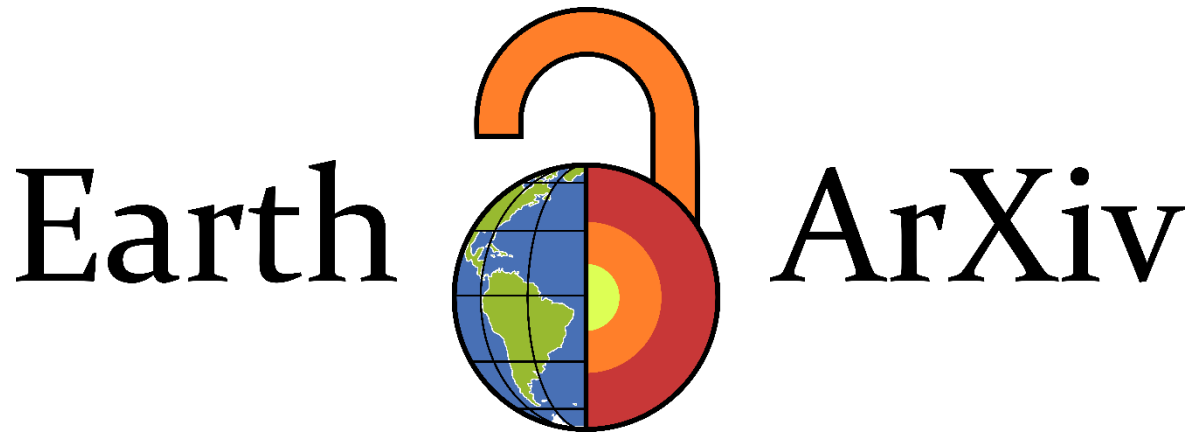




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High-resolution ^{14}C stratigraphy reveals decadal periodicity in stromatolite lamination

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ABSTRACT

Stromatolites constitute amongst the oldest evidence for life on Earth and preserve laminated records throughout most of geological time. However, the timescales represented by their lamination remain poorly constrained. Here, we report the first high-resolution ^{14}C dating combined with Bayesian age-depth modelling for three Holocene stromatolites from contrasting depositional environments. The two samples with stratigraphically coherent age-depth relationships yield time-averaged net accretion rates $< 25 \mu\text{m.yr}^{-1}$ and mean light-dark couplet durations of ca. 17-24 yr. These results demonstrate that successive laminae couplets do not represent consecutive annual increments. Spectral analyses reveal significant periodicities within the 10-30 yr range in both records, consistent with accretion modulated by decadal environmental forcing. Moreover, a radiocarbon age offset localized across a gypsum-rich interval in the Dead Sea stromatolite reveals a discontinuity, related to a previously dated dry climatic interval, for which laminae-based chronology effectively recovers its age and duration. Two major conclusions stem from this work. First, stromatolite lamination should not be assumed to represent consecutive annual increments. Second, ^{14}C -calibrated stromatolite records can be used to constrain accretion rates, identify cyclic intervals of environmental forcing, and reconstruct past climate events.

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INTRODUCTION

Stromatolites are characterized by structured lamination, growing from an initiation surface under the combined influence of microbial communities and environmental factors (Burne and Moore, 1987; Riding, 2011; Fogret et al., 2026). Present since at least 3.4 Ga, they constitute one of the most important archives of early life and paleoenvironmental evolution on Earth (Bosak et al., 2013). However, the relative contributions of biological, physicochemical, and sedimentary processes to their formation may vary, and the mechanisms and timescales associated with their distinctive lamination remain poorly constrained.

Stromatolite lamination is generally interpreted as a record of recurring changes in microbial growth, lithification, or depositional conditions (Szulc and Smyk, 1994; Petryshyn et al., 2012). Stromatolite accretion likely results from complex interactions between environmental conditions and microbial metabolism controlling carbonate precipitation, sediment delivery, dissolution, and erosion; and may therefore be intermittent rather than proportional to microbial productivity (Dupraz and Visscher, 2005). As with other rhythmic archives, such as tree rings, coral skeletons, and mollusk shells (Rodríguez-Tovar, 2014), interpreting stromatolite lamination requires determination of the amount of time represented by each rhythmic increment. Light-dark couplets in stromatolites have been attributed to seasonal, annual, or longer-term periodic variations (Pannella, 1976; Vanyo and Awramik, 1985; Petryshyn et al., 2012; Tang et al., 2014; Arenas and Jones, 2017; Pérez-Rivarés et al., 2019), but without robust radiometric age constraints, these attributions remain speculative.

Previous attempts to reconstruct stromatolite accretionary histories have been limited by the amounts of carbonate required for conventional radiocarbon dating. Here, we combine ultra-low-abundance ^{14}C dating with Bayesian age-depth modelling to provide the highest-resolution stromatolite chronologies produced to date, gaining unique insight into accretion rates, couplet durations, periodicity, and stratigraphic continuity in three Holocene stromatolites.

MATERIALS AND METHODS

High-resolution radiocarbon analyses were performed using a Mini Carbon Dating System, the *ECHoMICADAS* (at the Laboratory for Climate and Environmental Sciences; Thil et al., 2024), requiring only ca. 1 mg of carbonate per measurement and thereby enabling high-resolution micro-sampling (Text S1). We selected three carbonate-dominated Holocene stromatolites from the *Muséum National d'Histoire Naturelle* Microbialite Collection (Fogret et al., 2024), representing contrasting depositional settings: paleo-lacustrine (Richat Structure, Mauritania), lagoonal (Mari Ermi, Sardinia, Italy), and hypersaline (Dead Sea, Israel; Fig. 1).

Optical microscopy, SEM-EDX, and μXRF analyses show that light-dark laminae couplets differ petrographically among specimens (Text S2; Figs. S1-S3). The Richat Structure sample (hereinafter “Richat”) exhibits alternating light microsparitic and darker Mg-rich micritic laminae. The Mari Ermi sample (hereinafter “Mari Ermi”) is dominated by Mg-rich micrite where light laminae contain abundant vertically oriented filamentous microstructures, while dark laminae are more compact and contain fewer filaments. The Dead Sea sample (hereinafter “Dead Sea”) is comprised of alternating carbonate- and evaporite-bearing laminae, punctuated by a single distinctive Ca- and S-rich layer composed of spearhead-twinning crystals, consistent with gypsum.

For this study, we define a lamina as an individual light or dark layer distinguished by optical contrast and associated textural characteristics, and a couplet as the succession of one light and one dark lamina. Light and dark layer thicknesses were manually measured on optical images along one representative transect following the principal accretion axis, perpendicular to lamination and

coincident with the ^{14}C sampling transect (Text S3; Fig. S4). Along transects of ca. 2 cm, we identified 114 couplets in Richat, 40 in Mari Ermi, and 21 in Dead Sea (Table S1). Summary parameters and statistics for lamina and couplet thickness distributions are given in Tables S1 and S2.

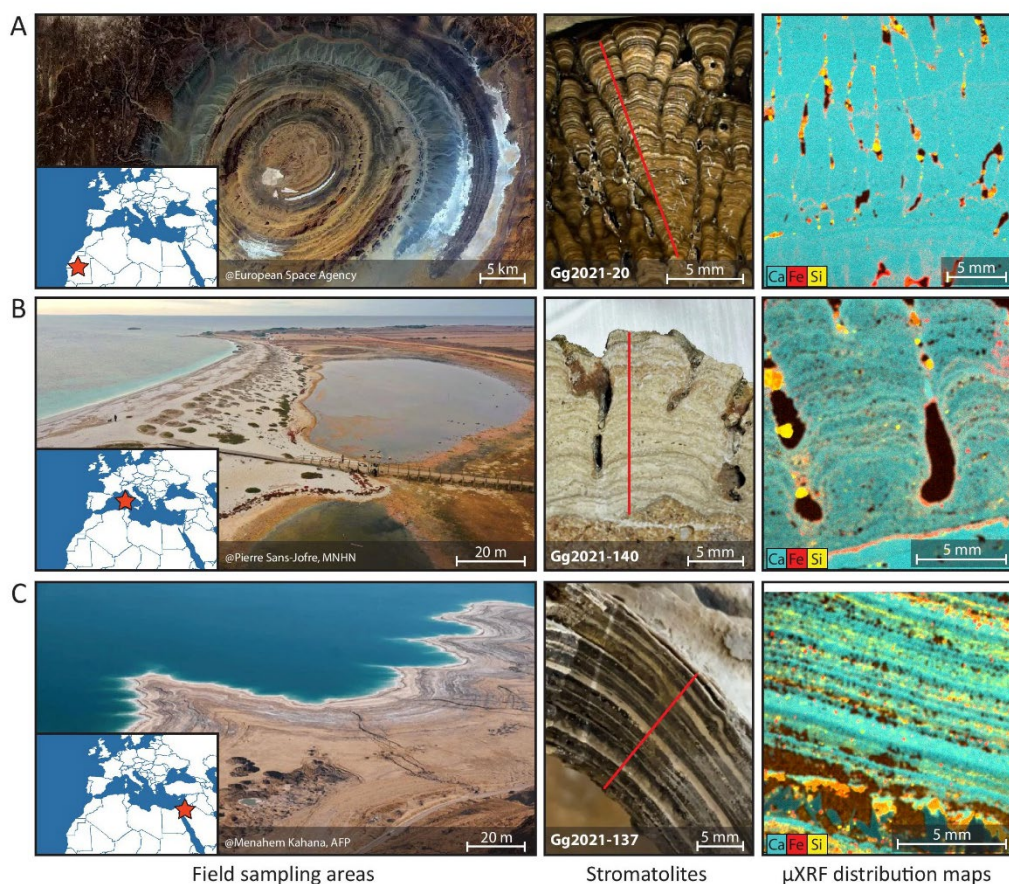


Figure 1. Studied stromatolites from (A) the Richat Structure, Mauritania, (B) the Mari Ermi North Pond, Sardinia, Italy, and (C) the Dead Sea, Israel. Left: Sampling areas and their locations. Center: Stromatolite cross-sections with red lines indicating the transects used for laminae measurements. Right: μXRF maps of Ca (blue), Fe (red), and Si (yellow).

