Diversity, Mechanisms of Formation, and Predicted Fate of Modern Microbialites on a Rapidly Changing Planet

Modern anthropogenized microbialites of Lake Alchichica, Mexico.

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Accurately interpreting ancient microbialites requires a detailed understanding of how they form, including teasing apart the respective roles of environmental factors versus microbial activity. Modern microbialites serve as essential tools for this purpose. Currently, microbialites form in both marine and continental settings, displaying remarkable diversity in terms of formation environments, size, morphology, texture, and mineralogical composition. Their growth involves various mineralization mechanisms, such as the onset of localized high-supersaturation zones and mineral templating by extracellular polymeric substances. Additionally, primary biogeochemical signals are often altered during early diagenesis. Finally, the study of modern microbialites increasingly focuses on their responses to anthropogenic pressures. This is vital knowledge for predicting their future and setting conservation efforts to preserve these natural archives.

KEYWORDS: modern microbialites; mineral nucleation; solution saturation; extracellular polymeric substance; early diagenesis

INTRODUCTION

Modern microbialites offer a rare opportunity to interpret the signals preserved in ancient microbialites through the principle of actualism. The use of modern analogs to understand ancient microbial structures dates back at least to the early 20th century, when Walcott compared modern tufas with Proterozoic stromatolites (Riding 1999). Moreover, some of the most historically influential analogs include the intertidal and subtidal columnar stromatolites of Hamelin Pool in Shark Bay, Western Australia (see Fogret et al. 2026 this issue) and those from the Bahamas. These structures, associated with microbial biofilms rich in cyanobacteria, supported early models that emphasized the role of oxygenic photosynthesis in microbialite formation. However, the validity of these analogies has been questioned since their early proposal (Serebryakov and Semikhatov 1974). For example, modern marine stromatolites often exhibit coarse-grained textures, whereas many ancient stromatolites are fine-grained (micritic). Additionally, some Proterozoic morphologies have no modern equivalents, and the presence of microbial eukaryotes such as diatoms in modern biofilms and metazoans introduces further discrepancies, as they could potentially add a level of diversity by affecting accretion and mineralization of microbialites.

Thus, while modern microbialites remain useful for interpreting their ancient counterparts, their study has also evolved into a distinct subdiscipline, focused on understanding the biological and geochemical functioning of these unique lithifying ecosystems. Advances in microscopy, molecular biology, and microbial ecology, alongside the discovery of over a hundred modern microbialite sites worldwide, have significantly expanded this research area.

All actively forming microbialites share a characteristic feature: the coexistence of a lithified structure with a microbial biofilm. These biofilms are complex microbial consortia comprising bacteria, archaea, viruses, and eukaryotes, embedded within a matrix rich in extracellular polymeric substances (EPS; see Toolkit). When organized into microbial mats, these biofilms exhibit vertical metabolic stratification on a centimeter-scale, shaped by steep physico-chemical gradients, which are regulated by microbial activity. The growth rates of modern microbialites vary considerably, from a few centimeters to several tens of centimeters per thousand years (Iniesto et al. 2021). Here, we first examine the remarkable diversity of modern microbialites in terms of morphology, fabric, mineralogy, chemistry, and environmental setting. Next, we explore the mineralogical and biological processes contributing to their formation. Finally, we address the early diagenetic transformations they undergo, which obscure the primary biological and environmental signatures they record. We finally question the future of modern microbialites in the face of global environmental changes driven by human activity.

MODERN MICROBIALITES ARE HIGHLY DIVERSE

A key lesson from studying modern microbialites is that they do not conform to a single profile. Instead, they exhibit a wide diversity in their environmental settings, mineralogical and chemical compositions, morphologies, and internal fabrics (FIG. 1).

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Microbialite-forming Environments: Broad and Variable

The global distribution, abundance, and total mass of modern microbialites likely remain incompletely documented and represent an ongoing research challenge. Current knowledge clearly shows that modern microbialites form in a wide range of environments. Using comprehensive databases, several studies have examined the similarities and differences in the geochemical conditions of their host environments, to better understand the complex interplay of biological and chemical processes involved in their formation. Key chemical parameters such as alkalinity, salinity, and the dissolved Mg/Ca ratio have emerged as primary controls on microbialite formation and mineral composition (Zeyen et al. 2021).

