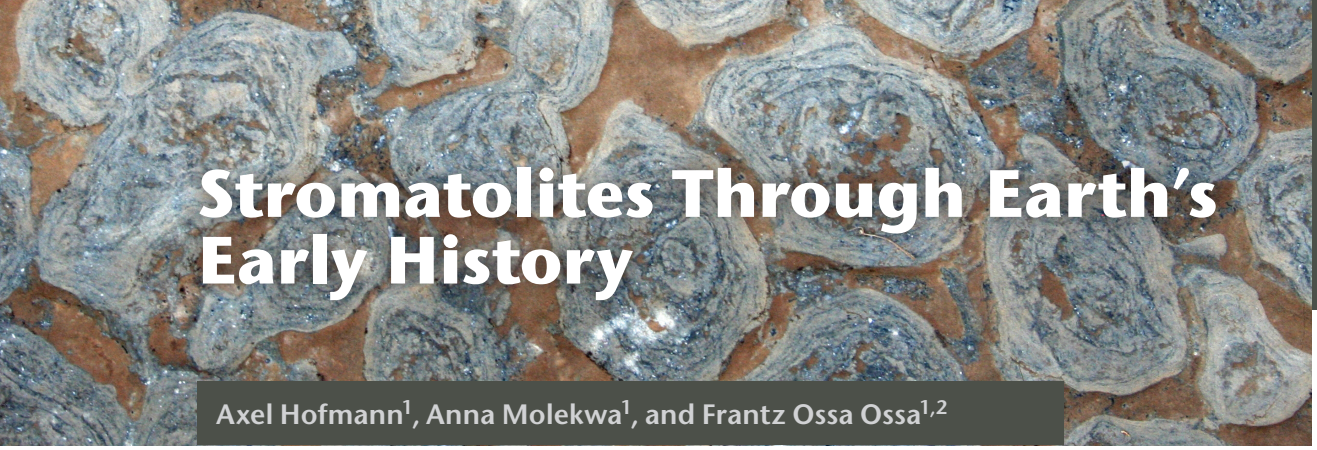

Stromatolites Through Earth's Early History

Plan view of columnar stromatolites, 2.55 Ga Reivilo Formation, Transvaal Supergroup.

Axel Hofmann[1], Anna Molekwa[1], and Frantz Ossa Ossa[1,2]

1811-5209/26/0022-0253$2.50 DOI: 10.2138/gselements.22.4.253

Stromatolites are widespread in Precambrian sedimentary successions and provide important insights into life, environmental processes, and surface conditions on the young Earth. Shaped by interactions among microbial processes, sediment deposition, and mineral precipitation, stromatolites have a record spanning most of Earth's history and are sensitive indicators for past hydrodynamic conditions and water chemistry. Significant variations in the composition, texture, and structure of stromatolites and associated sedimentary facies occur throughout the geological record, constraining the evolution of surface conditions. The ability of microbial communities to build large carbonate platforms in turn actively influenced the Precambrian hydrosphere and atmosphere. Stromatolites are direct, visible evidence of microbial ecological success that shaped the Precambrian Earth's surface.

KEYWORDS: stromatolite; Precambrian; early life; secular variation

INTRODUCTION

Stromatolites, through their composition, structure, and texture, offer invaluable insight into early life and environmental conditions in the Precambrian, a time interval that encompasses the Archaean (4.0–2.5 Ga) and Proterozoic (2.5–0.54 Ga) eons. Their ancient distribution paints a vivid picture of Earth's oceans and microbial ecosystems long before the appearance of more complex organisms, including carbonate-secreting marine invertebrates in the Cambrian.

Stromatolites are layered sedimentary rocks made of carbonate and, less frequently, chert and phosphorite (see Fogret et al. 2026 this issue for a definition). Apart from their intricate structures, which result in captivating sculptures crafted by nature (FIG. 1), stromatolites are useful in many areas of research. They support the sedimentologist to interpret past depositional environments, aid the geobiologist in the search for past microbial habitats, provide the structural geologist with way-up indicators in deformed terrains, and preserve an important record of past water chemistries for the geochemist. Most importantly, perhaps, stromatolite builders have provided some of the molecular oxygen that has driven the evolution and diversification of eukaryotes through time, with evidence for oxygenic photosynthetic organisms being part of the microbial assemblage of stromatolites as far back as 3.0 Ga (Bosak et al. 2013).

Stromatolites are complex depositional systems. They form from the interaction between the growth and degradation of microbial mats, sediment deposition, and mineral precipitation (Grotzinger and Knoll 1999). Microbes actively promote carbonate precipitation, as i) photosynthesis elevates pH, enhancing carbonate precipitation, and ii) extracellular polymeric substances (EPS) trap and bind carbonate grains, stabilising sediment and facilitating accretion (see Zeyen et al. 2026 this issue). Stromatolites largely accrete vertically, forming a variety of sizes and shapes at the macroscale, from stratiform layered rocks to columns that are easily recognisable in the field (FIG. 1; Grey and Awramik 2020). At the mesoscale, lamination is frequently irregular and convex upward, forming the archetypal domes and columns. The microscale only rarely allows insights into original builders of the structures, as diagenesis (i.e., processes acting during early and deep sediment burial), permineralisation, and recrystallisation obliterate fine organic details of the lamina. This is especially true for Archaean stromatolites that are invariably metamorphosed (FIG. 2).

