

FACIES VARIABILITY OF LATE QUATERNARY REEF TERRACES, OFFSHORE NORTHERN MOZAMBIQUE

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KEY FINDINGS

- Nine cores from two submerged reefal terraces show facies variability at three scales: between the terraces, vertically, and along strike over less than a kilometer.
- On the northern lower terrace, a lowstand reef system passes upward from slope skeletal sand through fore-reef framestone and reef-flat rubble into microbialite-rich reef-crest framestone, capped by coral rubble.
- Approximately 590 m to the south, fore-reef and reef-flat facies are absent, and a thin reef crest overlies tens of meters of finer-grained skeletal grainstone.
- On the upper terrace, two successions of coral framestone, rubble, and cemented skeletal rudstone are divided by an exposure horizon whose expression differs between cores.

BACKGROUND

On tropical margins, drowned reefs record reef growth during lower sea levels and commonly form stepped terraces built during successive sea-level cycles (e.g., Abbey et al., 2011). The deepest lowstand reefs grew during glacial maxima, when sea level stood about 120 m below present (e.g., Webster et al., 2018). Because these reefs are submerged, their internal composition is rarely sampled directly, and reefs from deeper water or sea-level lowstands remain poorly known (Gischler et al., 2013). The best-documented examples, from the last glacial maximum and deglaciation off the Great Barrier Reef and around Tahiti, were cored by the Integrated Ocean Drilling Program (IODP) (Camoin et al., 2012; Webster et al., 2018), but most boreholes penetrated less than 50 m below the seafloor, with average recovery of 27–57% (Camoin et al., 2007; Webster et al., 2011). In addition, the small number of cores and their wide spacing have prevented documentation of the vertical and lateral variability of these terraces.

Offshore northern Mozambique, the shelf margin seaward of the Quirimbas Archipelago has two submerged terraces (Fig. 1). The upper terrace, at about 30–40 m water depth, consists of reefal deposits divided by an exposure horizon. The lower terrace crests at about 90–100 m water depth, with a steep fore reef that extends to about 165 m. The lower-terrace reef and associated facies developed while sea level stood roughly 120 m below present, during the last glacial maximum and early deglacial sea-level rise. Nine geotechnical cores, four on the upper terrace and five on the lower, penetrate the reefal succession and the underlying slope to depths of up to about 120 m below the seafloor. Because the cores are situated in tight clusters with short lateral distances, lateral

variability can be assessed. This study documents the facies of each terrace, the vertical succession, and their variation between the terraces and along strike.

CORE LOCATIONS AND METHODS

The upper-terrace cores (ES-10, ES-11, ES-5, and ES-4, from north to south) span about 400 m along strike (Fig. 1). The lower-terrace cores form a northern group (ES-101, ES-107, ES-103) and a southern pair (ES-104, ES-102) about 590 m apart. Core lengths range from approximately 15 to 120 m, and recovery within cored intervals is about 83% overall. All depths are in meters below the seafloor.

Each core was slabbed, photographed, and described, with depositional textures following Dunham (1962) as expanded by Embry and Klovan (1971). Descriptions record skeletal components, coral taxa and growth forms, crustose coralline algae (CCA) and microbialite, matrix, grain size and sorting, cementation, and porosity. Lithofacies were defined within each core, grouped into interpreted depositional environments, and then correlated between cores on the basis of lithology, stratigraphic position, and depth. Preliminary U–Th ages on corals from ES-101, ES-103, and ES-11 place both terraces within the late Quaternary; the chronology will be presented separately and is not used for correlation here. One high-resolution seismic profile through ES-101 shows the internal geometry of the lower terrace.

