69-39

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PAPER 69-39

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ATTRIBUTES OF STROMATOLITES

(Report, 22 figures and 16 tables)

H. J. Hofmann

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ABSTRACT

Stromatolites are a highly polymorphous group of internally laminated organosedimentary structures. Their laminae have characteristic synoptic morphologies which represent successive surfaces of equilibrium between interacting physical, chemical, and biological factors. Two apparently contradictory points of view are currently held. One, based on studies of Holocene forms, maintains that gross morphology and shape of laminae are predominantly controlled by environmental conditions. The other, based on empirical data of the geographic and stratigraphic distribution of fossil stromatolites, holds that stromatolites are mainly biological features and, like organisms, show evolutionary development. Adherents to the latter hypothesis contend that the Late Precambrian can be zoned on the basis of stromatolites.

Although presumed to have been formed under the influence of algal or algal-bacterial communities, most Precambrian stromatolites are neither classified, nor classifiable, on a biological basis. A reasonable alternative is a grouping based on physical or geometric attributes, some of which are defined in this paper more specifically than heretofore. The characteristics that have been used in establishing the reported evolutionary trends include gross morphology, type of branching, marginal features, and microfabric. In view of the high environmental versatility of the Cyanophyta, and their geological record of strong morphologic conservatism, the biological-evolutionary importance of the physical features of fossil stromatolites remains uncertain. It is likely that the observed changes in laminar shape and gross morphology through geological time represent environmental changes rather than biological evolution.

Systematic studies of the lateral variation in attributes of stromatolites, like systematic studies of crossbedding, ripple-marks, and other appositional structures, should prove useful in reconstructing paleoenvironments. Such data on the horizontal variability of stromatolites can then be placed into an overall time-stratigraphic framework, to allow long-term vertical (evolutionary) changes in any of the attributes to be determined. Global correlation of stratigraphic units based on their contained stromatolites will only be practical if particular forms are not recurrent through geological time.

The classification of stromatolites is discussed. Attributes selected for analysis include the microfabric, configuration, linkage, spacing, relief, and inheritance of laminae; the characteristics of stromatolites as revealed by the habit of the accretion vector, surface ornamentation, and internal features; and dimensional, material, positional, and nominal attributes.

ATTRIBUTES OF STROMATOLITES

INTRODUCTION

Regions of the Canadian Shield and peripheral geosynclines contain a great volume of unmetamorphosed, or only slightly metamorphosed, Proterozoic sedimentary rocks. One of the interesting problems is their precise stratigraphic position, because they occur in isolated basins, and do not lend themselves to the biostratigraphic methods of correlation of Phanerozoic rocks. The methods of interbasinal correlation of these sequences that have been used until now are based on studies of field relationships, lithologic character, and radiometric age determinations.

Most of the sequences contain beds with abundant stromatolites of various morphologic types. Although Precambrian stromatolites have been known for about 100 years, very little progress has been made in Canada to determine their possible usefulness in correlation. Studies on modern algal stromatolites in the Bahamas, Florida, Bermuda, and Western Australia have shown that the growth of these structures is predominantly controlled by the environment (Black, 1933; Ginsburg, *et al.*, 1954; Ginsburg, 1960; Logan, 1961; Logan, *et al.*, 1964; Monty, 1965, 1967; Gebelein, 1967, p. 75; 1969, p. 64; Gebelein and Hoffman, 1968, p. 109; Kendall and Skipwith, 1968, Hoffman *et al.*, 1969, p. 28). It has therefore been assumed that they can be of only limited use in biostratigraphy (*see* also Cloud, 1942, p. 369; Anderson, 1950, pp. 6, 7; Johnson, 1961, p. 205; Howe, 1966, p. 72).

While their origin is still under investigation and discussion in North America and elsewhere, a comprehensive study of Proterozoic stromatolites has been under way in the Soviet Union for the last decade. During this time Soviet geologists have amassed large amounts of empirical data on the types of stromatolites and their stratigraphic and geographic distribution, often supported by radiometric age determinations. Based on these studies, they claim considerable success in subdividing and correlating the middle and late Proterozoic deposits of various basins within the Soviet Union (Korolyuk, 1960; 1963; Semikhatov, 1962; Krylov, 1963; 1967; Komar *et al.*, 1965; Komar, 1966; Komar and Semikhatov, 1968; Keller *et al.*, 1968; Raaben, 1969). Their work has resulted in the recognition of a four-fold subdivision of these deposits, each division being characterized by a distinct assemblage of stromatolites or other problematic organic remains (Table 1). (A similar scheme has now also been considered applicable to the Precambrian of Australia by Glaessner *et al.* (1969).)

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Table I

Subdivision of the Middle and Late Proterozoic in the USSR
(Keller, 1966, p. 133; Keller, 1968, p. 20;
Keller *et al.*, 1968, p. 190; Raaben, 1969)

	Radiometric age (m.y.)	Characteristic stromatolites
Cambrian		
	560 ± 10	
Vendian*		*Linella; Patomia*
	675 ± 25	
Upper Riphean		*Gymnosolen; Minjaria*
	950 ± 50	
Middle Riphean		*Baicalia*
	1350 ± 50	
Lower Riphean		*Kussiella*
	1600 ± 50	
Pre-Riphean		

* Some authors treat the Vendian as a separate unit within the Upper Riphean.

The Russian studies appear to show that there exists an evolutionary development in the shape and character of stromatolites, from simple, wall-less types, to complex, multibranched types with differentiated envelopes, as well as an evolution in the microfabric of the lamination (Korolyuk, 1963, p. 498; Krylov, 1963, p. 44, 128; Komar *et al.*, 1965, p. 63; Komar, 1966, pp. 50-53). But not all Soviet workers agree with these interpretations (e.g., see abstract by Miroshnikov *in* Matthes, 1967, p. 723).

We are thus confronted with two apparently contradictory lines of evidence, namely, that stromatolite forms reflect particular environmental conditions, and that they reflect time-dependent biological factors. The question is, which is real: environment or age, or both, or neither? This situation has led to a reconsideration of views on the stratigraphic usefulness of Precambrian stromatolites in Canada. In 1966 a program of systematic study of these structures was started in an attempt to determine whether a Proterozoic stromatolite stratigraphy can be established in North America. Fenton and Fenton (1937, 1938, 1939), Rezak (1957), Donaldson (1963), and Hoffman (1967, 1968) have already shown that stromatolites can be used with confidence in correlation of beds within a single depositional basin. They considered stromatolites to be lithologic markers that represent particular environments. Interbasinal correlation has not been demonstrated, but studies specifically investigating possible long-term evolutionary trends in stromatolite morphology have still not been made on this continent.

If stromatolites are to be used in interbasinal, and eventually intercontinental correlation, it must be demonstrated that their properties are controlled by biological factors, or other factors that can be shown to have evolved through geological time in a systematic fashion. They must furthermore be described and classified according to some objective criteria, using features that are consistent and 'taxonomically significant'. The literature demonstrates that, as yet, there has not been unanimity on these subjects, nor, indeed, on the subject of what constitutes a stromatolite, and how to recognize one (Ginsburg, 1967, p. 339).

The present paper discusses the basic terminology applicable to the description of stromatolite groups ('genera'), and the possible application of stromatolite morphology to the problem of biostratigraphic zonation and correlation in the Precambrian of Canada.

Acknowledgments

Thanks are here expressed to J.A. Donaldson, C.D. Gebelein, R.N. Ginsburg, and P.F. Hoffman for stimulating discussions on various aspects of the topic of stromatolites. R.T. Bell, J.A. Donaldson, and P.F. Hoffman critically read the manuscript. I.K. Crain and G.S. Sayant assisted in the writing of computer programs to obtain print-outs of simulated stromatolite growth forms.

WHAT IS A STROMATOLITE?

The history of the study of stromatolites has been reviewed in great detail by Maslov (1960), Vologdin (1962), Krylov (1963), and others, and need not be repeated here.

Kalkowsky (1908, pp. 68-69) originally coined the term *Stromatolith* (in German), to refer to beds with distinct calcareous masses of fine, more or less flat, laminated structures in the Triassic Buntsandstein of northern Germany. He related their formation to the life activity of the lower plants. He also proposed the term *stromatoid* (p. 101, 104) for the individual laminated structures making up the bioherm or biostrome. The distinction was intended to be analogous to that between *oolith* (oolite) as a rock term, and ooid for the individual spheroidal structures making up the rock (*see* Appendix). Twenhofel (1919, p. 342) later suggested the word *coenoplase* for the morphologically distinct growth forms. Although many authors have stated that Kalkowsky is the originator of the term stromatolith (stromatolite), it is curious that the word stromatoid has been consistently overlooked.[1]

The term "stromatolith" has also been applied to "a rock mass consisting of many alternating layers of igneous and sedimentary rocks in sill relationship" (Foye, 1916, p. 791). Fortunately, however usage in this sense has not continued, and has been made unnecessary with the introduction of the word "stromatite" (Niggli, 1948, p. 109; 1954, p. 150).

Stromatolites had been known for many years for some other parts of the world prior to 1914. Some had been described and named, but their origin has not been well understood. Speculations included, at one time or another, inorganic origin (concretions, deformed bedding), protozoan (*Cryptozoon*, *Archaeozoon*), spongal (*Somphospongia*, *Spongiostroma*, *Pycnostroma*, *Malacostroma*), and later also stromatoporoidal affinities (*Gymnosolen*). The concept that algal activity played an important role in their formation was explained by Walcott (1914), and has been confirmed by other workers who have studied Holocene stromatolites.

It is now recognized that modern stromatolites may be formed in certain environmental settings by a number of different processes and organisms, but predominantly by blue-green algae. The gross morphology of algal stromatolites reflects the environment in which they occur, representing the products

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[1] In fact, 'stromatolite' has been used when 'stromatoid' would have been correct. 'Stromatolite' has now become so widely entrenched in the literature for individual structures that it seems hopeless, and perhaps inadvisable, to try to correct the misuse of the term. Consequently, 'stromatolite' is employed in this paper in the sense in which it appears in the current literature.

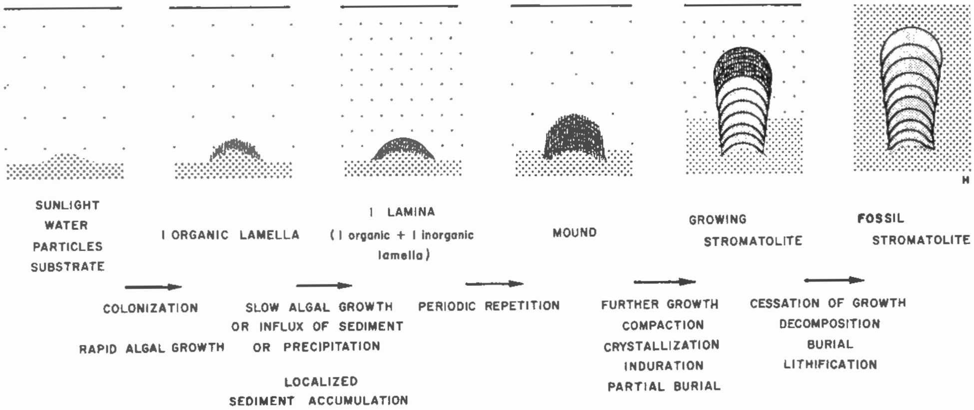

Figure 1. Schematic representation of development of an algal stromatolite.

of the interaction of physical and chemical sedimentation and organic films or plexuses. Laminated structures are built up by accumulations of successive thin layers.[1] They are best developed in the subtidal, intertidal, and supratidal zones of marine-basin margins. Oncolites are here considered as a special category of mobile stromatolites, following the views of Logan *et al.* (1964, p. 69).

There are some modern structures, and fossil analogues, that resemble the marine algal stromatolites, such as calcareous tufa and siliceous sinter (including algal filaments), caliche, folds chemical lamination, and laminated crusts due to subaerial weathering (*see* Donaldson, 1963, p. 8; Multer and Hoffmeister, 1968, p. 183). These may sometimes be difficult to distinguish from stromatolites.

Precambrian stromatolites generally do not contain structurally preserved organic remains or consistent cellular microstructure. This constitutes a serious problem with regard to the identification of the biological entities responsible for the growth of the stromatolite. All that is visible are sections of morphologically distinct structures with lamination. However, by analogy with morphology and geological setting of Paleozoic and modern forms, the partly biogenic origin of Precambrian forms is not seriously questioned now. Microfossils are preserved under special circumstances, such as in stromatolitic chert in the Gunflint Formation, where filamentous cyanophytes, acritarchs, and other micro-organisms can be identified. Nevertheless, the biological control of the shape of the stromatolite containing these microfossils is still uncertain (Hofmann, 1969, p. 19).

The fundamental feature of the stromatolite is the lamination. Individual laminae are composed of a couplet of lamellae that represent periodic growth. In some modern algal structures the couplet comprises a light coloured organic lamella, made up of a monospecific or polyspecific community of cyanophytes and other micro-organisms, with or without trapped detrital or precipitated mineral particles, followed by a thin dark lamella which contains sediment (Monty, 1965, pp. 270-271; 1967, p. 90), but in others, the pattern is reversed (Gebelein, 1969, pp. 59-60, 65). In fossil forms the organic lamellae have generally disappeared, and the lamination consists of texturally or mineralogically differentiated layers which may be alternately dark and light; or it may consist only of light laminae, delineated by thin, filmy boundaries. The development of a stromatolite head is shown schematically in Figure 1.

[1] Certain modern algal structures, such as some intertidal ones built by *Schizothrix calcicola*, are non-laminated (Monty, 1967, p. 86).

In a fossil stromatolite occurrence one may distinguish, aside from constituent mineral grains, 4 distinct structural entities according to their scale of development: (1) the stromatolite bioherm or biostrome (stromatolith of Kalkowsky), (2) the individual stromatolite form (coenoplase of Twenhofel and stromatoid of Kalkowsky), (3) the fundamental lamination, and (4) the rarely present cellular structure of micro-organisms. Each of these four entities has its own features, significant at its own scale of development, yet influencing and dependent in some way on the others. It is evident that the individual stromatolite form occupies the intermediate position, and that it should be considered not only a growth stage of a succession of thin organo-sedimentary laminae (products of the meso- and microenvironment), but also in the context of the larger biohermal system (macroenvironment). Assuming the existence of micro-organisms in a basin, the macroenvironment places limits on the overall extent, size, shape, and make-up of stromatolite development (cf. Logan, 1961, p. 529). For instance, the maximum relief which a columnar *intertidal* stromatolite may attain above the floor is governed by its position in the intertidal zone and by the tidal amplitude. But the development of high relief also requires early and progressive lithification of the column, because otherwise it could not withstand the currents and waves. Hypersaline conditions and a hot arid climate favour rapid lithification (Logan, 1961, p. 531). The maximum size of *subtidal* algal stromatolites ('biscuits', *Collenia*) is also controlled by current velocity, nature of substrate, and degree of induration (Gebelein, 1967, p. 75; 1969, pp. 57-58). When their internal strength is exceeded by the pressure of the current the biscuits are torn up and carried down current and buried, or they develop into passively moving stromatolites (oncolites) by peripheral encrustation.

The orientation, elongation, and sediment-trapping capabilities of fixed algal structures depend on the current pattern, with preferred elongation trending parallel to the current (Goldring, 1937, p. 531; 1938, p. 12, 17, Fig. 10; Logan, 1961, p. 523, 526, 527; Hoffman, 1967, p. 1044; Ahr, 1967, p. 66, 88; Donaldson, 1969, p. 157; Gebelein, 1969, p. 61, 65).

In intertidal and *supratidal* settings, prolonged periods of exposure to the atmosphere favours the formation of extensive encrusting algal mats whose characteristic morphology is a mosaic of polygonal plates resulting from repeated desiccation of the organic mat and bound and cemented sediment. Such forms are represented in the Middle Proterozoic Belt Supergroup (Rezak, 1957, p. 19, Fig. 6), but the application of the name *Newlandia* to them is incorrect (Walcott (1914) originally used it for a quite different type of structure, now interpreted as Liesegang rings, a diffusion phenomenon).

The effects of biological activity on the stromatolite assemblage manifest themselves at the lamination level (microenvironment). Biological activity involves cell growth, with the attendant production and concentration of organic matter into a multitude of small, viable structural entities covering a surface. These entities precipitate, agglutinate, or trap mineral matter, and eventually undergo bacterial decay, and only the hard constituents remain. The preservation of stromatolitic structure would not be possible without the accumulation of this mineral matter. Although precipitation is important in some supratidal algal plexuses (Monty, 1967, p. 75, 96), most mineral matter in modern intertidal and subtidal structures is believed to be agglutinated or trapped from suspension on or in the organic films (e.g., Gebelein, 1969, p. 59, 61). This means that a sediment supply of the proper fine grain size must be available within the macroenvironment. Were it not for the organisms, the removal of fine sediment from suspension would not occur at selected places, and the build-up and preservation of distinct structures could not occur. The sediment has to be localized by traps of sticky or velvety organic films. Yet, the location, extent, and makeup of the algal association are adaptions in balance with the environment, and may be controlled by factors such as sunlight, temperature, P_{CO_2}, water volume, turbulence, ionic concentration, and the presence or absence of competitors and scavengers. If the environment remains uniform, the superposition of successive laminae can continue uniformly, producing a simple stromatolite. If conditions change, the algal community will alter correspondingly, affecting the sediment-trapping capabilities of the plexus. If they fall outside the ecological limits of the community, as when the columnar growth of an intertidal association reaches the level of the high water mark, the algal growth and sediment trapping and binding activity will cease, and the final gross morphology of the stromatolite will have been attained. The latter will only be preserved if it is subsequently buried.