The composition, structure, and texture of stromatolites reveal much about early microbial life and ancient depositional environments (Grotzinger and Knoll 1999; Bosak et al. 2013; Suosaari et al. 2019). Throughout Earth's history, especially during the Precambrian, stromatolites were widespread and diverse. Their morphological diversity is assumed to have been highest in the Late Mesoproterozoic (Awramik and Sprinkle 1999; Semikhatov and Raaben 2000; see FIG. 5 in Fogret et al. 2026 this issue) and has since declined due to biological evolution and changes in seawater chemistry (Peters et al. 2017).

Stromatolites are a characteristic component of Archaean and Proterozoic carbonate successions, dating as far back as 3.49 Ga (Dresser Formation of the Warrawoona Group in Western Australia; Baumgartner et al. 2024). Their absence may indicate carbonate deposition in relatively deep water, typical of clastic carbonate derived from marine platforms by storms. Alternatively, post-depositional overprints, including strong recrystallisation during diagenesis and metamorphism, as well as deformation, may be reasons for their apparent absence in carbonate rocks. Stromatolites are thus present in most, if not all, sub-environments of

1 Department of Geology
University of Johannesburg
PO Box 524
Auckland Park 2006, South Africa
E-mail: ahofmann@uj.ac.za
E-mail: amolekwa@uj.ac.za
E-mail: frantz.ossaossa@gmail.com

2 Earth Sciences Department
Khalifa University of Science and Technology
PO Box 127788
Abu Dhabi, United Arab Emirates

Figure 1 Examples of stromatolites from southern Africa at the macroscale. (**A**) Domal chert stromatolite, 3.41 Ga Witkop Formation, Nondweni greenstone belt. Crestal thickening of lamina is a hallmark of stromatolites. (**B**) Silicified columnar to domical stromatolite in chert, 3.26 Ga Fig Tree Group, Barberton greenstone belt. A bedding plane is depicted by a white line to demonstrate synoptic relief. (**C**) Assemblage of variably silicified domical, columnar and conical stromatolites in dolostone of the 3.0 Ga Nsuze Group, Pongola Supergroup. (**D**) Limestone with domical stromatolites and isopachous beds of calcite-replaced aragonite fans, 2.73 Ga Cheshire Formation, Belingwe greenstone belt. (**E**) Columnar, branching stromatolites, 2.55 Ga Reivilo Formation, Transvaal Supergroup. (**F**) Domical stromatolites in dolostone of the c. 2.1 Ga Lucknow Formation, Keis Supergroup.

Precambrian carbonate factories, despite major changes of seawater chemistry through time, such as elevated concentrations of dissolved Si and Fe in Archaean oceans. Although stromatolites formed in both lacustrine and marine settings then and now, the Precambrian record is heavily skewed towards marine deposits. While some stromatolite-bearing successions as old as the Neoarchaean have been associated with lake environments (Awramik and Buchheim 2009), it remains difficult to unequivocally distinguish between the two. Compared with the extensive geological record of Precambrian stromatolites, modern stromatolites are rare and may therefore provide only a limited context for interpreting fossil examples.

STRUCTURE

Structurally, stromatolites are characterised by their macroscale morphologies and mesoscale lamination. Microbial mats have an irregular surface that may be enhanced or suppressed during stromatolite growth. This depends on the interplay between mat growth, which promotes surface roughness, and sedimentation, which leads to smoothening of any relief (Grotzinger and Knoll 1999). Macroscale morphologies range from simple tabular bodies to complex domical, columnar, and branching structures (Fig. 1). These forms reflect both biological processes, such as trapping and binding of detrital grains, carbonate precipitation, and micritisation, and environmental factors, such as water depth, energy level, tidal range, exposure time, and sediment supply. Hydrodynamic conditions exert

a strong influence on stromatolite morphology in high-energy environments, whereas biological controls take dominance in settings of low energy and low depositional gradients (Suosaari et al. 2019).

Morphological complexity is largely a result of the interplay among mat growth, mineral precipitation rate, and sediment flux (Grotzinger and Knoll 1999), with the latter strongly dependent on the depositional environment. In a very general sense, stromatolites appear to be smaller and more closely spaced in settings of shallower water and lower energy (Walter et al. 1992; Bosak et al. 2013). Large (metre-scale) domical stromatolites, for instance, are common in inferred subtidal environments. The same applies to conical stromatolites. Synoptic relief (i.e., the difference in the height of lamina; FIG. 1B), a reflection of the height of a stromatolite above its substrate, increases with water depth. Columnar stromatolites may be found in intertidal settings where intercolumn areas are characterised by sediment scouring and erosion, whereas column tops may be shielded from abrasion, allowing trapping of suspended sediment and vertical accretion. Elongation of stromatolite columns and domes is generally parallel to current direction, which is perpendicular to the shoreline in tide-dominated settings, and its degree is a function of current energy levels. Stratiform stromatolite facies may form in low-energy, shallow intertidal to supratidal settings, as commonly evidenced by the presence of desiccation cracks and intraclasts. In fact, details of the depositional environment of stromatolite-bearing strata generally need to be gleaned from associated sedimentary facies. The variation in stromatolite morphologies with water depth may best be appreciated in shallowing-upward cycles of stromatolitic carbonates, which record processes during relative sea-level changes (Hofmann et al. 2004).

