

## Chapter 2

# Christmas Tree Stromatolite

*Why not go out on a limb? Isn't that where the fruit is?*

Frank Scully (1892–1964)

**Abstract** What causes the unique shape of the Christmas tree stromatolite *Jacutophyton*? Branching in *Jacutophyton* appears to be controlled by both shade avoidance and by metazoan perturbation of the microbial mat at the edge of the stromatolite. Evidence suggests that heliotrophism in Proterozoic stromatolites is a real phenomenon.

Stromatolites are layered community fossils formed by accumulated successive layers of mineralized microbial mats or biofilms. These biofilms are typically bacterial in nature but this is not always the case (Awramik and Riding 1988). Cloud (1988) referred to stromatolites as “organo-sedimentary structures” to emphasize that they reflect an intimate interaction between life processes (biofilm growth) and sedimentological processes (layered sediment accumulation).

“Stromatolite” is thus a hybrid term of the type so useful in the Earth sciences. Another example is “time-rock unit”, used to describe all of the rocks deposited within a particular time interval. We may speak of the Cretaceous Period (a discrete unit of time), and also speak of the Cretaceous System (the body of all the rocks formed during the Cretaceous Period). The Cretaceous System is thus a time-rock unit.

Stromatolites have the longest geological range of any type of fossil that is visible to the naked eye. Some Proterozoic stromatolites reach the size of mountains. Non-living geological processes can form structures that greatly resemble stromatolites. Abiogenic domed or columnar sedimentary structures have been called “stromatoloids” (Dahanayake et al. 1985). Therefore, attempts to interpret ancient stromatolites must proceed with care. In most cases, however, whenever stromatolites are encountered in shallow marine or freshwater strata, their interpretation as having been formed by microbial biofilms is very likely correct and uncontroversial. When filamentous microbial fossils are present (as when the rocks are silicified to form chert), the evidence is clear that the stromatolite was formed by biofilms. Such microfossils, however, are typically difficult to preserve as fossils owing to their tiny size. Nevertheless, larger scale textures in stromatolites can

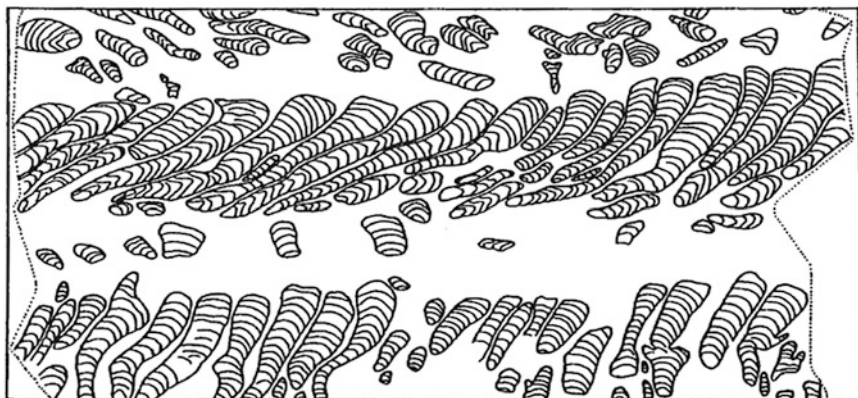
provide evidence for their derivation from biofilms. For example, characteristic fenestral patterns form in stromatolites due to oxygen bubbles formed by photosynthesis becoming trapped between the biofilms (Wilmeth et al. 2015). These distinctive features provide evidence for both a biogenic and photosynthetic nature for the biomats that formed the stromatolite. ‘Biofilm’ is thus an appropriate name as it emphasizes an ability to trap gas.

Biofilms are extensive and widespread for most (about 5/6th) of geological time, but it would be a mistake to dismiss biofilms as merely representing primitive life forms. Recent results suggest that the microbial species in modern multispecies biofilms collaborate to develop “enhanced resistance to antibiotics” (Denison and Muller 2016). Alternatively, single-strain biofilms are formed by the bacterium *Pseudomonas aeruginosa* by killing off other strains in the immediate vicinity (Oliveira et al. 2015). Clearly there is more complexity here than might initially meet the eye.

With their long geological history, it is no surprise that a variety of different shapes or forms of stromatolites have existed over the billions of years of Earth history. *Platella* is a unique stromatolite group that forms an elongate dome, oriented in the direction of the ebb and flow of tides (Keller and Semikhatov 1976). *Platella* was evidently sculpted by daily tidal flow, alternating currents that formed the distinctive elongate/parallel ridges of this stromatolite group (Cevallos-Ferriz and Weber 1980). Some columnar stromatolites bend into unidirectional currents, and others develop a sinusoidal curve in their column axis that has been hypothesized to track the position of the sun (Awramik and Vanyo 1986). The latter result was used to calculate the length of the Proterozoic year at  $400 \pm 7$  days. It has also been used to argue that the Earth had an essentially normal tilt on its axis, in other words, the obliquity of the Proterozoic ecliptic was not significantly different from current values (McMenamin 2004). Awramik and Vanyos’ (1986) claim of heliotropism in Proterozoic stromatolites has been vigorously debated; however, the specimens used as counterexamples also display the sine wave pattern (Williams et al. 2007). To date the inferred heliotropism has not been falsified.