An important question to be answered is: to what extent do the organisms populating the growing stromatolite determine the shape of its laminae and its final form? One would expect that algal anatomy, physiology, and growth cycles might play a significant role in this. For instance, the trapping and binding characteristics of a plexus of dispersed filamentous algae with thick mucilaginous sheaths are probably different from one with crowded, short and thin filamentous forms. However, as the authors cited in the introduction have pointed out, the same algal community, under variable conditions, can originate a variety of structural forms; and conversely, in similar environments similar structures can be built by different algal communities.

If these observations are applicable in general, one must conclude that the chances of using the morphology of fossil stromatolites to reconstruct phylogenetic series are very low indeed. They would also indicate that the evolutionary trends in Riphean stromatolite forms described in the recent Russian literature are controlled environmentally rather than genetically.

In summary, a stromatolite as understood in the present work, is a millimetre- to decametre-sized organosedimentary structure whose growth is recorded by a succession of laminae. These laminae represent intervals of accumulation of fine sediment on surfaces presumed to have been populated by a community of micro-organisms. The sedimentary material is accumulated by trapping or agglutination of particles from suspension on the organic film, or by direct or indirect precipitation resulting from the metabolic activity of elements of the microbiota.

As a supplementary remark one should mention the recent recovery of stromatolite-like structures from the deep sea. Stratiform, turbinate, and branching columnar forms with internal lamination occur as a ferro-manganese pavement on the San Pablo Seamount in the western Atlantic, at a depth of about 1,800 metres (6,000 feet) (Aumento *et al.*, 1968, p. 5, Figs. 3 and 5). The bodies, here reillustrated in Figures 2 and 3, have a resemblance to some of the stromatolites from Aphebian rocks associated with iron-formations (e.g., Donaldson, 1963, Pls. 4, 5; Hofmann, 1969, Form A). If they are considered stromatolites, the range of environments of stromatolitic structures extends beyond the terrestrial and shallow marine environments.

GEOMETRIC ATTRIBUTES OF STROMATOLITES

Regardless of what the ultimate nature of the biological contribution may have been, the fossil stromatolite is above all a body with certain geometric characteristics. They are all that is left for us to study, to describe, and to interpret.

The present discussion rests on the assumption that the essential feature of a fossil stromatolite is the existence of a mineralogically or texturally differentiated lamination. The laminae render a preserved record of successive periods of accumulation of sediment on surfaces presumed to have been inhabited by communities of micro-organisms. Microstructures definitely identifiable with biological entities are almost always lacking in Precambrian forms, so the biological makeup of the consecutive encrusting organic lamellae

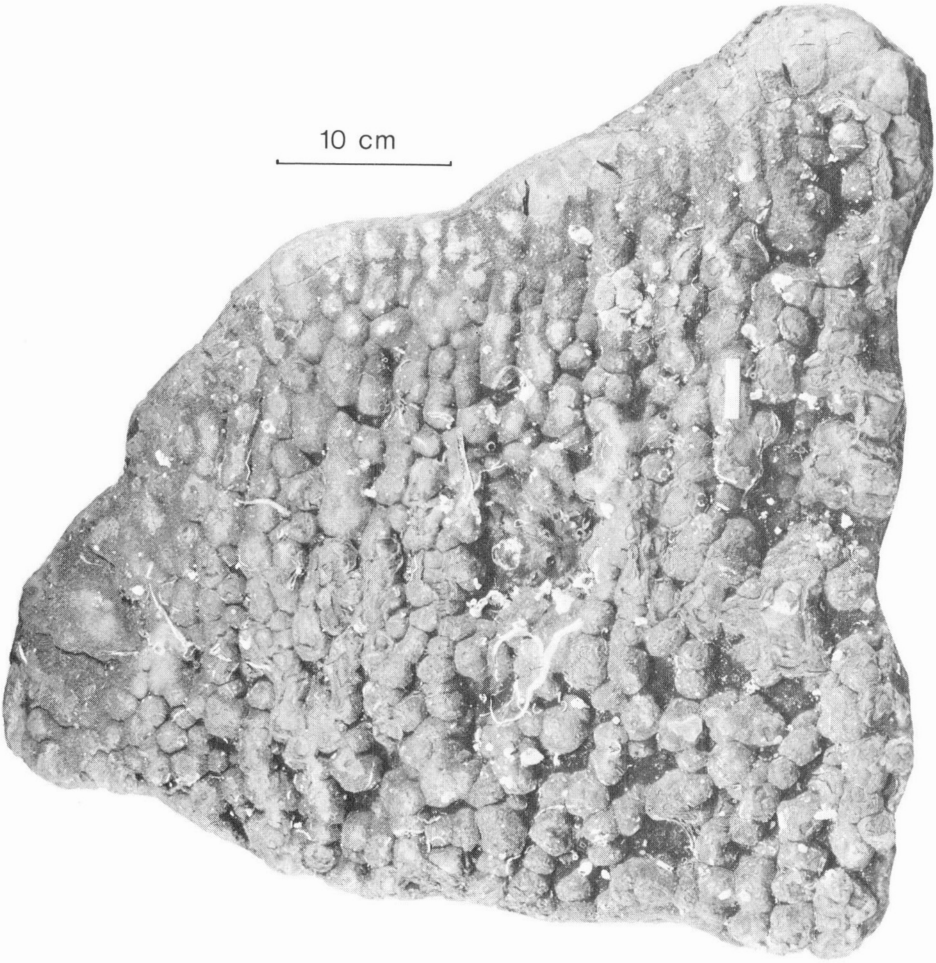

Figure 2. Deep sea stromatolitic structures. Top view of a large specimen of 'ferro-manganese pavement' from the San Pablo Seamount in the western Atlantic, from a depth of 1,800 metres. Note the close spacing and uniform size of the hemispheroids. (See also Aumento *et al.*, 1968, p. 4.) GSC specimen AG-67-54-1. (200435-B.)

remains obscure, and the structures remain unclassifiable on a biologic basis.[1] Some stromatolites may be completely inorganic. The only reasonable alternative scheme for the identification and grouping is one based on

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[1] The possibility of eventually assigning specific biologic taxa to certain morphologically distinct types of Precambrian stromatolites exists, but this seems extremely remote at present. In Holocene settings certain forms are built by pure communities, e.g., *Schizothrix calcicola* (Monty, 1965, p. 270), others are polyspecific. But even the taxonomy of modern Cyanophyta on the species level is a matter of disagreement amongst algologists.

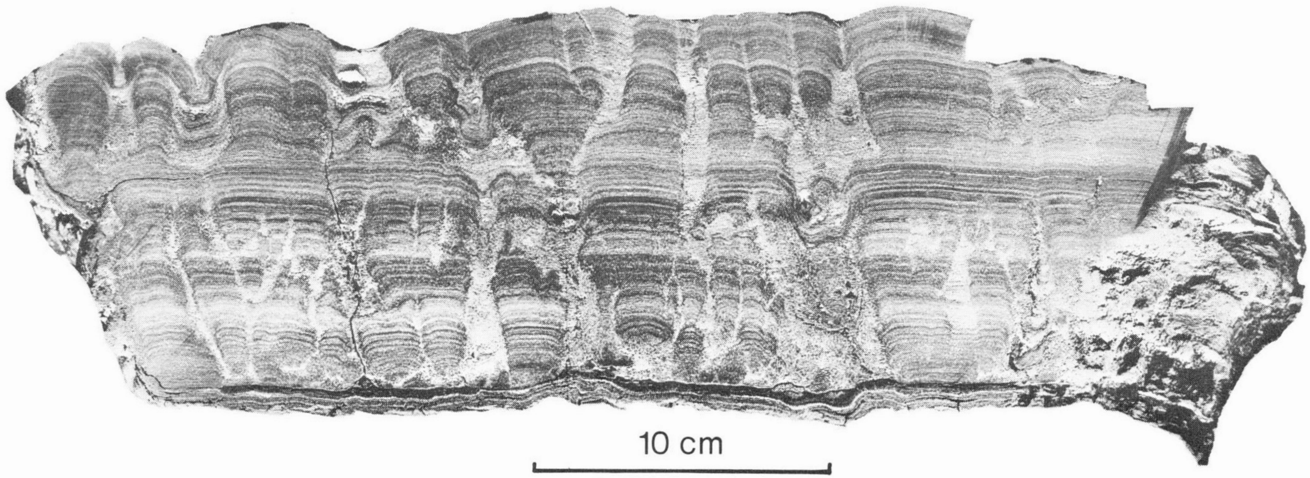

Figure 3. Deep sea stromatolitic structures. Vertical section of the slab illustrated in Figure 2, exhibiting branching columnar forms (*see* Aumento *et al.*, 1968, p. 8). GSC specimen AG-67-54-1. (200496).

geometric properties. The usefulness of such a geometric scheme will be limited, and will depend on the 'correct' choice of characteristics, as well as the observer's acuteness of perception.

An approach to the description and classification lies in the recognition that this problem is one of form and growth. The template of the assemblage is the basic lamina with a certain configuration (a 3-dimensional feature because it has thickness as well as length and width). The form is repeated more or less regularly while moving upward through space (4th parameter) and on through time of accumulation (5th parameter). This process of stacking of laminae generates the final gross structure which we call a stromatolite. A possible 6th parameter is that of biologic evolution of the stromatolite-building micro-organisms, insofar as changes in their morphology, communal makeup, etc. may result in evolutionary trends in stromatolite morphology through geological time.

In general, the shape of the first layer of accumulation will be inherited from the shape of the colonized substrate. That of later laminae will be governed more and more by the nature, distribution, and metabolic activity of the organisms populating the surface, on physical and chemical conditions of the environment, and on the availability and nature of suspended particles. As the stromatolite grows, a certain tropism becomes evident. Disregarding post-diagenetic effects, the final gross configuration is the result of the variability in the magnitude and direction of consecutive laminar increments. If the collective influences (physical, chemical, biological) are uniform on all sides of a point source, the stromatolite on a flat substrate will grow with equal increments on all sides to a hemisphere. If collective influences are anisotropic, growth will be favoured in one direction and retarded in others, and diverse gross morphologies will be generated. It is thus possible to treat the growth forms of stromatolites as vector quantities. One should here recall that, while we may be able to determine the biological influences in modern forms, in fossil forms we can only determine the preserved succession of growth surfaces and their shapes. The growth vectors are treated simply as geometric properties.

In most stromatolites the basic lamina approximate hemispheroids in form, and so the hemispheroid may be chosen as the fundamental unit whose shape and size evolves through the time of stromatolite growth (Fig. 4).

The centres of the successive partial spheroids (with radius = r) are displaced upward (Δu) and may be vertically superposed ($\theta = 90°$) or laterally shifted (stromatolite is inclined). The structure may grow with or without concomitant intermound sedimentation (matrix accumulation; Δs), and thus be without or with layers that envelop older ones (absence or presence of 'wall' or 'envelope' of Korolyuk, 1960). Or it may be partly walled if Δs varies (*see* also Krylov, 1963, pp. 47-49). The spacing (T) between consecutive laminae along the vector of displacement of hemispheroid midpoints corresponds to the thickness of the laminae. At any one time the growing body will have a relief (h), but the final structure may be much taller (H) than relief at any particular instant (this distinction between relief and total height of structure is important). The relief can be expressed relatively as low ($2r \gg h$), moderate ($2r \approx h$), and high ($2r \ll h$).

It is clear that the final growth form (gross morphology) is simply dependent on the rate of increase in the radius with respect to the displacement of the centres of successive hemispheroids $(\frac{\Delta r}{\Delta u})$. This ratio, which is a measure of the anisotropy of growth at constant laminar shape, is here designated the *growth factor* and given the symbol G. The concept of the growth factor provides for the expression of stromatolite form in numerical terms, and is amenable to computer processing.

In order to better visualize the usefulness, let us consider a co-ordinate system based on the hemispheroid and on *growth vectors*. Growth vectors are imaginary lines connecting *analogous points* on consecutive laminae

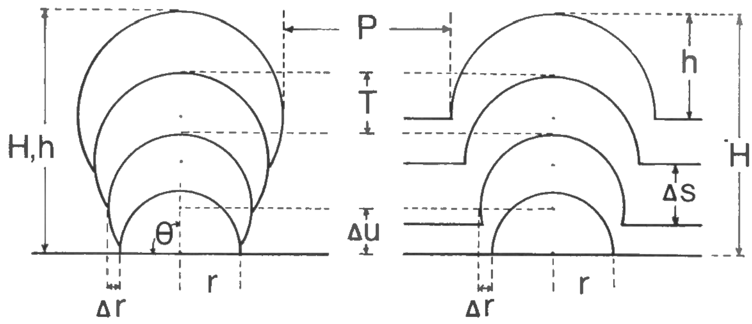

Figure 4. Schematic representation of growth of stromatolite structure: generation of gross morphology by superposition of the basic hemispheroid.

Left: stacking of successively larger hemispheroids without concomitant intermound sedimentation.
Right: stacking with concomitant sedimentation.

H - total height of structure
h - relief of lamina
P - spacing between adjoining hemispheroids (packing)
T - thickness of lamina
r - radius (half span) of hemispheroid
θ - angle of inclination of axis to bedding
Δr - increase in radius of successive hemispheroids
Δu - upward displacement of centre of successive hemispheroids
Δs - thickness of sediment matrix accumulated in intermound area during time in which corresponding hemispheroid was formed

The ratio $\frac{\Delta r}{\Delta u}$ is a measure of the anisotropy of growth (rate of expansion); it is designated the 'growth factor' and given the symbol G.

(Fig. 5). The ones shown in the figure are those connecting all points of tangency to the hemispheroids in the horizontal, 45-degree, and vertical positions. For instance, in the case of vertical superposition without change in radius ($G = \frac{0}{\Delta u} = 0$), all growth vectors are parallel because the analogous points are all displaced equally. Where the change in radius equals the upward displacement of the hemispheroid, G = 1. The numerical value of G is actually equal to the *tangent* of the angle subtended by the vector connecting the point of horizontal tangency and the vector connecting the points of vertical tangency. In the case where a change in radius occurs without displacement of the centre ($G = \frac{\Delta r}{0} = \infty$), we have concentrically stacked hemispheroids (or spheroids in oncolites).

It is interesting to note that all these growth forms can be considered to be basically the same, because one form can be changed into the others simply by transformation of the co-ordinate system (Thompson, 1942, p. 1026). In this context it is possible to view tabular stromatolites (flat laminations)

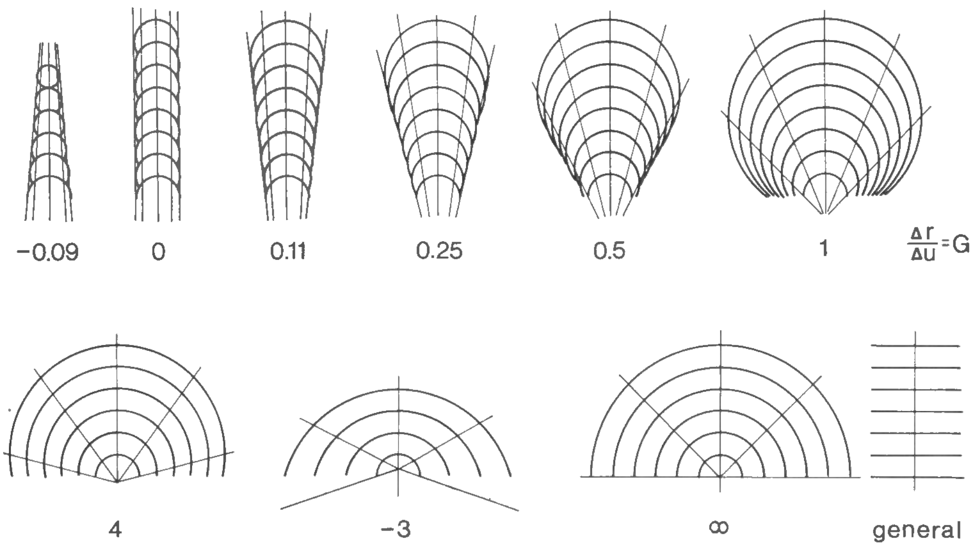

Figure 5. Generation of different morphologies by stacking of hemispheroids under various conditions of growth anisotropy. The straight lines represent growth vectors of analogous points on successive hemispheroids. The values of the growth factor ($\Delta r/\Delta u$) range from -0.09 to ∞. All the forms are related inasmuch as each can be transformed into all the others by deformation of the co-ordinate system.

as a general case for all others, with an infinite radius. Also, the concave-up laminated forms can be regarded as having a deformed, upwardly converging co-ordinate system.

In order to develop this aspect further, a simple computer program was utilized to print out growth forms for various values of G, with T, Δr, Δu constant, $\Delta s = 0$, $\theta = 90^\circ$, and no flattening of the spheroid (Fig. 6)[1]. The potential use of these quantitative data in description and classification of stromatolites is evident. Structures can be identified with better precision according to readily measurable or computable quantities. Or, if desired, they can be assigned to classes with arbitrary limits as suggested in Figure 4: columnar (terete[2], cylindrical, turbinate), bulbous, nodular, and stratiform. For example, *Archaeozoon* Matthew and *Colonella* Komar (and also *Conophyton* Maslov emend.) have G-values close to zero (they are columnar); those of the bulbous *Cryptozoon* Hall are between about 0.4 and 0.8; and *Nucleella* Komar is nodular. In addition to providing a visual expression of the various growth factor values, the computer print-out also demonstrates how geometric parameters limit the development of terete forms.

One may note here that the formation of the 'wall' or 'envelope' (Korolyuk, 1960, p. 117) is in part related to the growth factor, a purely geometric property. Forms with low numerical G-values are not as likely to

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[1] 3200 Fortran IV program written by G.S. Sayant; data obtained with CDC 3100 computer and Calcomp plotter.