Lamination in stromatolites arises from alternating microbial growth, sediment trapping, and mineral precipitation, and is expressed through differences in composition, texture, and geometry of lamina. At the mesoscale, lamination is frequently discontinuous and irregular and defined by variations in the size of carbonate crystals and trapped detritus, composition of primary and diagenetic phases, and the presence of organic matter (FIG. 2). Different textures may occur, including micritic (fine-grained), granular, and microfossiliferous (Grey and Awramik 2020), depending on mat consortia and the degree of preservation. Lamination is thus a response to physical, biological, and chemical variations in the depositional environment and is accentuated and strongly modified by post-depositional processes during both early and burial diagenesis.

TEXTURE

Textures within stromatolites illuminate their mode of formation. Fine lamination, resulting from rhythmic mat growth and sediment trapping and binding, is a hallmark feature. Micritisation of microbial mats, specifically via the encrustation of cyanobacterial sheaths and the decay of EPS, plays a major role (Riding 2000; Dupraz et al. 2009). Variation in microbial communities linked to environmental changes (e.g., water temperature, storms, and sand abrasion) may result in textural variability (Bowlin et al. 2012). Micritic textures often dominate Precambrian stromatolites, and trapped sediment is less common or obvious, possibly linked to Precambrian stromatolites encompassing depositional settings with subordinate clastic sediment on large carbonate platforms, in contrast to the more restricted settings of modern marine stromatolites. Fenestral (containing small cement-filled voids) and clotted (containing spheroidal patches) textures akin to thrombolites, a non-laminated microbialite common in the Cambrian (see FIG. 3 in Fogret et al. 2026 this issue), are also observed, suggesting early diagenetic cementation of pore space and variations in microbial mat builders.

Seafloor carbonate precipitates resembling stromatolites are common in Archaean to Palaeoproterozoic carbonate successions and include, amongst others, seafloor crusts, microdigitate precipitates, and aragonite fans (Grotzinger