Kusky and Vanyo (1991) advocated using stromatolite heliotropism to refine paleotectonic continental plate reconstructions. Williams et al. (2007) countered that the “acceptance and use of such data are premature... further data and tests relevant to the sinusoidal growth model are desirable.” Kusky and Vanyo (1991) cited Horodyski (1983) regarding the stromatolites of the Mesoproterozoic Belt Supergroup of Glacier National Park, Montana, noting that inclinations occur in these stromatolites, but left open the question of “whether stromatolite inclination could be a result of heliotropism or currents” (Horodyski 1989).

Horodyski (1983) published a sketch of inclined stromatolites of the Altyn Limestone near Appekunny Falls in Glacier National Park. His Fig. 5E is reproduced here as Fig. 2.1. Although he does not assign them to group, the stromatolites in Fig. 2.1 are “highly elongate and are shown on a joint surface oriented perpendicular to the direction of elongation,” and thus should be assigned to the stromatolite group *Platella*.



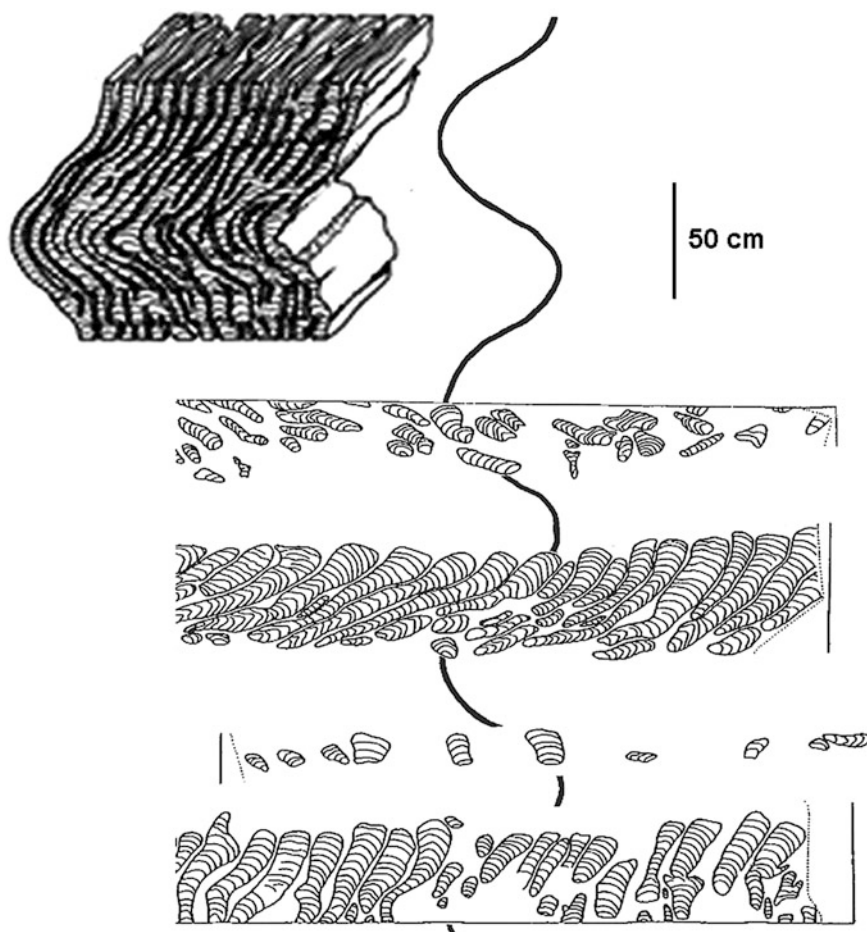
**Fig. 2.1** Horodyski's (1983) sketch of *Platella* stromatolites of the Altyn Limestone near Appekunny Falls, Glacier National Park, Montana. Height of outcrop seen in section (along a joint surface perpendicular to the elongation of the *Platella* columns) is approximately 1.6 m. Reprinted from *Precambrian Research*, volume 20, R. J. Horodyski, "Sedimentary geology and stromatolites of the Middle Proterozoic Belt Supergroup, Glacier National Park, Montana," pages 391–425, 1983, with permission from Elsevier

There does not at first glance appear to be a sinusoidal pattern to the inclinations of the *Platella* stromatolites in Fig. 2.1. To help with the analysis, it is important to recall that *Platella* lives in an intertidal environment. This explains the odd elongated shapes of its columns. *Platella* columns are mechanically sculpted to have this shape by the continual, daily ebb and flow of the tides.