[2] This is quite distinct from *conical*, as applied to the shape of individual laminae.

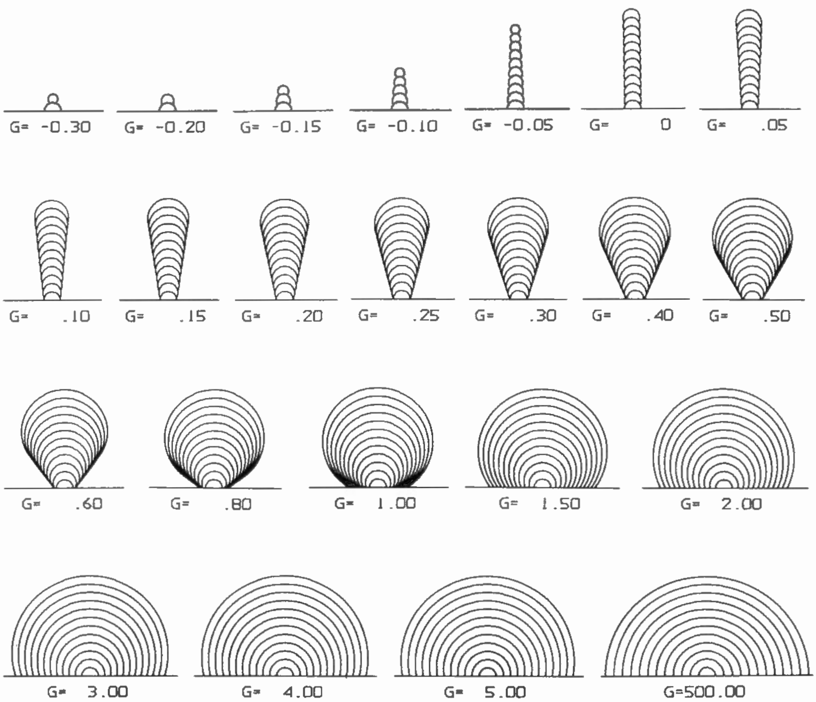


Figure 6. Computer-generated growth forms having different growth factors (G) but constant laminar shape (partial or extended hemispheroid). T, Δr, Δu are constant; $\Delta s = 0$, $E = 1$, and $\theta = 90^{\circ}$.

The forms can be grouped according to their G values as follows:

columnar {
- terete: $G < -0.087$ ($<\tan -5^{\circ}$)
- cylindrical: $G = -0.087$ to 0.087 ($\tan -5^{\circ}$ to $\tan 5^{\circ}$)
- turbinate: $G = 0.087$ to 0.41 ($\tan 5^{\circ}$ to $\tan 22\ 1/2^{\circ}$)

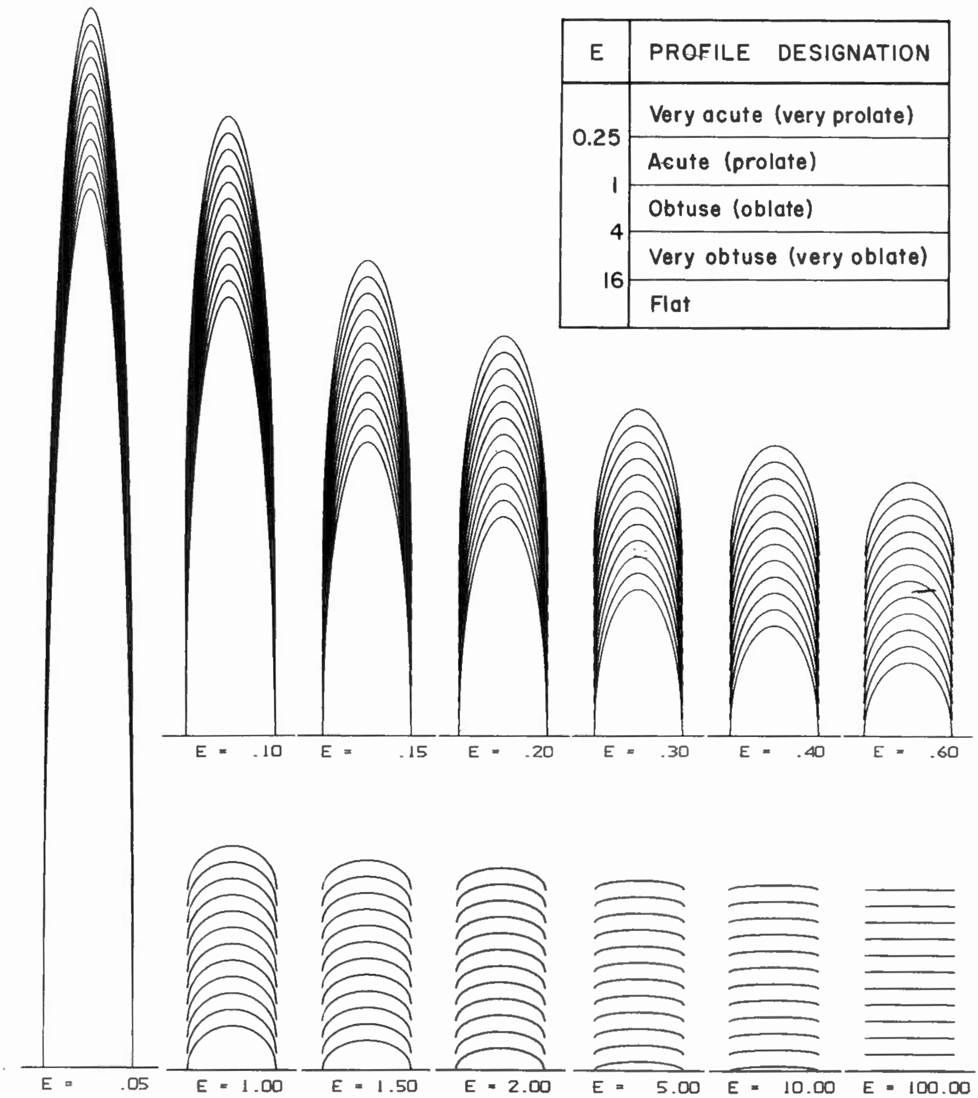
bulbous: $G = 0.41$ to 1.0 ($\tan 22\ 1/2^{\circ}$ to $\tan 45^{\circ}$)
nodular: $G > 1.0$ ($>\tan 45^{\circ}$)
stratiform: $G = \infty$ (with $r \to \infty$)

The above 3-dimensional terms can be applied if the forms are more or less equiform in plan view. If elongated, the forms can be identified as flattened cylindrical, etc., using the growth factor of the smaller diameter as reference.

have it as those with values higher than about 0.3. However, as mentioned further on, the presence of the wall also depends on the rate of matrix accumulation; if the rate is relatively high, even forms with G-values of 1 may be without walls.

Oncolites are a special group of detached and mobile stromatolites with extended hemispheroidal (globoidal) or complete, encapsulating laminae. Their G-values are larger than 1 because of their nucleated nature and centrifugal accretion. Technically, they can be included with stromatolites that have walls, because younger laminae enclose older ones.

Before continuing the discussion of gross morphology, let us digress briefly and look more closely at the geometry of the individual laminae. Although the general form approaches the hemispheroid or partial spheroid, most actual configurations are deviations from this ideal form of uniform curvature. They may be considered as 'deformed' partial spheroids, the simplest



E	PROFILE DESIGNATION
	Very acute (very prolate)
0.25	
	Acute (prolate)
1	
	Obtuse (oblate)
4	
	Very obtuse (very oblate)
16	
	Flat

Figure 7. Computer-generated growth forms having different degrees of elliptical laminar curvature (E), but the same growth factor (G = 0). The profiles can be grouped according to their E values as shown. By inverting the figures, concavities can be expressed quantitatively in a similar fashion. Terms expressing 3-dimensional configurations are given in brackets.

of which is the partial ellipsoid. Again using a simple computer program,[1] another family of growth curves (Fig. 7) was obtained for different degrees of elliptical laminar curvature (E), and uniform growth factor (G = 0). The value of E is the ratio of the horizontal axis of the ellipse, divided by its

[1] Program written by I.K. Crain.

CONFIGURATION OF LAMINAE

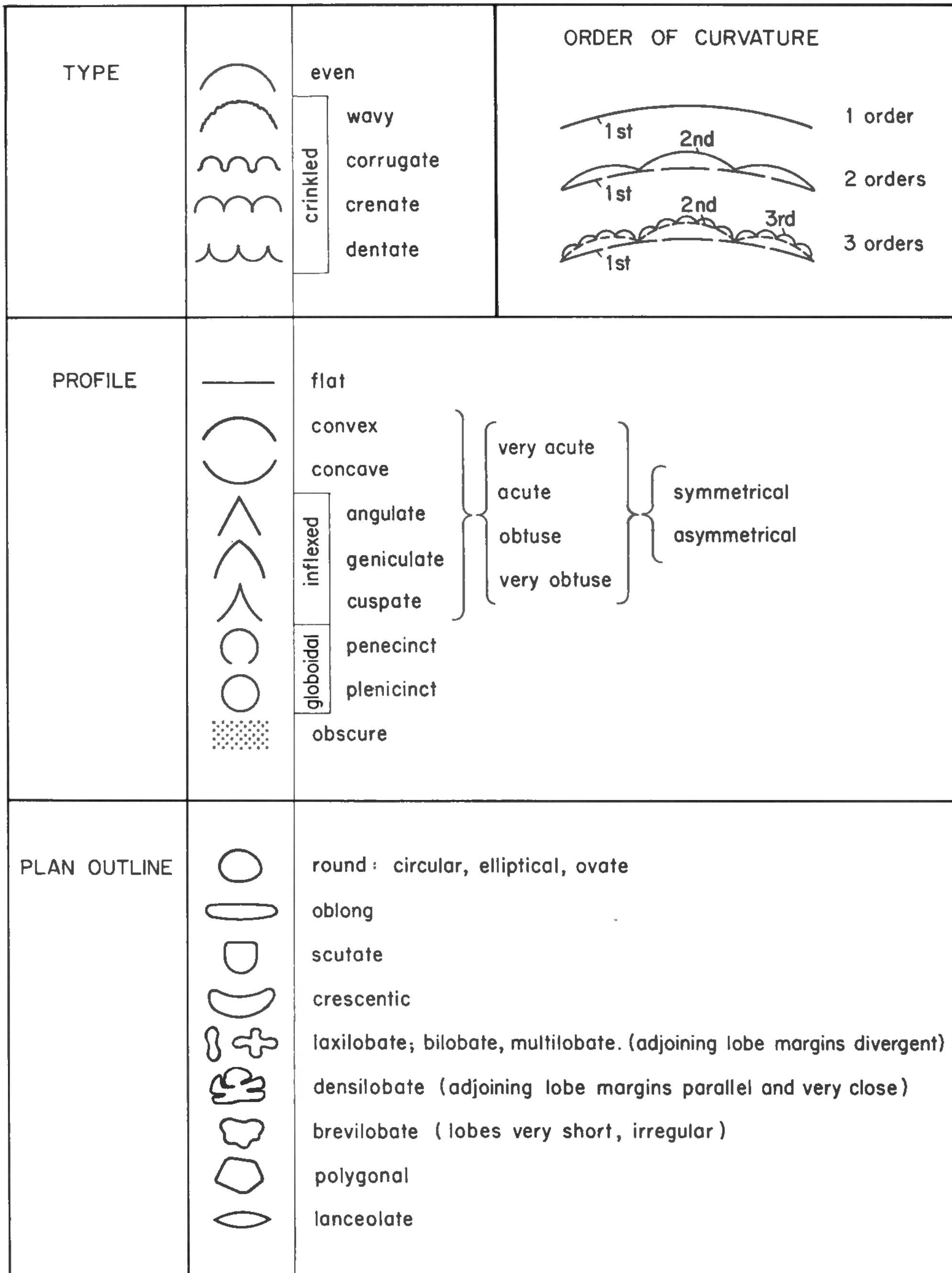


Figure 8.

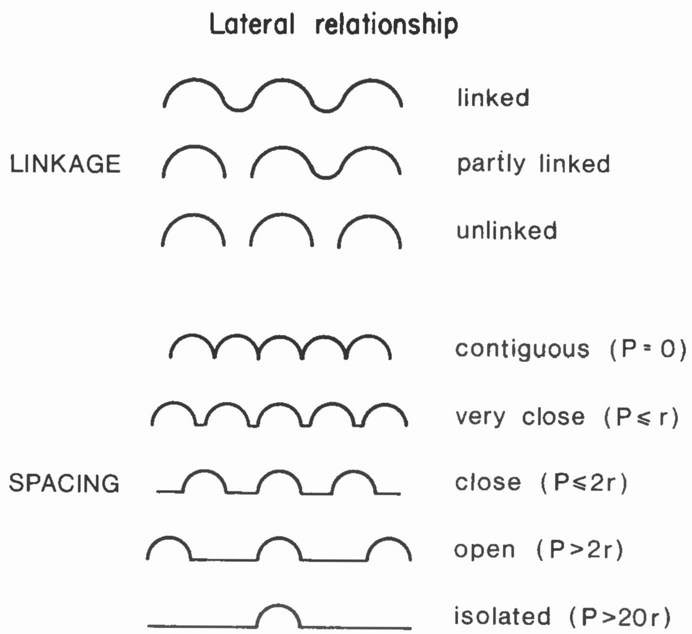


Figure 9. Lateral relationships of synoptic hemispheroids: linkage and spacing. P - spacing, r - radius.

vertical axis. The laminar profiles can be grouped into acute (prolate), obtuse (oblate), and flat types, as suggested in the illustration, using arbitrary boundaries. Once more it is evident that the presence or absence of the 'wall' is related to purely geometric factors, tending to be closely associated with acutely convex (prolate) forms.

Only two examples of growth curves have been illustrated here, but it is obvious that one could present illustrations encompassing many pages, simply by combining different values of G and E. There are, however, other configurations which should be mentioned, and these are summarized in Figure 8. The *concave* profile is sometimes encountered, and is attributed, as a rule, to stromatolites that result from desiccation of tabular assemblages exposed to the atmosphere. The curvature may thus be due entirely to mechanical factors, and therefore not a primary curvature. *Globoidal* profiles are obtained in oncolites, where laminae envelop a body completely or almost completely. Such profiles are made possible by the detached, nucleated, and mobile nature of these bodies. Profiles appearing with points or very small areas of inflection at the top are *angulate*, *cuspate*, and *geniculate*, depending on whether the sides are straight, concave, or convex, respectively; they may be acute or obtuse. Profiles with inflections are a characteristic of the enigmatic *Conophyton*, but are also found in other groups. If the points or areas of inflection are somewhat rounded we may speak of them as being subangulate, subcuspate, and subgeniculate. All such profiles may be symmetrical or asymmetrical. If the laminae are nearly obliterated the profile is *obscure*.

The laminae may also comprise *crinkled* forms, in which case the *orders* of curvature of a lamina both in profile and plan views can be distinguished. For example, a small hemispheroid (3rd order) may be part of a larger one (2nd order), which in turn is part of a still larger one (1st order), as in some specimens of *Cryptozoon* (e.g. Goldring, 1938, p. 34) or in the

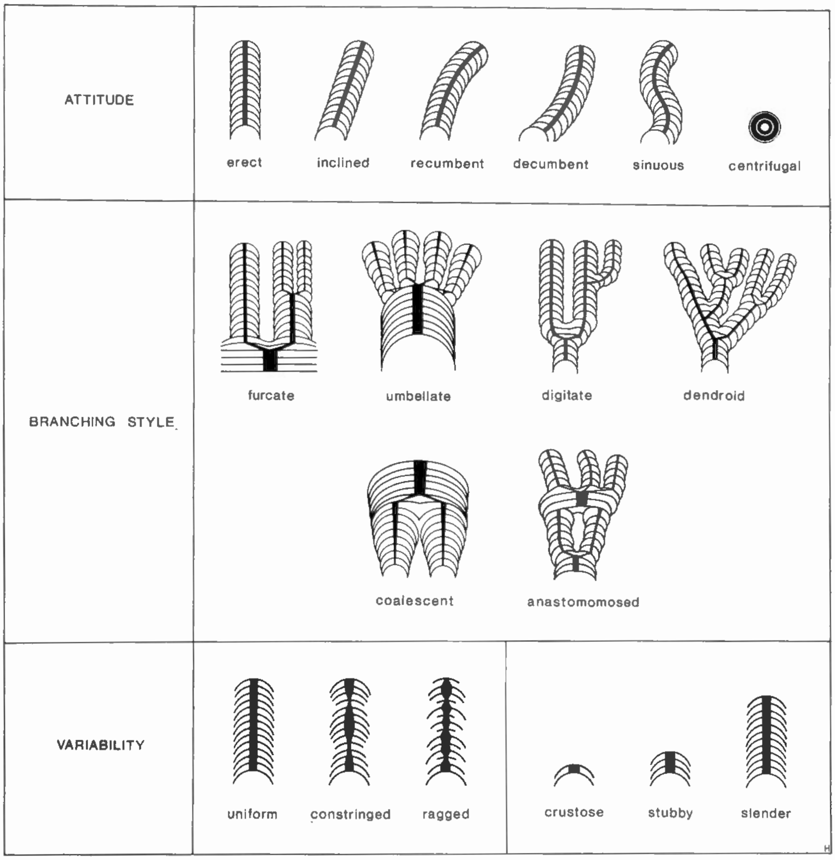


Figure 10. Habits of accretion vector.

oncolite *Ottonosia* Twenhofel. The crinkling can further be described as wavy, corrugate, crenate, or dentate, according to the nature of the indentations (Fig. 8).

To complete the description of laminar forms, the shape as seen in plan view needs to be considered. The terms suggested are also illustrated in Figure 8.