Figure 1 Modern microbialites growing in different locations and environments: (**A**) Marine hypersaline Shark Bay, Australia, with branching columnar stromatolites; (**B**) Alkaline crater Lake Alchichica, Mexico, with columnar and domal microbialites (**C**) Volcanic shallow Lake Specchio di Venere, Italy, with flat laminated microbialites; (**D**) Deep-sea conical microbialites from Makran, Arabian Sea (MARUM, University of Bremen); (**E**) Columnar and domal microbialites draping the wall of the Atexcac Crater Lake, Mexico; (**F**) Domal microbialites in the crater Lake La Preciosa, Mexico; (**G**) Cerebroid microbialites in the seasonally-evaporating Mari Ermi coastal pond, Sardinia, Italy; (**H**) Tabular microbialites in the hypersaline Laguna La Brava, Chile; (**I**) Lobe-shaped microbialites in the freshwater Fayetteville Green Lake, USA; (**J**) Tabular microbialites in the hypersaline Bakili Lake, Ethiopia. Aerial view; (**K**) Domal microbialites in the subtropical freshwater Laguna Bacalar, Mexico; (**L**) Domal and cerebroid microbialites in the subtropical freshwater lake in Cuatro Ciénégas (Pozas Azules), Mexico.

Historically, microbialites have been most associated with marine or hypersaline settings in semi-arid to subtropical climates. This perception stems from iconic sites such as Shark Bay (Australia) and Highborne Cay (Bahamas), which have long served as analogues for ancient microbialite systems. However, recent discoveries and compilations have broadened this view, showing that microbialites can form in a wider array of environments, including lagoons, coastal and inland lakes, streams, hot springs and low-temperature groundwater-fed systems (White 2020). These systems span a remarkable range of physicochemical conditions: salinities from ~0.5 to ~200 $g \cdot L^{-1}$, pH levels between ~6 and ~11, oxygen levels from fully oxic to anoxic, and temperatures from near-freezing (~0 °C) to nearly boiling (~98 °C). Some of the most extreme examples include permanently ice-covered Antarctic lakes and deep-sea sites with minimal light at depths up to several hundreds of meters. Modern microbialites occur across all continents, under a wide range of climatic regimes, from tropical to polar, and in both evaporitic and non-evaporitic settings.

Morphological and Textural Diversity of Microbialites

Modern microbialites exhibit a large diversity of morphologies, including domal, conical, cerebroid, flat-laminated forms, as well as branching and non-branching columns (Fig. 1). These morphological variations have been attributed to external environmental factors such as wave energy, water depth and/or the distance to the shore (Jahnert and Collins 2012). However, alternative explanations emphasize the role of microbial mat morphology and architecture prior to lithification (Batchelor et al. 2004). Numerical models have simulated various stromatolite morphologies and textures. A variety of complex morphologies observed in both Archean and modern microbialites have been successfully reproduced using diffusion-limited aggregation and cellular automata models. These simulations integrate environmental variables with organic-controlled processes, supporting the idea that microbialite morphology arises from the interplay between microbial activity and environmental forcing (Dupraz et al. 2006). In addition, microbialites display a wide range of sizes from few-hundred-micrometer-thick microbialites to meter-sized columns. This size variability has been positively correlated with water chemistry, particularly alkalinity (Zeyen et al. 2021), suggesting that geochemical conditions exert a strong control on the intensity of microbialite accretion.

Chemical and Mineralogical Variability in Microbialites

Although not exclusive, many modern microbialites contain abundant carbonate phases. There is a broad diversity of carbonate phases in microbialites from pure calcite to magnesium-substituted calcite, aragonite ($CaCO_3$), monohydrocalcite ($CaCO_3 \cdot H_2O$), (proto-)dolomite [$CaMg(CO_3)_2$], huntite [$CaMg_3(CO_3)_4$], hydromagnesite [$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$], nesquehonite [$Mg(CO_3) \cdot 3H_2O$], magnesite ($MgCO_3$), gaylussite [$Na_2Ca(CO_3)_2 \cdot 5H_2O$], or ikaite ($CaCO_3 \cdot 6H_2O$). The specific carbonate phase present is determined by the dissolved Mg/Ca ratio of the host water. At low Mg/Ca ratios, calcite and Mg-calcite dominate; above a critical threshold ratio of 10 (in mol/mol), aragonite becomes more prevalent; at a ratio higher than ~45 (in mol/mol), hydrated Mg-carbonate phases such as hydromagnesite become dominant phases (Zeyen et al. 2021). This ratio itself reflects a variety of parameters, including the nature of the weathered protolith in the catchment and the evaporative history of the water body.

