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Stromatolites

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Without Abstract

Synonyms

Laminated microbialites (see Chapter Microbialites)

Definition

Stromatolites are lithified laminated organosedimentary deposits produced by the sediment trapping, binding, and/or precipitation activities of microbial communities dominated by photosynthetic bacteria (modified from Awramik, [1992](#)).

Introduction

Stromatolites are Earth's earliest and most persistent reefs. They are conspicuous and widespread components of Precambrian carbonate platforms and are still forming in modern environments (Figure [1](#)). Despite over a 100 years of research, the significance, origin, and very definition of stromatolites are, however, still disputed (Semikhatov et al., [1979](#); Ginsburg, [1991](#); Grotzinger and Knoll, [1999](#); Riding, [1999](#); Awramik and Grey, [2005](#); Schopf, [2006](#)).



Stromatolites. Figure 1 Ancient and modern stromatolites. (a) Archean stromatolites on shallow platforms fringing volcanoes; painting by P. Sawyer, reprinted with permission from Natural History Museum, Smithsonian Institution. (b) Modern stromatolites on the margins of Hamelin Pool, Shark Bay, Western Australia.

Derived from the Greek “stroma,” meaning mattress or stratum, and “lithos,” meaning rock, the term stromatolite was introduced by Kalkowsky ([1908](#)) to refer to “organogenic, laminated calcareous rock structures, the origin of which is clearly related to microscopic life, which in itself must not be fossilized” (translated in Krumbein, [1983](#), p. 499). This definition requires that “microbial influence be interpretable from features of lamination and texture in the absence of direct paleontologic evidence for mat organisms” (Grotzinger and Knoll, [1999](#), p. 316). With such ambiguity, there is major disagreement as to whether the definition of stromatolite should be genetic or purely descriptive (see for example, Krumbein, [1983](#); Grotzinger and Knoll, [1999](#); Riding, [1999](#)). An often used non-genetic definition is that a stromatolite is an “attached laminated lithified sedimentary growth structure, accretionary away from a point or limited surface of initiation” (Semikhatov et al., [1979](#)). This purely descriptive definition allows for terms, such as “abiogenic stromatolite,” which, it could be argued, corrupt the original intent of the term (Awramik and Grey, [2005](#)).

In this review, the term stromatolite is used in the traditional sense of Kalkowsky for lithified,

laminated sedimentary structures formed as a result of microbe–sediment interactions. As such, stromatolites are a subset of microbialites, a term coined by Burne and Moore ([1987](#)) to include all organosedimentary deposits that have accreted as a result of benthic microbial communities trapping and binding sediment and/or forming the locus of mineral precipitation. Stromatolites are differentiated from other types of microbialites, such as thrombolites (with clotted textures), by their layered internal structure.

Dominating the fossil record for 80% of Earth history, stromatolites are potentially a major source of information on the early Biosphere (Awramik, [1992](#); Walter, [1994](#)). Scientists believe, moreover, that the photosynthetic activity of cyanobacteria (formerly known as blue-green algae and commonly regarded as the most important group of stromatolite-forming microorganisms) generated the oxygen of our atmosphere (Schopf et al., [1983](#)). An oxygen-rich atmosphere was critical to the development of higher forms of life on Earth.

Described at a variety of scales, stromatolites form ridges and bioherms composed of individual buildups with shapes ranging from simple domes to elaborately branched columns. Millimeter-scale lamination, visible with the naked eye, shows diverse microstructures when viewed in petrographic thin section. Variations in stromatolite structures, from megascale to microscale features, reflect the interaction of biological and geological activities on an evolving Earth.