RESULTS AND DISCUSSION

RADIOCARBON CHRONOLOGIES AND ACCRETION RATES

A total of 17 radiocarbon dates were obtained along the principal accretion transects: 6 from Richat, 8 from Mari Ermi, and 3 from Dead Sea (Table S3). The dates were corrected for reservoir effects according to their depositional settings and calibrated using Bayesian age-depth modeling (Text S1).

The Richat and Mari Ermi dates are stratigraphically ordered and were modelled as continuous age-depth sequences (Fig. 2). Ages range from 8618 ± 92 cal BP at the base to 7063 ± 73 cal BP at the top of the Richat stromatolite, and from 890 ± 57 to 74 ± 29 cal BP for Mari Ermi. Bayesian model ages were determined for all identified laminae boundaries, and all laminae durations and couplet-specific accretion rates were estimated individually. The resulting mean accretion rates are $12.5 \pm 5.6 \mu\text{m.yr}^{-1}$ for Richat and $22.8 \pm 4.6 \mu\text{m.yr}^{-1}$ for Mari Ermi ($\pm 1\text{SD}$; Fig. 2; Table S1). These mean accretion rates are significantly lower than previously published estimates of around 65 to $880 \mu\text{m.yr}^{-1}$ from

stromatolites formed in marine, lacustrine, or coastal-lagoon settings (Chivas et al., 1990; Paull et al., 1992; Petryshyn et al., 2012; Brook et al., 2013; Carvalho et al., 2018). Direct comparisons remain limited by differences in depositional setting, preservation, the importance of grain trapping, or dating resolution. The ultra-low accretion rate determined here for both samples implies either very low microbially induced mineralization in the uppermost layers of the stromatolites, or an important disconnect between microbial activity and long-term retention of carbon in the lithified structure.

Regarding the Dead Sea sample, the ages range from 3683 ± 90 to 2815 ± 50 cal BP. However, the age-depth relationship suggests that the gypsum-rich interval is linked to a significant age offset and represents a stratigraphic discontinuity. Consequently, we did not derive a single accretion rate for the entire Dead Sea sample transect.

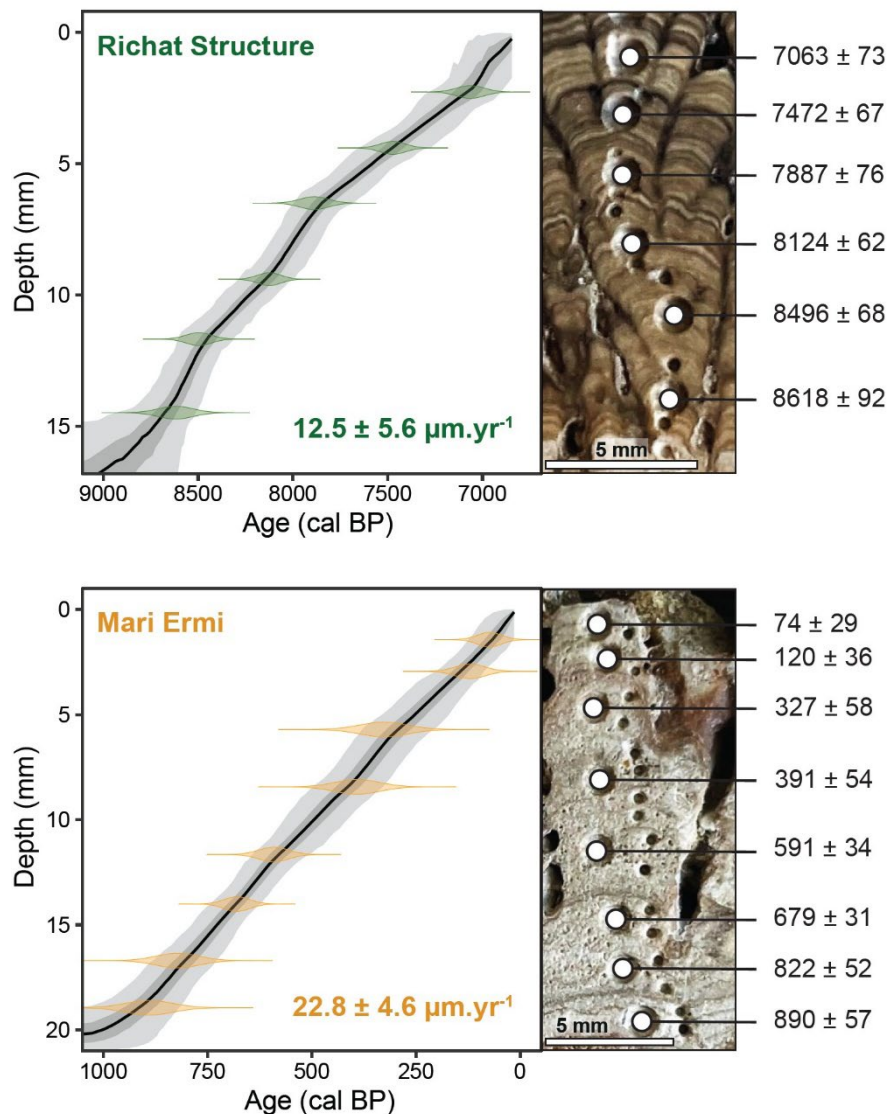


Figure 2. Bayesian age-depth models for the Richat and Mari Ermi stromatolites. The black curves represent the median modelled age-depth relationships, and the dark- and light-grey envelopes represent the 68% and 95% posterior credible intervals. Colored probability-density distributions show the calibrated ages and their uncertainties. Mean accretion rates are reported with 1 SD uncertainties. Sample photographs on the right show the positions of micro-drilled sampling points used for radiocarbon dating; corresponding calibrated ages are indicated next to each point.

STROMATOLITE LAMINATION SPANS MULTIANNUAL TIMESCALES

Bayesian age-depth modelling constrains the elapsed time between identified stromatolite lamina boundaries. The mean modelled couplet duration is 17.1 ± 12.1 yr in the Richat specimen and 24.3 ± 11.7 yr in the Mari Ermi ($\pm 1\text{SD}$; Table S1; Fig. S5). Direct comparisons remain limited by differences in depositional setting, detrital contributions, preservation, or dating resolution. While these results clearly demonstrate stromatolite lamination on decadal timescales, little more can be said about the nature and origin of stromatolite lamination given current chronological limitations. For example, in both stromatolites, light laminae account for most of the thickness of each couplet; however, the relative accretion rate of light and dark laminae is not resolved by our approach. It is thus possible that the relatively thick light laminae record periods of relatively rapid carbonate accumulation, while darker laminae represent slower accretion, and that their relative thicknesses are unrelated to the time they represent. Equally possible is that accretion may not be continuous over the measured duration of each couplet, i.e., accretion may occur over a shorter timescale, in one or multiple events, punctuated by periods of stasis, or even erosion, during the generation of a single lamina. Indeed, individual couplet thicknesses and durations show non-negligible variability. Future advances in low-level ^{14}C analysis and/or in-situ microsampling may also provide the necessary resolution for the determination of individual lamina accretion rates. While our data do not rule out formation of an individual couplet within a single season or year, the common assumption of a one-to-one correspondence between stromatolite lamination preserved in lithified specimens and consecutive years should be avoided.

DECADAL PACING OF STROMATOLITE LAMINATION

To better understand the rhythmic nature of stromatolite lamination, the couplet chronologies were subjected to ranked series cyclostratigraphic analysis (Olsen and Kent, 1996). As the Dead Sea succession contains a major stratigraphic discontinuity, multi-taper spectral analysis was restricted to the stratigraphically coherent Richat and Mari Ermi records. Peaks exceeding the 95% confidence threshold above an autoregressive noise model (AR1) are present in both spectra (Figs. 3 and S6). Despite their contrasting depositional settings and differences in couplet thickness and mean accretion rate, both records exhibit significant periodicities in the ca. 10-30 years range.