Carbonate minerals often coexist with other mineral phases, including authigenic silicates. For example, hydrated magnesium silicates such as kerolite [$Mg_3Si_4O_{10}(OH)_2 \cdot nH_2O$] and stevensite [$(Na_{2y} \cdot nH_2O)(Mg_{3-y}X_y)Si_4O_{10}(OH)_2$, where X denotes a vacancy and where the interlayer cation(s), here Na^+, can be interchangeable], have been increasingly recognized as common components of modern microbialites (Zeyen et al. 2015). However, the specific environmental and biogeochemical factors that govern the nucleation, inhibition, and precipitation sequences of these minerals remain poorly understood. In certain systems, such as Clifton Lake (Australia), stevensite has been proposed as an early-forming phase that entombs microbial cells, preserving delicate microbial structures. This phase can later be overprinted by aragonite, at least partly erasing biogenic traces (Burne et al. 2014). In contrast, other systems such as Lake Atexcac (Mexico) preserve metastable associations of both silicate and carbonate minerals (Zeyen et al. 2015).

Additional mineral phases, such as phosphates and sulfates, have also been documented within microbialites, often reflecting successive episodes of mineralization or environmental shifts. However, the extent to which these phases are microbially versus abiotically precipitated remains unclear. Seasonal variations, particularly in redox-sensitive parameters and water chemistry, can further influence microbialite mineralogy. Likewise, subsurface geology, including lithology and tectonic structures, can influence groundwater chemistry and circulation, shaping both the microbial community structure and the resulting mineral precipitates.

Altogether, the morphological and mineralogical diversity of modern microbialites reflects a dynamic interplay between microbial processes and heterogeneous environmental conditions. Understanding how microbial activity operates at microscale within these systems is essential for decoding the mechanisms underlying microbialite formation.

Despite their Diversity, Microbialite-forming Environments Share a Common Attribute

Despite the wide diversity of settings in which microbialites form, most, if not all, share a unifying characteristic: an elevated supersaturation with respect to calcite (Caumartin et al. 2023). More specifically, waters in these environments are typically saturated or supersaturated not only with respect to calcite but also with the most soluble (and metastable) calcium carbonate phases: monohydrocalcite (MHC, $CaCO_3 \cdot 1H_2O$), amorphous calcium carbonate (ACC), and vaterite.

This high supersaturation relative to calcite, close to the solubility of these metastable phases, suggests that the latter may precipitate in microbialite-hosting waters, exerting thermodynamic control over the chemical activities of Ca^{2+} and CO_3^{2-} ions, which in turn determine the overall saturation index. Because amorphous and/or hydrated carbonate phases have lower kinetic barriers to nucleation than more stable anhydrous and crystalline counterparts (such as calcite or aragonite), they may precipitate readily under such conditions. Consistently, hydrated, possible precursor phases such as MHC have been detected in a few actively forming microbialites, sometimes partially transforming into Mg-calcite (Zeyen et al. 2021). However, direct evidence of genuine ACC remains elusive in modern microbialites. On this basis, it has been proposed that a saturation state approaching the solubility of MHC and ACC is a prerequisite for microbialite formation.

Such highly saturated conditions can arise from several processes, including intense bedrock weathering, evaporation (which concentrates dissolved species), the mixing of alkaline waters with calcium-rich groundwater (or vice versa), and the inhibition of calcite precipitation by inhibitors such as phosphate ions. These mechanisms collectively promote an environment conducive to the precipitation of metastable carbonate phases, setting the stage for microbialite development. This model also supports the broader hypothesis that large-scale shifts in ocean chemistry (particularly those affecting carbonate saturation states) may have contributed to the global decline of microbialites at the end of the Proterozoic (Caumartin et al. 2023).