Note that intertidal depositional environments are highly erosive. Tidal sediment transport is constantly wearing away at any obstructions in the path of the abrasive sediment in motion. Flat bedrock surfaces, slightly inclined toward the sea, often result from this process and are called wave-cut terraces. As a general rule, interruptions in the continuity of sedimentation (diastems or hiatuses) become more frequent as one gets closer to the shoreline, and less frequent as one moves offshore and into deeper, quieter water.

Inhabiting a very shallow water environment, *Platella* is thus subjected to a great deal of erosive scour; its environment is so highly erosive that the preservation of *Platella* is probably more the exception than the rule. A close inspection of Fig. 2.1 shows horizons of *Platellas* inclined at odd angles with respect to horizons above and below. One may discern four separate horizons of *Platella* stromatolites in Horodyski's (1983) sketch.

If we separate these four *Platella* horizons, they each may be fitted to a sinusoidal curve as shown in Fig. 2.2. Erosional gaps separate the four horizons, as would be expected in *Platella*'s erosive intertidal environment. The period of the vertical sine wave is approximately 114 cm. A dramatic confirmation of the accuracy of this reconstruction, and the interpretation of the pre-erosional morphology of the stack of Montana *Platellas*, is seen in a book chapter by Serebryakov (1976) that includes



**Fig. 2.2** *Platella* stromatolite horizons of the Altyn Limestone, Montana, with their inclinations fitted to a sinusoidal curve interpreted here to represent the track of stromatolite heliotropism in *Platella*. The inclination fitting has revealed four hiatuses, diastems or gaps in deposition in the Altyn stromatolite succession. The period of the sine wave is approximately 114 cm. Inset image to the upper left is modified from Serebryakov's reconstruction (1976, his Fig. 1, p. 324) of sinusoidal *Platellas* from the Proterozoic (Riphean) Debengda suite of the Olenek Uplift of the Siberian Platform. If you look closely at the inset, you can see evidence for at least four brief gaps in deposition, as in the Altyn case but with only minor loss of the sequence erosion or non-deposition. Stromatolites from Montana and Siberia are drawn to scale. Scale bar = 50 cm

a block diagram (modified here as the upper left inset in Fig. 2.2) of sinusoidal *Platellas* from the Proterozoic (Riphean) Debengda suite of the Olenek Uplift of the Siberian Platform in eastern Siberia. Serebryakov nicely shows the wave shape of the Olenek *Platellas*. Very interestingly, and this is likely not mere coincidence, the period of the sine wave in the Siberian stromatolites is exactly the same as that of the Montana *Platellas*, namely, 114 cm. The comparison is even closer than it looks

at first—if you look closely at the inset, you can see in the block diagram evidence for at least four brief gaps in deposition, as in the Altyn case only with not as much of the sequence lost to erosion or non-deposition. This close comparison further supports the interpretation of a heliotropism signal in the *Platellas*, assuming as seems reasonable that the two sites were at roughly similar paleolatitudes at the time their respective stromatolites were deposited. Siberia and western North America were close to one another in the Rodinia supercontinent, but this assumption requires further evaluation by using modern plate reconstructions to assess stromatolite heliotrophism, which will effectively run the research program of Kusky and Vanyo (1991) in reverse.

The  $\theta$  angle (Vanyo and Awramik 1985; the theta value used in their calculations is  $\theta = 19.6^\circ$ ) of the Altyn Limestone stromatolites ( $\theta = 56^\circ$ ) is too large to provide a realistic measure of Earth-Sun-Moon dynamics, thus it appears that the *Platella* ridges were not just bending into the light but that their ridges (linear columns) were actively migrating toward the sun. Unfortunately, this will greatly complicate the study of stromatolite heliotropism because it introduces an additional parameter. Calculations of orbital dynamics will only work if you can assume that no stromatolite column sideways axis-shifting migration has taken place, or if you are able to calculate the rate at which the stromatolites have migrated (as opposed to simply leaned into) the sun. I will show below that stromatolite migration is a very real phenomenon. There does not seem to be evidence for stromatolite migration in the work of Awramik and Vanyo (1986), so we can accept their results as provisionally valid.

We must of course consider alternate explanations for the phenomenon. Changes in nearshore current directions might be invoked to explain the sinusoidal wave, but stromatolites tend to bend into currents, and current surge in *Platella*'s intertidally influenced environment runs parallel to the long axes of the columns, not perpendicular to it. Mars' obliquity can change up to  $60^\circ$ , but this takes place over the course of millions of years (Touma and Wisdom 1993), and proposing that the Earth's obliquity could change by this amount over the course of a season would be too much to ask of orbital mechanics to say the least.