In relation to adjoining ones, hemispheroids may be linked, partly linked, or unlinked, and they may show contiguous, close, open, or isolated spacing (Fig. 9).

In terms of size they may be grouped according to the span or diameter (2r) of the hemispheroid, into μ-sized (2r<1 mm), millimetre-sized (1-10 mm), centimetre-sized (1-10 cm), decimetre-sized (1-10 dm), and metre-sized (1-10 m) forms. Their relief (h) is partly a function of their shape. In terms of orientation, elongated shapes are recorded by azimuth.

The detailed expression (microstructure) of the laminae is extremely variable amongst different stromatolites, and even within a single stromatolite. Some have been described as ribboned, striated, lumpy (e.g., Komar, *et al.*, 1965), but many defy a description that can be translated into different languages without change in meaning. It is best to illustrate each type individually.

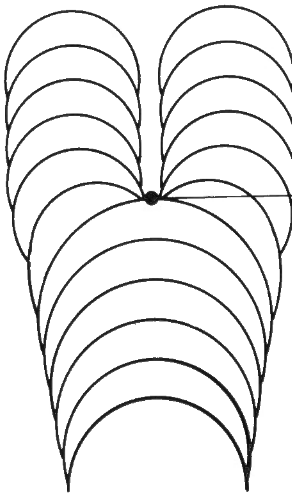


Figure 11.

Formation of constraint, interrupting uniformity of the inheritance process, and thereby developing a stromatolite with branches.

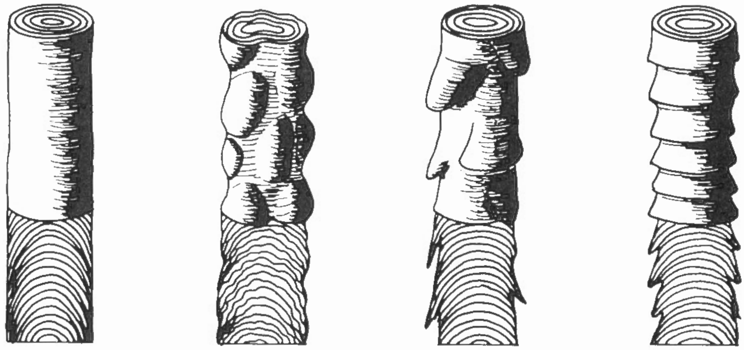
Now let us return to the discussion of gross morphology. The form of the stromatolite body is generated by the process of stacking of laminae and depends on the degree and duration of inheritance of the laminar form. Stromatolite growth in nature is very seldom uniform, that is, the upward maintenance of constant laminar shape and size through the time of accumulation of a column is variable. This variability is manifested in several ways, and can be visualized with reference to the habit of the *accretion vector*. The accretion vector is that growth vector which joins the mid-points (centres) of successive laminae, and whose strength at any one level is a measure of the surface area of the lamina at that level. It is a most useful concept in that it represents the stromatolite form reduced to its simplified geometric essentials (Fig. 10).

The patterns of these vectors, emphasized by heavy lines in the illustration, fall into different categories. One aspect of variability involves that of the value of the growth factor (G), which is an indication of the upward change in span of the laminae, and consequently, of degree of peripheral irregularity. This characteristic may be uniform (ΔG is 0), constringed (if ΔG variation is relatively slow), or ragged (if ΔG varies rapidly).

Another aspect involves the upward maintenance or duration of the stacking process. The accretion vector (and the stromatolite) can be described as crustose ($H \ll 2r$), stubby ($H \approx 2r$), or slender ($H \gg 2r$).

A third aspect of variability relates to the attitude of the accretion vector, for which adjectives such as straight, curved, and centrifugal are available. More specifically, the straight and curved attitudes can be described as erect, inclined, horizontal, recumbent, decumbent, and sinuous.

Then there is the style of branching, which is a basic feature of stromatolites with convex laminae, yet whose full significance is still obscure. The geometric aspect of branching entails the formation of points, lines, or areas of constraint or resistance which limit uniform inheritance (Fig. 11). These loci of constraint are associated with the splitting of one order of curvature into higher orders (formation of subsidiary convexities), usually accompanied by an increase in the degree of curvature (decrease in r) of the laminae in the proximal parts of the branches. Two different habits have been recognized by Russian geologist: active (true), in which the branches increase the width of the structure, and passive (false), in which columns branch into smaller ones without increase in total width of structure. The latter is illustrated in Figure 10 as *furcate*. With the furcate habit,



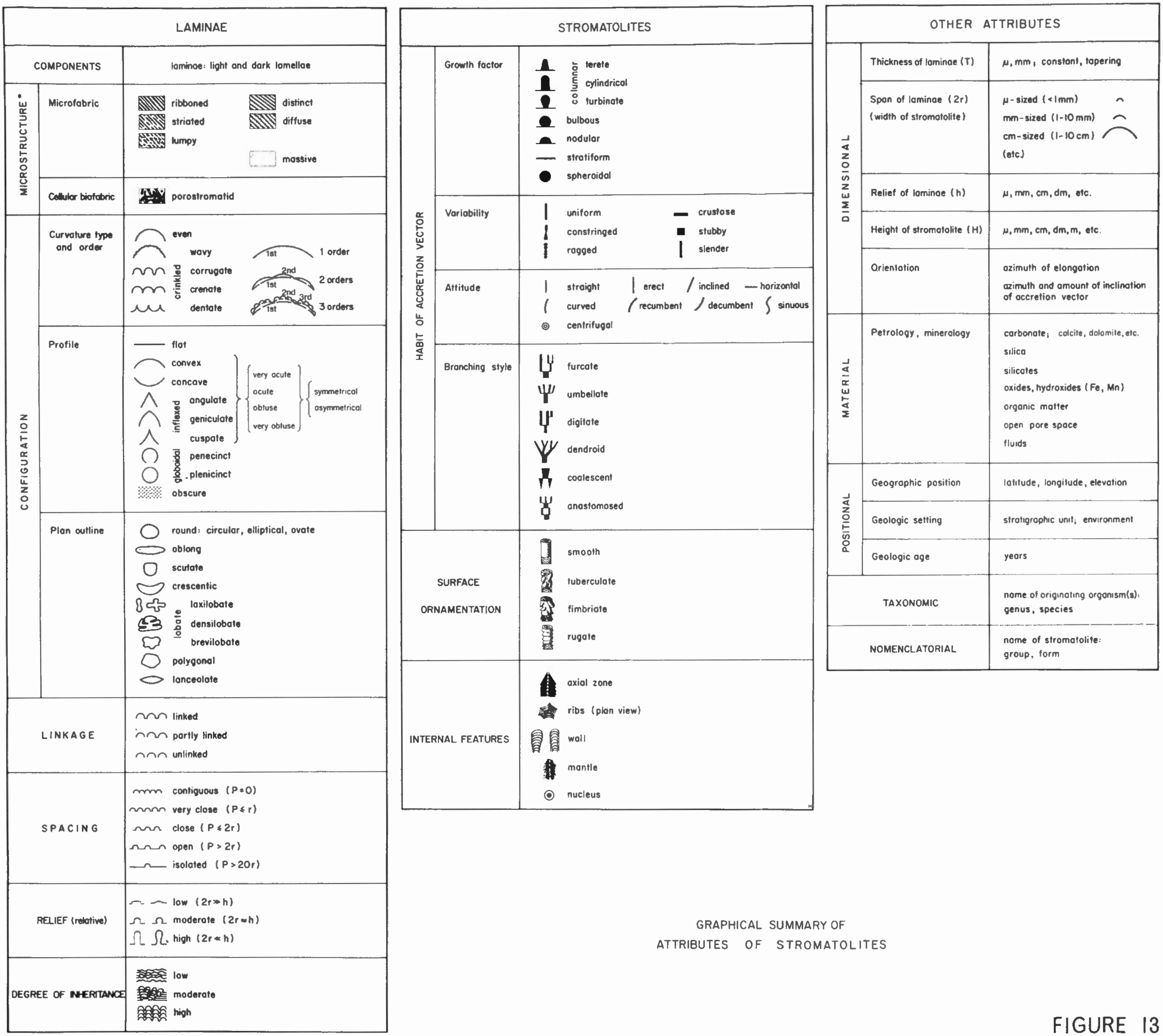
smooth tuberculate fimbriate rugate

Figure 12. Surface ornamentation.

the branches are as a rule erect and parallel, or nearly so. The active type of branching is here further characterized as *digitate* or *dendroid*, according to whether the branches are parallel to subparallel, or noticeably divergent. The term *umbellate* is introduced for structures that, at a certain level, pass into several considerably smaller, diverging branches. Less common are forms which are *coalescent* ('inversely branched'), that is, the stromatolite has root-like columns with laminae of small but increasing diameters, eventually growing together to fewer columns with large diameters. In these forms any initial constraining effect is progressively eliminated. Still others are *anastomosed*, exhibiting both branching and fusion. It should be kept in mind that the habits illustrated in Figure 10 are merely some representatives of a whole range of intermediate types. Additional terms may eventually be desirable.

Some stromatolites also contain internal features. *Axial zones* and radial *ribs* are characteristics of *Conophyton*. Viewed in 3 dimensions, the axial zones are narrow cylinders, and the ribs are actually sheet-like planar forms. They are zones containing the sharp inflections of the laminae, and lie along growth vectors. Two other structures one might consider are the *wall* or *envelope* (Korolyuk, 1960), and the *mantle* (Raaben, 1964; *see* Komar, *et al.*, 1965, p. 18). The wall contains the marginal, downwardly directed, encrusting portions of laminae which are in contact with a matrix whose accumulation postdates that of the lamina with which it is in contact. The mantle refers to a narrow peripheral zone of a nonlaminated microfabric different from the laminated central portion of the stromatolite. It is a characteristic of certain forms of *Conophyton*.

Finally, there is the variable external characteristic of the shape of the lateral boundaries of stromatolites. Ideally, this feature is determined only by viewing the entire stromatolite completely removed from the encasing matrix. Except for forms with some sort of chemical or physical contrast with respect to the matrix, which would allow them to be removed (e.g. silicified stromatolite in limestone), the lateral surface of fossil forms is not generally accessible. To determine their nature it is therefore necessary to make a reconstruction based on serial sectioning. Surfaces may then be described as smooth (no irregularities), tuberculate (with small nodes), fimbriate (fringes or lips hanging down), and rugate (rhythmically constringed) (Fig. 12). However, the method of serial sectioning is only practical in specimens of manageable size. Stromatolites several metres across, or of the height of a telephone pole, are hardly amenable to this technique.



GRAPHICAL SUMMARY OF ATTRIBUTES OF STROMATOLITES

FIGURE 13

* Only very few varieties of microstructure are illustrated here.

There is also the question of the value or significance of this information in classification. The nature of the peripheral surface is related to the formation of the wall and depends on how the laminae terminate against the matrix, and therefore in part on the relative rates of stromatolite accretion (Δu) an intermound sedimentation (Δs). Columns formed under low rates of matrix accumulation are more apt to be walled and smooth or tuberculate, than fimbriate and rugate. Fringed or veiled stromatolite forms do not represent streamlined conditions; moving water would soon tear off the fringes. The sedimentation rather kept more or less in step with stromatolite growth, allowing the laminae to partly cover intermound areas, sometimes completely so as to form connecting layers, or linked hemispheroids. The shagginess of a stromatolite surface thus appears to be important in so far as it records relative rates of sediment accumulation.

The basic terminology for properties of laminae and stromatolites has now been presented. The attributes are summarized graphically in Figure 13.

CLASSIFICATION OF STROMATOLITES

While some basic problems, such as what the lamination of fossil stromatolites signifies (diurnal, tidal, monthly, or seasonal cycles, etc.) are not yet fully understood, stromatolites nonetheless have unique characteristics which allow them to be properly recognized as a distinct group of phenomena requiring a classification of their own. A great diversity of morphological types exists, and a conviction that these can and should be subdivided or grouped for comparison into convenient categories has led to the publication of numerous schemes.

The classification of stromatolites is still a matter of contention. There are several reasons why no single scheme yet proposed has found favour with all geologists. One, which is due to the great morphological variability, is the lack of agreement on what constitute significant diagnostic features which can be used with some degree of consistency and objectivity. Another is that stromatolite studies have often been stratigraphically or geographically restricted, and have emphasized only one or the other of their characteristics. In addition, the significance of the biological aspects of the fossil forms is stressed by some, and discounted by others.

Fossil stromatolites have received binary names, a practice that originated when these structures were interpreted as skeletal remains of the lower forms of animal life. Later it became clear that ancient stromatolites are neither organisms, or parts of organisms, nor purely sedimentary structures. The propriety of using Linnéan names for them therefore had to be questioned (Høeg, 1929, p. 8; Cloud, 1942, p. 363, 366; Maslov, 1953, p. 108; and others).

The first classification of Precambrian stromatolites was made by Walcott (1914, p. 104) on the basis of external form. He divided his Beltian algal structures into 4 categories (Table 2). Of these 'genera' only *Cryptozoon*, *Weedia*, and *Collenia* can be considered stromatolites in the presently understood sense of the term. Other previously named forms, such as *Archaeozoon* and *Gymnosolen* were not recognized in the Belt Supergroup, and do not appear in Walcott's scheme.

A subsequent classification, based on growth form, was that of Pia (1927, pp. 36-37; 1928, p. 212), which was later followed, with modifications, by others (e.g. Johnson, 1943, 1961). Pia included in his thallophyte Class Schizophyceae two major groups, the Spongiostromata (without distinct organic microstructure, but often with characteristic growth forms), and the Porostromata (with distinct, microscopic tubes [these are assignable to algal taxa]). Pia questioned the validity of named 'species' as distinct entities, and only classified the 'genera'. His scheme for the Spongiostromata is reproduced in Figure 14 and Table 3.

TABLE 2

Classification of algal structures from Belt Supergroup
(Walcott 1914)

Massive-Cellular	*Camasia spongiosa*
Semisphaerical	*Cryptozoon* and its allies *?Newlandia concentrica* *Weedia tuberosa* *Collenia undosa* *Collenia compacta*
Flabelliform	*Newlandia frondosa* *Newlandia lamellosa* *Newlandia minor* *Kinneyia simulans*
Tubiform	*Greysonia basaltica* *Copperia tubiformis*

TABLE 3

Stromatolite classification of Pia (1927)

Spongiostromata

a) Stromalolithi (growing attached to substrate)

Weedia Walcott
Spongiostroma Gürich
Collenia Walcott
Cryptozoon Hall
Archaeozoon Matthew
Gymnosolen Steinmann

b) Oncolithi (growing loose; mobile on substrate)

Pycnostroma Gürich
Spongiostroma Rothpletz non Gürich
Osagia Twenhofel
Ottonosia Twenhofel
Wingia Seely

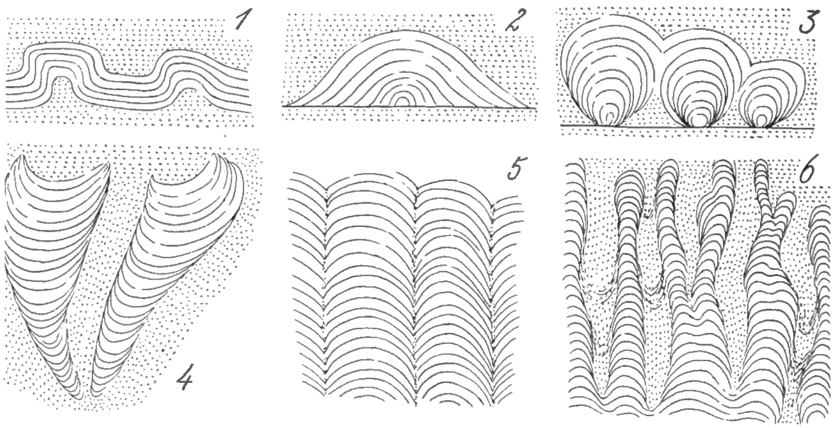


Figure 14. The most important growth types, according to Pia (1927, p. 37).
1. *Weedia* Walcott
2. *Collenia* Walcott
3. *Cryptozoon* Hall
4. '*Cryptozoon*' *boreale* Dawson
5. *Archaeozoon* Matthew
6. *Gymnosolen* Steinmann

Maslov (1937a, 1937b, 1938, 1939a, 1939b, 1939c) recognized only two major types of stromatolites. One with convex laminae, he assigned to *Collenia* (including in this the 'genera' *Cryptozoon, Archaeozoon, Weedia,* and *Gymnosolen*)(1939c, p. 306). The other, with conical laminae, he named *Conophyton* (1937b, p. 334, 344). He was the first to utilize the type of lamination together with gross morphology in the study of stromatolites, and the first to illustrate hypothetical phylogenetic relationships between the 'species' of the *Collenia* group (1939c, p. 298, 300). He also described oncolites, and gave the first descriptions of the microproblematica now known as katagraphs.

Another classification was introduced by Krasnopeeva (1946),[1] who, while considering the shape and microfabric of the laminae, placed the strongest emphasis on the mineralogy of the rocks which compose the stromatolite. Her scheme was based on the assumption that the physiochemical conditions of the environment controlled the biological and biochemical make-up of the organic lamellae. Four 'genera' were established (Table 4).

Anderson (1950, p. 7) found existing classifications unsatisfactory, and referred his Carboniferous stromatolites to diagrams of a series of 12 formalized growth forms (Forms A to L), which are reproduced in Figure 15. They include flat, nodular, bulbous, turbinate, cylindrical, branching and coalescent forms, but not oncolites. The 12 forms represent an infinite number of intermediate possibilities. While accepting existing 'generic' names he was against giving 'specific' names to new growth forms.

In a study of stromatolites of the Belt Supergroup in Montana, Rezak (1957, p. 131) used a simple classification basing 'genera' on the mode of growth, and 'species' on gross form of colony and nature of laminae. This classification is given in Table 5.