HOW MICROORGANISMS FORM MODERN MICROBIALITES

An additional advantage of studying modern (versus ancient) microbialites lies in the direct access to all key components involved in their formation: minerals, aqueous solutions, and microbial communities. This integrative perspective provides a unique opportunity to better understand the biological processes that mediate microbialite growth.

Microbialite Formation through Trapping and Binding and/or Mineral Precipitation

Modern microbialites form through (i) the trapping and binding of detrital particles and/or (ii) in situ mineral precipitation. Sediment trapping is enhanced by the adhesive properties of microbial mats. These grains can be secondarily reworked, fused, or cemented by the action of diverse microorganisms as observed in the intertidal microbialites of Shark Bay (Reid et al. 2003).

The role of microbes in promoting in situ mineral precipitation, which cements bound particles or fabricates the bulk mass of many microbialites, has attracted considerable attention. Empirical data suggest that calcification within biofilms occurs at a saturation index (log[IAP/Ksp]) of approximately 1 (Arp et al. 2001), corresponding to a tenfold supersaturation with respect to calcite. From a purely thermodynamic perspective, this implies that carbonatogenesis could proceed abiotically. Yet, microbes are consistently present at the very locations where microbialites form, within the thin surface pellicle covering these rocks, and in some cases, deeper inside.

The key point is that under Earth surface conditions, carbonate precipitation rarely occurs at equilibrium, and kinetics matter. This is where microbes play a role. Four main types of microbial contributions to mineral precipitation are recognized, although the relative importance of each remains a subject of ongoing debate (Fig. 2):

- *Modulation of local saturation state*: through their metabolic activity, some microorganisms locally increase the saturation of the surrounding solution with respect to carbonate phases, thereby accelerating precipitation kinetics. This is the case for all microbes increasing the local pH and/or carbonate alkalinity, driving what is called the alkalinity engine (Dupraz et al. 2009). Conversely, other microbial processes reduce the saturation index (e.g., by decreasing pH), exerting an opposite effect on precipitation.
- *Production or removal of inhibitors*: certain ions (e.g., PO_4^{3-}, SO_4^{2-}, and Mg^{2+}) and organic polymers (e.g., some EPS) inhibit carbonate precipitation. Microbial processes that trap, transform, or degrade these inhibitors can thus indirectly promote mineral precipitation.
- *Facilitation of nucleation*: some microbial extracellular polymers can template mineral formation via heterogeneous nucleation. By lowering the energetic barrier to nucleation, they enhance the kinetics of carbonate precipitation. The nucleation rates associated with the involvement of these polymers depend not only on their intrinsic properties (e.g., structure and charge density) but also on the saturation index of the solution (Giuffre et al. 2013).