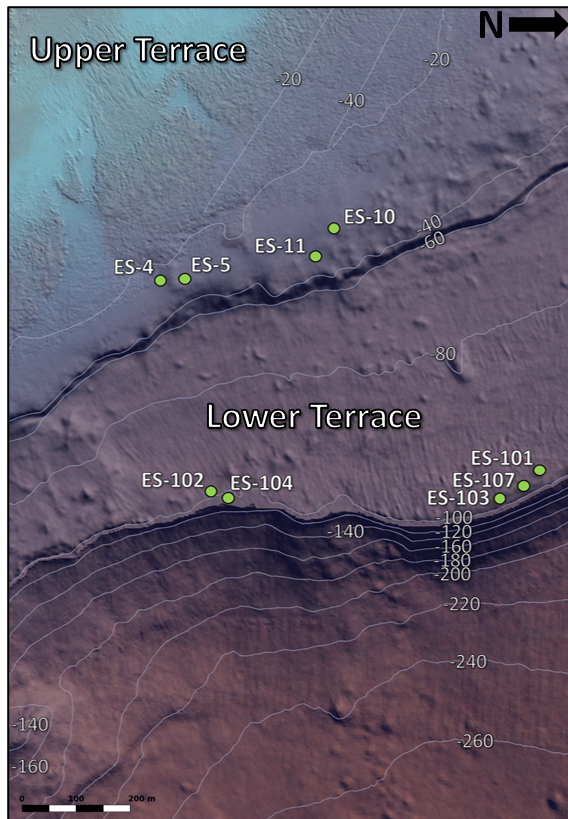


Figure 1: Bathymetric map of the study area showing the locations of the cores.

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

The lithofacies defined in individual cores are grouped into eight depositional environments, three on the upper terrace and five on the lower (Tables 1 and 2). The depositional environments are distinguished by five criteria: continuity of coral framework, coral growth form and taxa, microbialite encrustation, abundance and grain size of the skeletal matrix, and degree of cementation. Where lithologies overlap, stratigraphic position is also used. The reef flat and drowned shelf, for example, share a coral–microbialite rubble lithology but differ in interstitial sediment and lie below and above the reef crest, respectively. On the upper terrace, lithologies with soil-like pore fill, pendant cements, or moldic and vuggy porosity are assigned to a meteorically altered reefal terrace. The exposure horizon and the lower-terrace hardground are treated as surfaces.

Table 1. Lithofacies and depositional environments of the lower terrace. Depths are in meters below the seafloor. CCA, crustose coralline algae. Microbialite morphotypes: LM, laminated; ST, structureless; MCD, microbialite-coated debris.

Environment of Deposition	Lithofacies	Main components	Matrix, cement, and porosity
Lower terrace			
Drowned shelf	Coral-microbialite rubble rudstone	Coral and microbialite clasts (LM, ST, MCD, digitate); <i>Galaxea</i> abundant (ES-103)	Fine-grained interstitial sediment, abundant in ES-103 and sparse in ES-101 and ES-104; uncemented; open interclast porosity
Reef crest	Coralgal framestone-boundstone with CCA and microbialite	Massive <i>Acropora</i> and platy to branching <i>Montipora</i> (ES-103); thick microbialite; repeated coral-CCA-microbialite successions	Abundant open interframework, shelter, and intraskeletal porosity; minor fine sediment; microbialite-cemented infill
Reef flat	Coral-microbialite rubble rudstone	Branching <i>Acropora</i> and <i>Porites</i> ; <i>Stylocoeniella</i> , <i>Galaxea</i> ; microbialite clasts	Loose skeletal sand with minor fine sediment; open interclast porosity
Fore reef	Platy to branching coralgal framestone to skeletal rudstone	Tabular <i>Porites</i> grading upward to tabular <i>Acropora</i> (ES-103); large platy colonies (ES-101); variable CCA	<i>Halimeda</i> -rich rudstone to packstone infill; presumed microbialite binding; abundant interframework and shelter porosity
Slope	Rhodolith-bearing skeletal sand to uncemented rudstone	Rhodoliths 1–8 cm, commonly with coral nuclei; <i>Halimeda</i> , bivalves, echinoids, bryozoans, foraminifera; abraded coral fragments	Uncemented to weakly cemented; variably sorted, angular to subangular grains; orange fine-grained pore fill
Slope	Skeletal grainstone	Fine- to coarse-grained skeletal sand; dispersed coral clasts and rhodoliths; isolated framestone intervals	Uncemented, poorly sorted, angular grains; thin cemented <i>Halimeda</i> -rich rudstone beds
Hardground (surface)	Cemented skeletal rudstone to floatstone	Diverse skeletal debris (ES-101); skeletal-rich rudstone with branching coral (ES-102)	Dense, locally mottled cement; orange staining and black crusts (ES-101); interparticle pores locally preserved (ES-102)