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[1] Copy not available for examination. *Vide* Maslov, 1960, p. 44; Krylov, 1963, pp. 37-38.

TABLE 4

Stromatolite classification of Krasnopeeva (1946)

Genus	Light lamellae	Dark lamellae	External shape
Newlandiella	Coarsely crystalline calcite	Brown, finely crystalline dolomite	Conical, hemispherical
Algostroma	Finely crystalline calcite	Brown, finely crystalline dolomite	Conical, cylindrical
Kabyrsina	Crystalline calcite	Coarsely crystalline anthraconite	hemispherical
Sibirephycus	Coarsely crystalline dolomite	Finely crystalline dolomite	lamellar

TABLE 5

Classification of Belt stromatolites by Rezak (1957)

Cryptozoon	growth beginning from a point, enlarging by addition of widening, convex upward laminae	
Collenia	growth beginning as incrustation of a surface by addition of convex upward laminae not greatly increasing in area	
	Gross form	laminae
C. undosa	hemispheroidal or depressed spheroidal	conformable, coarsely crenulate
C. symmetrica	hemispheroidal or depressed spheroidal	conformable, smooth
C. multiflabella	hemispheroidal or depressed spheroidal	partly conformable, finely crenulate
C. frequens	irregularly cylindroidal	flat to strongly convex, smooth
Newlandia	growth beginning from a surface, by addition of concave upward laminae	
Conophyton	colonies of nested conical laminae with apex attached to substratum	

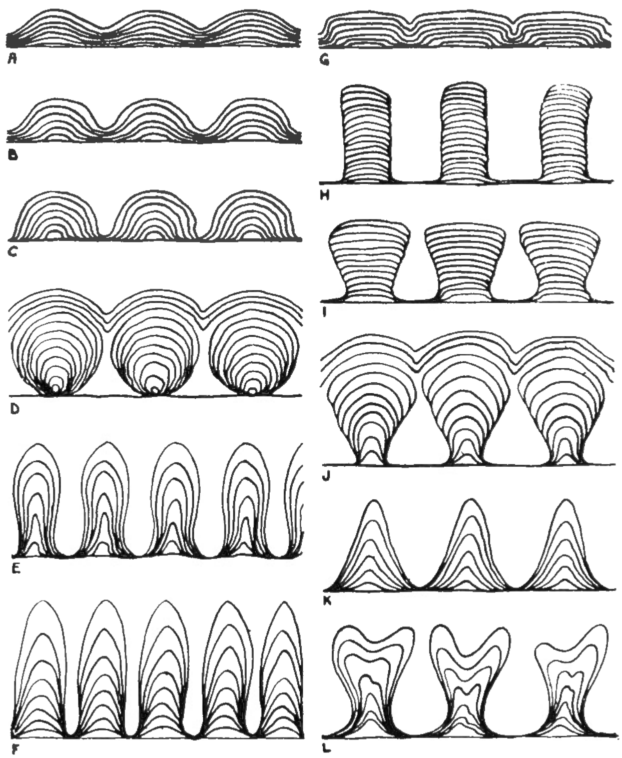

Figure 15. Diagrammatic representation of stromatolite growth-forms according to Anderson (1950, p. 9). Growth Forms A to L.

In his more recent comprehensive papers on the subject, Maslov (1953, 1960) suggested a formal, nonbiologic classification of phytolites (stromatolites and oncolites) for the basic morphological types shown in Figure 16 and Table 6. These types carry modifying designations that in effect are brief diagnostic descriptions. The classification is based on (1) the morphology of the structure, the name corresponding to the mode of formation or the character of the laminae; (2) the internal structure; and (3) individual pecularities. In this system, to cite an example, the polynomial designation *Collenia columnaris planolaminaris granulosa* refers to a column of *Collenia* with flat, granular laminae (previously described as *Collenia asiatica* Maslov, 1937b).

An innovation over previous classifications is that proposed for Cambrian and Precambrian stromatolites from the Irkutsk area by Korolyuk (1960). She considered as diagnostic features the nature of the contact between the stromatolite and the matrix, and the shape of the columns. The scheme is the first to utilize the concept of the wall or envelope - how the younger laminae envelop preceding laminae at the periphery. She distinguished the types, subtypes, and groups summarized in Figure 17 and Table 7.

A different approach was taken by Vologdin (1962) in his monographic study of Precambrian and lower Paleozoic algae. Vologdin regarded the microfabric as the significant characteristic, and proposed a large number of taxa based on the cellular microstructure presumed to be morphologic remains of algae. His classification of genera from the Precambrian is given in Table 8.

TABLE 6

Phytolite classification of Maslov (1960)

Phytolites	Morphological Type	Morphological Group	External form	Macrolayering	Microlayering	Orientation of the microlayering
Stromatolites	*Collenia*					convex-up, parallel
		C. frequens	domal	distinct	distinct	in separate domes
		C. columnaris	columnar	distinct	distinct	in separate domes
		C. pseudocolumnaris	wavy columnar	distinct	distinct	wavy
		C. flabelliformis	fan-shaped	distinct	distinct	fan-shaped
		C. nubeculariformis	irregular columns with cloud-like structure	distinct	indistinct	external
	Conocollenia	*Conocollenia*	broad cones, some-times grouped	distinct	distinct	conical
	Conophyton	*C. cylindricus*	cylinders	distinct	distinct	conical and cylindrical
	Crustella	*Crustella*	bun-shaped	distinct	none or complex; closely packed, porous	complex
	Glebulella	*Glebulella*	columnar	poorly developed	none, nodular	without envelope
		Fossella	columnar	poorly developed	none, nodular	without envelope
		Pycnostroma	nodular	poorly developed	none, nodular	without envelope
	Tubistromia	*Tubistromia*	tubular	poorly developed	none, nodular	well marked envelope
	Saccus	*Saccus*	columnar (like overturned sacks)	none	internal-none; external - distinct	As laminated envelope
	Macronubecularites	*Macronubecularites*	irregularly knobby	distinctly cloud-like	none	
Oncolites	*Osagia*	*Osagia*	ovoidal	distinct	distinct	concentric
	Ottonosia	*Ottonosia*	ovoidal	distinct	distinct	in small columns
		Eniseiella	Fan-shaped or star-shaped	none	distinct	in small columns
	Nubecularites	*Nubecularites*	cloud-like	none	almost none	cloud-like
	Katagraphia	*Katangasia*	irregular	none	none	
		'nodular lime-stones'	sinuous contours	none	none	

TABLE 7

Korolyuk's (1960) classification of Cambrian and Precambrian stromatolites from the Irkutsk area

Type: stratiform stromatolites (laminae continuous throughout bioherm)		
	Group *Stratifera*	simple wavy laminae, high degree of inheritance
	Irregularia	laminae crenulated; low degree of inheritance
Type: nodular stromatolites (structures with nodular shape)		
	Group *Collenia*	
	Colleniella	round, wall-less structures with internal tubercles
	Paniscollenia	bun-shaped structures with flat base
Type: columnar stromatolites (height of structure greater than diameter)		
Subtype I - without walls		
	Group *Collumnacollenia*	column broad, straight; laminae inherited, convex
	Conophyton	laminae conical
	Sphaeroconophyton	
	Compactocollenia	nodular, changing to columnar; walls in places
	Planocollenia	irregular columns; almost flat laminae
Subtype II - with thin, single-layered wall		
	Group *Schancharia*	small columns; almost every dark lamina is wall forming
	Linocollina	columnar to box-like; broken wall, very flat arches
	Collumnaefacta	walls uneven, vague; arches convex and smooth
Subtype III - with multilaminated, compound wall		
	Group *Boxonia*	even, straight columns; arches steep
	Ilicta	bent columns; laminae spongy, spotted tubular, noninherited
Subtype IV - walls formed by special tissue		
	Group *Sacculia*	broad, sacklike cover envelops structure

TABLE 8

Classification of Sinian algae (Vologdin, 1962, pp. 650-653)

Type	Cyanophyta			
Order		Chroococcales		
Family			Chroococcaceae (Nägeli) Greitler	
Genus				*Praechroococcus* Vologdin 1962
			Lermontovaephycaceae Vologdin 1962	
				Lermontovaephycus Vologdin 1962
				Angarophycus Vologdin 1962
				Lamellophycus Vologdin 1962
		Graniferales		
			Graniferaceae Vologdin 1962	
				Granifer Vologdin 1955
			Crustophycaceae Vologdin 1962	
				Crustophycus Vologdin 1962
			Lopatinellaceae Vologdin 1962	
				Lopatinella Vologdin 1962
				Tschichatschevia Vologdin 1955
			Vesiculariaceae Vologdin 1962	
				Vesicularia Vologdin 1962
				Bursiphycus Vologdin 1962
				Abruptophycus Vologdin 1962
				Columnaria Vologdin 1962
Class	Hormogoneae			
			Telastromaceae Vologdin 1962	
				Telastroma Vologdin 1962
				Cirriphycus Vologdin 1962
				Protoepiphyton Vologdin 1962
				Prennaria Vologdin 1962
			Trichostromataceae Vologdin 1962	
				Trichostroma Vologdin 1962
				Leptotrichomaria Vologdin 1962
				Fibrostroma Vologdin 1962
				Antiquophytolithus Vologdin 1962
		Sarmaellales		
			Sarmaellaceae Vologdin 1962	
				Sarmaella Titorenko et Virskaya
				Borlogella Vologdin 1962
				Cystostroma Vologdin 1962
			Plexostromataceae Vologdin 1962	
				Plexostroma Vologdin 1962
				Papulophycus Vologdin 1962
				Nerusiandella Vologdin 1962
				Ramulostroma Vologdin 1962
				Cyanostroma Vologdin 1962
				Vittophyton Vologdin 1962

TABLE 8 (Cont'd)

Class Hormogoneae		
	Scandophycaceae Vologdin 1962	
		Scandophycus Vologdin 1962
		Sphaerothallus Vologdin 1962
		Bulbistroma Vologdin 1962
		Crispophycus Vologdin 1962
	Lamellostromataceae Vologdin 1962	
		Lamellostroma Vologdin 1962
		Pilostroma Vologdin 1962
		Fillostroma Vologdin 1962
	Porostromataceae Pia 1927	
	Subfamily Agathidia Pia 1927	
		Girvanella Nicholson et Etheridge 1878
		Tubulistroma Vologdin 1962
Rhodophyta		
	Pustulariaceae Vologdin 1962	
		Pustularia Vologdin 1955
	Epiphytaceae Korde 1958	
		Epiphyton Bornemann 1887
	Solenoporaceae Pia 1927	
		Solenopora Dybowski 1877

TABLE 9

Donaldson's (1963) 'descriptive adjective' classification of stromatolites from the Proterozoic Denault Formation of the Labrador Geosyncline

Hemispherical stromatolites	*(Collenia)*
Bulbous stromatolites	*(Cryptozoon)*
Columnar stromatolites	*(Archaeozoon)*
Digitate stromatolites	*(Gymnosolen)*
Pisolitic stromatolites	*(Pycnostroma)*
Undulatory stromatolites	*(Weedia)*

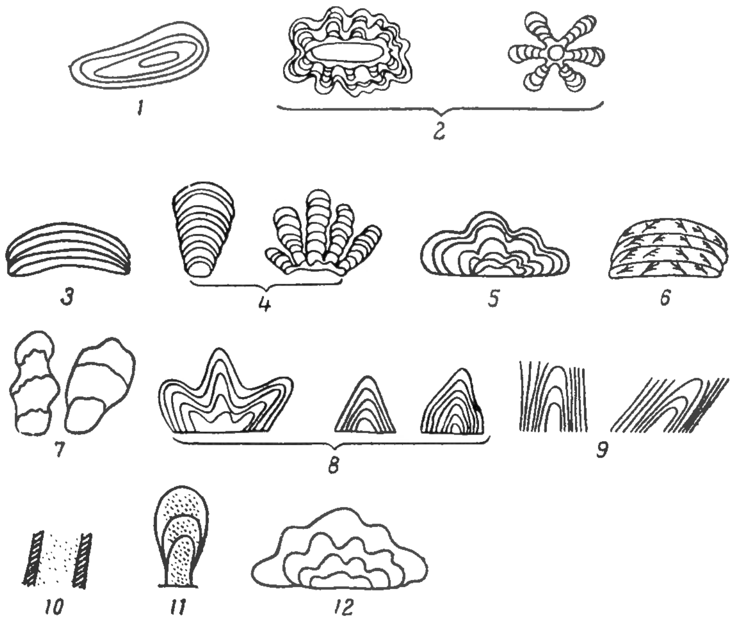

Figure 16. Morphological types of stromatolites according to Maslov (1960, p. 55).

1 *Osagia*, schematic section
2 *Ottonosia*, schematic section
3 *Collenia*, gently sloping form
4 *Collenia*, columnar form
5 *Collenia*, fan-shaped form
6 *Crustella*, schematic section
7 *Glebulella*, schematic section
8 *Conocollenia*, schematic section
9 *Conophyton*, schematic section
10 *Tubistromia*, schematic section
11 *Saccus*, schematic section
12 *Macronubecularites*, schematic section

The scheme is quite unrelated to those proposed by other Soviet stromatolite specialists, and follows that used much earlier by Gürich (1906) for his 'Spongiostromidae'. As an example, columnar stromatolites with conical laminae, which are identified by others as *Conophyton*, are assigned by Vologdin to such diverse categories as *Lermontovaephycus*, *Granifer*, and *Tschichatschevia*.

A simple form-classification ("descriptive adjective classification") similar to Anderson's (1950), and based on the growth forms of Pia (1927, 1928), was used by Donaldson (1963, p. 7, Fig. 4) in a study of Proterozoic stromatolites from the Denault Formation in the Labrador Trough. He recognized 6 basic types (Table 9), but the classification is amenable to expansion by the inclusion of other adjectives such as conical and discoidal.

Logan *et al.* (1960, 1964) introduced an entirely new concept to the classification of Holocene stromatolites. Instead of a binomial nomenclature, they proposed a descriptive nomenclature of structural formulae, which are

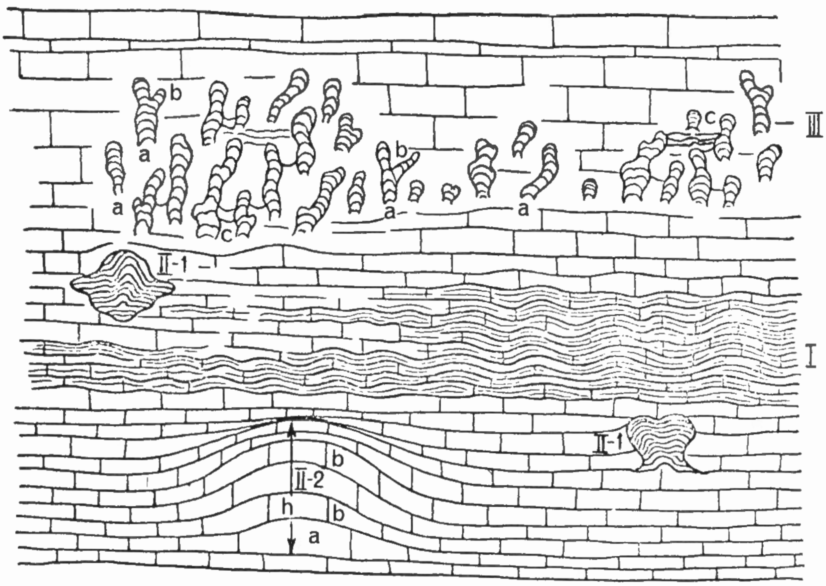

Figure 17. Stromatolite types according to Korolyuk (1960, p. 116).

I Stratiform stromatolites [*Stratifera*]
II Nodular stromatolites
II-1 Structures of the *Colleniella* type
II-2 Loaf-like structures [*Paniscollenia*]
a mound-forming laminae
b mound-enveloping laminae
h height of mound
III Stromatolite assemblage composed of columnar structures
a columnar structure
b daughter structure
c connecting bridges

combinations of initials of adjectives, adverbs, and nouns. The classification rests on the arrangement of basic geometric units (hemispheroids and spheroids), their lateral linkage, and their stacking (Table 10). It is the first to emphasize the importance of synoptic morphology of the laminae, that is, how the algal structures appeared at any one time.

The more recent Russian classifications are based on that of Korolyuk (1960), modified and refined to accommodate newly described configurations. Following the suggestion of Maslov (1953, p. 109), 'genera' are called *groups*, and 'species' are *forms*, and both are treated as paleontologic taxa, that is, stromatolites are given binary italicized names, holotypes are designated, etc. The first of these modifications is that made by Krylov (1963, p. 57), who gave attention to the following features, in order of importance: (1) structure and shape of a stromatolite bioherm (types and subtypes); (2) structure and shape of the columns comprising the bioherm (groups and forms); (3) structure and shape of the laminae comprising the columns; (4) microfabric of the laminae. Krylov's scheme for Riphean stromatolites from the Southern Urals emphasizes columnar branching types, as shown in Table 11.

TABLE 10

Classification of Holocene stromatolites by
Logan, Rezak, and Ginsburg (1964)*

Type	Symbol
1) laterally linked hemispheroids	LLH
a) close linkage (spacing between heads less than diameter of heads)	LLH-C
b) spaced linkage (spacing greater than diameter of structures)	LLH-S
2) Discrete, vertically stacked hemispheroids	SH
a) constant radius	SH-C
b) variable basal radius	SH-V
3) Spheroidal structures (oncolites)	SS
a) inverted stacked hemispheroids	SS-I
b) randomly stacked hemispheroids	SS-R
c) concentrically stacked spheroids	SS-C
4) Compound forms	
a) comprised of macrostructures (e.g. SH) and microstructures (e.g. LLH)	e.g. SH/LLH
b) vertical succession of different types (e.g. LLH growing into SH, and back into LLH types)	e.g. LLH→SH→LLH

* Kendall and Skipwith (1968, p. 1042) added inverted stacked hemispheroids (SH-I) to accommodate polygonal algal mats.