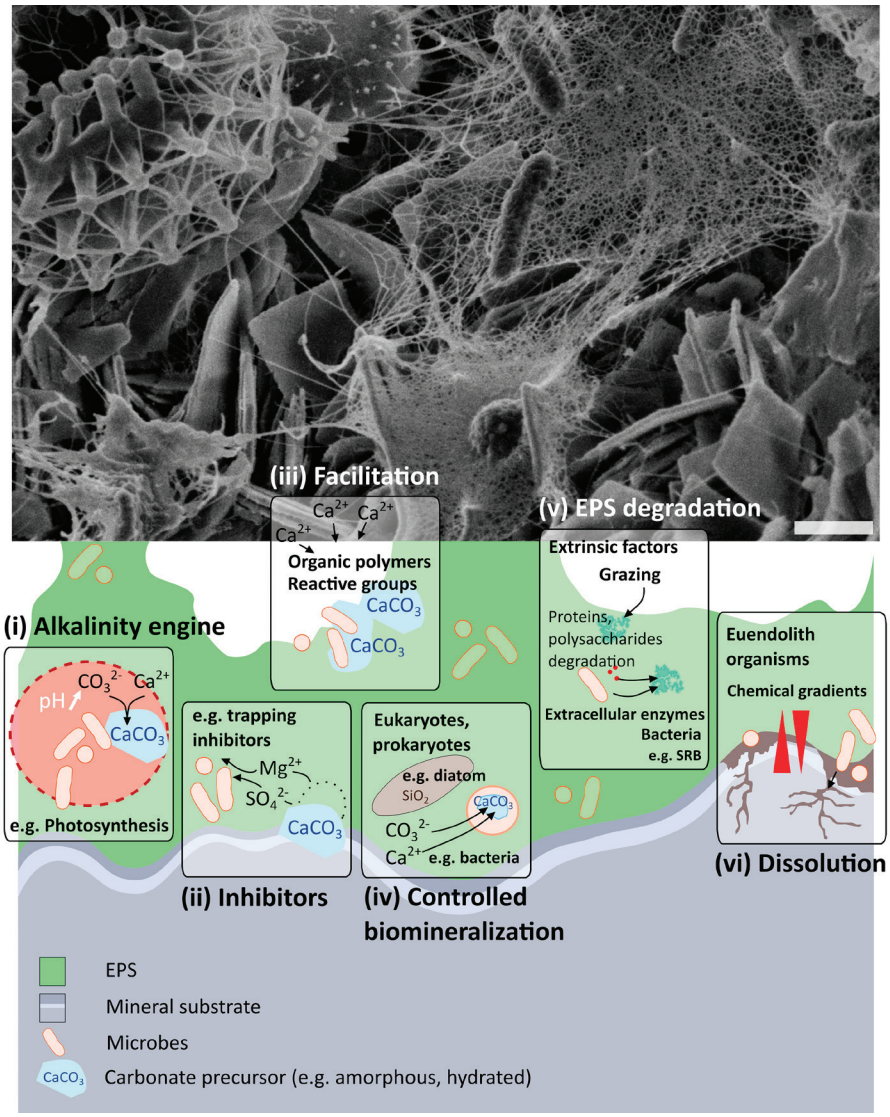

Figure 2 Schematic view of microbial processes involved in modern microbialite formation. (i) Increase of the local saturation state (alkalinity engine); (ii) production or removal of inhibitors; (iii) facilitation of nucleation; (iv) controlled biomineralization; (v) EPS degradation; (vi) mineral dissolution. Above: SEM image of a mineralizing biofilm in a modern microbialite from Lake Alchichica, Mexico. Hydromagnesite platelets and diverse rod-shaped bacteria are visible, along with a eukaryotic microorganism in the upper left, all embedded within an EPS mesh. Scale bar: 500 nm.

- *Controlled biomineralization*: some microbial eukaryotes control the formation of mineral phases (e.g., amorphous silica, calcite), which can play a direct or indirect role in the formation of microbialites. Metazoans can also contribute to modern microbialite accretion in open-sea systems, highlighting the co-existence of well-laminated structures with dense and diverse metazoan communities (Tarhan et al. 2013). Moreover, some bacteria control the intracellular precipitation of amorphous calcium carbonate, but the importance of this process in the accretion of microbialites has not yet been established.

Metabolic Profiles of Microbial Mats May Determine Their Precipitation Capabilities