LOWER-TERRACE FACIES

Northern sector. The three northern cores record a vertical succession of five environments, with a hardground within the lowermost slope deposits (Fig. 2). The deepest interval, penetrated only by ES-101, is uncemented to weakly cemented skeletal sand and rudstone with intermittent rhodoliths. Within it, at 79.4–79.8 m, a dense, orange-stained skeletal rudstone to floatstone with mottled cement and minor black crusts forms a hardground that contrasts sharply with the friable sand above and below. On the seismic profile, the hardground coincides with a high-amplitude reflection that rises updip toward the terrace top (Fig. 3).

Above the hardground, slope deposits extend to 45 m in ES-101 and form the base of ES-103 (53–65 m), beneath the fore reef. These slope deposits are poorly sorted, uncemented skeletal sand and rudstone with abraded coral fragments and orange fine-grained pore fill. Rhodoliths 1–8 cm across are abundant in core ES-103 and intermittent in core ES-101 (Fig. 4E). Isolated pockets of downslope coral debris occur within the sand.

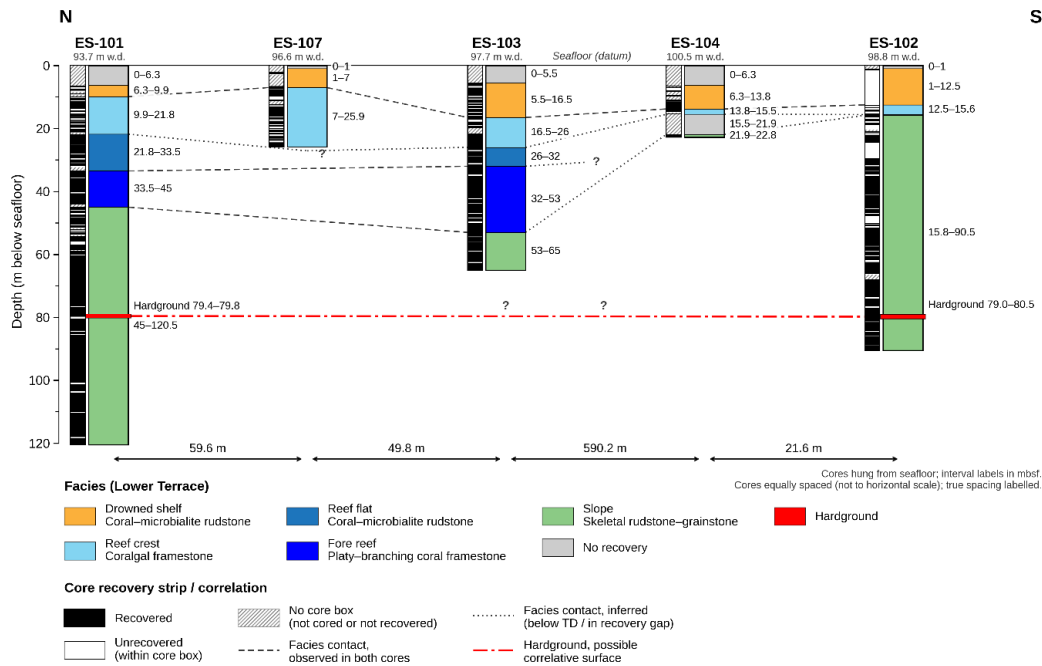


Figure 2: Lower-terrace cross-section (N-S) showing facies of the depositional environments (Table 1). Depths in mbsf.

The skeletal sand and rudstone of the slope pass upward into a fore-reef environment with platy to branching corallal framestone and skeletal rudstone (32–53 m in ES-103; 33.5–45 m in ES-101). In core ES-103, tabular *Porites* in the lower part gives way upward to tabular *Acropora* (Fig. 4D). Interframework cavities are filled with skeletal-rich rudstone to packstone that is presumably bound by microbialite.