Another classification for Riphean columnar stromatolites is that by Raaben (1964, 1969), which assembles groups into 4 'orders' or 'supergroups' according to their type of branching: Conophytonida, Kussiellida, Gymnosolenida, and Tungussida (Table 12).

The most recent of the Russian schemes is that of Komar (1966, p. 50) for Precambrian stromatolites from the northern part of the Siberian Platform. It considers (1) type of branching; (2) general form of columns; (3) character of lateral boundaries; and (4) textural features. The grouping of stromatolites into a hierarchy of types, subtypes, groups, and forms is accepted, and appears to be firmly established now with most Russian specialists. Komar's scheme is summarized in Table 13. (For a summary in English and illustrations of the columnar forms see Raaben (1969).)

In a study of lower Paleozoic carbonates in southwestern Alberta, Aitken (1967) used a new terminology for algal carbonates. Like Pia (1927, 1928), he distinguished between those with organic microstructure attributable

TABLE 11

Krylov's (1963) classification of stromatolites from the Riphean of the Southern Urals

Type: Stratiform stromatolites (sheet like structures consisting of laminae that extend through the whole bioherm)

Group *Stratifera* Korolyuk

Type: Columnar-stratiform stromatolites (structures consist of columns, but a large number of laminae extend through the whole bioherm)

Group *Schancharia* Korolyuk

Type: Columnar stromatolites (structures are columns clearly separated from the enclosing rock)

Subtype - nodular (composed of individual separated columns)

Group *Paniscollenia* Korolyuk

Subtype - columnar-nodular (closely spaced columns)

Group *Collenia undosa* Walcott

Subtype - columnar branching (branching columns clearly distinct from enclosing rock)

	Branching type	Shape of column	Lateral surface
Group *Pseudokussiella* n.g.	'whorl-like'	Subcylindrical, swollen at points of branching	smooth
Gymnosolen Steinm.	bushy	subcylindrical, bent, with swollen portions and con-strictions	smooth, sometimes with many envelopes
Katavia n.g.			finely tubercular, without lips
Minjaria n.g.	into two or three columns, as in a tree	subcylindrical, even columns	smooth, sometimes with many envelopes
Jurusania n.g.			smooth, sometimes with long lips
Inzeria n.g.	into several columns, with constriction in basal column	uneven, nodular, subcylindrical	small transverse ribs, no large lips and cornices
Baicalia n.g.	into two columns, with constric-tions	tuberous, nodular	coarse-tubercular, with lips
Kussiella n.g.	simple contin-uous division	straight, sub-cylindrical	transverse, ribs, with cornices

Subtype - stromatolites of the Conophyton group and related forms

Group *Conophyton* Maslov
Collenia frequens Walcott

TABLE 12

Classification of late Riphean columnar stromatolites from the Polyudov Range by Raaben (1964)

Unbranching and falsely branching (structures grow without increase in area)		True branching, actively branching (growth of columns by branching and increase in area)	
Unbranching CONOPHYTONIDA	falsely branching KUSSIELLIDA	parallel branches GYMNOSOLENIDA	non-parallel branches TUNGUSSIDA
unbranching columns	columns disintegrate into smaller ones	columns progress-ively branching	columns progress-ively branching
growth of laminae without lateral shift	growth of laminae without lateral shift	growth of laminae without lateral shift	growth of laminae with lateral shift
axes of columns parallel	axes of columns parallel	axes of columns parallel	axes of columns with different orientations
Conophyton Masl. **Conocollenia* Masl.	*Kussiella* Kryl. *Jurusania* Kryl. **Omachtenia* Nuzhn. **Schancharia* Korol.	*Gymnosolen* Steinm. *Inzeria* Kryl. **Boxonia* Korol. **Katavia* Kryl. **Minjaria* Kryl.	*Tungussia* Semikh. *Poludia* n.g. *Parmites* n.g. **Baicalia* Kryl. **Compactocollenia* Korol.

* Groups marked with asterisk not studied in the material, but assigned by Raaben to the appropriate category on the basis of data given in the literature.

TABLE 13

Komar's (1966) classification of Precambrian stromatolites from the northern part of the Siberian Platform

Type: Columnar stromatolites Subtype - unbranching Group *Colonella* Komar (*Collenia frequens*) *Conophyton* Maslov (emend. Kom., Raab., Semikh.) Subtype - branching passively (columns branch into smaller ones without increase in total width of structure) - without differentiated microfabric Group *Kussiella* Krylov *Microstylus* Komar n.g. *Platella* Korolyuk - with differentiated microfabric Group *Boxonia* Korolyuk Subtype - branching actively (branching increases area of daughter columns and width of structure) - without differentiated microfabric Group *Baicalia* Krylov *Anabaria* Komar - with differentiated microstructure (character of laminae changes laterally) Group *Kotuikania* Komar *Gymnosolen* Steinmann
Type: Stratiform stromatolites Group *Stratifera* Korolyuk *Gongylina* Komar n.g.
Type: Nodular stromatolites Group *Paniscollenia* Korolyuk *Colleniella* Korolyuk *Nucleella* Komar n.g.

to skeletal calcareous algae, and those without cellular structure, in which the work of noncalcareous algae is largely inferred. The latter he termed *cryptalgal carbonates* (*see* Appendix). The structures forming cryptalgal bioherms were further grouped into two categories: one exhibits internal lamination (stromatolites, oncolites, and cryptalgalaminate carbonates [essentially flat, stratiform algal stromatolites])[1]; and the other lacks the lamination, and is characterized by a macroscopic clotted fabric. He proposed the term *thrombolite* (*see* Appendix) for the second group without lamination. For further subdivision Aitken preferred to follow the descriptive adjective classification of Donaldson (1963), introducing the additional term 'polygonal' for structures identified as *Newlandia* by Rezak (1957) (*non Newlandia* Walcott 1914).

Finally in studying the Jurassic stromatolites of Poland, Szulczewski (1968) found traditional systems of classification useless, and established one based on the character of the stromatolitic layers as whole, together with the extent and nature of their fragmentation (Table 14).

TABLE 14

Szulczewski's (1968) classification of Jurassic stromatolites of Poland

A.	Stromatolitic layers
	1. smooth
	2. holed
	3. grooved
	4. polygonal
B.	Isolated stromatolitic forms
	1. clumps
	2. single domes

DISCUSSION

From the survey in the last chapter it is clear that most workers have preferred their own classification. It is nonetheless also evident, that gross morphology (external form, type of branching, etc.) and nature of the lamination are accepted by most as important characteristics in stromatolite classification (Table 15). The reasons for the choice of gross morphology as the most significant feature are not always clear. For instance, in terms of the interacting relationship between the organic plexus and the physiochemical environment, why should gross form be more significant in classification than the morphologic aspect of individual constituent laminae throughout a stromatolite bioherm (synoptic morphology)? The laminae represent the microbathymetry during an interval of time at which each was at the active interface between already bound sediment below and the moving water with suspended particles above. It is at or near the interface, not at places already deeply buried, where biotic activity takes place, particles accumulate, the shape develops, and inheritance is determined (Fig. 18). It is the microbathymetry and makeup of the mound surface which will affect, and be affected by, the sediment-laden currents. The configuration of the plexus reflects the equilibrium conditions between organic activity, sediment supply and accumulation, and water conditions.

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[1] Abandonment of the term 'cryptalgalaminate' in favour of 'algal mat' is advocated by Cys (1969).

TABLE 15

Summary of some stromatolite classifications

	Gross morphology (External form; mode of growth; type of branching)	Shape of laminae	Microstructure	Mineralogical composition	Nature of lateral termination; linkage; spacing	Provision for compound forms
Walcott 1914	x					
Pia 1927	x		x			
Maslov 1939	x	x				
Kransnopeeva 1946	x	x	x	x		
Anderson 1950	x	x				
Rezak 1957	x	x				
Maslov 1960	x	x	x			
Korolyuk 1960	x	x	x		x	
Vologdin 1962			x			
Donaldson 1963	x					
Logan, Rezak and Ginsburg 1960, 1964	x	x			x	x
Krylov 1963	x	x	x		x	
Raaben 1964, 1969	x	x			x	
Komar 1966	x	x	x		x	
Szulczewski 1968		x			x	

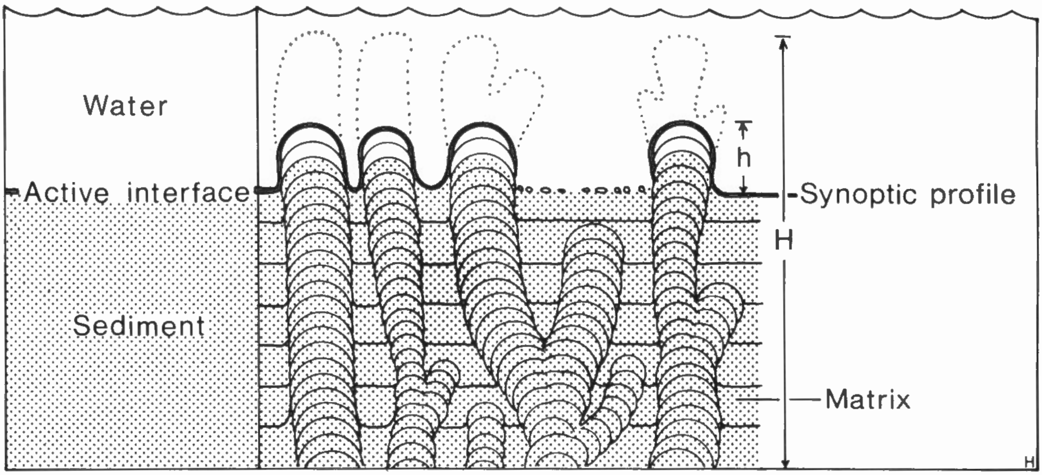

Figure 18. Synoptic morphology of a lamina, representing the active interface and the microbathymetry at an instant in time. Stacking of laminae along accretion vectors produces gross morphology of the stromatolite.
h - relief of lamina
H - height of stromatolite

The final gross morphology is very much dependent on the *duration* and *variation* of the accretion process (*see* Fig. 10). Morphologically identical laminae, presumably of identical biological characteristics, may be stacked only a few times or very many times, resulting in crustose or very slender forms. Should we assign these to different groups ('genera')? Also, identically curved laminae may have different degrees of completeness at different stages of accretion, producing uniform, constringed, ragged, or constringed-ragged stromatolites. It is not possible to demonstrate, in Precambrian forms, that a lack of constancy in the mean accretion vectors is attributable to biologic factors. This variability is just as reasonably explained, if not more so, as being related to minor secular changes in environmental conditions at the active interface, such as relative rates of matrix accumulation and stromatolite accretion. Is one then justified in assigning uniform, constringed, and ragged stromatolites to different groups?

One aspect related to gross form is the style of branching. This feature has received attention only quite late in the history of stromatolite studies. Its biological significance, if any, is problematic. Some specialists have thought it to be of time-stratigraphic significance, and it is an important item in the recent Russian classifications. As already mentioned, these workers recognize 2 major types - passive (or false) and active (or true) - depending on whether the structures grow without, or with increase in hemispheroid diameter. Passive branching is said to be more primitive and characteristic of, but not restricted to, Lower Riphean forms, whereas active branching is found in the Middle and Upper Riphean (Krylov, 1963, p. 44- 128; Komar, 1966, p. 50, 52; Raaben, 1969, pp. 7-8). The stratigraphic significance of branching is now in doubt, not only with the known occurrence of actively branching forms from the Aphebian (Pre-Riphean) (Fig. 19; Hofmann, 1969, Forms B, C, and F), but also with the observation that within a single hand specimen actively, passively, and unbranched forms can occur together (e.g., Fig. 20). It may also be pointed out that among certain Phanerozoic

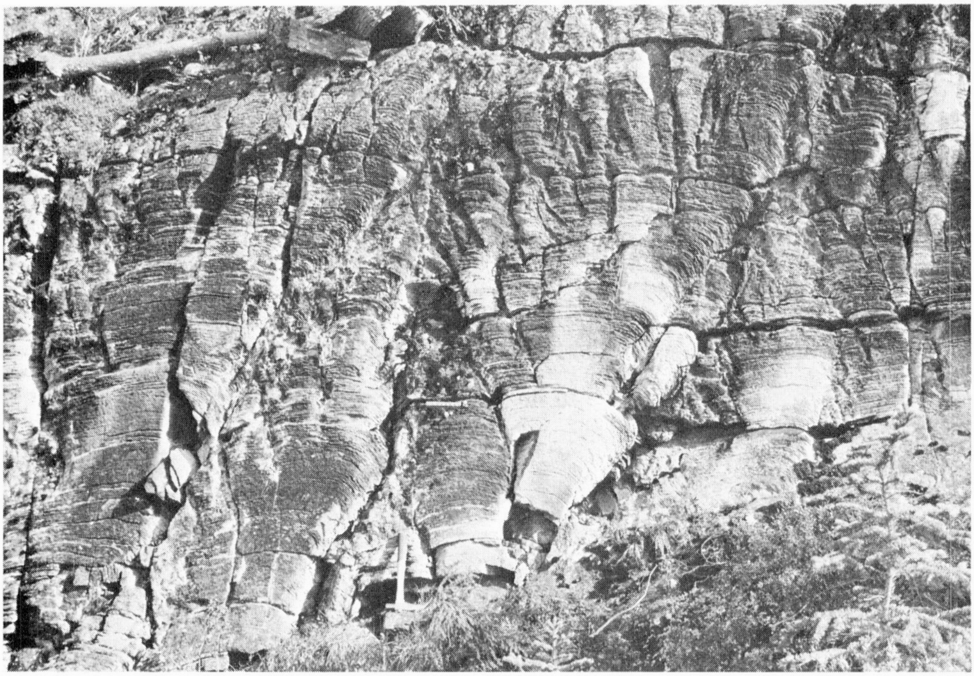

Figure 19. Aphebian stromatolites exhibiting active branching.

Taltheilei Formation, Pethei Group, Pethei Peninsula, Great Slave Lake (62°42'35"N, 111°01'15"W). These branching columnar forms with turbinate sections are composed of very closely spaced, linked, oblate hemispheroids, elongated in the direction of the view (azimuth 140°). They form part of a large biohermal complex. (118065.)

encrusting, colonial animal groups (e.g., stromatoporoids, corals, and bryozoans), we find that some genera occur with different growth forms in different colonies. One may therefore rightly question the validity of branching as a biologically significant evolutionary feature in stromatolites. Stromatolites, after all, are structures which are only partly biologic in origin. What, then, is the taxonomic significance of branching?

One widely occurring property of stromatolites is that of compound growth forms, resulting from certain changes in the orders of curvature of the laminae. This aspect has been neglected in most schemes. Only Logan *et al.* (1960, 1964) successfully devised a nomenclature to express this characteristic in a classification, but while solving one problem, it creates others, such as in indexing or cataloguing, and in the treatment of forms other than those based on the hemispheroid or spheroid.

The configuration of the individual laminae should receive thorough consideration, for the lamina is the fundamental, intrinsic unit of stromatolites. Most are convex, with varying degrees of oblateness or prolateness and elongation. But again, the relationship between curvature and biological and environmental factors is not very clear, and probably complex. It was mentioned earlier that the same species of modern alga can construct stromatolites of disparate shapes in different environmental settings. Also, the primary elongation and orientation and sediment accumulating capabilities in Holocene, Paleozoic, and Precambrian situations is known to be related to current patterns (Goldring, 1938; Logan, 1961; Hoffman, 1967; Ahr, 1967; Donaldson, 1969; Gebelein, 1969). Hence, one may wonder about the time-stratigraphic usefulness of categories based on shape. Moreover, the blue-green algae provide one of the most striking examples of evolutionary conservatism yet encountered in the geological record (Schopf, 1968, p. 653), so that the same species may have built similar stromatolites during long spans of geological time. For example, structures such as *Platella* Korolyuk and *Collenia columnaris* Fenton and Fenton (1937) could have been constructed, in an intertidal environment with a strong bimodal current pattern, by organisms which elsewhere might have built uniform columns of *Colonella* or *Kussiella*.

In stratiform stromatolites a similar relationship exists. The shape of the lamination and the degree of inheritance depends greatly on the nature of the substrate. *Gongylina* Komar appears to be nothing more than a form dependent on the periodic influx of sand- or silt-sized material. This material passes over an established plexus, is heaped into ripple- or dune-forms, and is then stabilized by the next plexus which again conforms to the microbathymetry. The degree of inheritance is low, but the general undaform lamination corresponds to the hydrodynamic conditions responsible for the accumulation of the ripples. In many places the rippled material is entirely composed of well-sorted ooids.

Among the nodular groups, *Nucleella* Komar appears to be simply a mat draped over an isolated clast or small erosion remnant. Without such accidental irregularity the laminae would have conformed to a more regular surface. *Paniscollenia* Korolyuk likewise could be a crustose form, whose development to full, slender columns was precluded because of physical limits imposed by the environment.