Some of the detected periodicities overlap with timescales associated with solar and lunar variability, including the ca. 11-yr Schwabe, 18.6-yr lunar nodal, and 22-yr Hale cycles (Schwabe, 1844; Hale et al., 1919; Pugh, 1987). Similar decadal periodicities have also been reported in other laminated sedimentary archives, such as varve deposits (Schimmelmann et al., 2016). Pérez-Rivarés et al. (2019) previously suggested periodicities near 10 and 22 yr in Miocene lacustrine stromatolites, albeit without the support of radiometric chronologies, and proposed possible links with solar activity and large-scale atmospheric variability. The high-resolution chronological framework presented here provides novel support for decadal environmental pacing of stromatolite lamination at timescales of 30 yr and below. Multiple rhythmic climate forcings operate on these timescales (e.g., NAO, ENSO; Joshi et al., 2023), but significant variability in their timing, and the multiple periodicities identified in the stromatolite couplet records, make it unclear at present if stromatolite lamination is dominated by one particular rhythmic forcing, and whether this varies between localities. In any case, the detected periodicities indicate that stromatolite accretion is subject to decadal rhythmic forcing, likely by the environmental variability they induce.

Potential pathways linking periodic environmental variability to stromatolite accretion involve the modulation of local sediment, water, and carbonate budgets. Changes in runoff, groundwater input, evaporation, and water residence time can modify water chemistry, including salinity and alkalinity,

altering the activities of Ca^{2+} and CO_3^{2-} , and thus the carbonate saturation state (Caumartin et al., 2023). This applies both to freshwater (e.g., Richat Structure) and marine / lagoonal settings (e.g., Mari Ermi), where changes in sediment delivery, microbial activity, carbonate precipitation or dissolution, and diagenetic preservation are all potential forcing agents controlling stromatolite accretion.

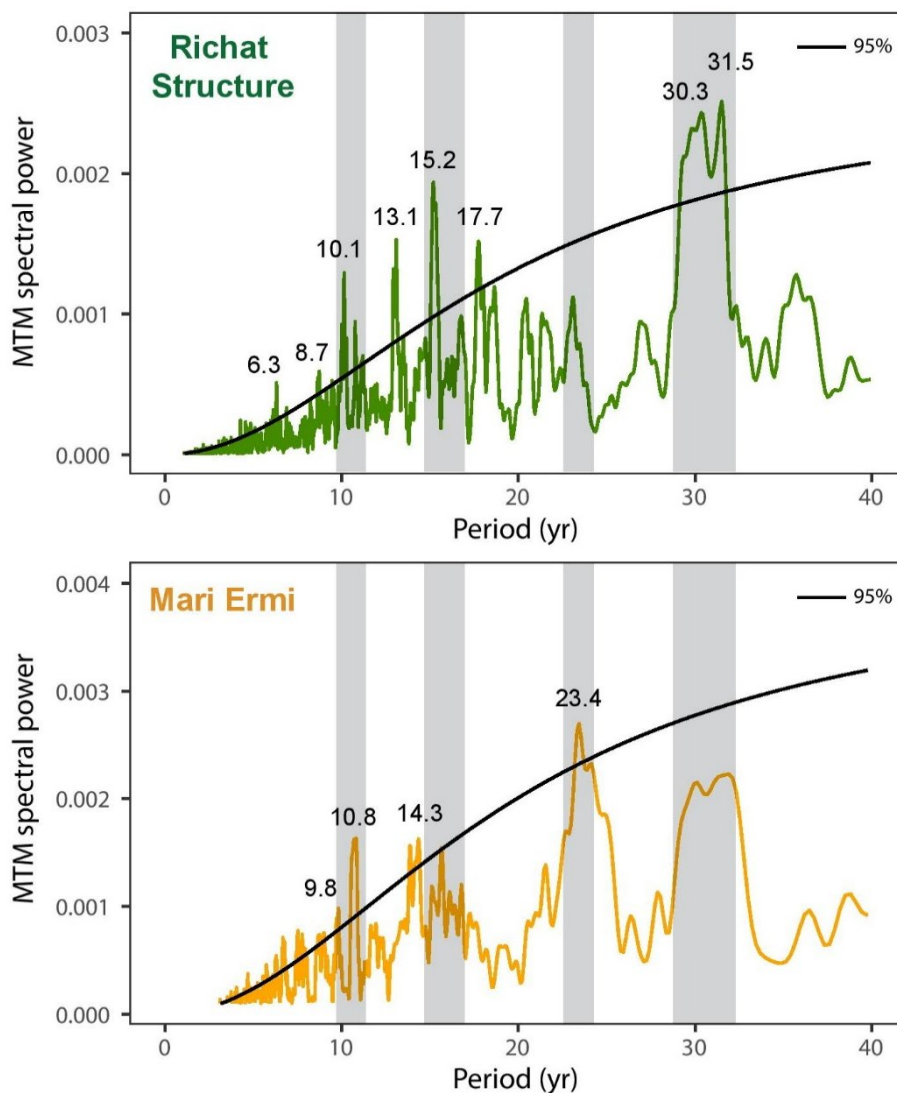


Figure 3. Multi-taper spectra of ^{14}C -calibrated light-dark lamination rank series analyses for the Richat and Mari Ermi stromatolites. Labelled peaks exceed the 95% confidence threshold above the autoregressive noise model (AR1; black line; Meyers, 2014).

CHRONOLOGICAL RECONSTRUCTION OF A CLIMATIC EVENT

Unlike the Richat and Mari Ermi records, the Dead Sea chronology is inconsistent with uniform accretion across the analyzed transect. Although the lower and middle ^{14}C ages differ by approximately 734 yr, only 4 preserved couplets occur between their respective positions, whereas 7 couplets in the younger interval represent only ca. 134 yr (Fig. 4). This abrupt change in the age-depth relationship coincides with the gypsum-rich interval and identifies it as a stratigraphic discontinuity. Indeed, this interval coincides with a well-documented dry period in the Dead Sea region, with an estimated lake-

level fall of approximately 45 m, dated to around 3600-3200 cal BP (Migowski et al., 2006; Neugebauer et al., 2015). On the western margin of the Dead Sea, outcrop captures this event as a massive sand deposit, whereas it is expressed as massive halite in a deep-basin drill core recently obtained by the ICDP DSDDP project (Neugebauer et al., 2015). Analogous to dendrochronology, stromatolite couplet chronology provides an opportunity to independently estimate the age and duration of the hiatus represented by the gypsum interval.

The 7 couplets in the younger, stratigraphically coherent laminations of the upper part of the stromatolite yield a mean elapsed duration of 19.14 yr per couplet. Using this couplet duration as a reference, the 4 couplets preserved between the lower and middle dates would represent ca. 77 yr. The gypsum interval can thus be estimated to represent 657 ± 145 yr ($\pm 1SD$) of missing time, or approximately 34 missing couplets (Fig. 4; Text S4). This does not imply that 34 couplets were formed and subsequently removed; the discontinuity more likely reflects simple non-accretion, dissolution, erosion, or a combination of these processes. The duration indicated for the dry period by the missing couplets is slightly longer than the median values obtained by Neugebauer et al. (2015) based on ^{14}C dating above and below the corresponding halite interval in the DSDDP core, but falls within the 95% uncertainty range. This remarkable correspondence illustrates how high-resolution ^{14}C chronologies of stromatolite lamination can be used for temporal reconstruction of climatic events in a manner analogous to dendrochronology.

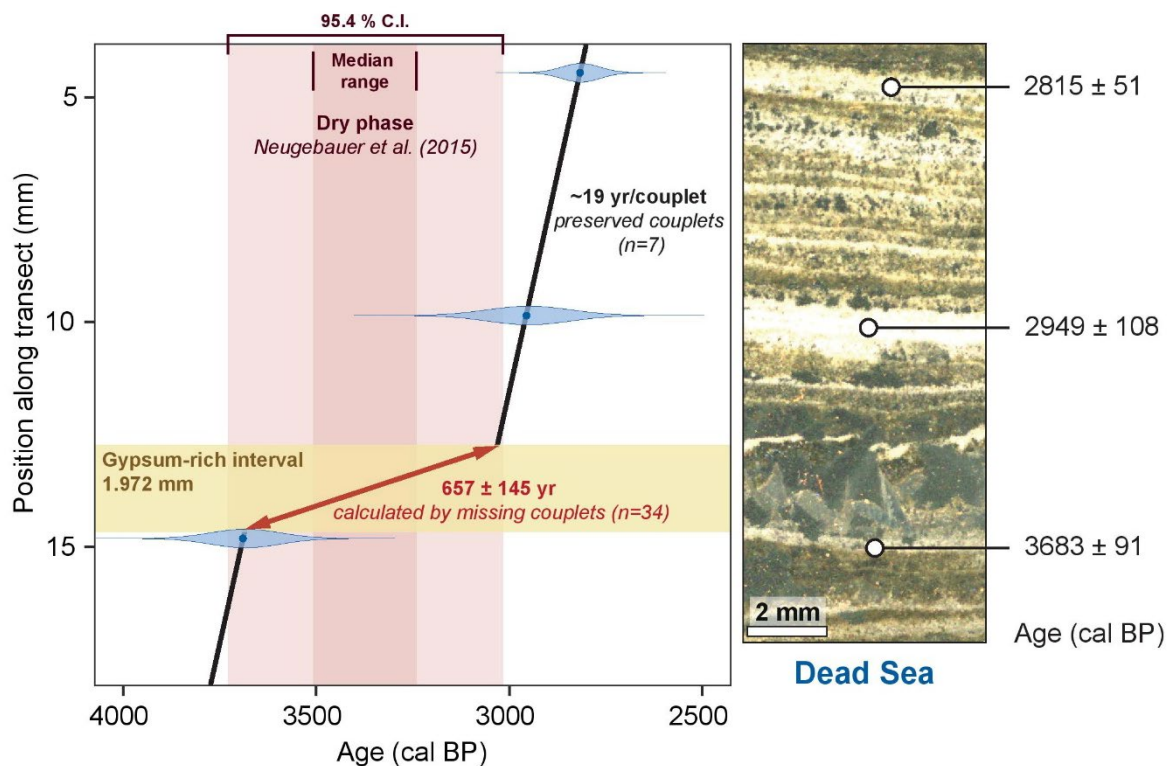


Figure 4. Reconstruction of a climatic event in the Dead Sea stromatolite. Left, depth-age plot showing the gypsum-rich interval and its age and duration estimated by laminae chronology vs. estimates for the same dry period from the DSDDP core (Neugebauer et al., 2015).

