

LATERAL VARIABILITY OF A SINGLE SUBAERIAL EXPOSURE SURFACE IN A SUBMERGED REEF TERRACE, OFFSHORE NORTHERN MOZAMBIQUE

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KEY FINDINGS

- An exposure surface on the upper terrace offshore northern Mozambique separates reef growth during late MIS 5d to early MIS 5c from Holocene reef growth that recolonized the terrace during post-glacial sea-level rise. The bracketing U-Th ages, 103.22 and 10.94 ka, are 92.3 kyr apart, an upper limit on the duration of exposure.
- Four closely spaced cores penetrate this single exposure surface, but its appearance varies from core to core. It is conspicuous in ES-4, where it is overlain by a paleosol breccia, and in ES-5, where it forms a laminated crust, but subtle in ES-10 and ES-11, and no single macroscopic criterion occurs in all four.
- Petrographic and geochemical signals document meteoric alteration: alveolar-septal fabrics and pore-lining calcite cement beneath the surface, and a sustained $\delta^{13}\text{C}$ depletion of 3.1 to 3.5 per mil, three to four times the accompanying $\delta^{18}\text{O}$ shift.
- Because one exposure event is expressed this differently over tens of meters, the absence of a diagnostic feature in any single core is weak evidence against exposure.

PROJECT RATIONALE

Late Quaternary reef terraces record how shallow-water carbonate systems responded to repeated changes in relative sea level. At any single location, though, a sea-level cycle is rarely preserved in full (Braithwaite, 2016). The last phase of reef growth, emergence of the substrate, subaerial modification, renewed inundation, and the return of reef growth are separate events, and long intervals may separate them. Where two reef units meet at an unconformity, all of that history collapses into one surface.

This creates two practical problems for anyone correlating carbonate successions. The first is recognition. Subaerial exposure is conventionally identified from features such as karst breccia, rhizoliths, and pedogenic fabrics, but these develop unevenly, and their absence at one location does not demonstrate the absence of the event (Esteban and Klappa, 1983; Kerans et al., 2019). The second is duration. Dated corals above and below a surface bracket it without dating the emergence, alteration, or reflooding it represents (Kerans et al., 2019).

Offshore northern Mozambique, a submerged reef terrace seaward of the Quirimbas Archipelago (Fig. 1), offers an unusually direct test of both problems. Four cores spanning roughly 400 m of the terrace, with adjacent pairs as little as

50 and 80 m apart, penetrate a single exposure surface, and datable corals are preserved on both sides of it. The cores therefore allow the same exposure event to be examined in four different precursor facies, with chronological control from one dated core. Here we combine core stratigraphy, U–Th geochronology, petrography, and stable-isotope geochemistry to establish what the surface records, how consistently it is expressed, and what its bounding ages can and cannot say about the time it represents.

METHODS

This study uses four cores from a nine-core geotechnical suite: ES-10, ES-11, ES-5, and ES-4, from north to south, which penetrate an upper terrace now lying beneath approximately 30 to 40 m of water. Each core was slabbed, photographed, and logged at high resolution, with depositional textures following Dunham (1962) as expanded by Embry and Klovan (1971), and with descriptions recording skeletal components, coral growth forms, matrix, cementation, and porosity alongside the post-depositional features that overprint them. Depths are in meters below the seafloor, on a single register in which unrecovered intervals are retained at their drilled thickness. Ultra-high-resolution seismic profiles across the terrace are used only to assess how many exposure surfaces are resolved within the cored interval.

Corals from stratigraphically constrained intervals above and below the surface were dated by U–Th at an external laboratory. Thin sections were prepared from above, within, and below the surface in each core, and carbonate samples spanning the surface in cores ES-11 and ES-4 were analyzed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. Ages and petrographic results are reported here for ES-11; analyses of the other three cores are in progress.