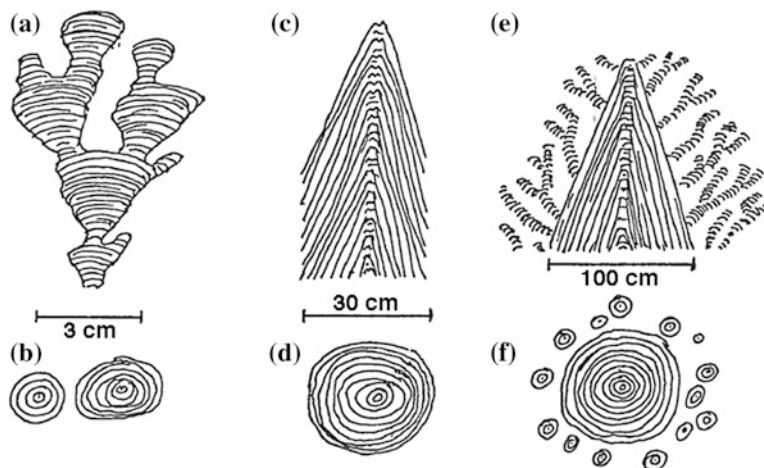
Stromatolite diversity peaks in the Proterozoic about 1.25 billion years ago, and drops off rapidly afterwards. This sharp decline has been attributed to the rise of grazing animals (Awramik 1971). By the Cambrian, global stromatolite diversity is reduced by at least 20 %, and today stromatolites form only where high salinity or other environmental factors inhibit grazing aquatic animals that would otherwise disrupt the biofilm fabric and prevent stromatolites from forming. Interestingly, it has been argued that stromatolites make a brief comeback as “disaster forms” in the Early Triassic, during global biotic recovery after the horrific Permo-Triassic mass extinction (Schubert and Bottjer 1992). Domal stromatolites from the Cambrian and later, including the splendid Cambrian “cabbage heads” at Lester Park, Saratoga Springs, New York, often show evidence of animals burrowing between and through the stromatolitic layers.

Stromatolites come in three main shape varieties: domal, columnar and conical. Awramik and Semikhatov (1979) use the term “stratiform stromatolite” for stacked planar biofilm laminae with little or no synoptic relief. Stromatolite morphogenesis

has been attributed to the operation of the four variables of the Kardar-Parisi-Zhang (KPZ) non-linear stochastic partial differential equation (Grotzinger and Rothman 1996). The surface fractal or Eden growth model has also been used to describe the growth of microbial cluster colonies and accumulation of material around the edges of the microbe clusters (Family and Vicsek 1985). Although it may be possible to describe some stromatolites by means of these four processes, a Laplacian nonlocal growth model better describes most stromatolites (Batchelor et al. 2003).

As their name suggests, domal stromatolites take on the form of an inverted salad bowl. Their internal structure consists of domal layers. Columnar stromatolites, in side view, appear as straight or gently curving columns consisting of tall stacks of arched laminae. Conical stromatolites are quite different in form when compared to the other two types. They project upward a considerable distance from the sea floor; in stromatolites, the distance they project above the sea floor is called their synoptic relief. Conical stromatolites consist of steep-sided, conical laminae that often have a disturbed zone at the top of the cone. In a longitudinal cross-section through the exact center of a conical stromatolite such as *Conophyton*, the stacked disturbed zones resemble a zipper running down the center of the stacked cones.

Perhaps the strangest and most wonderful of all stromatolites is *Jacutophyton*. It often occurs in the same Proterozoic stratigraphic sequences as does *Platella*. *Jacutophyton* is nicknamed “Christmas Tree stromatolite” because of its branch configuration—a conical core surrounded by inclined columnar branches that resemble the branches of a fir tree (McMenamin 1982). Figure 2.3 shows a comparison between the columnar stromatolite *Baicalia*, the conical stromatolite *Conophyton*, and the conical stromatolite with branching sub-columns *Jacutophyton*.