Assessing the lithifying capability of microbial mats requires the identification of the metabolic functions present in them (see Iniesto et al. 2026 this issue). Microbial mats are very diverse taxonomically and functionally, and the balance between microbial activities favoring and inhibiting precipitation determines the overall response of the system. This balance is influenced by extrinsic factors such as day and night alternation, variations of climatic and environmental conditions, or predation and biological competition (Reid et al. 2024). Based on the alkalinity engine paradigm, some metabolisms favor carbonate precipitation, such as oxygenic photosynthesis, performed by cyanobacteria and algae, anoxygenic photosynthesis found in diverse phyla, at least during daytime when they are active, and more generally all CO_2-fixing metabolisms. With the decrease of the global atmospheric pCO_2 over geological time, a set of biochemical processes called carbon concentrating mechanisms (CCM) has been selected by evolution (Riding 2006). This allows microorganisms to actively concentrate bicarbonates (HCO_3^-) within their cells, which, following CO_2 fixation, enhances alkalinization of the environment, and promotes calcification. The importance of CCM may thus be key in mineralizing capabilities of microbial mats. In addition to carbon-based metabolisms, nitrogen-based metabolisms such as nitrate reduction, amino acid deamination, or ureolysis (i.e. hydrolysis of urea [$CO(NH_2)_2$]) can also promote calcification, although they have received less attention in general (Görgen et al. 2020). In turn, metabolisms such as aerobic respiration or those oxidizing sulfur into sulfates tend to release protons, which inhibit carbonate precipitation. Alternatively, some EPS have been considered to inhibit carbonate precipitation by lowering Ca^{2+} activity. If true, heterotrophs degrading them may favor carbonate precipitation despite their negative impact on the alkalinity engine [Fig. 2(v)]. Many of the sulfate-reducing bacteria found within the class of Deltaproteobacteria, have been emphasized as important actors driving the alkalinity engine, especially in marine microbialites, where sulfate is abundant. However, this depends on the electron donor they metabolize, hydrogen and formate feeding positively the alkalinity engine, while lactate has the opposite effect (Gallagher et al. 2012). Last, while some cyanobacteria clearly induce carbonate precipitation, others may inhibit it by the copious amounts of EPS they form or, in the case of euendoliths, literally dig into carbonates to live buried within them [Fig. 2(vi)]. Overall, this emphasizes that while a complete taxonomic description of microbial mats is useful to predict their mineralizing capabilities, it is insufficient, and we still miss keys to achieve such a prediction accurately.

Templated Precipitation on Microbial Cells

Metabolism-driven processes and the involvement of cell surfaces in nucleation explain how mineral precipitation sometimes localizes around microbial cells (Arp et al. 2001). This results in the formation of microfossils. In the literature, some cyanobacterial orders and genera, such as the coccoid Pleurocapsales or the filamentous *Rivularia*, *Lyngbya* and *Phormidium* seem especially prone to calcification. However, it remains unclear whether this biased taxonomical record of calcified cells results from specific properties of these bacteria or if it is simply due to the facility to recognize them. Moreover, some of the aforementioned microbial processes may locally impact the mineralogy. For example, the capability of some microbial polymers to increase the dehydration rate of Mg facilitates its incorporation within calcite. Consistently, mineralogical heterogeneities at micro- to nanoscales have been evidenced using high-resolution microscopy and spectroscopy with localized magnesium enrichments in calcite associated with microbial remains (Debrie et al. 2022). More generally, all these microbial processes can impact the morphology and fabric of mineral byproducts, as well as their chemical and isotopic composition, leaving potential imprints of microbial activity in the geological record.

The Role of Microorganisms in the Formation and Stabilization of Precursor Phases

Growing evidence suggests that carbonate precipitation commonly proceeds through intermediate precursors such as amorphous calcium and/or magnesium phases and more or less hydrated calcium and/or magnesium carbonate phases. This raises the fascinating question of how microorganisms and their extracellular polymers may affect the formation and stability of these phases, and how their formation, in turn, influences the trace chemical composition of microbialites. Moreover, for low-temperature authigenic and poorly crystalline magnesium silicates, microbial processes similar to those mediating carbonate precipitation (e.g., metabolic pH modulation; EPS production) may also play a role. These silicates could even act as precursors to the carbonate phase through their carbonation.

EARLY DIAGENETIC TRANSFORMATION OF MODERN MICROBIALITES

Abiotic Early Diagenesis

Following the initial mineralization of microbial biofilms, a variety of chemical, mechanical, and biological processes take place, transforming the nascent deposits into a consolidated material, i.e., a microbialite in the strict sense (Fig. 3). These modifications fall under the umbrella of diagenesis, which includes all processes affecting sediments after their deposition. Early diagenesis generally begins at the nano- to microscale, within localized micro-environments (De Boever et al. 2017). Key diagenetic processes include shrinkage, cementation, compaction, fracturing, dissolution-reprecipitation (Fig. 3), and an overall increase in fabric coarseness and homogenization of primary microtextures. The intensity of the processes depends on both the reactivity of the primary mineral phases and the surrounding physicochemical conditions. Modern microbialites found at greater depths below the water surface show clear evidence of diagenetic overprinting, largely due to increased hydrostatic pressure and a higher water-to-rock ratio. These conditions facilitate water infiltration and promote chemical alteration. Shifts in water chemistry, such as changes in groundwater pCO_2, can further drive dissolution and subsequent mineral precipitation.