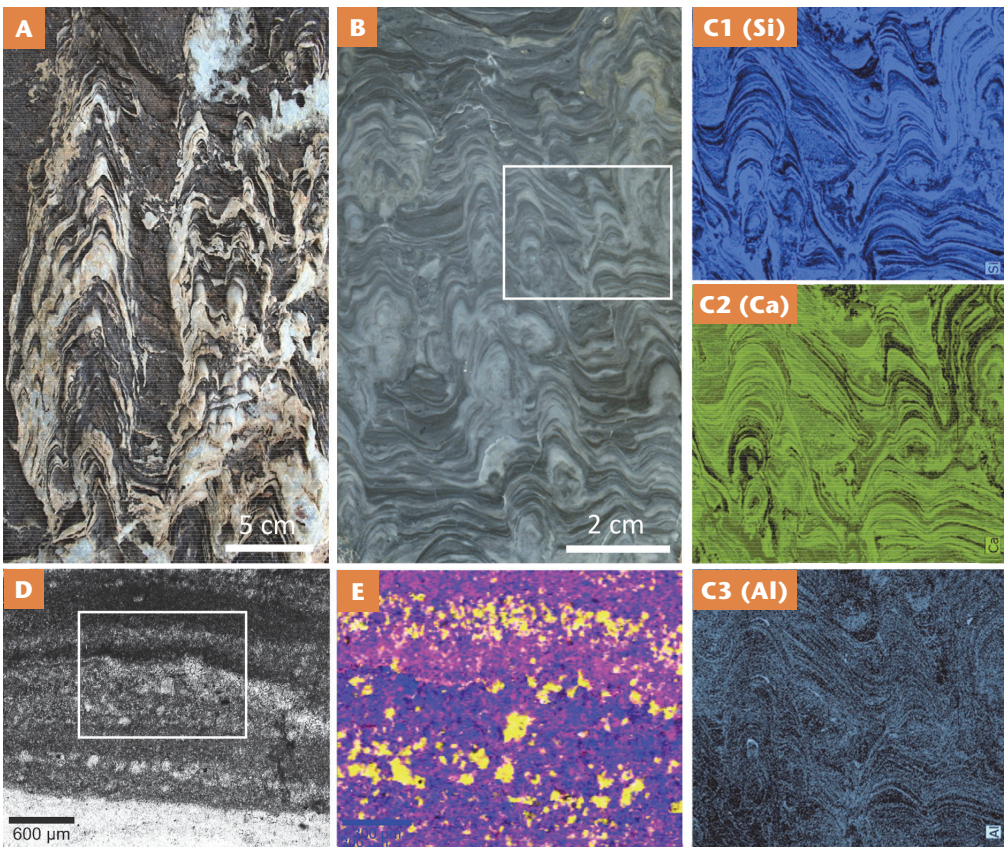

FIGURE 2 Conical-columnar stromatolites of the 3.0 Ga Nsuze Group of the Pongola Supergroup at various scales. (**A**) Outcrop photograph. (**B**) Polished slab of the same facies shown in **A**. (**C**) Micro-XRF element maps of Si, Ca, and Al of area depicted in **B**, showing Si-rich laminae in dolostone (revealed by Si and Ca distributions) and abundant siliciclastic material (revealed by Al distribution). The latter likely represents mud-sized material trapped from suspension. (**D**) Thin section photomicrograph of the same sample showing variably silicified micritic and microsparitic laminae. (**E**) Raman spectroscopy map of area in **D**, showing the distribution of quartz (yellow), dolomite (blue), and carbonaceous matter (purple). The latter represents the degraded remains of microbial mats.

and James 2000). Precipitation of these features may have been modulated by microbial processes, although establishing a direct link is generally difficult. Different types of seafloor crusts have been reported, for example, from ~2.5 Ga Transvaal Supergroup carbonates of southern Africa. A common type of crust superficially resembling stromatolites shows even, laterally continuous lamination with laminae having isopachous geometry and largely lacking trapped clastic detritus (Fig. 3). Seafloor carbonate precipitates declined in abundance through the Proterozoic, potentially linked to a decrease in the carbonate saturation rate of shallow-marine waters over time (Higgins et al. 2009).

COMPOSITION

The mineralogical composition of a stromatolite is largely influenced by the chemistry of the ambient water and the metabolic activity of the microbial mats (see Zeyen et al. 2026 this issue). In supersaturated carbonate environments, microbial mediation facilitates calcium carbonate precipitation. Modern stromatolites are predominantly made of calcite or its polymorph aragonite, although dolomite can be found in alkaline or hypersaline settings (Petrash et al. 2017). Precambrian carbonate successions may be dominated by limestone or dolostone. Many of the latter formed during early diagenesis, resulting in good fabric retention, whereas late-diagenetic dolomitisation, driven by Mg-rich subsurface brines, may strongly alter primary textures. Some Precambrian dolostones may be primary: a high magnesium-to-calcium ratio in ancient seawater may have enabled early dolomite precipitation (Warren 2000). Peters et al. (2017) reported a positive correlation between the proportion of carbonate units in the geological record that are dolomitic and those that are stromatolite-bearing, either because microbial consortia promoted dolomite precipitation or because stromatolite-bearing depositional settings were more prone to early diagenetic dolomitisation. Early diagenetic degradation of organic matter also promotes dolomitisation by increasing pore-water pH and alkalinity. Dolostones are generally more common in shallow-water facies than in deeper-water facies (Cantine et al. 2020).

In environments rich in dissolved silica, such as modern hot springs, cherty stromatolites may form (Jones et al. 2005), with silica precipitation possibly entirely abiogenic. Chert stromatolites common to Palaeoarchaean time intervals (Fig. 1A) may thus point to silica-supersaturated settings in the vicinity of hydrothermal springs (Djokic et al. 2017). Many younger stromatolitic carbonates show early diagenetic silicification of individual beds, laminae, or patchy domains. This may be linked to high Si concentrations in Precambrian oceans and microbially mediated silica precipitation (Moore et al. 2023). Early diagenetic silicification allows for good preservation of microbial