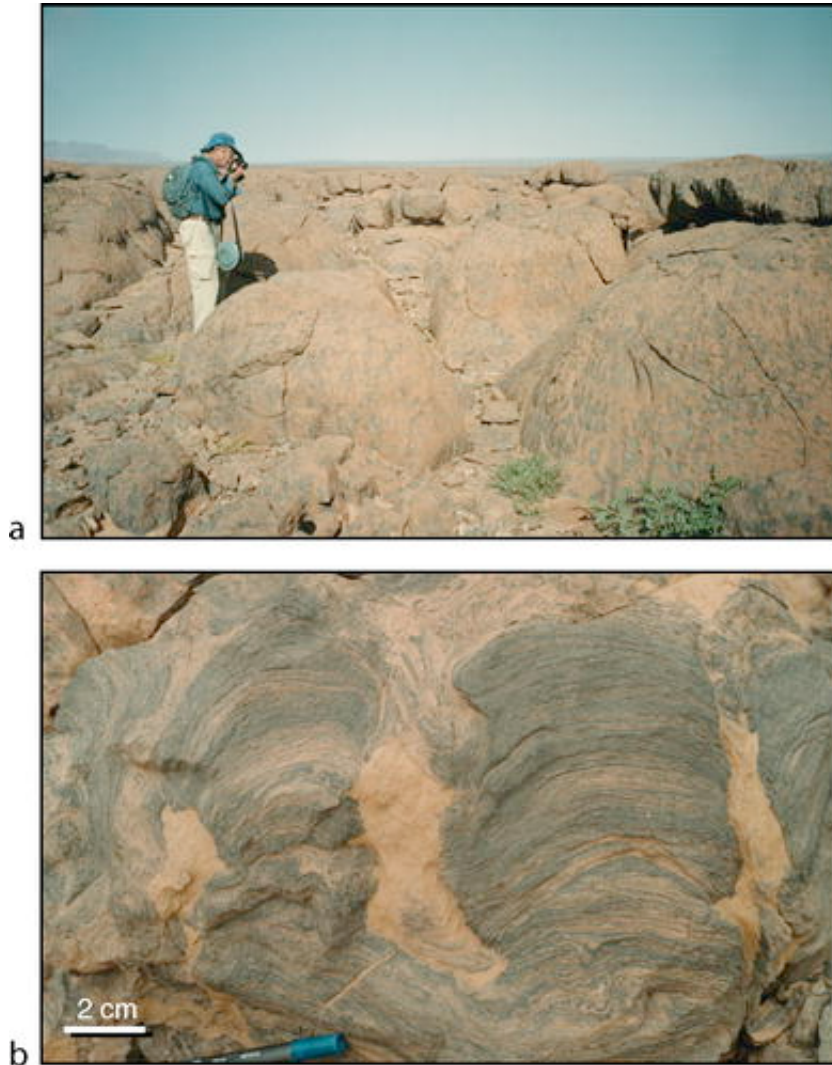
Stromatolites on early Earth

The fossil record of stromatolites spans more than three billion years, dating back to the Archean. Precambrian stromatolites constructed impressive reef complexes, rivaling any in later periods. Individual stromatolites are the “framebuilding” constituents of Precambrian reefs- analogous to the calcified metazoans of Phanerozoic reefs. The overall geometry and growth morphology of Precambrian reefs was a function of platform position and is similar to the distribution of metazoan reefs on Phanerozoic platforms. This illustrates the universal importance of bioherms in carbonate facies development, regardless of reef-building organisms (James and Geldsetzer, [1988](#); Aitken, [1988](#)).

The first stromatolites occur in the Early Archean (3.8–3.3 billion years ago). Although the Early Archean was dominated by active tectonism and volcanism, small isolated carbonate platforms with stromatolites formed during brief quiescent periods. Despite reports questioning the biogenicity of Early Archean stromatolites (e.g., Lowe, [1994](#); Brasier et al., [2004](#)), there is compelling evidence that these ancient structures are products of mat-building communities (Schopf, [2006](#); Awramik, [2006](#)). Stromatolites in the Strelly Pool Chert in Western Australia, for example, are unusually well preserved and morphologically diverse (Allwood et al., [2006](#), [2007](#)). These stromatolites formed in shallow marine environments with low rates of terrigenous sedimentation and no direct input from high temperature hydrothermal systems; the compositions and textures of the stromatolites are indicative of microbially influenced sedimentation (Allwood et al., [2006](#), [2007](#)). The remarkable Strelly Pool Chert stromatolites thus provide “ecosystem-scale insights into early life on Earth” (Allwood et al., [2007](#), p. 198).

With the gradual development of stable continents during the Middle and Late Archean (3.3–2.5 billion years ago), carbonate platforms and stromatolites became increasingly common. One of the best known Late Archean examples is the stromatolite-rimmed Campbellrand carbonate belt of South Africa, which

is more than 1.5 km thick (Grotzinger, [1994](#)). Full development of large continents with spacious shallow water platforms allowed extensive development of stromatolite reef systems on a global-scale during the Proterozoic (2.5–0.5 billion years ago; Figure 2). Early Proterozoic stromatolite barrier reefs in Canada, for example, attained thicknesses of 1 km and lengths of 600 km (Hoffman, [1988](#); Hoffman and Grotzinger, [1988](#)). During Early and Middle Proterozoic time, high energy reef margins were characterized by belts of strongly elongated stromatolitic mounds, with isolated domes in protected inner shelf environments and stromatolitic pinnacle reefs on deep water ramps.