Biological Degradation during Early Diagenesis

In addition to abiotic processes, biological degradation can also play a role in microbialite alteration during early diagenesis [Figs. 2(v), 2(vi), and 3(iii)]. For example, while well documented in coral reef systems, bioerosion and bioweathering remain largely underexplored in microbialites. In corals, these processes occur across multiple scales

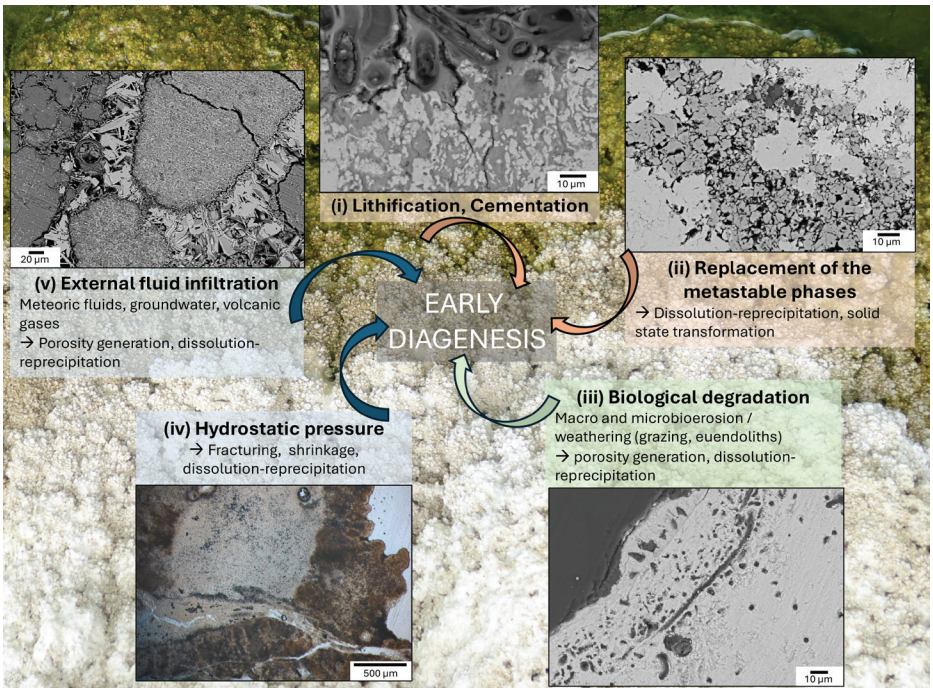

Figure 3 Schematic view of the different mechanisms involved during early diagenesis for microbialites: (i): lithification/cementation; (ii) replacement of the metastable phases; (iii) biological degradation; (iv) hydrostatic pressure; (v) external fluid infiltration.

(Tribollet and Golubic 2005): (i) micro-bioerosion and micro-bioweathering by euendolithic microorganisms; (ii) grazing by e.g., gastropods; and (iii) macro-bioerosion and macro-bioweathering by e.g., bivalves. Long-term investigations are needed in microbialite systems to assess how bioerosion and bioweathering by the different biological agents affect the long-term stability and preservation of these soft rocks after deposition.

Diagenetic Overprinting of Primary Signals

Chemical and isotopic proxies within microbialites have proved useful for paleoenvironmental reconstruction (see Thomazo et al. 2026 this issue and Bruggmann et al. 2026 this issue). Yet, diagenesis can drastically alter the original environmental and biological signals preserved in microbialites, requiring special care. For example, redox-sensitive isotopic signatures, such as the U isotopic signature, and trace element anomalies, such as the cerium anomaly, used as proxies for geochronological and paleoenvironmental reconstructions, respectively, can be significantly overprinted (Lau and Hardisty 2022). Primary mineralogy is also vulnerable. For example, in deep microbialites from Lake Alchichica, the secondary formation of huntite results from localized dissolution of aragonite and hydromagnesite (Caumartin et al. 2025). Interestingly, although huntite was predicted as the thermodynamically stable phase under prevailing conditions, it forms secondarily.