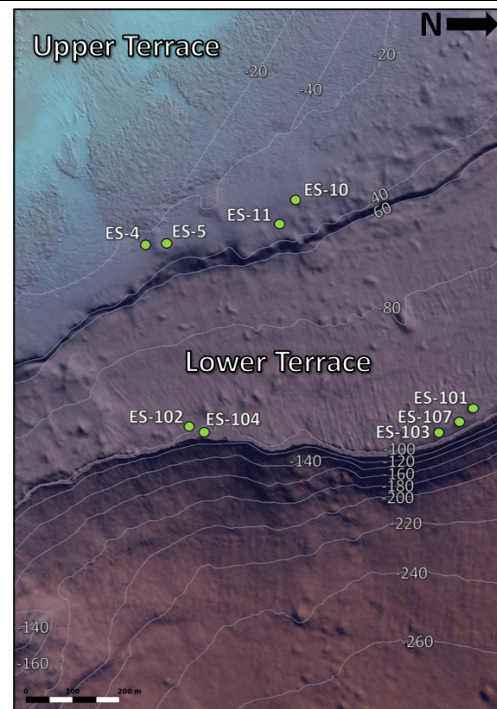


Figure 1: Bathymetric map of the study area showing the locations of the cores.

EXPRESSION OF THE EXPOSURE SURFACE

The four cores recover laterally variable reefal-terrace facies, including coral framestone, coral rubble, and cemented skeletal rudstone (Fig. 2), and the exposure surface is expressed differently in each (Fig. 3).

In core ES-4, the surface is overlain by a 0.6 m breccia of coral rubble and muddy skeletal sand, interpreted as a paleosol. Below the surface, the cemented skeletal rudstone has pink-orange staining and abundant moldic and vuggy porosity after dissolved *Halimeda*. In this core, the surface would be identified as an exposure surface on core inspection alone. Core ES-5 is also distinct: the surface is a dark, irregular laminated crust capping a thin gastropod-rich rudstone

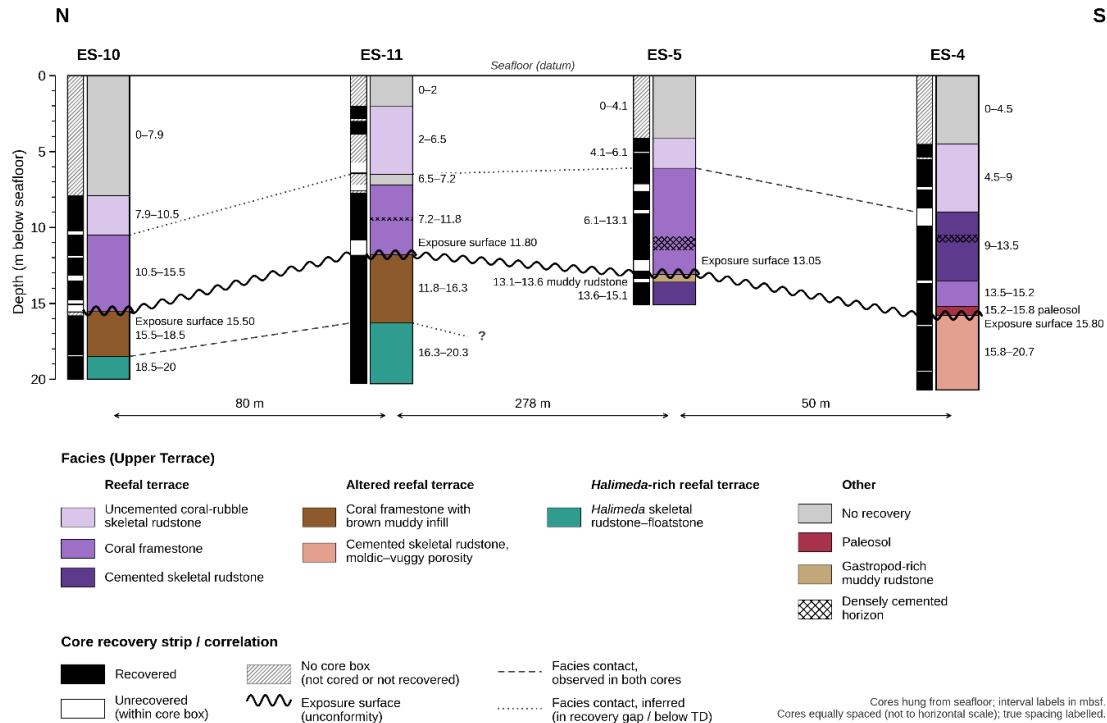


Figure 2: Upper-terrace cross-section (N-S) showing facies and the exposure surface in each core. Cores are hung from the seafloor and equally spaced; true spacing is labeled. Depths in mbsf.