Stromatolites. Figure 2 One billion year-old stromatolites in the Atar group, Mauritania, West Africa. (a) Meter-scale patch reefs. (b) Fine scale lamination in radiating columns of the stromatolite *Tungussia confusa*.

The widespread occurrence of stromatolites on Precambrian platforms had major implications for carbonate budgets. Stromatolites were not only depositories, but were also factories for carbonate production, with microbial activities inducing precipitation of carbonate within the stromatolitic mats, and/or in the water column above the stromatolites (Grotzinger, [1988](#)). There were, moreover, notable changes in the style and mode of stromatolite accretion throughout the Precambrian, with precipitation dominating in Archean stromatolites, trapping and binding of micrite (fine grained carbonate, $<4 \mu\text{m}$)

dominating in Late Proterozoic stromatolites, and both modes of accretion in the intervening periods (Grotzinger, [1994](#)). To add to this complexity, inorganic seafloor precipitation was ubiquitous on Late Archean platforms, and may have formed layered domal structures that mimic stromatolites (Sumner and Grotzinger, [2000](#)).

Stromatolite decline

After reaching a peak in abundance and diversity during the Proterozoic, stromatolites subsequently declined. The exact timing of the decline remains a subject of debate, reflecting differing computational methods (Grotzinger and Knoll, [1999](#); Riding, [2006](#)). The most recent estimates of the commencement of decline range from 1,250 to 700 million years ago (Walter et al., [1992](#); Awramik and Sprinkle, [1999](#); Riding [2006](#)). Reasons for the decline are similarly controversial, and include diversification and radiation of seaweeds capable of outcompeting microbial mats for space on the seafloor (Fischer, [1965](#); Monty [1973](#); Knoll and Swett, [1990](#); Grotzinger and Knoll, [1999](#)), changes in seawater chemistry (Grotzinger, [1990](#); Fischer, [1965](#)), and grazing, burrowing, and competition for space by metazoans (Awramik, [1971](#); Garrett, [1970](#); Walter and Heys, [1985](#)).

Stromatolites show marked fluctuations throughout the Phanerozoic (Pratt, [1982](#); Riding, [2006](#)). They are common features of Cambrian and Lower Ordovician platforms, although the first sessile metazoans began to share reef construction, with archeocyathids in Lower Cambrian reefs and corals and sponges in Lower Ordovician reefs. Stromatolites declined markedly with major diversification of reef-building metazoans in Middle Ordovician, although microbial buildups remained locally important (Pratt, [1982](#)). Stromatolites showed a resurgence during the Late-Devonian–Early Mississippian, and again in the Early Triassic, giving rise to the concept that they are “disaster biotas” (Schubert and Bottjer, [1992](#)), thriving in the aftermath of mass extinctions, when competition from eukaryotic plants and animals was greatly reduced. Stromatolites were generally scarce during the Cenozoic.

Modern stromatolites

For years, living stromatolites were thought to be extinct. Then, in the 1960s, modern stromatolites were found in Shark Bay, Western Australia, where the seawater is too salty for most animals and plants to survive (Figure [1b](#); Logan, [1961](#); Playford and Cockbain, [1976](#)). Since the Shark Bay discovery, stromatolites have been found in a wide variety of modern environments, including saline lakes in Australia (e.g., Lake Thetis and lakes on Rottneest Island; Reitner et al., [1996](#)); hypersaline lakes on Bahamaian islands (e.g., Storr’s Lake on San Salvador; Mann and Nelson, [1989](#); Neumann et al., [1988](#)), a brackish water lagoon in Belize (Chetumal Bay, Rasmussen et al., [1993](#)), fresh water lakes in Antarctica (Parker et al., [1981](#)), alkaline lakes in Tonga (e.g., Caldera lakes of Niufo’ou Island; Kazmierczak and Kempe, [2006](#)), and continental or subaerial settings (e.g., Verrecchia et al., [1995](#)). In these examples, local development of harsh environmental conditions excludes most eukaryotes and allows stromatolite-building microorganisms to become the dominant community.