The degree of preservation of the microfossils depends on the local environment, the identity and size of precipitated crystallites, and the degradation/preservation of the cellular material that composes the cell wall, a process governed by taphonomy. As already mentioned, authigenic Mg-rich clays, often associated with EPS, are notable for their excellent ability to preserve microfossil morphology at the nanometer scale (Zeyen et al. 2015). However, these labile, gel-like phases are susceptible to replacement by more stable crystalline carbonates, erasing both morphological and geochemical biosignatures.

Overall, evaluating the extent of diagenetic alteration in microbialites is essential for correctly interpreting their original formation conditions. Distinguishing primary mineral phases from diagenetic overprints remains a key challenge in both modern and ancient systems. Ongoing field studies across modern microbialite-bearing environments, combined with controlled laboratory experiments simulating early diagenesis, are critical to advancing our understanding of microbialite evolution and improving the interpretation of ancient stromatolitic records.

CONCLUSIONS AND PERSPECTIVES

In conclusion, microbialites are remarkable, unique ecosystems, prone to lithification and therefore to preservation in the geological record. Their long-term persistence, spanning billions of years, makes them valuable archives of Earth's environmental and biological history. However, using modern microbialites as direct analogues for their ancient counterparts remains problematic due to diagenetic alteration, long-term environmental shifts, and the evolutionary transformation of microbial life (Serebryakov and Semikhatov 1974). Nevertheless, when well characterized and placed in an appropriate context, modern microbialites offer essential insights into the formation mechanisms of ancient ones.

In the face of current dramatic global warming and a strong erosion of biodiversity, the resilience and future of microbialite ecosystems must be questioned (Rishworth et al. 2020). The truth is that we know little about the sensitivity of these ecosystems to perturbations.

In some environments, modern microbialites exhibit short-term adaptive responses to Holocene water-level fluctuations (Villafañe et al. 2021). Moreover, as previously discussed, the increased atmospheric pCO_2, evaporation, and alkalinity may favor microbialite formation. This speculation is consistent with a remarkable resilience, as evidenced by their persistent presence throughout Earth's history, even after major environmental perturbations and mass extinction events (Pomar et al. 2022). However, on a rapidly changing planet, microbialites might be increasingly threatened by other anthropogenic pressures.

Lakes situated in agricultural landscapes often receive elevated nutrient loads from surrounding watersheds, leading to eutrophication. This nutrient enrichment favors the proliferation of micro- and macroalgae (Doddy et al. 2019), which may compete with microbialites for light and space. Additionally, agronomic practices such as soil liming, involving the application of calcium and magnesium carbonate amendments, can strongly modify natural cation cycles, particularly through altered groundwater chemistry that ultimately feeds into lake systems. How this affects microbialite growth remains unknown.

Changes in terrestrial vegetation cover, which normally acts as a nutrient buffer, can also affect nutrient delivery to lakes, thereby influencing microbialite growth. Beyond nutrient dynamics, sharp salinity increases due to climate-driven aridification, reduced precipitation, and intensive groundwater extraction may pose significant risks to microbialite ecosystems. It is known that the composition

of microbial communities is very sensitive to salinity, and how this may influence their mineralization capability remains to be assessed (Hsieh et al. 2025).

Furthermore, human exploitation of lake waters for purposes such as lithium extraction has led to significant declines in water levels, exposing microbialites to air and halting their growth. For example, in Lake Clifton, Yalgorup National Park (Australia), notable degradation of microbialite structures has been observed. A formal list of conservation recommendations was submitted to the Australian Minister for the Environment, Heritage, and the Arts, identifying elevated nutrient input, altered vegetation, and rising salinity as key threats. Understanding and quantifying the impacts of human activity on microbialite development across different environments is critical for developing effective conservation strategies.

Finally, modern microbialites are complex biogeochemical systems whose formation strongly depends on the physicochemical properties of their host environments. Within this context, assessing the role of microbialite growth in CO_2 fluxes, whether as a sink or source, under varying environmental conditions is essential. Such an understanding is crucial before microbialites can be considered natural analogues for mineral carbonation strategies aimed at mitigating atmospheric CO_2.

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