**Fig. 2.3** Three different groups of Proterozoic stromatolites. Each is shown in longitudinal and transverse section. **a, b**, *Baicalia*, a branching columnar stromatolite, scale bar = 3 cm; **c, d**, *Conophyton*, a conical stromatolite, note disturbed central axis, scale bar = 30 cm; **e, f**, *Jacutophyton*, a conical stromatolite with branching sub-columns, scale bar = 100 cm





**Fig. 2.4** *Jacutophyton sahariensis* from the Atar Formation of Mauritania. Three stromatolite central cores are visible. Note the petaloid shapes of the satellite stromatolites surrounding the central cones. The specimen on the *left* has the petaloid fabric reaching all the way to the center of the stromatolite. Scale bar = 10 cm

In life, *Jacutophyton* resembled a *Conophyton* surrounded by low synoptic relief satellite columns. The branching columns are typically elliptical in transverse cross-section, but in *Jacutophyton sahariensis* from the Atar Formation of Mauritania, Africa, the branches form low ridges (resembling miniature concentrically-curved *Platellas*; Fig. 2.4) that give *Jacutophyton sahariensis* a petaloid aspect (Swart et al. 2009) in transverse section that somewhat resembles a dental tubercle of *Romundina*. The overall impression of a living *Jacutophyton sahariensis* would be similar to that of flower of the titan arum *Amorphophallus titanum*, with its towering central spadix (up to 3 m tall) surrounded by a spathe that resembles large curving petals. In transverse cross-section the curved branches of *Jacutophyton sahariensis* do seem to radiate out from the central cone in waves, much like curved, nested flower petals.

*Jacutophyton* is abundant in the Late Proterozoic Gamuza Formation near the town of Caborca in Sonora, México. Stratigraphically beneath the Gamuza Formation is the famous Clemente Formation, known for its very ancient Ediacaran fossils (McMenamin 1996). An unanswered question about *Jacutophyton* is just how this stromatolite acquired its odd shape. Stromatolites are usually either domal, columnar or conical, not combinations of the above. Columnar stromatolites will sometimes transition stratigraphically upward into domal stromatolites, and vice versa, but combinations of stromatolite types at the same level (i.e., same lamina) are rare.

If we follow a single lamina of *Jacutophyton*, as seen in longitudinal cross-section (Fig. 2.3e), passing from left to right we encounter one small column, then a second, then a third, then the conical upward projection of the core of the *Jacutophyton*, then three small columnar stromatolites on the far side. Field

observations show (Swart et al. 2009) that “branches [in *Jacutophyton*] initiate along a single lamina of the central cone.”

We can answer this question of how *Jacutophyton* acquired its unusual shape by means of an analysis of its growth. A stromatolite is generally thought to begin as an upward rumple, pustule or irregularity in an otherwise roughly planar microbial mat or biofilm on the sea floor or on the floor of a lake. Microbial mats typically develop this surface roughness. This texture can be preserved in the sedimentary rock record in both Precambrian and post-Cambrian strata (Bailey et al. 2006), and when it does preserve, it is called “elephant skin texture,” a type of microbially induced sedimentary structure. The faster a biomat grows, the rumplier its surface becomes as the mat expands and is forced to wrinkle like a rumpled rug. Light is attenuated fairly rapidly in water, and rumples that bow upwards have access to detectably more sunlight than the surrounding flat mat. Light-hungry microbes migrate to the top of the lumps. These upward facing wrinkles thus often become the establishment sites of new stromatolites.

Interestingly, microbial mat wrinkles are comparable to those formed experimentally on 3-D layered gel models of the cortical convolutions of the brain. The artificially produced cortical crenulations are remarkably similar to those of actual brains. According the authors (Tallinen et al. 2016), the “placement and orientations of the folds” in the simulated brain “arise through iterations and variations of an elementary mechanical instability modulated by early fetal brain geometry.” This suggests an intriguing mechanical similarity to elephant-skin texture and the crenulations of the brain. In the former, biomat layering probably helps influence the appearance of the mat crenulations.

With cyclical (in some cases daily) growth of the mat microbes, successive layers are formed over the rumple and this upwardly domal mat becomes, with successive layers, the stromatolite. If the stromatolite is broad and wide, it becomes a domal stromatolite; if it is smaller and button-shaped it will form a columnar stromatolite of the successively accreted layers. The synoptic relief of the dome- or column-forming mat may only be a few millimeters. It is the numerous accreted laminae that form the dome or tall column as seen in longitudinal cross section (Figs. 2.3a, c, e). Conical stromatolites are typically the only type of stromatolites that show, in life, significant synoptic relief, and their actively-growing cones project some distance upward into the water column. A patch of sea floor hosting conical stromatolites would resemble a parking lot covered with green traffic safety cones.

A *Jacutophyton*-colonized sea floor would be somewhat similar, except that one or more concentric rings of low curved ridges or small domes would surround each cone. Looking closely at the later, they would not have a perfectly symmetrical domal profile, but rather would lean away from the vertical and erect central cone. What could lead to such a curious configuration?