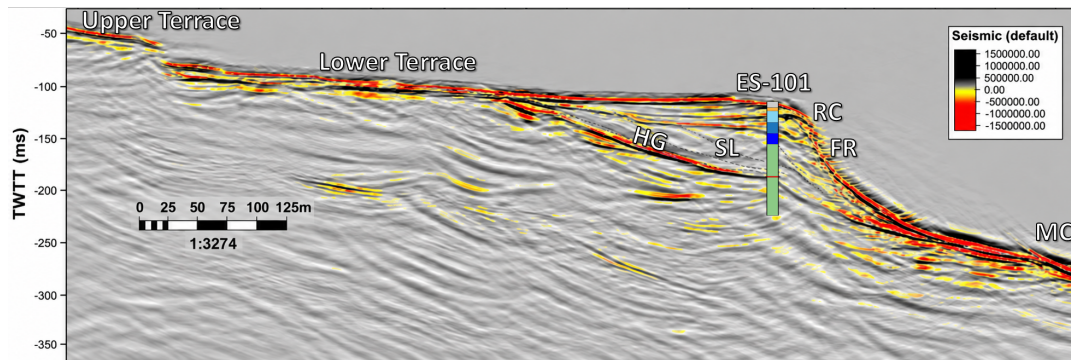


Figure 3: SW-NE seismic profile through ES-101, with core facies as in Fig. 2. HG, hardground; SL, slope; RC, reef crest; FR, fore reef; MC, toward the Mozambique Channel.

A sharp change at about 32–33 m marks the base of the reef flat, which consists of loosely packed rubble of branching *Acropora* and *Porites* in skeletal sand (26–32 m in ES-103; 21.8–33.5 m in ES-101; Fig. 4C). It is overlain by rigid reef-crest framestone of massive *Acropora* and platy to branching *Montipora* (16.5–26 m in ES-103; 9.9–21.8 m in ES-101), built of repeated coral-CCA-microbialite successions in which microbialites locally equal or exceed coral in volume (Fig. 4B). The succession is capped by coral-microbialite rubble with abundant fine-

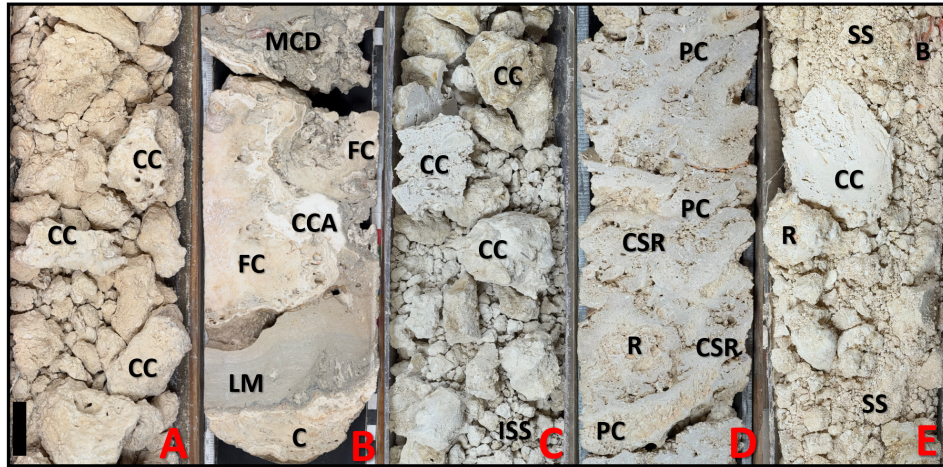


Figure 4: Core photographs of reefal environments of the lower terrace. (A) Granule- to cobble-size coral clasts (CC) of the drowned shelf (ES-103, 8.70–8.90 m). (B) Stacked successions of framework coral (FC), crustose coralline algae (CCA), laminated microbialite (LM), and microbialite-coated debris (MCD) in the reef crest (ES-103, 21.67–21.95 m). (C) Coral rubble of large coral clasts (CC) with coarse-grained interstitial skeletal sand (ISS) of the reef flat (ES-101, 22.48–22.80 m). (D) Rigid framework of platy corals (PC) with cemented skeletal rudstone (CSR) containing diverse skeletal grains, including rhodoliths (R) in the fore-reef environment (ES-101, 39.30–39.77 m). (E) Slope succession of skeletal rudstone composed mainly of uncemented skeletal sand (SS), with coral clasts (CC), rhodoliths (R), and other skeletal fragments, including bivalves (B) (ES-101, 55.14–55.39 m). Scale bar 3 cm.

grained interstitial sediment, 11 m thick in ES-103, which is interpreted as drowned shelf (Fig. 4A). ES-107, which penetrates about 26 m, records only the reef crest and drowned shelf. On the seismic profile (Fig. 3), seaward-dipping clinoforms correspond to the slope deposits in ES-101, and the reef crest and fore reef occupy a mounded reflection package at the shelf edge.