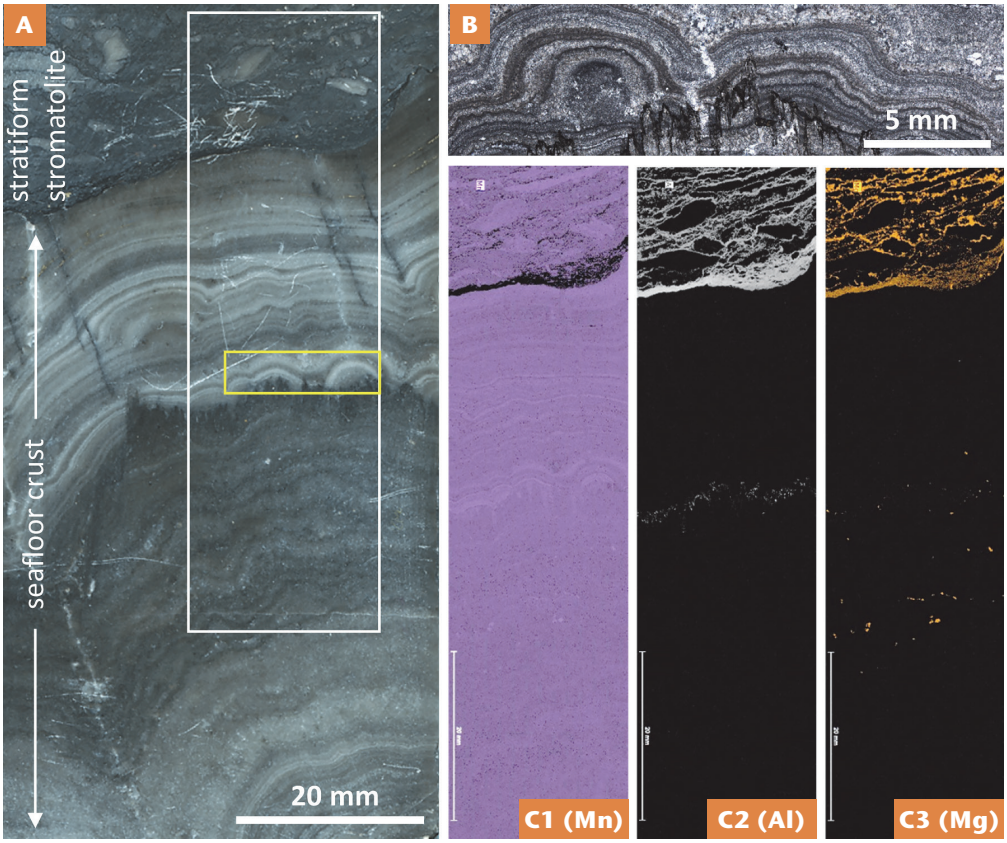

Figure 3 Example of laterally continuous isopachous lamination of seafloor precipitate. (**A**) Polished drill core from the Lime Acres Member of the ca. 2.5 Ga Campbellrand Subgroup, Transvaal Supergroup, showing small domical seafloor crust overlain by stratiform stromatolite. The latter experienced early diagenetic disruption and stylolite formation. (**B**) Thin section photomicrograph of the area depicted in yellow box in **A**, showing micritic and microsparitic laminae of the seafloor precipitate overprinted by stylolite. In contrast to stromatolite laminae, laminae in seafloor crusts show a large degree of inheritance, which is the extent to which a lamina conforms in shape to underlying laminae. (**C**) Micro-XRF element maps of Mn, Al, and Mg of the area depicted in **A** by a white box. Calcite (revealed by Mn in C1), dominates the laterally isopachous lamination of the seafloor precipitate. Stratiform stromatolite, in addition to calcite, also contains trapped, fine-grained siliciclastic detritus in discontinuous and irregular laminae as revealed by Al in C2. Magnesium distribution (in C3) largely reflects the presence of secondary dolomite and clastic detritus in the stratiform stromatolite facies.

textures and, in rare cases, the mat builders themselves. Early diagenetic pyritisation of organic matter may yield similar results (Fig. 4; Baumgartner et al. 2024).

SECULAR VARIATION IN ENVIRONMENTAL PARAMETERS

The chemistry of seawater has changed through time. The concentration of CO_2 in the Precambrian atmosphere was much higher than today, resulting in lower ocean pH levels (Halevy and Bachan 2017). Seawater in the Palaeoarchaean was mildly acidic (pH of ~ 6.5 to 7), not allowing carbonates to precipitate in open marine settings. Direct geological evidence can be found in the almost complete lack of shallow-marine carbonates prior to 3.0 Ga. Shallow-marine environments away from clastic coastlines were instead dominated by chert precipitation, with carbonate precipitation largely restricted to alkaline settings below the seafloor (Hofmann 2024).

In contrast to CO_2, oxygen concentrations were lower in the Precambrian hydrosphere. While deep waters may only have become oxygenated in the Neoproterozoic,

shallow parts of the ocean experienced oxygenation in the Palaeoproterozoic during the Great Oxidation Event (GOE, Holland 2006), apart from oxygen oases that may have been widespread in epicontinental seas as far back as 3.0 Ga (Eickmann et al. 2018). As a result, the concentration of redox-sensitive minor and trace elements, such as Mn and Mo, and their distribution in the water column were substantially different (see Bruggmann et al. 2026 this issue). In concert with the change of seawater chemistry, the make-up and ecology of microbial consortia responsible for the formation of stromatolites likely experienced changes through time (see Iniesto et al. 2026 this issue).

Apart from changes in the composition of the atmosphere–hydrosphere system through time, several other factors may have influenced stromatolite evolution. These include the dynamics of the Earth–Moon system, affecting Earth's rotation rate and day lengths, and potentially influencing photosynthetic benthic ecosystems (Klatt et al. 2021). Although the Moon's tidal forcing was larger during the Earth's early history, the smaller amounts of emerged continental crust may have resulted in weaker tides. Tidal range would have varied widely depending on continent configurations (Blackledge et al. 2020), thus affecting stromatolite depositional environments differently from place to place.

Linked to changes in tectonic processes, the evolution of sedimentary basins differed over time. The stabilisation of cratons in the Archaean, which occurred at 3.1 Ga for some (Kaapvaal, Pilbara, Singhbhum) and at 2.6 –2.5 Ga for most cratons, marked the timing of the widespread emergence of continental crust. This crust provided a slowly subsiding substrate suitable for the formation of thick carbonate platforms akin to the Great Barrier Reef today. Prior to this stabilisation, carbonates were deposited in environments typical of greenstone belts, such as volcanic islands prone to rapid tectonic movements. These environments yielded only relatively thin carbonate successions similar to those found today on volcanic Pacific Ocean islands.