The first modern stromatolites growing in open marine conditions were discovered in Schooner Cays, Bahamas in the early 1980s (Dravis, [1983](#)). Additional occurrences of open marine stromatolites have since been found at several additional localities along the margins of Exuma Sound, Bahamas, including Lee Stocking Is., Stocking Island, Highborne Cay, and Little Darby Island (Figure [3a](#)) (Dill

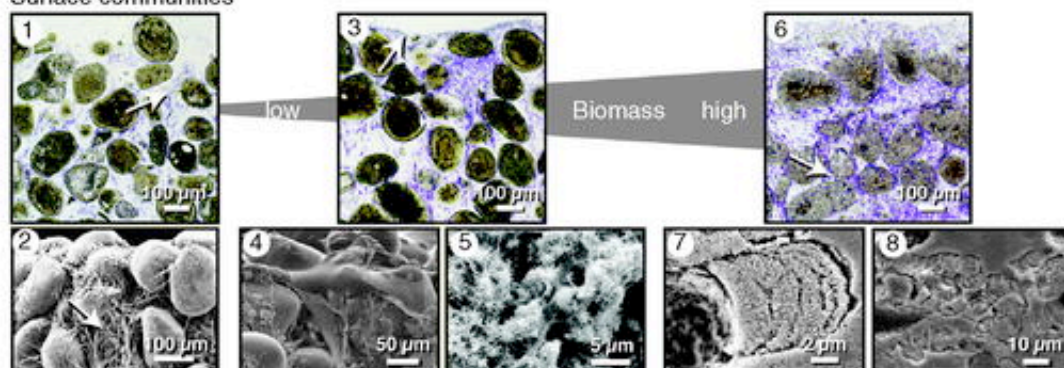
et al., [1986](#); Reid et al., [1995](#)). As the only known examples of modern stromatolites forming in open marine environments similar to those of Precambrian carbonate platforms, Exuma stromatolites have been a subject of intense investigation for the past decade (e.g., Stolz et al., [2009](#); Dupraz et al., [2009](#); Baumgartner et al., [2006](#), [2009](#); Decho et al., [2009](#); Foster et al., [2009](#); Desnues et al., [2008](#); Eckman et al., [2008](#); Visscher and Stolz [2005](#); Reid et al., [2000](#); Visscher et al., [2000](#); and additional publications listed at <http://www.stromatolites.info>). These studies serve as a basis for studying stromatolite morphogenesis and investigating factors leading to a dominance of microbes vs. metazoans as dominant reef builders (e.g., Reid et al., [2000](#); Andres and Reid, [2006](#); Andres et al., [2009](#)).

Modern marine stromatolites, Exuma Cays, Bahamas



a

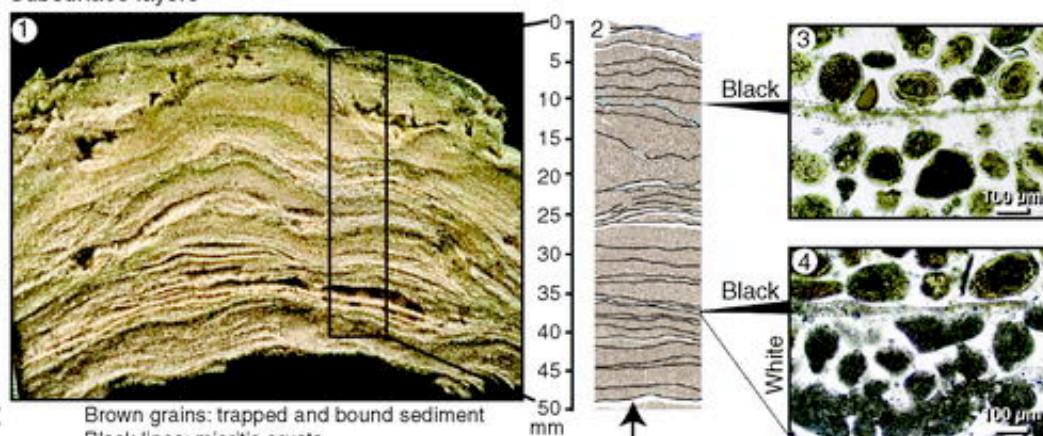
Surface communities



b

Filamentous cyanobacteria: grain trapping & binding
 Heterotrophic biofilm: precipitation of micritic crust
 Coccoid endoliths: micritization and grain fusion by precipitation in bore holes

Subsurface layers



c

Brown grains: trapped and bound sediment
 Black lines: micritic crusts
 White lines: fused, micritized grains

Subsurface layers represent a chronology of former surface mats!