Southern sector. The two cores farther south on the lower terrace (ES-104 and ES-102) contain only three of the depositional environments identified in the northern cores: slope, reef crest, and drowned shelf (Fig. 2). The fore reef and reef flat are absent, and the reef crest is much thinner. In core ES-104, reef-crest framestone is only about 1.7 m thick (13.8–15.5 m), with thin CCA and minor microbialite. In core ES-102, a largely unrecovered drowned shelf interval (1–12.5 m) and about 3 m of reef crest (~12.5–15.6 m) overlie skeletal grainstone that makes up most of the remaining 75 m of the core. Compared with the northern slope deposits, the grainstone is finer-grained, with far fewer coral clasts and rhodoliths. Below about 59 m, most coral occurs as sand-size fragments. Reef framework occurs only in short, isolated intervals, while thin cemented *Halimeda*-rich rudstone beds occur near 54.5 m and between 59 and 65 m. A cemented skeletal-rich rudstone with branching coral at about 79–80.5 m lies at the same depth as the ES-101 hardground (Fig. 2).

UPPER-TERRACE FACIES

The four upper-terrace cores are short, 15–21 m long. In all four, two successions of reefal-terrace facies are separated by an exposure horizon at 11.8–15.8 m (Fig. 5).

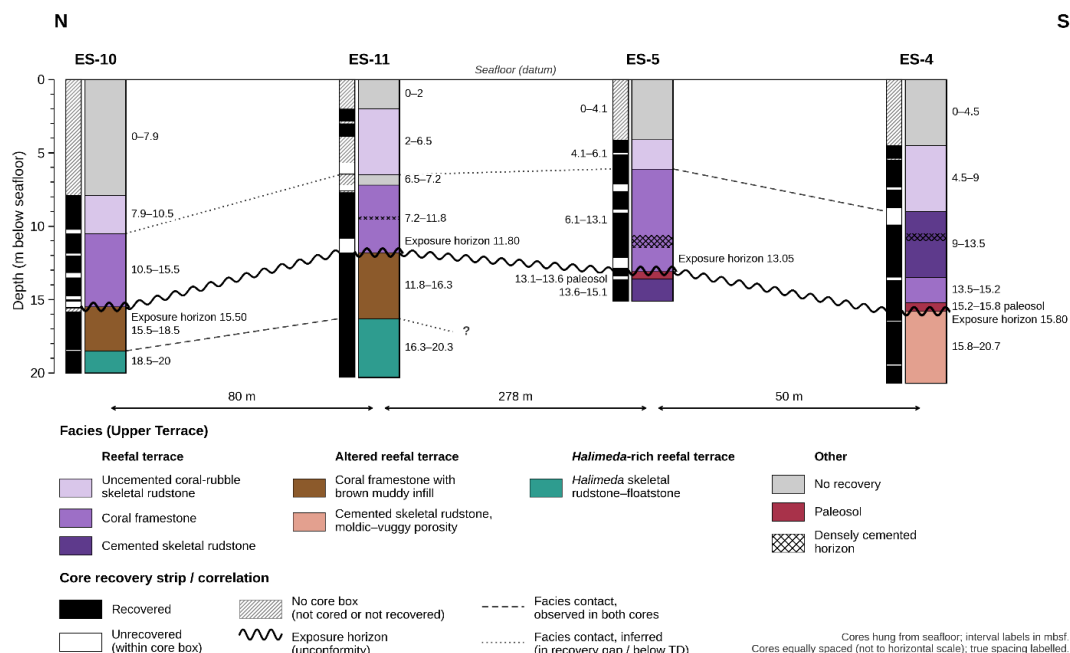


Figure 5: Upper-terrace cross-section (N-S) showing lithofacies and depositional environments (Table 2). Depths in mbsf.