with a friable brown muddy matrix. The exposure surface in cores ES-10 and ES-11 is far subtler. Both preserve coral framestone across the boundary with little change in primary facies, and the surface is marked only by alteration of the underlying framework: dark brown, soil-like sediment filling framework and skeletal pores, with increased cementation and orange staining in core ES-11. In core ES-11, the surface itself falls within a 0.90 m unrecovered interval (10.90–11.80 m).

In every core, an altered or pedogenically modified interval separates coral-bearing carbonate below the surface from marine carbonate above, and that overprint is absent from the section above. The exposure surface, however, occurs at different depths (Fig. 2): 11.80 m in core ES-11, 13.05 m in core ES-5, about 15.5 m in core ES-10, and 15.80 m in core ES-4. The thickness of deposit above it therefore varies by 4.0 m across the four sites. The closest pairs show this variability best. Cores ES-5 and ES-4 are only 50 m apart, but the surface is 2.75 m deeper in ES-4; likewise, cores ES-10 and ES-11 are 80 m apart, but the surface is about 3.7 m deeper in ES-10. The seismic profiles resolve only one exposure surface within the cored interval across the terrace, consistent with this correlation.

CHRONOLOGY

In core ES-11, two corals beneath the surface, the shallower 1.22 m below it, date to 107.56 and 103.22 ka. These ages fall between the MIS 5d and 5c peaks at 109 and 96 ka, placing the preserved pre-exposure reef growth in late MIS 5d

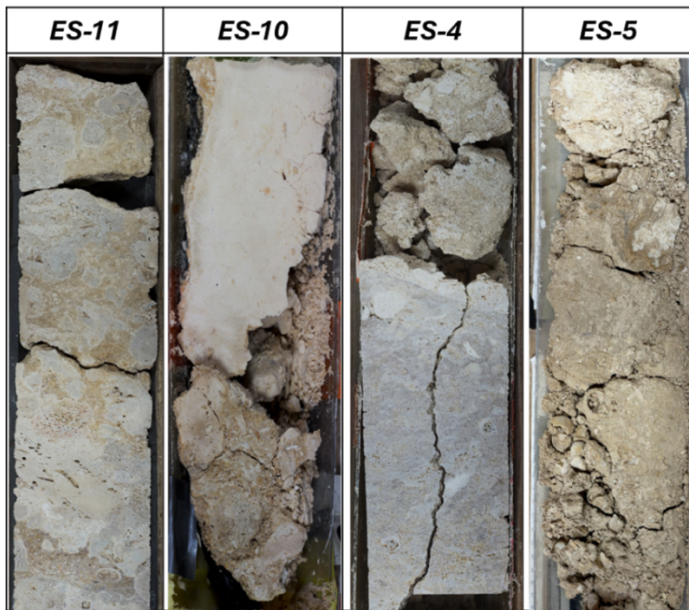


Figure 3: Core-scale expression of the exposure surface across the upper terrace. From left to right: ES-11, where the surface falls in an unrecovered interval above framestone with brown muddy pore fill and orange staining; ES-10, where coral framestone continues across the surface, which is marked only by alteration of the underlying framework; ES-4, where a 0.6 m breccia of coral rubble and muddy skeletal sand overlies cemented skeletal rudstone with moldic and vuggy porosity; and ES-5, where a dark, irregular laminated crust caps a thin gastropod-rich rudstone with a brown muddy matrix.

to early MIS 5c (Lisiecki and Raymo, 2005). The oldest coral above the surface, 0.15 m above the unrecovered interval, is dated at 10.94 ka, and six stratigraphically higher corals become progressively younger, to 7.67 ka (Fig. 4).