Stromatolites. Figure 3 Modern marine stromatolites from Exuma Cays, Bahamas. (a) Underwater photograph of columnar stromatolites about 40 cm high, Little Darby Island (b) Surface communities. B_{1,2} – Type 1 mats; filamentous cyanobacteria (arrows) bind carbonate sand grains. B_{3,4,5} – Type 2 biofilm; a continuous sheet of exopolymer with abundant heterotrophs drapes the surface, aragonite needles (B₅) precipitate in this biofilm.

B_{6,7,8} – Type 3 mats; a surface biofilm overlies filamentous cyanobacteria and endolith infested grains, which appear gray and are fused. Banded pattern of fibrous aragonite in bore holes (B₇) indicates progressive infilling. Precipitation in tunnels that cross between grains leads to fusion (B₈) (c) Subsurface layers. C₁ – vertical cut section shows mm-scale lamination resulting from an alternation of hard and soft layers. C₂ – low magnification thin section photomicrograph of boxed area in C₁ showing the distribution of lithified layers (*black and white lines*). C₃ – micritic crust, equivalent to the black lines in C₂. C₄ – layer of microbored fused grains, equivalent to the white lines in C₂, underlying a micritic crust. Modified from Reid et al. (2003).

Exuma stromatolites form as columns and ridges, ranging in height from several centimeters to 2 m. Millimeter-scale lamination in these stromatolites is visible in cut sections as alternations of hard and soft layers (Figure 3c; Reid et al., 1995). The soft layers, which are 1–2 mm thick, are composed primarily of unconsolidated fine-grained carbonate sand with average grain size of 125–250 µm. There are two types of hard layers, which stand out in relief on the cut sections: (1) thin crusts of micrite, 20–50 µm thick, and (2) cemented layers of fused carbonate sand grains, 1–2 mm thick.

A model for the formation of laminae in Exuma stromatolites was developed on the basis of integrated studies relating subsurface microstructure to microbial populations on the surfaces of the stromatolites (Reid et al., 2000). Three surface “mat types,” each characterized by a distinct community are recognized (Figure 3b): Type 1 mats are characterized by a filamentous cyanobacterial community; Type 2 mats are a biofilm community dominated by heterotrophic bacteria; and Type 3 mats are characterized by an abundance of endolithic coccoid cyanobacteria. Each surface community is associated with the accretion of a distinct type of mineral deposit (Figure 3c): Type 1 filamentous cyanobacterial mats accrete unconsolidated layers of trapped and bound sand grains; Type 2 biofilms precipitate micritic crusts (Visscher et al., 1998, 2000); and coccoid endoliths of the Type 3 mats form cemented layers of fused microbored (micritized) grains (Macintyre et al., 2000). Stromatolite lamination results from a cycling of the three surface mats, with each subsurface layer representing a community that was, at one time, at the stromatolite surface (Figure 3c). It is important to note that lamination in stromatolites is fundamentally different from lamination in microbial mats. Lamination in microbial mats results from community stratification due to gradients in light intensity, whereas lamination in stromatolites results from interactions of mats with depositing sediment and/or precipitating minerals (Grotzinger and Knoll, 1999, p. 324).

As a result of the sandy textures of marine Bahamian stromatolites, some authors have proposed that these coarse grained structures, as well as similar sandy stromatolites in Shark Bay, are not appropriate analogs for fossil stromatolites, which are typically composed of micrite (e.g., Awramik and Riding, 1988). It has further been proposed that the differences in grain size reflect an evolution of stromatolite-building communities, from Precambrian prokaryotic communities, which trap, bind, and precipitate micrite, to Cenozoic communities that include macro and microalgae, in particular diatoms, which accrete sand (Awramik and Riding, 1988; Riding, 2000). Detailed growth studies of Bahamian stromatolites show, however, that modern marine sandy stromatolites can be accreted by purely prokaryotic communities (Reid et al., 2000). Moreover, the ecological model developed for Bahamian stromatolites, in which lamination results from the cycling of prokaryotic communities on stromatolite surfaces, may be applicable to other modern and fossil stromatolites. Of particular interest is precipitation of micritic crusts by the Type 2 biofilm community, as these crusts resemble micritic crusts in fossil stromatolites.