Below the exposure horizon. In cores ES-10 (18.5–20.0 m) and ES-11 (16.3–20.3 m), the deepest interval is cemented. It consists of Halimeda-dominated skeletal rudstone to floatstone and is overlain by coral framestone. In cores ES-4 and ES-5, the interval below the exposure horizon is a cemented skeletal rudstone, interbedded with corallgal framestone in ES-4 and uncemented coarse skeletal sand in ES-5. In ES-10, ES-11, and ES-4, the lithologies immediately below the horizon are meteorically altered, as indicated by dark brown muddy pore fill, recrystallized corals, pendant cements, or moldic and vuggy porosity, in combinations that differ between cores (Fig. 6D, E).

The exposure horizon. The horizon is expressed differently in each core. In ES-5 (13.05 m), it is a dark, irregular laminated crust capping a thin, gastropod-rich rudstone with a friable brown muddy matrix, and in ES-4 (15.80 m), a 0.6 m karst breccia of coral rubble in a muddy matrix rests on altered skeletal rudstone (Fig. 6C); the muddy rudstone in ES-5 and the breccia matrix in ES-4 are interpreted as paleosols. In ES-10 (~15.5 m) and ES-11 (11.80 m), coral framestone continues across the horizon, which is marked only by alteration of the underlying framework. Its expression and diagenesis are described in a companion abstract (Wright et al., this volume).

Above the exposure horizon. Coral framestone (Fig. 6B) forms most of the section above the horizon in ES-10, ES-11, and ES-5. Vertically stacked colonies, separated by CCA crusts, are extensively bored by lithophagine bivalves, serpulids, and vermetids. In core ES-4, a thin framestone (13.5–15.2 m) is overlain by 4.5 m of cemented Halimeda-rich skeletal rudstone. Densely cemented horizons occur 1.5–5 m above the exposure horizon in ES-11 (~9.45 m), ES-5 (10.6–11.5 m), and ES-4 (10.5–11.0 m). All four cores are capped by 2–4.5 m of uncemented rudstone of angular, pebble- to cobble-size coral clasts in poorly sorted skeletal sand (Fig. 6A).

Table 2. Lithofacies and depositional environments of the upper terrace. Depths are in meters below the seafloor. CCA, crustose coralline algae. Microbialite morphotypes: LM, laminated; ST, structureless; MCD, microbialite-coated debris.

Environment of Deposition	Lithofacies	Main components	Matrix, cement, and porosity
Upper terrace			
Reefal terrace	Uncemented coral-rubble skeletal rudstone	Angular pebble- to cobble-size coral clasts; <i>Halimeda</i> , bivalves, echinoids, gastropods, <i>Homotrema</i>	Poorly sorted, angular skeletal sand beneath clasts; interparticle and intraskeletal porosity
Reefal terrace	Coral framestone	Robust colonies in stacked growth successions separated by CCA; extensive endolithic borings (lithophagine, serpulid, vermetid)	Interframework cavities largely open (ES-10, ES-5) or variably filled with skeletal sand, rudstone, or cement (ES-11); framework rigid to loosely constructed (ES-5); densely cemented horizons (ES-11 ~9.45; ES-5 10.6–11.5)
Reefal terrace	Cemented skeletal rudstone	Abundant <i>Halimeda</i> , echinoids, bivalves, gastropods; subordinate coral	Clast-supported, locally rind-like cement; interparticle porosity; irregular cemented horizon (ES-4, ES-5, ES-11)
Altered reefal terrace	Coral framestone with brown muddy infill	Robust coral framework; <i>Galaxea</i> (ES-10)	Dark brown, soil-like cavity and pore fill; pendant and occluding cements; recrystallization; orange staining
Altered reefal terrace	Cemented skeletal rudstone with moldic and vuggy porosity	Skeletal grains with <i>Halimeda</i> preferentially dissolved; interbedded coralgall framestone	Pink-orange staining; abundant moldic and vuggy porosity; muddy pore fill
<i>Halimeda</i> -rich reefal terrace	<i>Halimeda</i> -dominated skeletal rudstone to floatstone	<i>Halimeda</i> dominant; echinoids, bivalves, large benthic foraminifera (ES-10); scattered rhodoliths and subordinate coral framestone (ES-11)	Pervasive cement, mottled with rind-like zones (ES-11); moldic porosity after <i>Halimeda</i> near base (ES-10)
Exposure horizon (surface)	Coral framestone above and below the horizon (ES-10, ES-11); top of a thin gastropod-rich muddy rudstone with a dark laminated cap (ES-5); overlain by a 0.6 m karst breccia with a brown muddy paleosol matrix (ES-4)		