The two dated growth phases are therefore 92.3 kyr apart, but exposure lasted less than that. Because the youngest Pleistocene coral lies 1.22 m below the surface, carbonate continued to accumulate after 103.22 ka, and emergence is younger than that age. The oldest Holocene coral lies within about 1 m above the surface, so reflooding is more closely constrained, although inundation preceded the return of reef growth by an interval the chronology cannot resolve, since reef initiation commonly lags transgression (Davies and Hopley, 1983). Emergence therefore postdates early MIS 5c, and the sea-level history suggests that the exposure ending in the Holocene most likely began with the MIS 4 sea-level fall, possibly preceded by a brief exposure during MIS 5b.

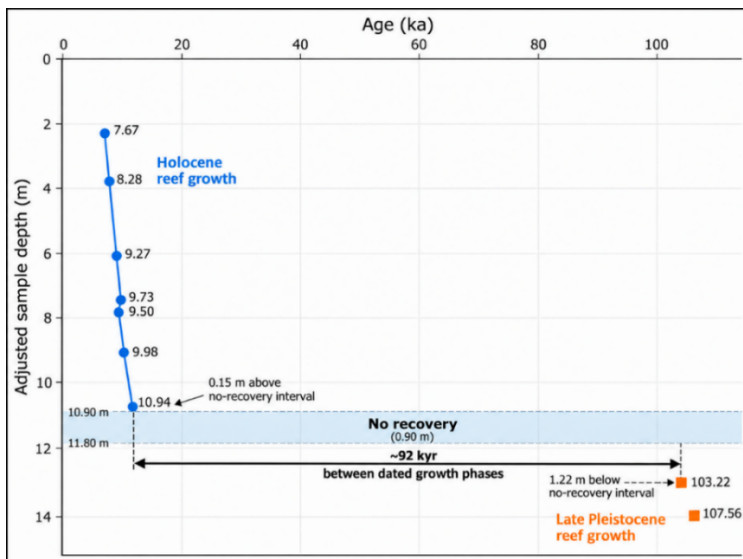


Figure 4: Age-depth relationship across the subaerial exposure surface in core ES-11. Holocene marine carbonates above the surface date from 10.94 to 7.67 ka and overlie an unrecovered interval, beneath which Pleistocene carbonates date to 103–108 ka. The 92.3 kyr separation spans the sea-level fall after late MIS 5d to early MIS 5c reef growth, the last glacial maximum, and the sea-level rise that reached the terrace by about 11 ka.

PETROGRAPHIC RESPONSE

Petrography of core ES-11 supports meteoric alteration and constrains its distribution (Fig. 5). Alveolar-septal fabrics occur beneath the surface but not above it, recording vadose or pedogenic modification (Esteban and Klappa, 1983; Wright, 1986). Pore-lining calcite cement occurs in the same interval, and although its morphology alone is not diagnostic, its distribution is: well-developed cement occurs at 13.10, 13.26, and 13.35 m, within 1.6 m below the surface, while a skeletal interval at 15.30 m retains open intraskeletal and moldic porosity with no comparable cement.

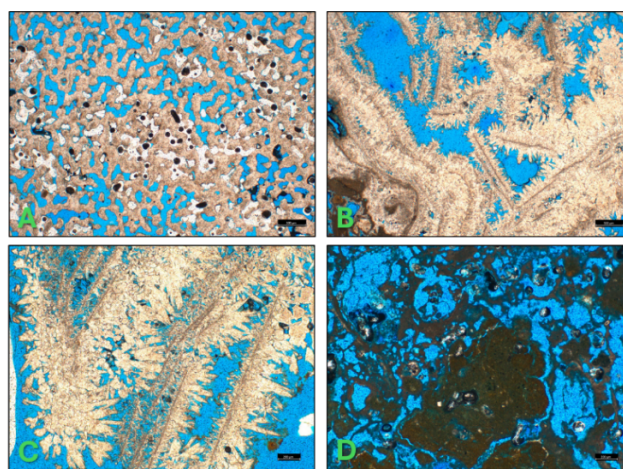


Figure 5: Petrographic expression of meteoric diagenesis across the exposure surface in ES-11: (A) open pore space above the surface; (B–C) bladed pore-lining calcite cement below the surface; and (D) alveolar-septal fabric beneath the surface.