The response by microbes to the high levels of UV radiation prior to the development of an ozone shield during the GOE has been widely studied. No major limitation to microbes is indicated, as a variety of physical and biological screens may have been available (Cockell and Raven 2007). These include dissolved Fe^{2+}, which was abundant in Archaean oceans and may have affected the photosynthetic potential of shallow-marine environments (Avila-Alonso et al. 2017). However, a stronger influence would have been exerted by the availability of nutrient elements such as phosphorus and nitrogen, which may have varied substantially over time (see Bruggmann et al. 2026 this issue).

DISTRIBUTION THROUGH PRECAMBRIAN TIME

During the Precambrian, stromatolites experienced their most extensive development and morphological diversity (Awramik and Sprinkle 1999; Semikhatov and Raaben 2000; Fig. 5 in Fogret et al. 2026 this issue). Archaean stromatolites are most abundant near the Proterozoic boundary as part of the large carbonate platforms of the Transvaal and Hamersley basins in southern Africa and western Australia. Farther back in time, they are reasonably common in shallow-water successions of greenstone belts and intracontinental basins but become rare in the pre-3.0

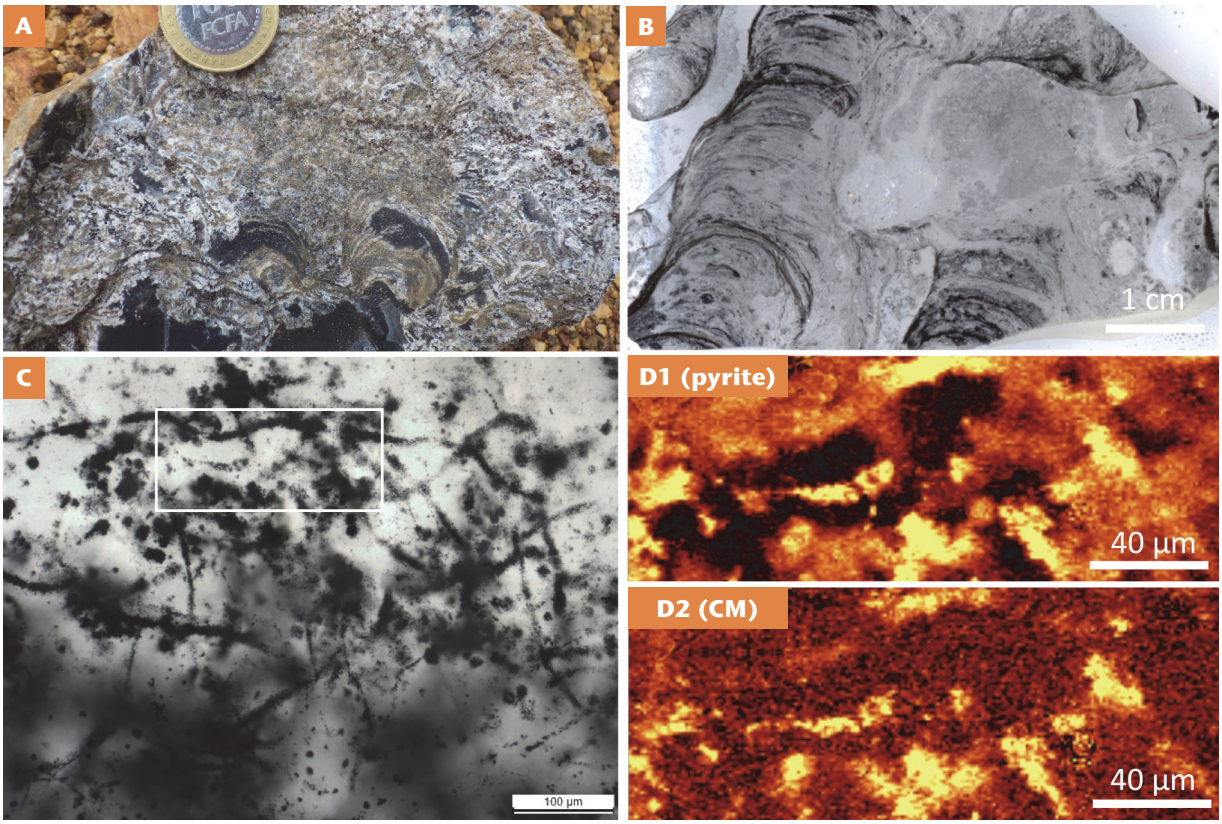

Figure 4 Silicified stromatolites of the 2.1 Ga FC Formation, Francevillian Group, Gabon, at various scales. (**A**) Outcrop photograph of domical stromatolites surrounded by silicified microbial mat intraclasts. (**B**) Thin section scan of columnar stromatolites with black lamina consisting of carbonaceous matter and pyrite in a groundmass of chert. (**C**) Extended depth of field transmitted light photomicrograph of black lamina showing pyritised filamentous and spherical features interpreted as replaced cellular sheaths of fossil microbes. (**D**) Raman spectroscopy maps of area marked with white box in **C**, showing a close spatial correlation between the distribution of pyrite (Raman band at ~380 cm^{-1}) and carbonaceous matter (CM, Raman band at ~1600 cm^{-1}). This association is interpreted to reflect early diagenetic pyritisation of microbial remains. Brighter areas within Raman maps reflect higher intensities of mineral-specific spectra.

