaller North Bank and the larger South Bank, the latter of which is the focus of this study.

The South Bank has a west-east extent of 230 km and a north-south extent of 290 km. It is fringed by a horseshoe-shaped submerged reef rim, which lies at a minimum water depth of 8 m and opens to the south (Fig. 1B) (Fedorov

CITATION: Betzler, C., et al., 2021, Current and sea level control the demise of shallow carbonate production on a tropical bank (Saya de Malha Bank, Indian Ocean): Geology, v. 49, p. 1431–1435, https://doi.org/10.1130/G49090.1
Barotropic tidal currents can reach 0.3–0.7 m s$^{-1}$ at 10°S and 16°S flows at the South Equatorial Current, which is between the Indian and Pacific Ocean Drilling Program sites using an Airy isostatic model (Coffin, 1992). Through use of a low-resolution seismic line (Purdy and Bertram, 1993), the bank’s succession was interpreted as an atoll, which eventually drowned.

Saya de Malha Bank lies in the direct path of the South Equatorial Current, which between 10°S and 16°S flows at 0.3–0.7 m s$^{-1}$ (Fig. 1B) (New et al., 2007). Barotropic tidal currents can add 0.35 m s$^{-1}$ in the east-west direction during spring tides. The main flow of the South Equatorial Current is diverted north and south of the bank, and is strongest between 11°S and 13°S where it is funneled between Saya de Malha and Nazareth Banks (Fig. 1). The current transports ~50 Sv (sverdrup; 50 $\times$ 10$^6$ m$^3$ s$^{-1}$), primarily driven by the strong southeast trade winds. In the upper well-mixed layer (50–100 m), the currents are nearly uniform and weaken toward water depths of 500–1000 m.

**RESULTS AND INTERPRETATION**

**Geology and Seismic Stratigraphy**

The seismic data we collected in 2019 allow a subdivision of the Saya de Malha Bank succession into three units (Fig. 2). The base of the lowermost unit 1 is not imaged in the profiles; at the top, it is delimited by an unconformity at 0.9–1.2 s two-way traveltime, which corresponds to a depth of 1.3–1.6 km below seafloor, using International Ocean Discovery Program (IODP) data from seismically comparable Maldives carbonates (Lüdmann et al., 2013; Betzler et al., 2018). The nature of unit 1 is not fully interpretable with the available data because the reflection pattern is mainly chaotic.

In unit 2, a basin was imaged, which was laterally infilled by progradational clinoform strata (Figs. 2A and 2B). Clinoform bottomsets pass into subhorizontal and subparallel layering. In the topset, layering is subhorizontal and laterally discontinuous. In view of the isolated nature of Saya de Malha Bank without any siliciclastic input, the architecture is interpreted to reflect a flat-topped carbonate platform (Eberli and Ginsburg, 1987). Such platforms have an edge formed by reefs or shoals, inclined slopes, and flat-lying inner platform deposits. The carbonate edifice enclosed a basin several tens to hundreds of meters deep and at least 60 km wide (Figs. 2A and 2B). Locally in the basin, there are isolated buildups as much as 5 km wide, which rest on the unconformity separating units 1 and 2. The progradation of the inner platform edge toward the inner basin was not controlled by margin orientation (Figs. 2A–2C), which favors the interpretation that Saya de Malha Bank was an atoll at the time of unit 2 deposition (Purdy and Bertram, 1993).

The growth mode illustrated by unit 2 terminated at a pronounced and platform-wide seismic reflection (drowning unconformity, DU) (Fig. 2). Above horizon DU, the succession is layered (unit 3), reaching up to the seafloor and thinning out toward the south. In the northeast-southwest-oriented sections, unit 3 has a backstepping carbonate ramp–like geometry (Fig. 2C). The layered sedimentation pattern of unit 3 is interrupted by flat-topped minor bodies as much as 12 km wide, which reach up to a water depth of 20 m (Fig. 2A). These bodies are wide near the bank margins and

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and narrow in the bank interior. Some show an internal stratification (Fig. 2A), with a succession of parallel to subparallel strata in the center and some inclined and prograding strata toward the margins. At present, the surfaces of the bodies are populated by mesophotic coral ecosystems with red algae, corals, and green algae (Fig. 2D). The rims of the marginal bodies facing the open sea are located farther platformward compared to the outer platform margins of unit 2; i.e., the edges of these relict banks stepped back over time.

The establishment of the horseshoe-shaped bank rim appears to correlate with changes in the stratal patterns above horizon DU. In northeast-southwest–oriented seismic lines (Fig. 2C), it is apparent that horizon DU crops out at the seafloor as a hardground dissected by fissures (Fig. 2E), in parts infilled by soft sediment. The hardground has a local cover of submarine dune fields (Fig. 2C). The surface also displays large and scattered circular to subcircular depressions (Fig. 2C) as much as 1 km wide and as much as 160 m deep, which are interpreted as karst features.