A stromatolite-like structure known as a thrombolite (its name refers to its clotted internal structure) is common in late Precambrian and early Paleozoic marine strata. A thrombolite is essentially the same thing as a stromatolite, and both are classified as a type of microbialite. Each type forms in the same way by the sediment-binding activity of a biofilm. Thrombolites differ from stromatolites in



**Table 2.1** Types of calcimicrobe structures

Type	Internal fabric	References
Stratiform stromatolite	Planar laminae	Awramik and Semikhatov (1979)
Stromatolite	Domed laminae	Awramik and Semikhatov (1979), Kennard and James (1986), Shapiro (2004)
Thrombolite	Mesoclots	Kennard and James (1986), Shapiro (2004)
Dendrolite	Clusters	Shapiro (2004)
Leiolite	Not recognizable	Riding (2000), Shapiro (2004)

that the laminated internal fabric has been profoundly disrupted by the activities of burrowing animals (Kennard and James 1986). The stromatolite-to-thrombolite transition appears to be part and parcel of the overall decline during the late Proterozoic of stromatolite groups, a process that has been attributed as noted above to the rise of burrowing and grazing animals that appear millions of years before the Cambrian Explosion.

In addition to stromatolites and thrombolites, other microbiolites are known including dendrolites (characterized by calcimicrobe clusters; Shapiro 2004) and leiolites (internal fabric not discernible; Riding 2000). Table 2.1 summarizes the main types of microbiolites.

I propose here that *Jacutophyton* represents a conical stromatolite that has experienced the early stages of what might be called “thrombolitization.” In this scenario, burrowing animals of the sea floor impinged against the edge of an undisturbed *Conophyton*, at the perimeter circle where the cone of the stromatolite begins to rise up from the sediment-water interface. This occurred because the earliest metazoans are thought to have been undermat miners, feeding on organic matter underneath the biofilm, and their mat-mining routine was impacted when, while burrowing in the horizontal plane, they ran into the nearly vertical wall of a conical stromatolite. The small animal would try to climb the column, turn around, or make some other unfamiliar maneuver, and in so doing would cut through, thin, or otherwise disrupt the mat at the base of the cone.

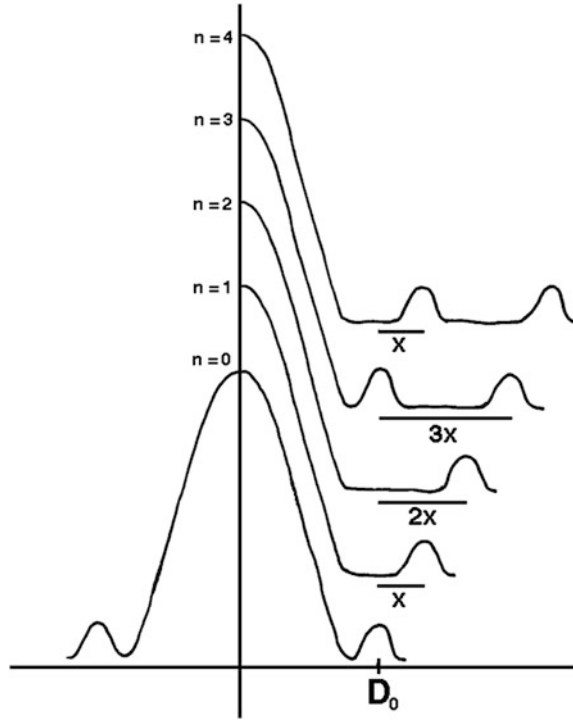
These minor disruptions would initiate new, smaller satellite stromatolites that began to form columns. The columns are inclined away from the main conical core, and thus form tilted branching columns, as they seek areas away from the shade of the main cone. This causes the satellite domes to progressively migrate away from the main cone, as the diagram in Fig. 2.5 indicates.

Let  $D_0$  be the initial distance of the satellite stromatolite from the axis of the main conical center of a *Jacutophyton*. With successive growth stages (Fig. 2.5), the distance of the satellite stromatolite from the central axis at interval  $n$  is

$$D_n = D_0 + xn \tag{2.1}$$

with  $n$  equaling the number of growth increments elapsed on the main cone (as shown by successive stromatolitic laminae), and  $x$  the distance that the satellite

**Fig. 2.5** Growth of the *Jacutophyton* stromatolite. This diagram shows four growth intervals of the stromatolite, from  $n = 0$  to  $n = 4$ . These intervals can be considered as accretionary stages in the upward growth of the stromatolite.  $D_0$  is the initial distance of a nascent satellite stromatolite from the central cone axis. The satellite stromatolite moves a distance  $x$  away from the main axis with each growth increment ( $n$ ). When it reaches a critical distance from the axis  $G$ , a new satellite stromatolite forms at a distance  $D_0$  from the central axis



cone migrates away from the axis with each iteration.  $G$  is a particular critical distance from the main stromatolitic axis. In Fig. 2.5 the  $G$  value equals the initial distance  $D_0$  plus three sideways growth increments  $x$ , or  $G = D_0 + 3x$ . When:

$$D_n > G \quad (2.2)$$

a new satellite stromatolite is generated at a distance  $D_0$  from the main axis. Successive “waves” of satellite stromatolites thus migrate away from the main central cone, and this is what gives *Jacutophyton* its Christmas Tree shape as seen in longitudinal cross section. The stacked branches are satellite stromatolites migrating away in increments from the shade of the central cone as they add their incremental layers.