Ga record, partly due to preservation bias. Palaeoarchaean stromatolites are restricted to a few sites in greenstone belts of the Pilbara and Kaapvaal cratons, where variably siliceous domical and conical forms occur. Fossil microbial mats are widespread in Palaeoarchaean cherts, but the absence of carbonate precipitation limited widespread microbial buildups (Hofmann 2024).

In the Proterozoic Eon, stromatolites became abundant and morphologically diverse. Following the stabilisation of most cratons by the end of the Archaean and continued continental growth, carbonate platforms expanded, providing extensive shallow marine settings ideal for stromatolite proliferation. Key Proterozoic formations, such as the Palaeoproterozoic Belcher Island Group (Canada), the Mesoproterozoic Billyakh Group (Siberia), and the Neoproterozoic Bitter Springs Formation (Australia), showcase highly varied stromatolite structures, from large, complex columns to broad domal forms. Their widespread occurrence during this time reflects stable surface environments and favorable conditions of the atmosphere–hydrosphere system, promoting widespread shallow marine carbonate precipitation. Some Proterozoic rock successions have experienced only very low degrees of metamorphic overprinting, thus allowing the preservation of microfossils through early diagenetic silica permineralisation in silicified stromatolite domains (Fig. 4).

By the Neoproterozoic, stromatolites began to decline, coinciding with the rise of more complex life forms that disrupted microbial mat communities and their environments. Nonetheless, their Precambrian dominance underscores their ecological success and their role in shaping Earth's early biosphere.

ACKNOWLEDGMENTS

We thank S. Viehmann, K. Benzerara, and S. Hohl for the invitation to contribute to this issue and acknowledge reviews by Mark van Zuilen and Raphael Baumgartner. AH acknowledges financial support by the DSTI-NRF Centre of Excellence in Palaeosciences (Grant 86073) and the Palaeoproterozoic Mineralisation (PPM) Research Group. FOO acknowledges financial support from Khalifa University of Science and Technology and Polar Research Center.

REFERENCES

Avila-Alonso D, Baetens JM, Cardenas R, De Baets B (2017) Assessing the effects of ultraviolet radiation on the photosynthetic potential in Archean marine environments. International Journal of Astrobiology 16: 271-279, doi: 10.1017/S147355041600032X

Awramik SM, Sprinkle J (1999) Proterozoic stromatolites: the first marine evolutionary biota. Historical Biology 13: 241-253, doi: 10.1080/08912969909386584

Awramik SM, Buchheim HP (2009) A giant, Late Archean lake system: the Meentheena Member (Tumbiana Formation; Fortescue Group), Western Australia. Precambrian Research 174: 215-240, doi: 10.1016/j.precamres.2009.07.005

Baumgartner RJ and 9 coauthors (2024) Pyritic stromatolites from the Paleoarchean Dresser Formation, Pilbara Craton: resolving biogenicity and hydrothermally influenced ecosystem dynamics. Geobiology 22: e12610, doi: 10.1111/gbi.12610

Blackledge BW, Green JAM, Barnes R, Way MJ (2020) Tides on other Earths: implications for exoplanet and palaeo-tidal simulations. Geophysical Research Letters 47: e2019GL085746, doi: 10.1029/2019GL085746

Bosak T, Knoll AH, Petroff AP (2013) The meaning of stromatolites. Annual Review of Earth and Planetary Sciences 41: 21-44, doi: 10.1146/annurev-earth-042711-105327

Bowlin EM and 5 coauthors (2012) Environmental controls on microbial community cycling in modern marine stromatolites. Sedimentary Geology 263-264: 45-55, doi: 10.1016/j.sedgeo.2011.08.002

Bruggmann S, Viehmann S, Mukherjee I, Hohl SV (2026) Stromatolites as recorders of major oxygenation events and biogeochemical metal cycling through Earth's history. Elements 22: 266-271

Cantine MD, Knoll AH, Bergmann KD (2020) Carbonates before skeletons: a database approach. Earth-Science Reviews 201: 103065, doi: 10.1016/j.earscirev.2019.103065

Cockell CS, Raven JA (2007) Ozone and life on the Archaean Earth. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365: 1889-1901, doi: 10.1098/rsta.2007.2049

Djokic T, Van Kranendonk MJ, Campbell KA, Walter MR, Ward CR (2017) Earliest signs of life on land preserved in ca. 3.5 Ga hot spring deposits. Nature Communications 8: 15263, doi: 10.1038/ncomms15263