CONCLUSION

We demonstrate that high-resolution ^{14}C chronology can bring important new perspectives on the temporal interpretation of stromatolite lamination. In the Richat and Mari Ermi specimens, the mean modeled elapsed time between couplets is multiannual, demonstrating that successive light-dark couplets do not represent consecutive annual increments. Individual couplets may nevertheless have formed during shorter depositional episodes, potentially within a single favorable season or year, separated by intervals without formation or preservation of a resolvable boundary. In these two specimens, significant lamination periodicities are observed at decadal timescales, despite contrasting depositional settings, couplet thicknesses, and mean accretion rates, suggesting external climate forcing. In the Dead Sea specimen, lamination chronology constrains a stratigraphic discontinuity beginning ca. 3683 ± 91 cal BP to an estimated duration of 657 ± 145 yr, which corresponds in age and duration to a previously identified regional dry period. These findings show that annual recurrence cannot be inferred from stromatolite lamination without independent chronological control and demonstrate the potential of age-calibrated stromatolite records for reconstructing accretion dynamics and past environmental events.

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DECLARATION OF INTERESTS

The authors declare no conflict of interest.

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SUPPLEMENTAL MATERIAL

This Supplemental Material provides detailed methods and sample descriptions, explains the identification of stromatolite laminae, and describes the reconstruction of missing time in the Dead Sea stromatolite. It includes Texts S1-S4, Figures S1-S6, and Tables S1-S3.

TEXT S1 - DETAILED METHODS

Sample Preparation and Micro-sampling

The three stromatolites analyzed in this study were selected from the Microbialite Collection of the *Muséum National d'Histoire Naturelle* (MNHN, Paris; Fogret et al., 2024). Preliminary optical and compositional observations indicated that their laminae are carbonate-dominated and contain only limited siliciclastic material. Each stromatolite was cut perpendicular to the lamination to expose a cross-section parallel to its principal accretion axis. Micro-sampling was performed using a MicroMill system (New Wave Research), consisting of an Olympus SZ61 microscope coupled to a high-precision computer-controlled micro-milling device. Approximately 1 mg of powder was extracted per point using a 600- μm -diameter tungsten carbide drill bit. The reported measurements therefore represent bulk carbonate from each sampling position. No mineral-specific physical separation of micritic, microsparitic, and sparry calcite was performed. The complete transects and micro-sampling positions are shown in Figs. 1,2,4 and S1-S3.

Radiocarbon Dating

The radiocarbon (^{14}C) measurements were performed using a next-generation compact accelerator mass spectrometer (AMS), a Mini Carbon Dating System (MICADAS, IonPlus) of the Laboratory for Climate and Environmental Sciences (Gif-sur-Yvette, Université Paris-Saclay): the *ECHoMICADAS*, operated under the supervision of François Thil. Approximately 1 mg of carbonate powder was employed per analysis, corresponding to ca. 100 μg of carbon. Prior to AMS injection, each powdered sample was placed in a screw-cap vial equipped with a septum (Labco Exetainer®). Vials were then loaded into a Carbonate Handling System (CHS2, IonPlus) device, a fully automated carbonate preparation system. The carbonate surface was first weakly leached with 0.01N HNO_3 to reduce potential surface contamination. The sample was then hydrolyzed using anhydrous H_3PO_4 under a helium flow, releasing CO_2 . The resulting gas mixture ($\text{He} + \text{CO}_2$) was directed through a water trap before entering the Gas Interface System (GIS, IonPlus). There, the CO_2 was adsorbed onto zeolite traps, heated to 450 $^\circ\text{C}$ to release pure, dry CO_2 , which was then diluted again in helium. The gas mixture was continuously injected into the *ECHoMICADAS* ion source via a capillary line. Finally, the *ECHoMICADAS* measures radiocarbon by accelerating ionized carbon atoms and separating them by mass using two stages of mass spectrometry, separating nearly all molecular interferences and passing a highly pure $^{14}\text{C}^+$ ion beam to the detectors, allowing for accurate and sensitive ^{14}C dating.

Data Processing and Corrections

Radiocarbon data were processed using the BATS software (v. 4.07; Wacker et al. 2010). Measurements were corrected for time, isobaric interferences, and chemical fractionation. Radiocarbon ages are reported as conventional uncalibrated Before Present ages (BP, *i.e.*, before 1950) and calculated using the following formulas:

$$\text{Radiocarbon age} = -8033 \times \ln(F^{14}\text{C})$$

$$Uncertainty = -8033 \times \left(\frac{uncertainty\ of\ F^{14}C}{F^{14}C} \right)$$

where 8033 years corresponds to the inverse of the ^{14}C decay constant. $F^{14}C$ values, which represent the normalized $^{14}C/^{12}C$ ratios, were corrected for background contamination (based on IAEA-C1 blanks) and instrumental fractionation (based on the OxII standard; NIST SRM 4990C). For small samples, an additional correction accounts for both constant contamination (estimated at 0.14 μgC , $F^{14}C = 0.423$) and cross-contamination (memory effects) from previously measured samples, estimated at 0.4%. $F^{14}C$ values and analytical uncertainties are reported in Table S3.

Reservoir Effects and Corrections

Radiocarbon dating of carbonate rocks may be affected by the reservoir effect, which occurs when ^{14}C concentrations in the depositional environment differ from the atmospheric level, often leading to age overestimations, especially in marine settings. To account for this, we applied a standard -400-year marine reservoir correction to the Dead Sea samples (Reimer and Reimer, 2001), a -360-year correction to the Mari Ermi samples based on data from local sediments (Siani et al., 2000; Faivre et al., 2019), and no correction to the Richat Structure samples, which likely reflect equilibrium with atmospheric ^{14}C due to their continental lacustrine setting. $F^{14}C$ values are reported to allow future re-evaluation of reservoir corrections if needed.

Age Calibration

All reservoir-corrected conventional radiocarbon ages were calibrated with the program CALIB (v. 8.2; Stuiver and Reimer, 1993) and the IntCal20 calibration curve for the Northern Hemisphere (Reimer et al., 2020). Calibrated ages are given in Calibrated Years Before Present (cal BP). Median calibrated ages and their 95% probability ranges are provided in Table S3. The correction of ^{14}C BP ages has little influence on the results of this study, as they are largely based on comparative ages determined between layers from the same sample.

Age-Depth Modelling and Rank Series Analyses.

Binary facies shifts (light vs. dark laminae) were recorded along ca. 2-cm transects following the principal accretion axis of each sample. These transitions were then temporally constrained using age-depth relationships derived from the radiocarbon data. Age-depth modelling was performed using the *Behron* R package (Haslett and Parnell, 2008), as implemented by the *geoChronR* R package (McKay et al., 2021), which applies a Bayesian Markov chain Monte Carlo (MCMC) framework to interpolate calibrated radiocarbon dates along the stratigraphic profile. Each model run included 100,000 MCMC iterations, assuming a monotonic sediment accumulation model with default priors for accretion rate and error structure. The resulting posterior distributions were used to estimate the age of each lamina transition and the duration of individual facies intervals. Spectral analyses were performed on bi-facies rank-series (Olsen and Kent, 1996) data (light vs. dark laminae) calibrated directly in the time domain, with ages calculated at all points using the Bayesian age-depth models, using the multi-taper method (MTM) with autoregressive noise model 1 (AR1) of the *astrochron* R package (Meyers, 2014).

TEXT S2 - DETAILED SAMPLE DESCRIPTION

Richat Structure stromatolite

The stromatolite originates from Holocene lacustrine deposits within the Richat Structure, an eroded alkaline-hydrothermal dome in Mauritania (Aucour, 1988; Matton and Jébrak, 2014). The available collection information does not provide details on the particular section from which the sample was collected nor an independently constrained accumulation rate for the surrounding deposits. The specimen exhibits alternating light and dark laminae arranged in slightly convex to undulating couplets with generally high lateral continuity (Figs. 1 and S1). Along the measured transect, we distinguished 114 light-dark couplets. Light laminae range from 20.6 to 334.0 μm in thickness, whereas dark laminae range from 9.0 to 253.8 μm .

In optical and electron-microscopy images, the light laminae are predominantly microsparitic and locally display palisade-like fabrics; some are associated with thin clay-rich seams. The dark laminae are predominantly micritic and locally contain fan-shaped filamentous microstructures, ca. 30-150 μm long, oriented broadly perpendicular to lamination. The optical light-dark contrast is accompanied by compositional differences: dark laminae show greater Mg enrichment and contain more Mg-bearing calcite, whereas light laminae are dominated by comparatively low-Mg calcite.