It would be interesting to discover what controls the value of  $x$  between the various forms of *Jacutophyton*. Higher values of  $x$  will generate more horizontal branches, and lower values of  $x$  will generate more upright or vertical branches. One might plausibly speculate that the value of  $x$  is inversely correlated to light intensity at any particular site. Low light levels might cause the satellite stromatolites to move away from the main cone more rapidly in order to capture whatever light is still available, hence a higher  $x$  value.

It is easy to imagine how this might happen. Filamentous cyanobacteria will tend to congregate on the side of the satellite stromatolite apex that is away from the main cone. This is virtually the same effect that explains the disturbed zone (longitudinal section “zipper”) seen in the axis of a typical *Conophyton*. The apex of the cone gets the most light, and microbes congregate there in such numbers that they form a tiny, very rumpled patch of elephant skin texture right at the tip of the cone. This explains the laminae disturbance that runs up through the exact center of a *Conophyton* (Fig. 2.3c).

We might also speculate on the critical distance value  $G$ . It might very well also be light dependent, but could also be influenced by other factors such as the intensity of disruption of the microbial mat by animals burrowing in the vicinity of the stromatolite. This latter consideration might also influence whether the *Jacutophyton* forms branches or, alternatively, forms “petals” as in *Jacutophyton sahariensis*.

The beautiful form of *Jacutophyton* thus provides us with a glimpse into the dynamics between Proterozoic stromatolites and early animal burrowers as the marine biosphere approached a critical point marking the beginning of the Cambrian. *Jacutophyton*s of the Gamuza Formation are like fancy hats for a “graduation party” marking the transition from Microbe World to Metazoan Planet.

*Jacutophyton sahariensis* occurs in the Atar Formation of Mauritania. The Atar Formation is approximately 800 million years old, and this is an early date for putative animal burrowers; however, the putative burrowers may have been living in a symbiotic relationship with *Jacutophyton sahariensis* that led to the unique petaloid shape. This would be in contrast to complete destruction of the laminar fabric as in subsequent thrombolites. Figure 2.4 shows three *Jacutophyton sahariensis* stalks, in one of which the petaloid fabric goes all the way to the center of the stromatolite as seen in transverse section. In this case the conical core appears to be lost, suggesting perhaps that the burrowers were in fact capable of disrupting even the central cone. The morphology of the *Jacutophyton* to the left in Fig. 2.4 is approaching that of a thrombolite. Table 2.2 shows the relationship between internal fabric and burrowing disturbance in organo-sedimentary microbialites.

**Table 2.2** Fabric and burrowing disturbance intensity in organo-sedimentary microbialites

Organo-sedimentary structure	Fabric	Burrowing disturbance intensity
Stratiform stromatolite	Planar laminated	Low
Oncolite	Concentrically laminated oncoliths (oncoids; Shapiro 2004)	Low
<i>Conophyton</i> , <i>Platella</i>	Laminated	Low
<i>Jacutophyton</i>	Branched to petaloid	Intermediate
Thrombolite	Clotted	High
Dendrolite	Clusters	Variable

*Jacutophyton* provides a fine example of morphogenesis, where a well-defined geometrical form (conical stromatolite) undergoes a dramatic shape change (to Christmas Tree Stromatolite) by application of a new outside influence (burrowers), leading to a new regime of morphogenesis (satellite stromatolites). With increased disruption the Christmas Tree shape changes to a petaloid configuration, and finally to a thrombolite where the mound or dome shape reappears, but without any internal laminae because the biomats have been destroyed by intensive burrowing.