Dupraz C and 5 coauthors (2009) Processes of carbonate precipitation in modern microbial mats. Earth-Science Reviews 96: 141-162, doi: 10.1016/j.earscirev.2008.10.005

Eickmann B and 5 coauthors (2018) Isotopic evidence for oxygenated Mesoarchaean shallow oceans. Nature Geoscience 11: 133-138, doi: 10.1038/s41561-017-0036-x

Fogret L, Sansjofre P, Hohl SV, Viehmann S, Benzerara K (2026) The story of stromatolites – mineralising ecosystems and geo-biological archives. Elements 22: 233-238

Grey K, Awramik SM (2020) Handbook for the Study and Description of Microbialites. Geological Survey of Western Australia, 147 pp

Grotzinger JP, Knoll AH (1999) Stromatolites in Precambrian carbonates: evolutionary mileposts or environmental dipsticks? Annual Review of Earth and Planetary Sciences 27: 313-358, doi: 10.1146/annurev.earth.27.1.313

Grotzinger JP, James NP (2000) Precambrian carbonates: evolution of understanding. In: Grotzinger JP, James NP (eds) Carbonate Sedimentation and Diagenesis in the Evolving Precambrian World. Society for Sedimentary Geology (SEPM) Special Publication 67, Claremore, pp 1-20

Halevy I, Bachan A (2017) The geologic history of seawater pH. Science 355: 1069-1071, doi: 10.1126/science.aal4151

Higgins JA, Fischer WW, Schrag DP (2009) Oxygenation of the ocean and sediments: consequences for the seafloor carbonate factory. Earth and Planetary Science Letters 284: 25-33, doi: 10.1016/j.epsl.2009.03.039

Hofmann A, Dirks PHGM, Jelsma HA (2004) Shallowing-upward carbonate cycles in the Belingwe Greenstone Belt, Zimbabwe: a record of Archean sea-level oscillations. Journal of Sedimentary Research 74: 64-81, doi: 10.1306/052903740064

Hofmann A (2024) The Barberton Drilling Project's Buck Reef Chert core BARB3 – sedimentary facies and depositional environment of a 3.4 Ga marine platform succession. Precambrian Research 414: 107584, doi: 10.1016/j.precamres.2024.107584

Holland HD (2006) The oxygenation of the atmosphere and oceans. Philosophical Transactions of the Royal Society B: Biological Sciences 361: 903-915, doi: 10.1098/rstb.2006.1838

Iniesto M, Moreira D, López-García P (2026) Microbialite-associated microbial communities, present and past. Elements 22: 246-252

Jones B, Renaut RW, Konhauser KO (2005) Genesis of large siliceous stromatolites at Frying Pan Lake, Waimangu geothermal field, North Island, New Zealand. Sedimentology 52: 1229-1252, doi: 10.1111/j.1365-3091.2005.00739.x

Klatt JM, Chennu A, Arbic BK, Biddanda BA, Dick GJ (2021) Possible link between Earth's rotation rate and oxygenation. Nature Geoscience 14: 564-570, doi: 10.1038/S41561-021-00784-3

Moore KR and 5 coauthors (2023) A review of microbial-environmental interactions recorded in Proterozoic carbonate-hosted chert. Geobiology 21: 3-27, doi: 10.1111/gbi.12527

Peters SE, Husson JM, Wilcots J (2017) The rise and fall of stromatolites in shallow marine environments. Geology 45: 487-490, doi: 10.1130/G38931.1

Petrash DA and 6 coauthors (2017) Microbially catalyzed dolomite formation: from near-surface to burial. Earth-Science Reviews 171: 558-582, doi: 10.1016/j.earscirev.2017.06.015

Riding R (2000) Microbial carbonates: the geological record of calcified bacterial–algal mats and biofilms. Sedimentology 47: 179-214, doi: 10.1046/j.1365-3091.2000.00003.x

Semikhatov MA, Raaben ME (2000) Proterozoic stromatolite taxonomy and biostratigraphy. In: Riding RE, Awramik SM (eds) Microbial Sediments. Springer, Berlin, pp 295-306, doi: 10.1007/978-3-662-04036-2_32

Suosaari EP, Reid RP, Andres MS (2019) Stromatolites, so what?! A tribute to Robert N. Ginsburg. The Depositional Record 5: 486-497, doi: 10.1002/dep2.72

Walter MR, Grotzinger JP, Schopf JW (1992) Proterozoic stromatolites. In: Schopf JW, Klein C (eds) The Proterozoic Biosphere: A Multidisciplinary Study. Cambridge University Press, Cambridge, pp 253-260, doi: 10.1017/CBO9780511601064

Warren J (2000) Dolomite: occurrence, evolution and economically important associations. Earth-Science Reviews 52: 1-81, doi: 10.1016/S0012-8252(00)00022-2

Zeyen N, Caumartin J, Benzerara K (2026) Diversity, mechanisms of formation, and predicted fate of modern microbialites on a rapidly changing planet. Elements 22: 239-245 ■