Precipitation of calcium carbonate in stromatolites is commonly linked to photosynthesis, resulting

from an increase in alkalinity triggered by the uptake of CO₂ by cyanobacteria (Pentecost and Riding, 1986; Arp et al., 2001; Aloisi, 2008). Although autotrophic primary production by cyanobacteria is of key importance in stromatolite mats, producing sticky exopolymeric substances (EPS), other microbial groups can play key roles in increasing carbonate saturation (Visscher and Stolz, 2005; Dupraz and Visscher, 2005; Dupraz et al., 2009). Indeed, micrometer-scale mapping of microbial activities in Exuma stromatolites shows correlations between carbonate precipitation in Type 2 biofilms and high rates of sulfate-reduction (Visscher et al., 1998, 2000). Precipitation of micritic crusts in these biofilms is attributed to an increase in alkalinity resulting from sulfate reduction and Ca²⁺ release from degraded EPS (Visscher et al., 1998, 2000; Reid et al., 2000). The result is precipitation of a thin crust of aragonite with an isotopic signature that confirms the role of sulfate reducing bacteria (Andres et al., 2006). Various microbial metabolisms driving the “alkalinity engine,” together with the exopolymeric matrix, are recognized as fundamental controls of carbonate precipitation in microbial mats (Dupraz et al., 2009).

Finally, living stromatolites in the back reef lagoons of coralline algal fringing reef complexes at Stocking Island and Highborne Cay, Bahamas, provide insight into controls governing the spatial distribution of microbial vs. metazoan reef builders in a modern setting (Andres et al., 2009). The reefs systems at Stocking Island and Highborne Cay have comparable histories. The microbial buildups are relatively recent additions to these reefs, with growth initiating 1,500–1,000 years ago (Macintyre et al., 1996; Andres et al., 2009). The distribution of metazoans (corals and coralline algae) vs. microbial components in the reefs is controlled by intensity and frequency of sediment stress, sand abrasion, and burial of reef biota (Steneck et al., 1998). Although the metazoans can stand some sediment stress, they cannot cope with extended periods of burial (Steneck et al., 1998). In contrast, cyanobacterial mats are largely unaffected by burial (Kromkamp et al., 2007; Perkins et al., 2007). Increasing sediment stress in the back reef lagoon of a coralline algae ridge led to the demise of metazoans and prolific growth of stromatolites. The study of these modern analogs provides a process-oriented understanding of microbial reef development in time and space, which can be applied to the rock record (Andres et al., 2009).

Summary

Stromatolites form an unusual and special type of reef. Unlike modern coral reefs, stromatolites are formed by microorganisms. These microorganisms trap and bind sand grains together and/or precipitate calcium carbonate to form laminated mounds of limestone. The layered internal structure of these reefs is a characteristic feature and the name “stromatolite” in Greek means “layered rock.”

Stromatolites dominated the planet for 80% of Earth history, forming massive reef complexes comparable to any built by corals or other frame-building organisms. The golden age of stromatolite growth was 2.5–1 billion years ago, during Early and Middle Proterozoic. Suffering a major decline with the appearance of eukaryotic plants and animals in the Late Proterozoic, stromatolites were confined to harsh environments lacking eukaryotes for much of the Phanerozoic.

Living stromatolites were unknown until the 1960s when they were discovered in Shark Bay, a hypersaline lagoon in Western Australia. They have since been found in numerous modern environments including saline, fresh water, and brackish settings. The only known examples of

stromatolites forming in open marine environments similar to those of Precambrian platforms are on the margins of Exuma Sound, Bahamas. Exuma stromatolites are ideal model systems for studies of stromatolite morphogenesis. Lamination in these stromatolites results from a cycling of prokaryotic surface communities, with each layer in the subsurface “fossil” part of the stromatolite representing a former surface mat. Lithification of surface mats is syndepositional, and microbially induced. Exuma stromatolites are less than 1,500 years old; they thrive in locations where sediment stress restricts the growth of coral, macroalgae, and other reef-building eukaryotes. Studies of living stromatolites provide models for biogeochemical cycling, population dynamics, and mineral formation in the three billion year old microbial reef ecosystem.

Cross-references

[Algae, Coralline](#)

[Algae-Macro](#)

[Bahamas](#)

[Devonian Reef Complexes of the Canning Basin](#)

[General Evolution of Carbonate Reefs](#)

[Micrite](#)

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