## References

- Awramik SM (1971) Precambrian columnar stromatolite diversity: reflection of metazoan appearance. *Science* 174:825–827
- Awramik SM, Riding R (1988) Role of algal eukaryotes in subtidal columnar stromatolite formation. *Proc Nat Acad Sci* 85(5):1327–1329
- Awramik SM, Semikhatov MA (1979) The relationship between morphology, microstructure, and microbiota in three vertically intergrading stromatolites from the Gunflint Iron Formation. *Can J Earth Sci* 16(3):484–495
- Awramik SM, Vanyo JP (1986) Heliotropism in modern stromatolites. *Science* 231:1279–1281
- Bailey JV et al (2006) Microbially-mediated environmental influences on metazoan colonization of matground ecosystems: evidence from the Lower Cambrian Harkless Formation. *Palaios* 21:215–226
- Batchelor MT et al (2003) Mathematical and image analysis of stromatolite morphogenesis. *Math Geol* 35(7):789–803
- Cevallos-Ferriz S, Weber R (1980) Arquitectura, estructura y ambiente de deposito de algunos estromatolitos del Precámbrico sedimentario de Caborca, Sonora. *Revista, Universidad Nacional Autonoma de México, Instituto de Geología* 4:97–103
- Cloud P (1988) *Oasis in Space*. Norton, New York
- Dahanayake K et al (1985) Stromatolites, oncolites and oolites biogenically formed in situ. *Naturwissenschaften* 72:513–518
- Denison RF, Muller K (2016) The evolution of cooperation. *The Scientist* 30(1):40–46
- Family F, Vicsek T (1985) Scaling of the active zone in the Eden process on percolation networks and the ballistic deposition model. *J Phys A: Math Gen* 18:L75–L81
- Grotzinger JP, Rothman DH (1996) An abiotic model for stromatolite morphogenesis. *Nature* 383(6599):423–425
- Horodyski RJ (1983) Sedimentary geology and stromatolites of the Middle Proterozoic Belt Supergroup, Glacier National Park. *Montana Precam Res* 20(2–4):391–425
- Horodyski RJ (1989) Stromatolites of the Belt Supergroup, Glacier National Park, Montana. In: Winston D et al (eds) *Middle Proterozoic Belt Supergroup, western Montana, field trip guidebook T334*. 28th International Geological Congress. American Geophysical Union, Washington, pp 27–42
- Keller BM, Semikhatov MA (1976) Stratigraficheskie rubezhi v dokembrii. In: Keller BM (ed) *Granitsy geologicheskikh sistemy. Iztadel'stovo "Nauka," Moscow*, pp 9–30
- Kennard JM, James NP (1986) Thrombolites and stromatolites: two distinct types of microbial structures. *Palaios* 1(5):492–503
- Kusky TM, Vanyo JP (1991) Plate reconstructions using stromatolite heliotrophism: principles and applications. *J Geol* 99:321–335
- McMenamin MAS (1982) Precambrian conical stromatolites from California and Sonora. *Bull So Calif Paleo Soc* 14(9–10):103–105

- McMenamin MAS (1996) Ediacaran biota from Sonora, Mexico. *Proc Nat Acad Sci* 93:4990–4993
- McMenamin MAS (2004) Climate, paleoecology and abrupt change during the late Proterozoic: a consideration of causes and effects. In: Jenkins GS et al (eds) *The extreme Proterozoic: geology, geochemistry, and climate*. American Geophysical Union Geophysical Monograph 146, Washington, pp 215–229
- Oliveira NM et al (2015) Biofilm formation as a response to ecological competition. *PLoS Biol*. doi:[10.1271/journal.pbio.1002191](https://doi.org/10.1271/journal.pbio.1002191)
- Riding R (2000) Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. *Sedimentology* 47:179–214
- Schubert JK, Bottjer DJ (1992) Early Triassic stromatolites as post-mass extinction disaster forms. *Geology* 20:883–886
- Serebryakov SN (1976) Biotic and abiotic factors controlling the morphology of Riphean stromatolites. In: Walter MR (ed) *Stromatolites developments in sedimentology* 20. Elsevier, Amsterdam, pp 321–336
- Shapiro RS (2004) Neoproterozoic-Cambrian microbialite record. *Paleontol Soc Pap* 10:5–15
- Swart PK et al (eds) (2009) *Perspectives in carbonate geology: a tribute to the career of Robert Nathan Ginsberg*, Special Publication 41, International Association of Sedimentologists
- Tallinen T et al (2016) On the growth and form of cortical convolutions. *Nat Phys Let*. doi:[10.1038/NPHYS3632](https://doi.org/10.1038/NPHYS3632)
- Touma J, Wisdom J (1993) The chaotic obliquity of Mars. *Science* 259(5099):1294–1297
- Vanyo JP, Awramik SM (1985) Stromatolites and Earth-Sun-Moon dynamics. *Precam Res* 29:121–142
- Williams GE et al (2007) No heliotropism in Neoproterozoic columnar stromatolite growth, Amadeus Basin, central Australia: Geophysical implications. *Palaeogeogr Palaeoclimatol Palaeoecol* 249:80–89
- Wilmeth DT et al (2015) Punctuated growth of microbial cones within Early Cambrian oncoids, Bayan Gol Formation, Western Mongolia. *Palaios* 30(12):836–845

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