INTERPRETATION AND IMPLICATIONS

The cores recover a prograding clinoform package in which the reef framework is only part of the succession. In the three northern cores, reef facies occupy the upper part of the succession at the shelf edge, above seaward-dipping clinoforms composed of slope skeletal sand (Fig. 3). About 590 m to the south, the same terrace consists mainly of finer-grained skeletal grainstone beneath a thin reef crest, a marked change over such a short distance along the terrace. One possibility is that the shelf-edge reef was removed by margin collapse. The underlying slope succession, however, is finer-grained, and a hardground within it lies at a similar depth to that in the northern cores. It is therefore more likely that the shelf-edge reef in the south never developed as robustly as in the north.

Both terraces contain discrete, densely cemented horizons within less-cemented deposits: the hardground near 80 m on the lower terrace, and cemented horizons 1.5–5 m above the exposure horizon on the upper terrace. For subsurface carbonate systems, heterogeneity at this scale limits how far observations from a single core can be extrapolated.

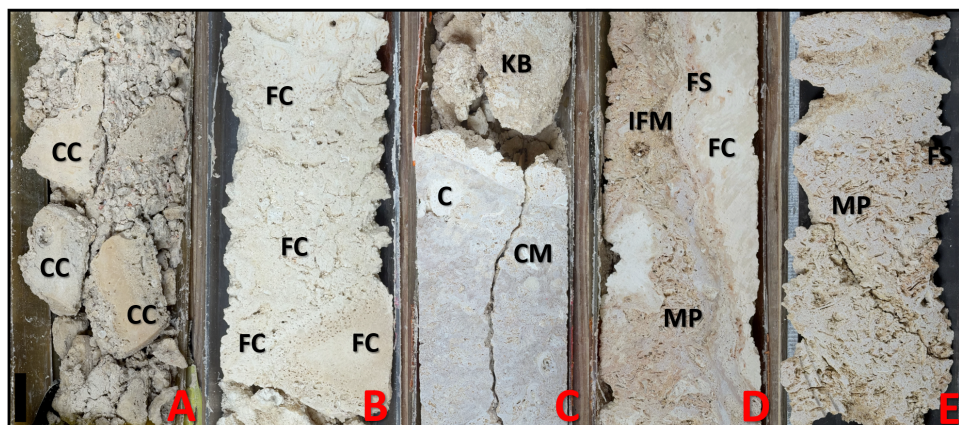


Figure 6: Core photographs of facies of the upper terrace. (A) Uncemented coral-rubble rudstone of coral clasts (CC) in a poorly sorted, fine- to coarse-grained skeletal matrix of the reefal terrace (ES-5, 4.65–4.86 m). (B) Stacked successions of unaltered framework corals (FC) of the reefal terrace in core ES-4 (14.17–14.37 m). (C) Exposure horizon in core ES-4 at 15.75–16.0 m: uncemented karst breccia (KB) with a paleosol matrix, overlying cemented skeletal rudstone with isolated corals (C) and cemented mud (CM). (D) Meteorically altered reefal terrace (ES-4, 17.25–17.48 m): framework corals (FC) with ferruginous staining (FS); interframework mud (IFM) occludes framework cavities, and moldic porosity (MP) records dissolved *Halimeda*. (E) Meteorically altered reefal terrace, *Halimeda*-dominated (ES-4, 18.80–19.04 m): skeletal rudstone with abundant moldic porosity (MP) after dissolved *Halimeda* plates, and ferruginous staining (FS). Scale bar 3 cm.

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