SEM-EDX and μXRF mapping also reveal isolated Si-rich and Fe-rich grains, interpreted as minor detrital silicate and Fe-bearing components. Detrital material is concentrated within the intercolumnar spaces and was not observed along the analyzed transect. Some diagenetic sparry calcite and secondary mineralized overgrowths can be observed, but constitute only a very minor component of the transect. Where present, sparry calcite locally lines pore spaces, and thin secondary mineralized bands locally overprint the earlier laminated fabric. These features indicate diagenetic modification, although the original light-dark architecture remains recognizable along the analytical transect. Thin, laterally continuous P-rich laminae are also observed and are consistent with a Ca-phosphate phase, tentatively attributed to fluorapatite.

Mari Ermi stromatolite

The stromatolite formed around a fossiliferous limestone pebble composed of silt- to sand-sized carbonate and detrital grains (Saint Martin and Saint Martin, 2015; Debie et al., 2022). The stromatolite part exhibits concentric lamination organized into branching columns that widen upward. Individual columns are approximately 0.8-2.2 cm high and 0.2-1.5 cm wide (Figs. 1 and S2). Along the analysed transect, we distinguished 40 light-dark couplets. Light laminae range from 102 to 1030 μm in thickness, whereas dark laminae range from 16.7 to 199 μm . The couplets are therefore strongly light-dominated along this transect.

In optical and electron-microscopy images, the light laminae consist predominantly of micritic Mg-bearing calcite and contain abundant filamentous microstructures, ca. 10-15 μm wide and 100-150 μm long, oriented broadly perpendicular to lamination. These structures are consistent with fossilized filamentous microorganisms. Both the abundance of filamentous structures and visible pore spaces appear to increase toward the top of the stromatolite. The dark laminae contain fewer visible filamentous structures and exhibit a more compact micritic fabric.

Minor Si-rich and Fe-rich grains detected by SEM-EDX and μXRF are interpreted as detrital silicate and Fe-bearing components. These grains are sparse and occur mainly within the intercolumnar spaces, indicating that detrital material constitutes only a minor component of the stromatolitic fabric and of the analysed transect.

Dead Sea stromatolite

The specimen originates from the margin of the Dead Sea, a terminal hypersaline lacustrine basin characterized by pronounced hydrological fluctuations and evaporite deposition (Druckman, 1981; Enzel et al., 2006). It has a stratiform morphology with flat to slightly convex lamination (Figs. 1 and S3). The laminae are generally smooth and laterally continuous across the cross-section of the specimen. Along the analysed transect, we distinguished 40 light-dark couplets and one distinct gypsum-rich interval. Light laminae range from 127 to 1423 μm in thickness, whereas dark laminae range from 119 to 1100 μm ; the gypsum-rich interval is 1972 μm thick.

In optical and electron-microscopy images, the light laminae are predominantly microsparitic and display relatively low visible porosity. Some contain radially arranged acicular carbonate crystals consistent with aragonite and local Mn-rich dendritic features. The dark laminae display greater visible porosity and contain rod-shaped Ca-carbonate crystals associated with fibrous Mg-silicate phases.

Large Na-Cl-rich and K-Cl-rich crystals, consistent with halite and sylvite, respectively, occur locally within the laminated fabric. A distinctive evaporite-rich interval contains spearhead-twinned Ca-S-rich crystals, consistent with gypsum. SEM-EDX and μXRF mapping further show alternation between carbonate-rich and sulfate-rich layers. Minor Si-rich and Fe-rich grains occur locally within interlaminar spaces and are interpreted as detrital silicate and Fe-bearing components. The gypsum-rich interval corresponds to the principal textural transition evaluated separately in the chronological analysis.

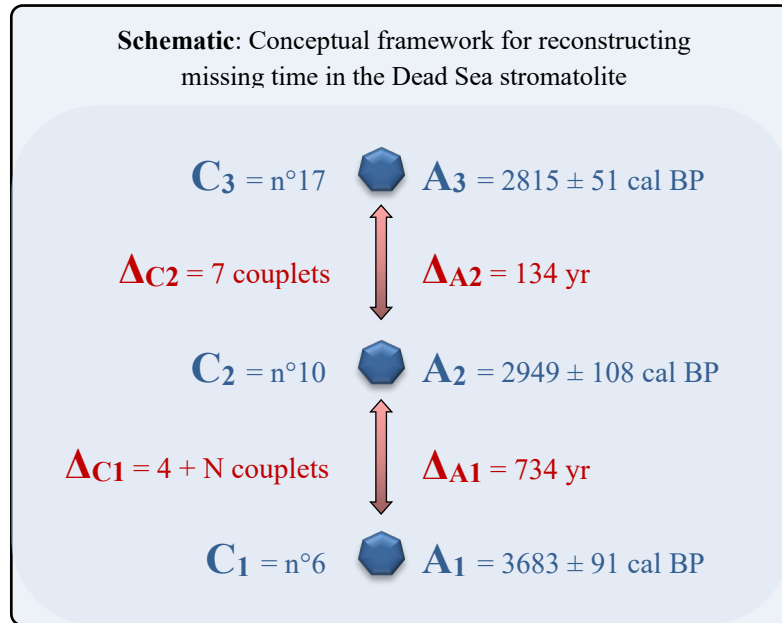
TEXT S3 - STROMATOLITE LAMINATION IDENTIFICATION

In this study, a lamina is defined as an individual light or dark layer distinguished by its optical contrast and associated textural characteristics, whereas a couplet comprises the succession of one light and one dark lamina along the accretion direction. Couplets were treated as fundamental recurring units of lamination, without assigning them an a priori temporal significance. Lamina boundaries were visually identified on optical images because their recognition relies on spatially variable combinations of optical contrast, texture, mineralogy, and porosity that cannot be reliably represented by a single color- or pixel-intensity threshold. Only clearly distinguishable boundaries that could be traced laterally across the analyzed area were retained, thereby minimizing the risk of subdividing individual laminae based on local heterogeneities or secondary features. For each specimen, individual light- and dark-lamina thicknesses and total couplet thicknesses were measured along one representative transect following the principal accretion axis of the selected stromatolite column. This axis is perpendicular to local lamination and corresponds to the stratigraphic transect used for radiocarbon micro-sampling. Because measurements were obtained along one representative transect per specimen, the resulting counts constitute conservative estimates and may not capture subtle lateral variability or visually unresolved boundaries.

TEXT S4 - RECONSTRUCTION OF MISSING TIME IN THE DEAD SEA STROMATOLITE

The reconstruction of the temporal discontinuity in the Dead Sea stromatolite assumes that the mean couplet duration calculated for the preserved upper interval provides an appropriate reference for the interval containing missing time. The identified hiatus may represent non-accretion, dissolution, erosion, or a combination of these processes. Our primary objective was to estimate the duration of the stratigraphic gap; its expression as a number of missing couplets provides a lamination-equivalent measure and does not imply that these couplets necessarily formed before being removed.

The notation and stratigraphic relationships used in the calculation are illustrated in the schematic below, including the ^{14}C ages (A_1 - A_3), cumulative couplet positions (C_1 - C_3), and the corresponding age and inferred couplet counts (Δ_A and Δ_C).



Let A_1 , A_2 , and A_3 denote the modelled ages associated with cumulative couplet positions C_1 , C_2 , and C_3 , respectively. The mean couplet duration D_C in the preserved upper interval was calculated as:

$$D_C = \frac{A_2 - A_3}{C_3 - C_2} \approx 19.14 \text{ yr. couplet}^{-1}$$

Four couplets are preserved between C_1 and C_2 in the lower interval. Assuming that their mean duration is equivalent to D_C , the amount of time represented by preserved lamination between the two lower dated positions is:

$$t_{\text{preserved}} = \Delta_{C1} \times D_C \approx 76.6 \text{ yr}$$

The missing time is therefore estimated as:

$$t_{\text{gap}} = \Delta_{A1} - t_{\text{preserved}} \approx 657.4 \text{ yr}$$

Finally, the lamination-equivalent number of missing couplets is:

$$N_{\text{missing}} = \frac{t_{\text{gap}}}{D_C} \approx 34.4 \text{ couplet equivalents}$$

This reconstruction, with all errors propagated in quadrature, yields an estimated stratigraphic gap of 657 ± 145 yr (1SD), corresponding to ~ 34 missing couplet-equivalent intervals.