Macroscopic evidence of meteoric alteration continues downward in the form of soil-like mud filling pore space, iron staining, and moldic porosity. In three cores, alteration extends 3.0 to 4.9 m below the exposure surface and reaches the base of core ES-4. Moldic porosity after *Halimeda* also persists into the underlying *Halimeda*-rich facies near the base of core ES-10. In core ES-11, a cementation-dominated zone immediately beneath the surface passes down into dissolution-dominated strata.

GEOCHEMICAL RESPONSE

Stable isotopes record the surface with markedly different amplitude in the two cores analyzed (Fig. 6). Core ES-11 is uniform above the surface, with $\delta^{13}\text{C}$ between +0.79 and +1.81 per mil, and falls to –8.41 per mil in the first sample beneath it at 11.94 m. The eight deeper samples average 3.1 per mil below the mean above the surface. Core ES-4 shows no comparable spike but a broader depletion: $\delta^{13}\text{C}$ is –2.01 per mil just below the surface at 15.97 m and between –4.32 and –4.60 per mil from 17.35 m to the base of the core, averaging 3.5 per mil below the mean above the surface. In both cores, the sustained $\delta^{13}\text{C}$

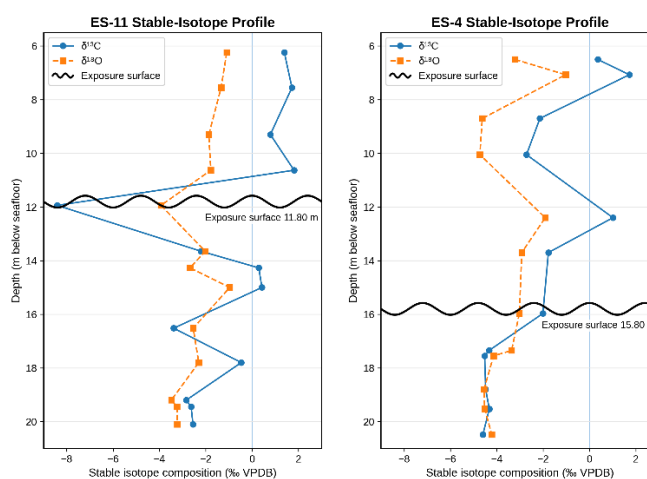


Figure 6: Stable-isotope profiles from cores ES-11 and ES-4 across the exposure surface, showing negative $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ shifts consistent with spatially variable meteoric alteration.

shift is three to four times the accompanying $\delta^{18}\text{O}$ shift (1.0 per mil in ES-11 and 0.9 per mil in ES-4). A larger shift in $\delta^{13}\text{C}$ than in $\delta^{18}\text{O}$ is expected of meteoric diagenesis, in which $\delta^{18}\text{O}$ reflects the composition of the meteoric water while $\delta^{13}\text{C}$ responds to soil-derived carbon (the meteoric calcite line of Lohmann, 1988). Core ES-4 is also more variable above the surface than core ES-11: two samples at 8.70 and 10.05 m, near a densely cemented horizon at 10.5–11.0 m, are depleted in both isotopes ($\delta^{13}\text{C}$ –2.14 and –2.72 per mil; $\delta^{18}\text{O}$ –4.63 and –4.73 per mil).

SIGNIFICANCE AND IMPLICATIONS

The upper terrace shows how differently one exposure event can be preserved over short lateral distances. Across four cores spanning roughly 400 m, the same surface ranges from a paleosol breccia, a laminated crust, and strongly altered rudstone to a subtle diagenetic overprint within otherwise continuous coral framestone, even between cores only 50 and 80 m apart. Precursor facies appears to exert an important control. In practice, an exposure surface is identified most securely where independent petrographic, geochemical, and seismic criteria converge, and it should be correlated as an event rather than traced as a lithology.

Preservation is equally uneven in time. Late Pleistocene reef growth is recorded below the surface and Holocene reef growth above it, while erosion, non-deposition, meteoric alteration, inundation, and any lag before renewed growth are all compressed into a single discontinuity. Bounding ages must be read according to their stratigraphic position rather than treated as dates for the surface itself.

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