There remains, however, one most important line of evidence in support of a time-stratigraphic significance of the shape and character of the lamination, and that is in the realm of empirical data. While flat, convex, and concave forms are found from the Precambrian to the present, columnar stromatolites with conical lamination and characteristic axial zones (i.e., *Conophyton*) are at present known only from the Precambrian (Komar *et al.* 1965, p. 58). Where are the Phanerozoic Conophytons? This is a challenging problem, quite apart from a satisfactory explanation of the origin of the conical lamination itself, for which we are still searching. It is possible that the real, significant difference between stromatolites, from a biological and evolutionary point of view, is that between those having conical and those having hemispheroidal (partial spheroidal) laminae. To take this matter full

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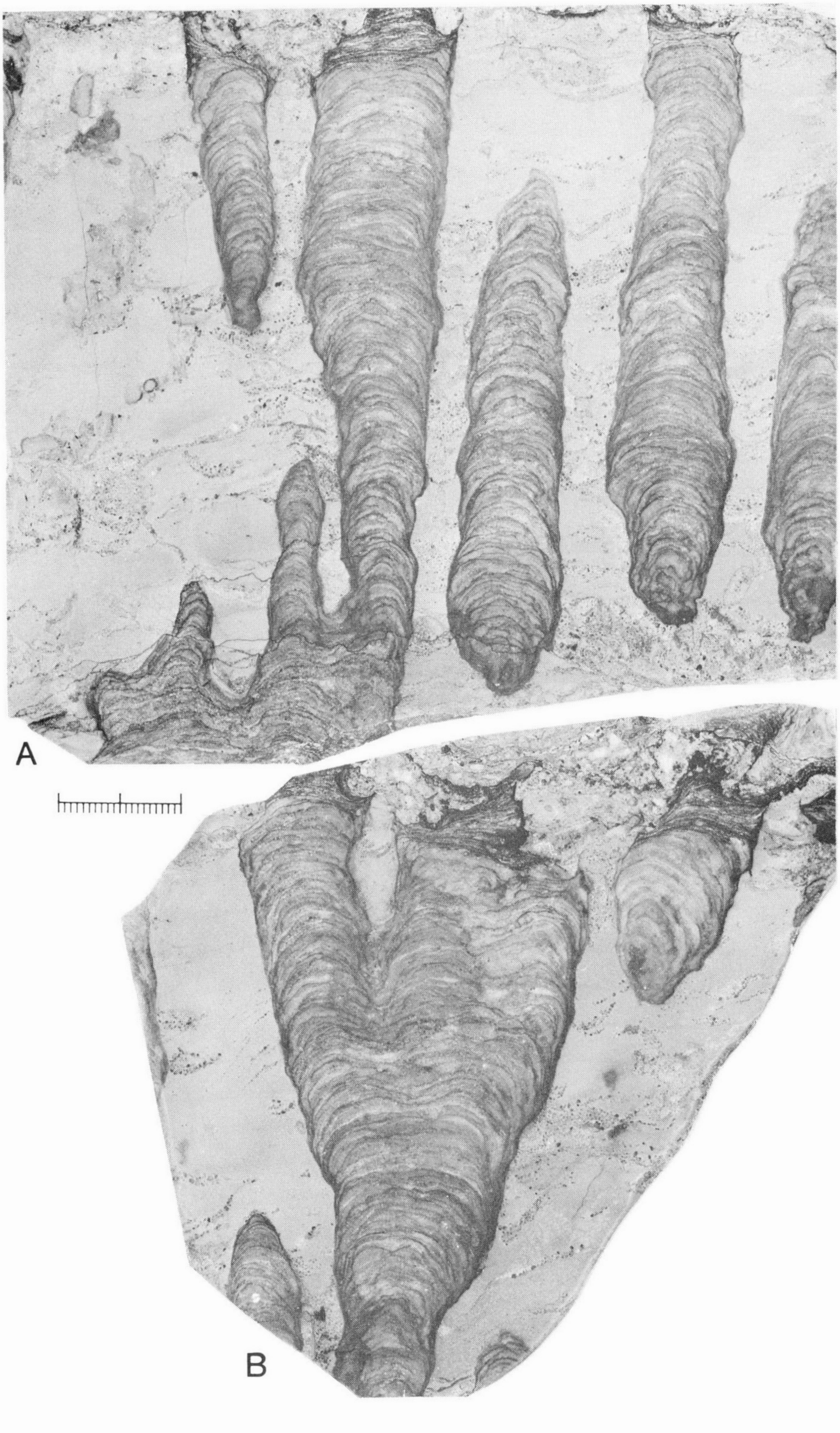
Figure 20 (opposite page)
Stromatolites from the Aphebian Manitounuk Gp., east coast of Hudson Bay. The photographs illustrate the two main branching styles and the walled nature of columns in a single hand specimen (GSC type 24857).

- A: Vertical section of unbranching and passively branching (Furcate) columns (GSC type 24857c, 200744-A).
- B: Vertical section of actively branching (dendroid) column, cut perpendicular to, and along the straight right margin of A (GSC type 24857a, 200744-E).

The scale at left is 20 mm long. Horizontal cross sections of the columns are essentially subcircular.

This form has the characteristics of the group *Katavia* (cf. Krylov, 1963, Pl. 34), which, in the Southern Urals, is characteristic of the Upper Riphean.


A
B

circle, one may well ask whether Maslov's (1939c, pp. 305-306) original views do not have more merit than one may be prepared to admit, namely that, aside from oncolites, there are really only two 'genera', *Collenia* (i.e.,*Cryptozoon-Archaeozoon-Gymnosolen*), and *Conophyton*.

Microfabric has also been considered important in the more recent literature, and is the basis for Vologdin's (1962) taxonomy. The microstructures, if well preserved, can give a clue to the identity of the stromatolite-producers. Unfortunately, most Precambrian stromatolites have no recognizable, consistent, demonstrably *biogenic*, cellular microstructure preserved, although certain consistent textural features may occur. In the absence of definite biogenic microstructures it becomes a matter of interpretation as to how much of a particular textural feature is biogenic, and how much is sedimentogenic or diagenetic in origin. Also, the vast majority of stromatolites occur in carbonates, which can readily respond to physiochemical changes in aqueous environments, resulting in alteration of textural features. It is therefore likely that a classification based mainly on microstructure will have limitations for fossil forms. The practice of recognizing categories at the same hierarchical level (groups) according to different sets of references, namely gross morphology on one hand, and microfabric on the other, makes a classification such as Komar's (1966) internally inconsistent.

Another property used in classification is mineralogical composition, which, together with textural features, was held to be of diagnostic value by Krasnopeeva (1946). Most workers have disregarded mineralogy entirely, or treated it incidentally. Bulk mineralogy can form a basis for broad lithologic distinctions between stromatolites of carbonate, chert, or other compositions, and thus allow distinction between major environmental conditions.

Other concepts used in classification are those of the wall (Korolyuk, 1960), and the mantle (Raaben, 1964). It seems that in modern stromatolites in Shark Bay, Australia, both walled and wall-less structures occur (Logan, 1961, Plate 1), as well as those with a mantle or cellular rim of special tissue (Logan, 1961, Fig. 2). Some workers (Krylov, 1963, p. 47, 128; Komar *et al.*, 1965, p. 64; Komar, 1966, p. 53; Raaben, 1969, p. 1) believe that these peripheral characteristics have time-stratigraphic significance. According to them, Lower and Middle Riphean stromatolites are generally characterized by the lack of walls (*viz. Kussiella, Baicalia*), whereas in the Upper Riphean walls are well developed. Also, the appearance of the mantle of special nonlaminated tissue in *Conophyton* is said to coincide with the beginning of Upper Riphean sedimentation (Komar *et al.*, 1965, p. 64). These observations have not yet been corroborated by thorough studies in North America. However, indications are that columnar and bulbous stromatolites with well developed walls are found in Canada as far back as the Aphebian (Gunflint Formation: Hofmann, 1969, Form F; Great Slave Supergroup: Fig. 21; and the Manitounuk Group: Fig. 20). From the discussion earlier, it is also clear that the formation of the wall is related to geometric and sedimentologic factors. The use of the wall, as an evolution-related property, in classification and time-stratigraphic correlation is therefore questionable.

With all the different views on classification, can the existing schemes, each with its advantages and disadvantages, be reconciled and incorporated into a workable, unified framework? Although objections have been expressed every so often, it would seem that a classification based on categories with uninomial or binomial names would be advantageous. There are two reasons for this. One is that standard paleontological practices can be followed (designation of types, descriptions, curating, synonymies, etc.), while fully realizing that the structures are not biological entities, but partly biogenic structures. The other is that stromatolites can be easily catalogued, listed, and indexed for ready reference and information retrieval. Perhaps it is best to illustrate this by the following example.

Stromatolites occupy a position somewhat akin to that of trace fossils, between the realms of paleontology and sedimentology. Trace fossils have

Figure 21. Aphebian stromatolites with walls. Taltheilei Formation, Pethei Group, northeastern tip of Blanchet Island, Great Slave Lake, Northwest Territories (62°07'20"N, 112°01'40"W). The erosional surface illustrated here cuts somewhat obliquely across parts of 2 turbinate columns with walls. Tabular fragments of stromatolite mats form an intercolumn breccia (118071).

received binary Latin and Latinized names, yet the 'genera' and 'species' are not taxonomic but purely nomenclatorial categories. They, too, reflect ecological setting (and behavioural aspects), inasmuch as similar traces may be formed by taxonomically little related species; or, the same species may produce other structures under different conditions. A trilobite may make a resting burrow (*Rusophycus*), and then move on to make the corresponding crawling trace (*Cruziana*). When, as very infrequently happens, the trilobite skeleton is found preserved within the burrow or trace, the marking can be assigned to a particular biologic taxon, for example, "a *Rusophycus* of *Isotelus*" or a "*Cruziana* of *Isotelus*".

Similarly, there is no objection to referring to a modern stromatolite with preserved filaments as "a biscuit of *Schizothrix calcicola*" or "a mat of *Schizothrix* and *Scytonema*". To take it one step further, it is possible to speak of "a *Cryptozoon* of *Schizothrix* and *Entophysalis*", or "an *Osagia* of *Girvanella*". The nomenclatorical categories *Cryptozoon* and *Osagia* simply express geometric appearances, just as *Rusophycus* or *Cruziana* do. That they are environmentally or otherwise conditioned is secondary to their geometry.

The usage of italicized names in this fashion can be criticized in so far as it may cause confusion between true genera and 'genera', and true species and 'species'. Cloud (1942, p. 366) has suggested that the names for the familiar growth forms be retained, but that they should not be italicized or capitalized. Though it has considerable merit, his suggestion has not been followed by Russian specialists, nor by others in North America and elsewhere. One might propose to emphasize the 'generic' names in some other style of type such as Gothic, cursive, boldface, or extended, but this would be impractical, because types in ordinary office typewriters are limited. Perhaps the name could be underlined with dots in manuscript (e.g., Cryptozoon) and a new style used in printed type. The problem might eventually be resolved by agreement among palichnologists and stromatolitologists, if they should ever meet to decide on how the nomenclature of organosedimentary structures ought to be treated. For the purposes of the present paper, it was convenient to have the 'genera' italicized.

Having concluded that a uninomial, if not binomial nomenclature, however imperfect, is a convenient method of treating stromatolites, one may now turn to the question of what these categories with names should represent. This is the real crux of the problem. The individual 'genera' or groups ideally should be just as distinct geometrically as nominally, and they should be objectively based on the same attributes to afford an internally consistent classification. Unfortunately, because of the high degree of polymorphism the limits of groups are vague, precluding a precision in identification comparable to that in body fossils. For purposes of comparison, currently used groups are illustrated in a scheme that follows the classifications of Krylov (1963) and Raaben (1964, 1969) (Fig. 22). This illustration shows how little difference there is among many of the groups, especially the columnar branching ones. Coupled with uncertain significance of the peripheral features and of the branching, the validity of certain named categories becomes rather tenuous. Perhaps the already named groups are not diagnosed with sufficient objectivity. For instance, the similarities between such groups as *Katavia*, *Patomia*, *Inzeria*, and *Jurusania* are quite great. The differences between them appear to be no greater than variations between individual columns assigned to the same group. Even if they are different, one may well ask: are the disparities between these groups really of consequence? The answer to this is bound to be somewhat subjective. Perhaps it is not advisable to define the groups too narrowly, at least not without adequate statistical data. To statistically characterize a stromatolite on the basis of width of the columns (2r) and their height (H) alone is unsatisfactory; as was indicated previously, the height is dependent predominantly on the duration of the accretion process. What we really need to characterize quantitatively are 2 significant parameters: (1) a sort of "*average synoptic morphology*" of the laminae, and (2) the *accretion vector*, representing the geometric aspect of the variation in laminar size during the complete inheritance process as well as the final gross form. The average synoptic morphology is the model or stereotype with which the gross form of the stromatolite is generated by stacking, in accordance with the dynamic geometric aspects of an accretion vector.

With the use of terms such as given in Figure 13 the geometry of stromatolite groups may be described in a consistent manner, expressing both synoptic morphology and accretion vectors. A tabular summary of the attributes of currently used groups is given in Table 16.

While in this paper we have been concerned almost exclusively with stromatolite groups ('genera'), a few brief comments concerning the recognition of forms ('species') may also be in order. In general, the named forms are also a highly polymorphous lot, classified according to different criteria in different groups, or even by different criteria in the same groups by different authors. Properties that have been used are minor differences in gross morphology, number of branches, shape of laminae, size, peripheral irregularities, presence of swelling or constrictions, as well as microfabric, in fact the same properties as those used for distinguishing the groups. It thus is rather doubtful that named forms are adequately defined, and that they have a significant practical value, despite the optimism expressed by some workers. This follows the views already expressed some time ago by Pia (1927, p. 37).