SUPPLEMENTAL FIGURES

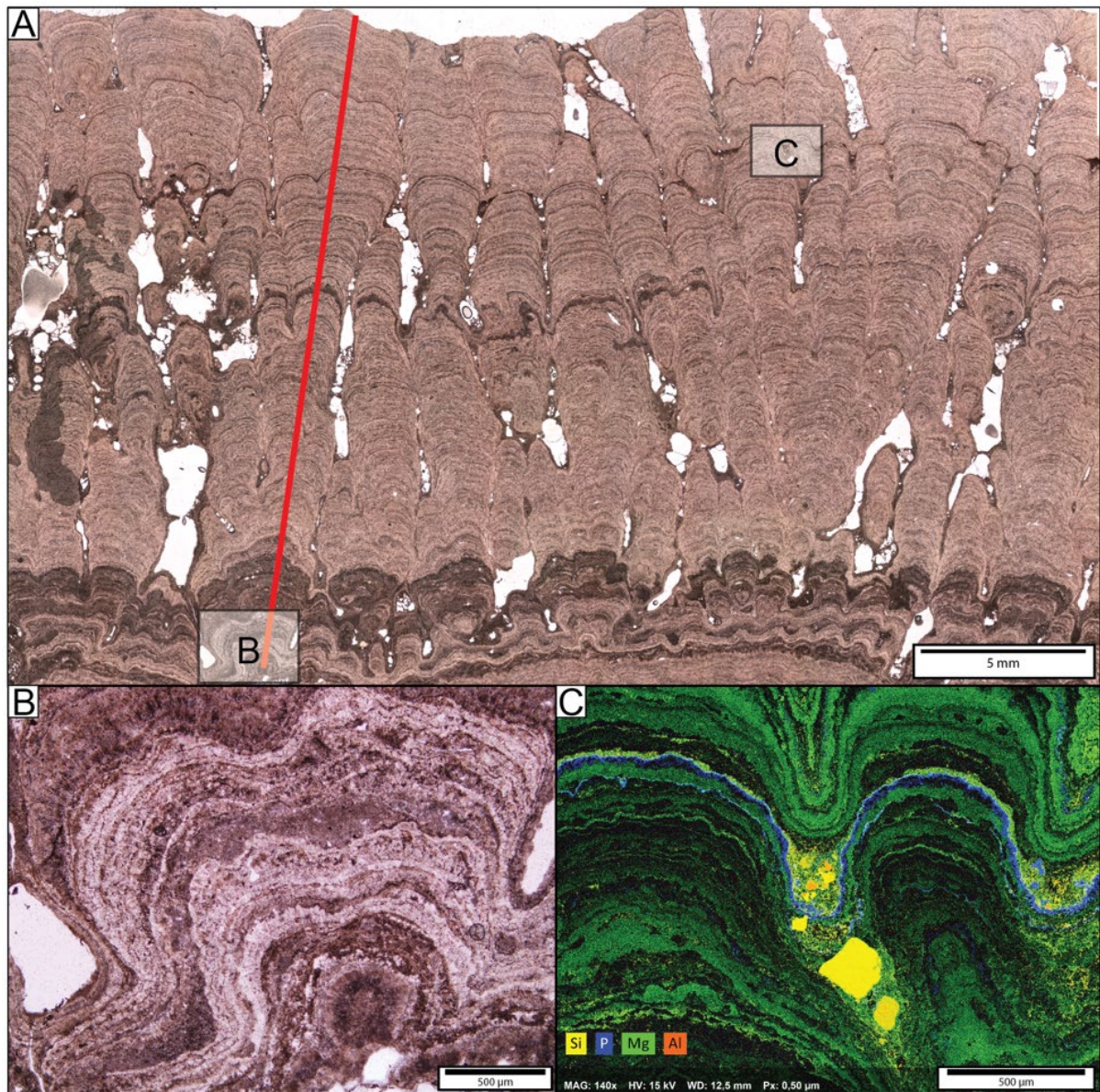


Figure S1. Optical microscopy images and SEM-EDX elemental map of the Richat Structure stromatolite. (A) Overview of stromatolite columns in sample Gg2021-20. The red line indicates the transect used for lamina identification and thickness measurements. (B) Detail of column initiation around an oncoidal nucleus and the alternation of light and dark laminae. (C) Elemental map showing the distribution of silicon (Si), phosphorus (P), magnesium (Mg), and aluminum (Al) within the lamination.

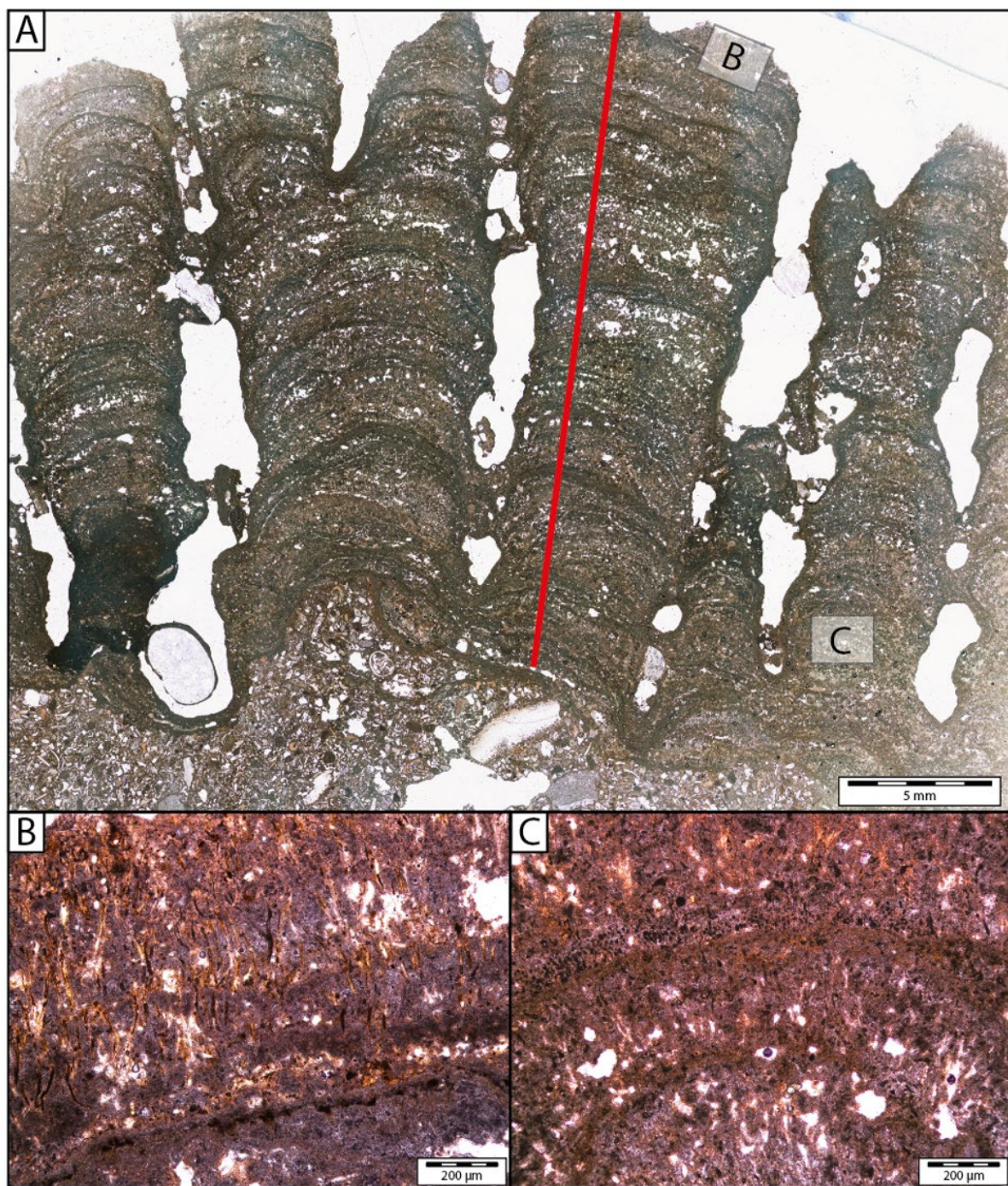


Figure S2. Optical microscopy images of the Mari Ermi stromatolite. (A) Overview of the elongated stromatolite columns in sample Gg2021-140. The red line indicates the transect used for lamina identification and thickness measurements. (B, C) Detailed views of laminae containing abundant filamentous microstructures, located respectively near the top (B) and base (C) of a stromatolite column.