Oceanography

Temperature, salinity, and oxygen concentrations over the Saya de Malha Bank indicate tropical surface waters of low salinity, and more saline water of Arabian Sea provenance near the surface (Fig. 3A). Salt-rich subtropical surface water and Indonesian Throughflow water that is low in oxygen mix at ∼200 m water depth (Figs. 3A and 3B). Below, there is the relatively oxygen-rich Southern Indian Central Water (300–500 m water depth), in turn underlain by oxygen-poor Red Sea–Persian Gulf Intermediate Water. In October 2019, during R/V SONNE cruise SO270 (Lindhorst et al., 2019), the mean sea-surface temperature was 26.9 °C. This temperature, and the mean salinity of 34.8 psu (practical salinity units), the low productivity, and the phosphate concentration of 0.11 µM (Figs. 3C and 3D) are well within the tolerance limits of coral reefs.

Zones of the Saya de Malha Bank impacted by the highest current velocities (Fig. 1B) coincide with the areas where horizon DU is at the seafloor (Figs. 2C and 2E). In spite of the blocking position of the bank in the massive South Equatorial Current water flow, there is no indication of topographic upwelling of nutrient-rich sub-thermocline waters into the euphotic zone (Figs. 3C and 3D). Instead, low phosphate and chlorophyll-alpha concentrations in the waters over the bank mark the region as being nutrient limited, with only low levels of pelagic productivity.

DISCUSSION

The depositional geometries (Fig. 2) of the Saya de Malha Bank indicate that the present-day platform state of partial drowning was established during the younger Neogene. The platform factory eventually changed from shallow-water carbonate growth—with the platform top at or near sea level—to a mode with carbonate producers unable to fill the available accommodation at any location of the platform.

Because no rock or well data are available, age interpretation for horizon DU formation relies on indirect evidence. The thermally controlled subsidence rate for this part of the Maastrichtian Plateau was ∼0.1 m k.y.−1 for the past 7 m.y. (Coffin, 1992) (Fig. 1B). Assuming that horizon DU traces the pre-drowning top of the shallow-water carbonate platform, the surface thus would have formed during the Plioocene. This is endorsed by data from the conjugate margin (Indian plate) with a similar thermal history. Industry well NMA1, located in the Maldives at a depth of 300–330 m below sea level, recovered a facies of an early Pliocene drowning event (Aubert and Droxl, 1992). Correlation with seismic horizons and ages of sediments recovered during IODP Expedition 359 (Lüdmann et al., 2013) delimits this interval with sequence boundaries formed at 2.1 and 3.0 Ma (Betzel et al., 2018).

The most straightforward explanation for the Saya de Malha Bank drowning thus appears to be the response to a sea-level rise. Other isolated carbonate platforms such as the Bahamas, the Maldives, or the platforms off northeastern Australia also record this episode of high Pliocene eustatic sea level (Eberli and Ginsburg, 1987;
tensification started at ca. 3 Ma as documented in upwelling records of the Benguela Current (Marlow et al., 2000), which is connected to the South Equatorial Current through the Agulhas leakage (Durgadoo et al., 2017). Whether a shallow-water carbonate factory keeps up with sea-level rise depends on the amplitudes and frequencies of sea-level changes, but also on the antecedent topography. Coral colonization of a substrate during a rapid sea-level rise as high as 19 mm yr⁻¹ (Montaggioni and Martin-Garin, 2020), can drown if the sediment production rate of the carbonate factory is too low to infill accommodation. The seismic evidence of relict banks with margin progradation (Fig. 2A) in this context reflects ephemeral past stages with bank-top carbonate production and export; i.e., short episodes when the bank tops were at sea level.

The onset of eccentricity-driven sea-level fluctuations at ca. 3 Ma resulted in high amplitudes and rates of change, which later during the Pleistocene became even more pronounced. This induced a change from flat-topped banks to atolls on many Pacific and Indian Ocean carbonate platforms (Droxler and Jorry, 2021).

The Saya de Malha Bank drowning is therefore not attributed to one factor alone. It was rather a combination of two processes, i.e., sea-level change and current intensification, which were the reasons that the reef systems, although situated in a suitable setting, did not produce sufficient sediment to infill the available accommodation. These findings are applicable to other drowned Tertiary platforms in the Indo-Pacific region, such as, e.g., in the South China Sea. Nutrient injection into shallow waters, a process invoked as a platform-drowning trigger elsewhere, is not seen as relevant in the case of the Saya de Malha Bank drowning.

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