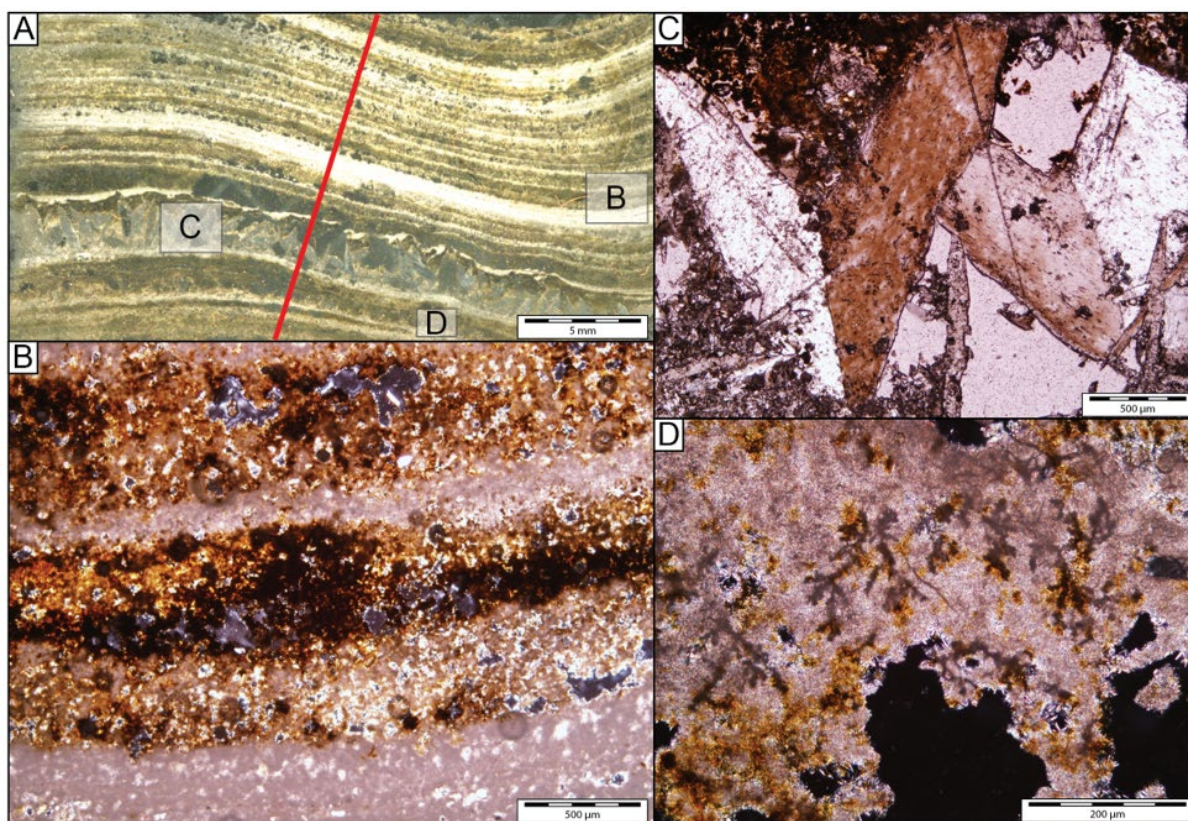


Figure S3. Optical microscopy images of the Dead Sea stromatolite. (A) Overview of the heterogeneous lamination in sample Gg2021-137. The red line indicates the transect used for lamina identification and thickness measurements. (B) Detailed view showing textural variations within the stromatolite laminae. (C) Gypsum-rich layer with spearhead twinned crystals. (D) Microsparitic lamina containing radially arranged acicular carbonate crystals (~10 µm long), consistent with aragonite, and dendritic microstructures.

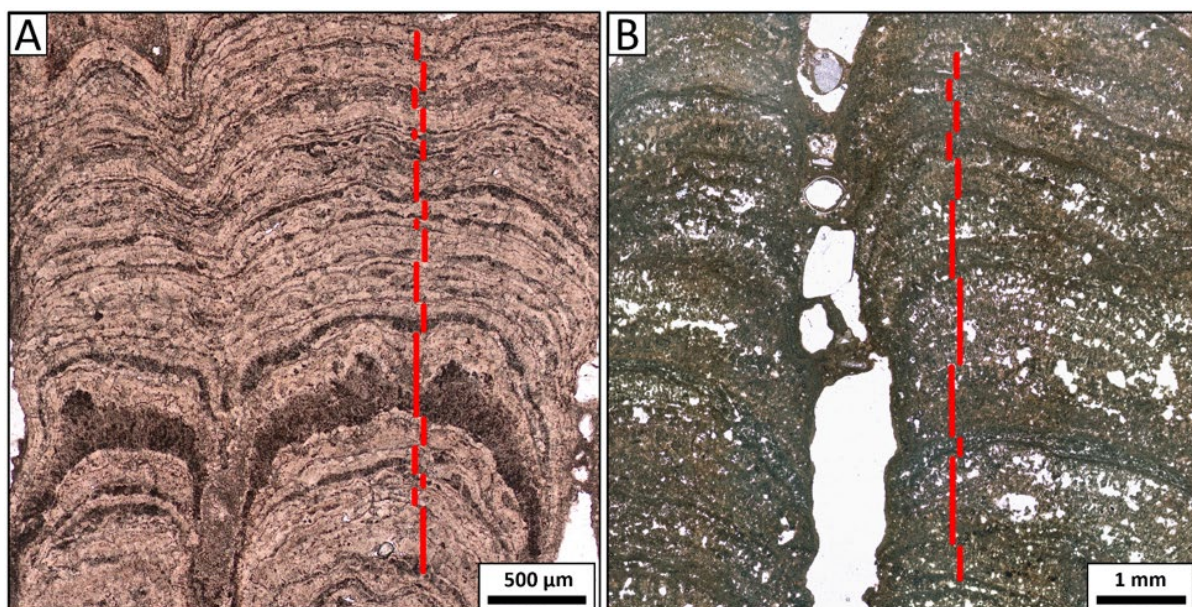


Figure S4. Examples of couplet identification and thickness measurements in the Richat Structure (A) and Mari Ermi (B) stromatolites. Optical microscopy images reveal variations in mineralogical texture and color, enabling the identification of individual lamina couplets in each sample. Red vertical segment lines along the analytical transect show the measured thickness of successive couplets following the main accretion axis.

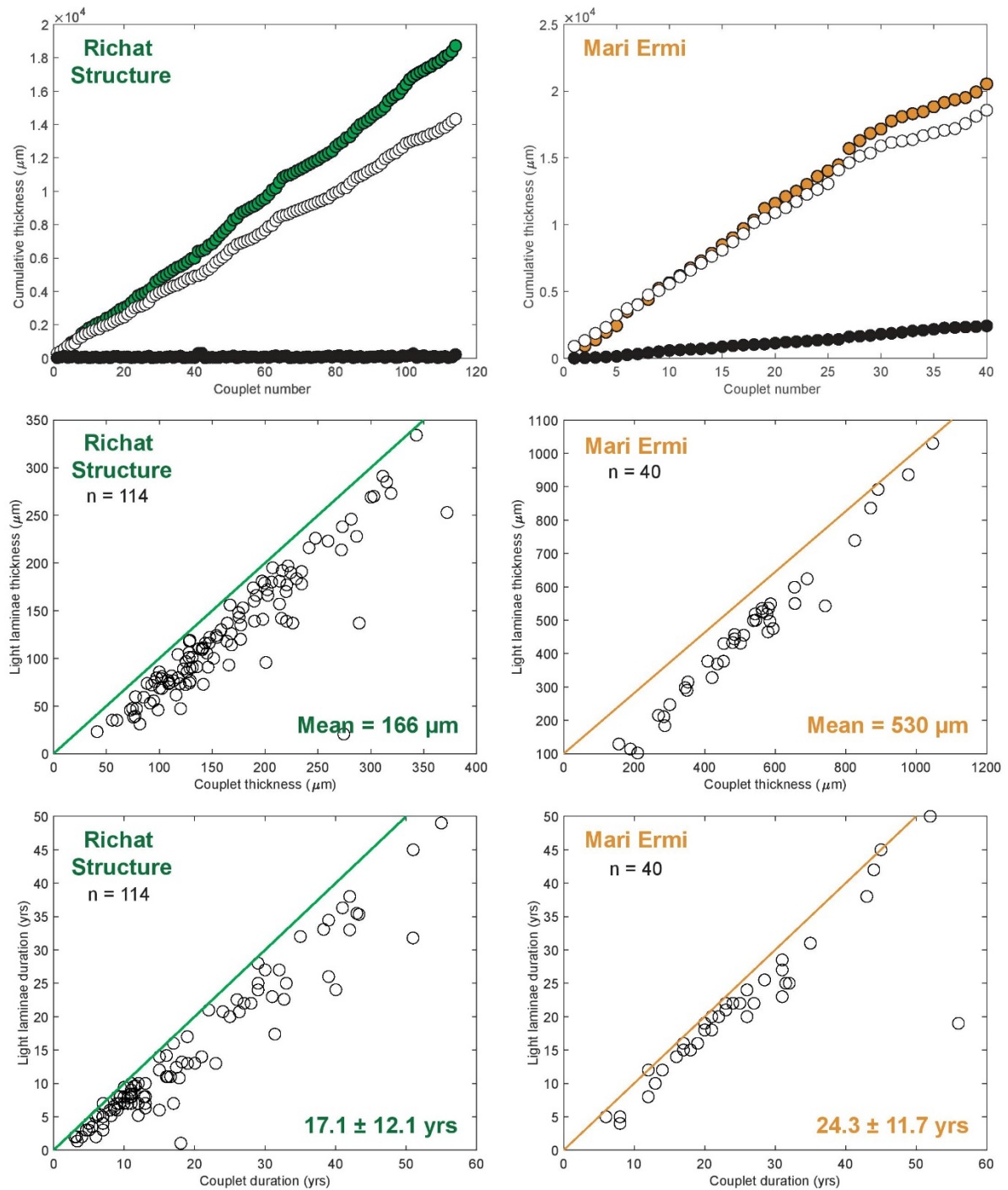


Figure S5. Contributions of light and dark laminae to couplet thickness and duration in the Richat Structure and Mari Ermi stromatolites. Top: cumulative thickness of complete couplets (colored circles) and their light (white circles) and dark (black circles) laminae. Middle: light-lamina thickness plotted against total couplet thickness. Bottom: modelled light-lamina duration plotted against total couplet duration; light- and dark-lamina durations were estimated separately, and their sum defines the corresponding couplet duration. Colored lines indicate the 1:1 relationship; proximity to this line indicates a greater contribution of the light lamina to couplet thickness or duration. The number of measured couplets n, mean couplet thickness, and mean couplet duration $\pm$ 1 SD are indicated.

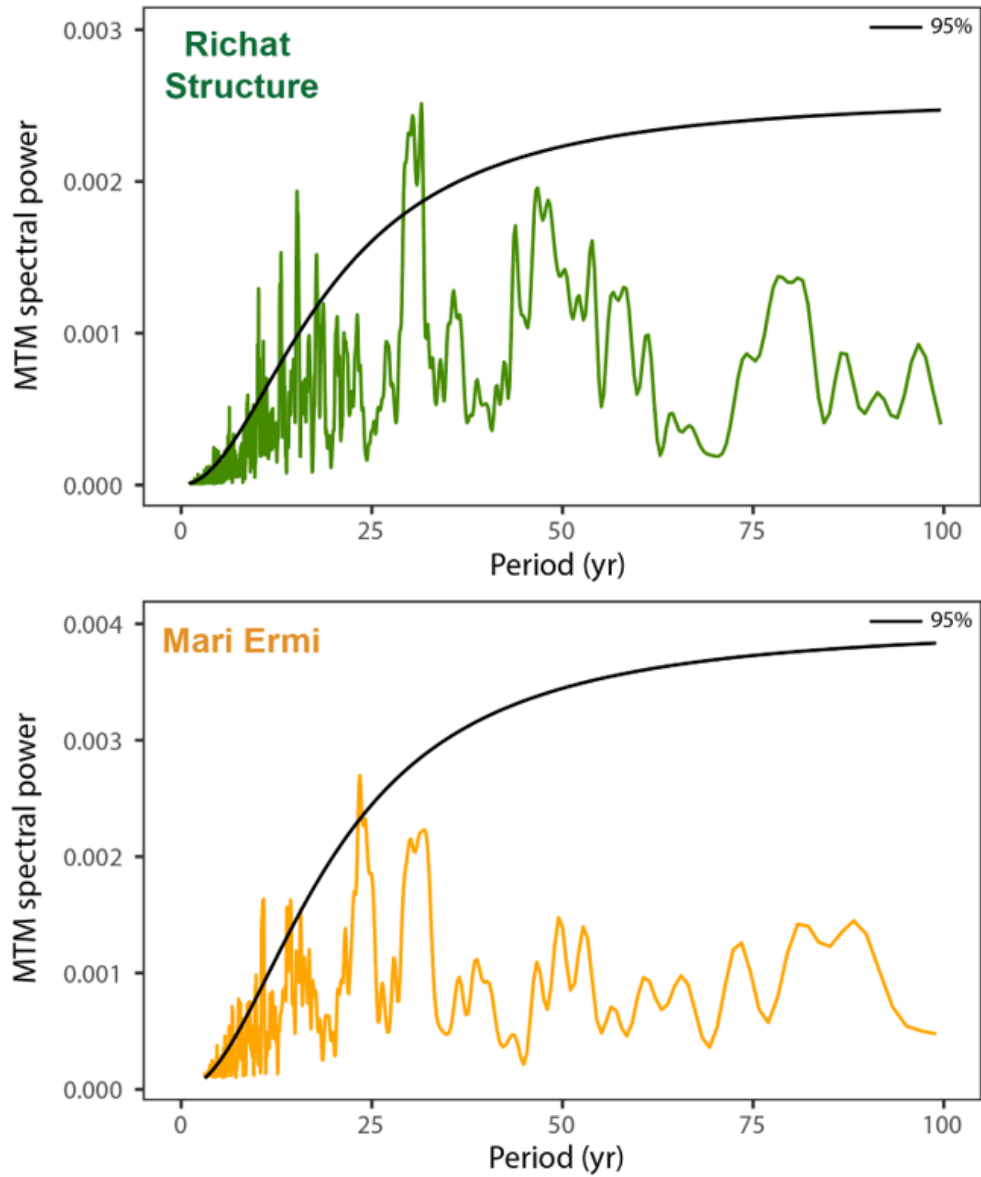


Figure S6. Multi-taper-method spectra of the temporally calibrated binary light-dark lamination series for Richat and Mari Ermi stromatolites, extended to 100 years (identical analysis to Fig. 3). Labelled peaks exceed the 95% confidence threshold above the autoregressive noise model (AR1; black line; Meyers, 2014).

SUPPLEMENTAL TABLES

Table S1. Summary of accretion parameters, lamina and couplet thicknesses, and modelled durations of the studied stromatolites. Accretion rates, thicknesses, and durations are reported as arithmetic means $\pm$ 1 SD. Modelled durations were derived from the Bayesian age-depth models (see Fig. 2). Accretion rate and lamina and couplet durations were not calculated for the Dead Sea stromatolite because the age-depth relationship indicates a stratigraphic discontinuity.

	RICHAT STRUCTURE	MARI ERMI	DEAD SEA
Thickness (μm)	18,857	20,992	18,438
Accretion rate ($\mu\text{m.yr}^{-1}$)	12.5 ± 5.6	22.8 ± 4.6	-
Number of couplets	114	40	21
Mean couplet thickness (μm)	165.4 ± 69.6	515.4 ± 201.1	752.1 ± 452.2
Mean light-lamina thickness (μm)	125.7 ± 65.9	464.4 ± 213.2	400.2 ± 364.4
Mean dark-lamina thickness (μm)	39.7 ± 29.5	62.0 ± 35.5	383.9 ± 256.2
Couplet duration (yr)	17.1 ± 12.1	24.3 ± 11.7	-
Light-lamina duration (yr)	13.0 ± 10.4	20.6 ± 10.2	-
Dark-lamina duration (yr)	4.1 ± 3.5	3.7 ± 5.7	-

Table S2. Summary statistics for lamina and couplet thickness distributions. The analysis includes the total couplet thicknesses, as well as the individual dark and light laminae thicknesses for Richat Structure stromatolite (green) and Mari Ermi stromatolite (orange). Anderson-Darling tests indicate that thicknesses are generally characterized by log-normal distributions (p-values > 0.05 in bold). Fitted log-normal distribution parameters μ and σ are provided, from which the mean, median, and modes of the thickness distributions (i.e., the most frequent thicknesses) were calculated analytically.

	COUPLET THICKNESS	DARK LAMINA THICKNESS	LIGHT LAMINA THICKNESS
Anderson-Darling Test p-value. Log-normal distribution	0.6665	0.0404	0.2754
	0.0968	0.9648	0.0032
Log Normal Stats - μ	5.0175	3.5306	4.6890
	6.1798	3.9875	6.0207
Log Normal Stats - σ	0.4298	0.5536	0.5642
	0.4313	0.5316	0.5334
Mean of the log-normal distribution (μm)	165.65	39.80	127.51
	529.96	62.10	474.83
Median of the log-normal distribution (μm)	151.03	34.14	108.74
	482.90	53.92	411.87
Mode of the log-normal distribution (μm)	125.56	25.13	79.10
	400.93	40.65	309.88

Table S3. Compilation of radiocarbon dating results from this study. The raw radiocarbon results are presented as $F^{14}\text{C}$ values, corresponding to the fraction of modern carbon measured in each sample analyzed for the Richat Structure stromatolite (Gg2021-20, green), the Mari Ermi stromatolite (Gg2021-140, orange), and the Dead Sea stromatolite (Gg2021-137, blue). The associated analytical uncertainty (1σ) is reported for each measurement. The $F^{14}\text{C}$ values were converted to radiocarbon ages (^{14}C age BP) using a conventional decay model (Stuiver and Polach, 1977). Ages were then corrected for a potential reservoir effect and calibrated using appropriate calibration curves (see Text S1), with 2σ calibrated age ranges (95.4% confidence level) provided in the final column.

Sample ID	Distance from nucleus (± 0.06 cm)	Carbon mass ($\mu\text{g C}$)	$F^{14}\text{C}$	$F^{14}\text{C}$ uncertainty (1σ)	Uncalibrated ^{14}C age (yr BP)	Age uncertainty (1σ)	Corrected age (yr BP)	Calibrated age (cal yr BP)	Calibrated age range (2σ)
Gg2021-20	0.45	53	0.3779	0.0038	7 820	80	7 820	8 618	92.25
	0.75	54	0.3830	0.0039	7 710	80	7 710	8 496	68.25
	1.05	54	0.4021	0.0039	7 320	80	7 320	8 124	62.25
	1.25	89	0.4145	0.0040	7 070	80	7 070	7 887	76.00
	1.45	116	0.4413	0.0041	6 570	80	6 570	7 472	67.00
	1.65	93	0.4638	0.0042	6 170	70	6 170	7 063	73.00
Gg2021-140	0.10	98	0.8438	0.0062	1 360	60	1000	890	57.00
	0.32	71	0.8541	0.0063	1 270	60	910	822	51.75
	0.55	80	0.8717	0.0062	1 100	60	740	679	31.25
	0.86	39	0.8912	0.0063	930	60	570	591	35.75
	1.16	85	0.9172	0.0065	690	60	330	391	53.75
	1.43	83	0.9249	0.0067	630	60	270	327	57.50
	1.65	56	0.9451	0.0069	450	60	90	120	36.00
	1.81	109	0.9610	0.0068	320	60	-40	74	29.00
Gg2021-137	0.45	56	0.6204	0.0051	3 830	70	3 430	3 683	90.75
	0.95	20	0.6700	0.0085	3 220	100	2 820	2 949	107.50
	1.55	72	0.6798	0.0053	3 100	60	2 700	2 815	50.50

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