TABLE 16

SUMMARY OF PROPERTIES OF SOME NAMED STROMATOLITE GROUPS

STRATIFORM	NODULAR	BULBOUS	ONCOLITE	COLUMNAR: UNBRANCHING	COLUMNAR: PASSIVELY BRANCHING	COLUMNAR: ACTIVELY BRANCHING	COLUMNAR: ANASTOMOSED	GROUP	STROMATOLITE: HABIT OF ACCRETION VECTOR: GROWTH FACTOR AND VARIABILITY	STROMATOLITE: HABIT OF ACCRETION VECTOR: BRANCHING STYLE	STROMATOLITE: HABIT OF ACCRETION VECTOR: ATTITUDE	STROMATOLITE: LATERAL SURFACE	STROMATOLITE: INTERNAL FEATURES	LAMINAE: CONFIGURATION: CURVATURE	LAMINAE: CONFIGURATION: PROFILE	LAMINAE: CONFIGURATION: PLAN	LAMINAE: LINKAGE	LAMINAE: SPACING
1	2	3	4	5	6	7	8											
						7		Anabaria Komar 1964	cylindrical; slender, uniform	denroid to digitate	straight, erect to steeply inclined	smooth, slightly rugate, with and without walls		even, wavy	convex	round to lobate	unlinked	very close to open
						7		Archaeozoon Matthew 1890	columnar: slender, constringed to uniform	digitate	straight to curved, erect to steeply inclined	smooth in undeformed specimens, with walls		even, wavy	convex	round	unlinked	very close
						7		Baicalia Krylov 1962	columnar: stubby to slender, strongly constringed and ragged	dendroid	straight, erect to inclined	fimbriate, no walls		even, wavy	convex	round to lobate	unlinked	close
					6			Boxonia Korolyuk 1960	cylindrical: slender, uniform	furcate	straight, erect	smooth, with walls	laterally differentiated microfabric	even, wavy	convex	round to lobate	unlinked	close
	(2)		4					Collenia Walcott 1914	nodular, crustose; spheroidal	furcate, umbellate, dendroid	centrifugal	smooth to tuberculate	arched nucleus (mobile)	wavy, corrugate, crenate	globoidal, concavo-convex			
	2							Colleniella Korolyuk 1960	nodular; crustose to stubby	(furcate, umbellate, dendroid)	(erect)	smooth to tuberculate, or merging with matrix		corrugate, crenate	convex	round to lobate	linked	open to isolated
				5				Colonella Komar 1964	cylindrical; slender, uniform	unbranching	straight, erect	smooth, sometimes fimbriate, no walls	evenly laminar microfabric	even	convex	round	linked, unlinked	close
				5				Conophyton Maslov 1937	cylindrical to prismatic: slender, uniform	unbranching	straight, erect to inclined	smooth to uneven, merging with matrix, no walls	axial zone, ribs; mantle	even, wavy	angulate	round, lanceolate, polygonal, dentate	linked	contiguous to close
		3						Cryptozoon Hall 1883	bulbous to turbinate	unbranching, umbellate, coalescent	erect to steeply inclined	smooth to tuberculate, with walls		even, wavy, corrugate, crenate	convex, globoidal	round to lobate	unlinked, linked	contiguous to open
1								Gongylina Komar 1966	stratiform; crustose		very variable	merging with matrix	ripples or microdunes	wavy	flat	undefined	linked	contiguous
						7		Gymnosolen Steinmann 1911	cylindrical: slender, slightly constringed	digitate	straight to slightly curved, erect	smooth, with walls	laterally differentiated microfabric	even, wavy	convex	round to lobate	unlinked	close
						7		Inzeria Krylov 1963	columnar: slender with stubby branches; constringed, ragged	digitate	straight, erect	niche-like constrictions, slightly rugate, walls rare		even, wavy	convex	round to lobate	unlinked	close to very close
1								Irregularia Korolyuk 1960	stratiform, crustose, very irregular		variable, inclined (deformed?)	merging with matrix	microfaults?	corrugate, crenate	convex	round?	linked	irregular
					6			Jacutophyton Shapovalova	cylindrical: slender, uniform, constringed, ragged	furcate, umbellate	straight, erect, with inclined branches	uneven, merging with matrix, no walls	axial zone?	even?	irregular	round?	linked?	close
						7		Jurusania Krylov 1963	cylindrical; slender, uniform to ragged	digitate	straight, erect	fimbriate, walls rare		even, wavy	convex	round to lobate	unlinked	close
						7		Katavia Krylov 1963	cylindrical; slender, constringed	digitate	straight, erect	tuberculate, with walls		wavy, corrugate	convex	round to lobate	unlinked	close to open
						7		Kotuikania Komar 1964	columnar: stubby to slender	dendroid	sinuous, inclined	smooth, tuberculate, with walls	laterally differentiated microfabric	even, crinkled	convex	round to lobate	unlinked	close
					6			Kussiella Krylov 1962	cylindrical; slender, slightly constringed, ragged	furcate	straight, erect	rugate, uneven, no walls		even, wavy	convex	round to lobate	unlinked	close to open
						7		Linella Krylov 1967	cylindrical; slender, constringed	dendroid	straight to sinuous, erect	tuberculate, sometimes rugate, partly walled		wavy	convex	round to lobate	unlinked	very close to open
					6			Microstylus Komar 1966	cylindrical: slender, uniform	furcate	straight, erect	smooth, no walls	fibrous - incrustational microfabric	even, wavy	convex	round	unlinked	very close to close
						7		Minjaria Krylov 1962	cylindrical: slender, uniform	digitate	straight, erect	smooth, with walls		even, slightly wavy	convex	round to lobate	unlinked	very close to close
	2							Nucleella Komar 1966	nodular; crustose: passing into stratiform		encrusting a nucleus	smooth	nucleus of foreign object (fixed)	even, crinkled	convex	round	linked	open to isolated
					6			Omachtenia Nuzhnov	cylindrical: slender, uniform, ragged	furcate	straight, erect	rugate, no walls		even	convex	round to lobate	linked?	close
			4					Osagia Twenhofel 1919	spheroidal		centrifugal	smooth	nucleus (mobile)	even, slightly corrugate	globoidal, encapsulating			
			4					Ottonosia Twenhofel 1919	spheroidal	furcate, umbellate dendroid	centrifugal	tuberculate	nucleus (mobile)	corrugate	globoidal, encapsulating			
				5				Paniscollenia Korolyuk 1960	columnar; crustose to stubby	unbranching	erect	smooth, partly walled		even, wavy	flat to convex	round	linked	open to isolated
							8	Parmites Raaben 1964	columnar: crustose to stubby segments: ragged	anastomosed	straight, curved; inclined	merging with matrix, no walls		even?	convex	round?	unlinked?	close?
						7		Patomia Krylov 1967	cylindrical; slender with stubby branches, constringed	digitate to dendroid	straight to sinuous: erect to steeply inclined	tuberculate, with walls		wavy, corrugate	convex	round to lobate	unlinked, linked	very close to open
						7		Pitella Semikhatov 1962	flattened cylindrial; slender with stubby branches, constringed	digitate	straight, slightly curved, erect	smooth, slightly tuberculate, with walls		even, slightly wavy	convex	oblong (deformed?)	unlinked	close to very close
					6			Platella Korolyuk 1963 (Komar 1966)	flattened columnar: slender, uniform	furcate	straight, erect	smooth, no walls		even?	convex	oblong	unlinked	very close
						7		Poludia Raaben 1964	columnar: slender, constringed	dendroid	sinuous, inclined	smooth to fimbriate		even, wavy?	convex	round to lobate	unlinked?	close to open
						7		Pseudokussiella Krylov 1963	columnar: stubby to slender: constringed	dendroid	curved, erect to inclined	smooth, with walls		even, wavy	convex	round to lobate	unlinked	very close to close
1								Stratifera Korolyuk 1959	stratiform		erect	merging with matrix		crinkled	flat to convex	undefined	linked	contiguous
						7		Svetliella Shapovalova	columnar: stubby to slender, constringed	dendroid	straight to curved, erect to inclined	smooth, partly walled		even?	convex	round to lobate	unlinked, linked	very close
					6			Tenupalmaella Golovanov 1965	cylindrical; slender, uniform to slightly ragged	furcate	straight, erect	smooth, partly merging with matrix, no walls		even, wavy	convex	round to lobate	partly linked	close
						7		Tungussia Semikhatov 1962	columnar: stubby to slender, uniform, constringed, ragged	dendroid	straight, curved, sinuous: inclined	smooth, merging with matrix: walls rare		even, wavy	convex	round to lobate	unlinked	very close
						7		Turuchania Semikhatov 1962	cylindrical: stubby to slender, constringed	dendroid	curved erect, inclined branches decumbent	smooth, tuberculate: no walls		crinkled	convex	round to lobate	partly linked	close
						7		Vetella Krylov 1967	columnar: slender, constringed: stubby branches	dendroid	straight to sinuous, inclined	very tuberculate, with walls		even, wavy	convex	round to lobate	unlinked	very close to open
1								Weedia Walcott 1914	stratiform - columnar		erect to inclined	smooth: merging with matrix		corrugate	flat to convex	undefined?	linked	close to very close

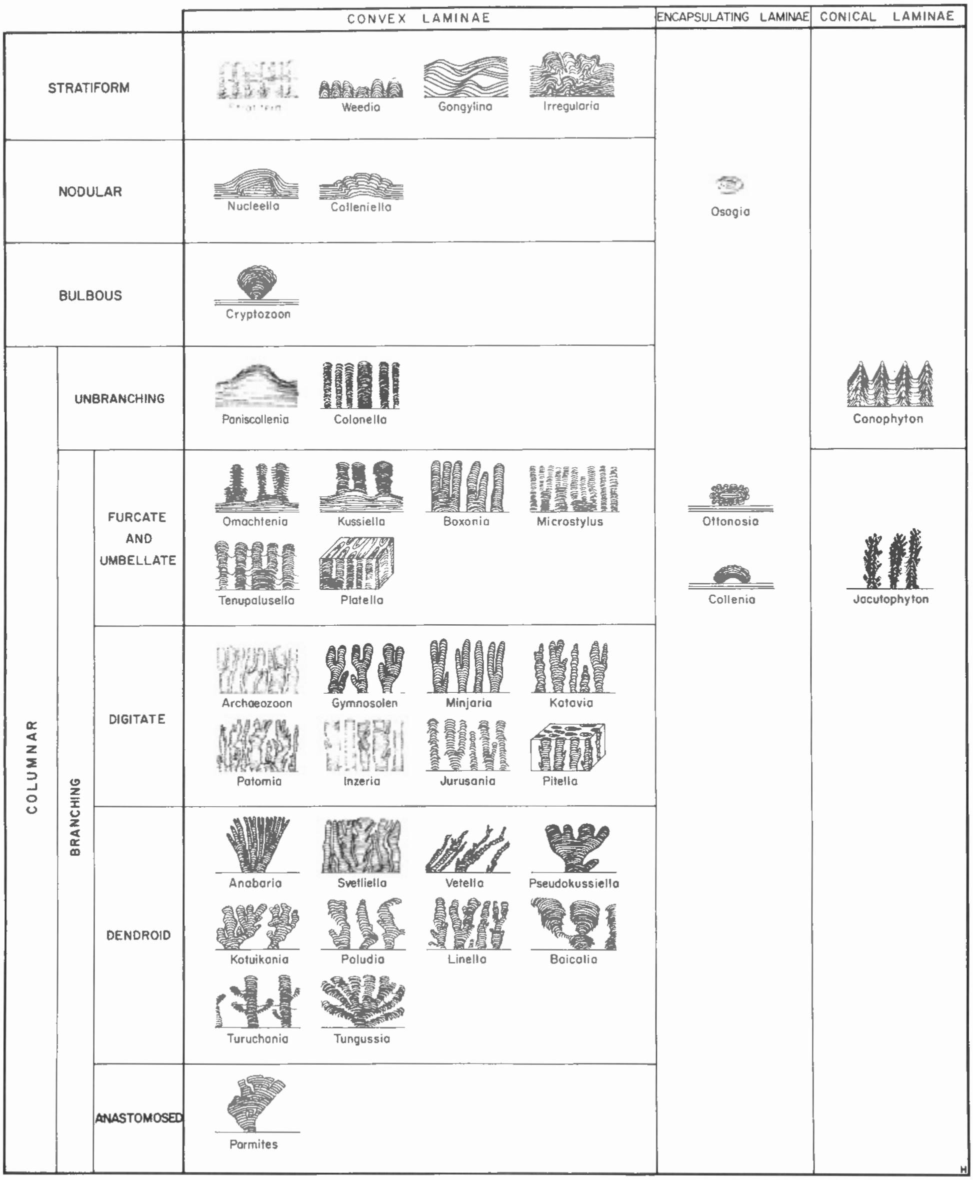


Figure 22. Comparison of some named stromatolite groups.

At present, the most consistently (and objectively) defined forms are those of *Conophyton* (Komar *et al.*, 1965). They are based on biometrically determined differences in the character of the microfabric in axial sections. It is stated by these authors (op. cit. 1965, p. 20, 55) that spacing and size of columns, and the shape of the laminae are not of diagnostic value. This was also observed in *Conophyton* from the Sibley group, where the differences in shape appear to be a function of the crowding of the columns (Hofmann, 1969). If variations in laminar morphology and size and spacing of columns are not of diagnostic value in one group, are they also without value in others? If character of the microfabric is used (successfully) in segregating forms in one group, should not forms in other groups also be based on microfabric to afford a consistent classification? In practical terms, as mentioned earlier, diagenetic alteration of textural features poses a problem.

CONCLUSIONS

This paper has summarized some of the knowledge concerning stromatolites, with an emphasis on attributes that are used in describing and classifying different categories. It has made obvious the great complexity of the stromatolite problem, and shown that there still is no ideal solution to the dilemma of classification. In fact, it has posed more questions than it has answered. The following conclusions can be stated, some of them not new:

1. The fundamental feature of a stromatolite is its mineralogically or texturally differentiated lamination. The synoptic morphology of the laminae in an assemblage is taken to be at least as important a geometric property as gross morphology, because it represents the dynamic equilibrium conditions as well as the microbathymetries of the biologically, chemically, and mechanically active interfaces in the environment. The gross morphology of the final stromatolite represents the variations of consecutive inherited laminae, all stacked on top of each other according to a certain accretion vector. This vector expresses the total duration and variations of the growth.

2. It has not been demonstrated that the shape of the laminae and the gross morphology of Precambrian stromatolites is predominantly dependent on biologic (genetic, physiologic, anatomical) attributes. In fact, empirical evidence from Holocene intertidal algal stromatolites,presumed to be analogues of most Precambrian stromatolites, indicates that gross morphology is predominantly controlled by environmental factors.

3. Precambrian stromatolites are not classifiable on a biological basis because of the general lack of characteristic and consistent cellular microstructure definitely attributable to organisms. This necessitates usage of a scheme based on gross geometric characteristics as a reasonable alternative.

4. Geometric properties of stromatolitic laminae and stromatolites can be described more consistently than in the past by a more precise specification of the terms used.

5. Stromatolites with convex lamination are the most common and exhibit the most extreme polymorphism. They have been classified into nomenclatorial categories or groups based on a variety of properties, but generally on gross morphology, laminar shape, and microfabric. None of the classifications is ideal, nor universally accepted. One now widely in use among Russian geologists appears promising, but not all its categories are well or consistently defined. It seems advantageous to have uninomial, if not binomial, designations to refer to defined categories.

6. The stromatolite group with the most definite and consistent characteristics, and also the one which is the most readily identified, is *Conophyton*. However, the origins of its conical lamination and axial zone are still a mystery.

7. The significance of branching in stromatolites is not clear. It is a common feature of stromatolites with convex laminae, and involves the formation of constraints and the development of subsidiary convexities. Both active and passive branching are found as far back as the Aphebian.

8. The peripheral features of stromatolites, such as walls and fringes, and also linkage and spacing, are dependent on relative rates of stromatolite growth and intermound sediment accumulation, and geometric factors. Their time-stratigraphic value is uncertain. Columnar structures with walls are known from rocks as old as Aphebian.

9. Inasmuch as named Precambrian stromatolite groups are neither classified, nor classifiable, on a biological basis, and inasmuch as the laminar and gross morphological characteristics are conditioned by environmental and geometric parameters, there is uncertainty about the biological significance of some of the evolutionary trends reported for the Riphean stromatolite groups *with convex lamination*. This doubt is strengthened by empirical evidence from North America: the occurrence of actively branching and walled stromatolites in the Aphebian. It now appears that the purported evolutionary trends in morphology are likely to represent environmental changes more than they do biological evolution of the stromatolite-building organisms. The Cyanophyta, in any case, have a geological record exhibiting extreme evolutionary conservatism. This opens the possibility that similar environments may have recurred more than once. The time-stratigraphic value of the structures thus needs to be constantly re-examined.

10. *Conophyton* is at present known only from the Proterozoic, and appears to be a real and useful index fossil to the Precambrian.

11. Future stratigraphic investigations of Precambrian sedimentary basins on the Canadian Shield and bordering geosynclines should include integrated, systematic studies of the stromatolites, carried out similar to, and in conjunction with those made on crossbedding, ripple-marks, sole marks, etc., to reconstruct paleoenvironments. Determinations should be made on as many attributes as possible, particularly the synoptic morphologies of laminae, habits of accretion vectors and microstructures, as well as dimensional, material, and positional attributes. These data can then be put into a time-stratigraphic framework, where the direction and magnitude of any changes in the attributes of stromatolites through geologic time can be determined.

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APPENDIX

APPENDIX

This is a selection of definitions or descriptions of the word *stromatolite* and related terms, arranged according to chronological authorship. It includes the following terms:

Stromatolith	(1, 3, 11)
Stromatolite	(9, 10, 13, 14, 15, 16, 17, 18, 19, 20, 23)
Stromatoid	(2)
Coenoplase	(4)
Spongiostromata	(5)
Stromatolithi	(6)
Oncolithi	(7)
Oncolite	(8, 12, 13, 24)
Thrombolite	(21)
Cryptalgal	(22)

1. Stromatolith (Kalkowsky, 1908, pp. 68-69)

"Unter dem neuen Namen *Stromatolith* werden Kalksteinmassen von besonderer Struktur und besonderem Aufbau verstanden, die mit Rogenstein im norddeutschen Buntsandstein zusammen vorkommen ... Der Name *Stromatolith* soll im Gegensatz zu Oolith Kalkmassen bezeichnen, die eine feine, mehr oder minder ebene Lagenstruktur besitzen im Gegensatz zu der zentrischen Struktur der Oolithkörner."

Translation: The new term *stromatolith* refers to limestone masses with distinct structure and distinct construction, associated with oolith* beds in the Buntsandstein of northern Germany ... In contrast to oolith, the name *stromatolith* is meant to designate limestone masses that have a fine, more or less flat layered structure as compared to the concentric structure of oolith grains.

2. *Stromatoid* (Kalkowsky, 1908, pp. 101-102, 104)

"Es fehlt den Stromatolithen im allgemeinen der durch eigene Form allseitig begrenzte, individualisierte Stock der organischen Bildner der Ooide,es können aber in analoger Weise jene dünnen Lagen von kohlensaurem Kalk mit eigener Struktur als Stromatoid eingeführt werden, denn sie verdanken in ähnlicher Weise einem organischen Bildner ihre Entstehung, der dem Bildner der Ooide offenbar verwandt ist. ... Der Stromatolith ist ein in situ gewachsener Kalkstein; sein characteristischer Bestandteil ist das Stromatoid, dessen einzelne Lagen sich weit ausdehnen können und alles fest verbinden, was etwa von sonstigen Dingen noch hinzukommt."

Translation: Stromatoliths generally lack the individualized body completely delineated by its own form like that produced by the organisms constructing the ooids; however, we may introduce the term *stromatoid* for those thin layers of calcium carbonate that have their own particular configuration, for they are similarly caused by organic originators which evidently were related to that forming the ooids. ... The stromatolith is a limestone grown in place, its characteristic component is the stromatoid, whose individual laminae may have wide lateral spread, and bind anything else that may be added.

3. *Stromatolith* (Foye, 1916, p. 791, footnote)

"The noun 'Stromatolith' may be defined as a rock mass consisting of many alternating layers of igneous and sedimentary rocks in sill relationship."

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* The meaning of oolith (p. 71) and ooid (p. 72): "According to generally accepted practice, the actually quite silly term oolith designates the whole rock, whose individual grains happen to have predominantly spherical form and a distinct structure." "The chief constituents of an oolith are ooids."

4. *Coenoplase* (Twenhofel, 1919, p. 342)
A suitable name for individual algal structures, composed of encrusting, laminated calcium carbonate.

5. *Spongiostromata* (Pia, 1927, p. 36)
Colonial structures with characteristic gross morphology, but without distinct organic microstructure, built, or presumably built, by algae. Considered a category belonging to the Class Schizophyceae.

6. *Stromatolithi* (Pia, 1927, p. 37)
A division of the Spongiostromata containing structures that grew attached to the substrate.

7. *Oncolithi* (Pia, 1927, p. 37)
A division of the Spongiostromata containing structures that grew mobile on the substrate.

8. *Oncolite* (Young, 1941, p. 20)
Oncolites "are small unattached finely laminated bodies which assume a great variety of shapes, frequently grotesque. The laminae are crenulate in section, and in typical oncolites, are not, except in the earlier formed portions, concentrically arranged, but overlap one another. They invariably envelop some foreign body. The irregular shapes of the oncolites are produced by the successive additions of groups, crescentic in section, of laminae at different points along the surface of the growing bodies. The internal structure is finely radiate".

9. *Stromatolite* (Cloud, 1942, p. 362)
"... laminated but otherwise structureless objects variously called cryptozoon, collenia, gymnosolen ... formed by lime-secreting algae."

10. *Stromatolite* (Am. Geol. Inst., 1957, p. 283)
"Laminated but otherwise structureless calcareous objects; commonly called fossil calcareous algae (after Cloud, P.E.,Jr., p. 365, 1942) Syn. Cryptozoon; Collenia; Gymnosolen."

11. *Stromatolith* (Am. Geol. Inst., 1957, p. 283)
"1. Term proposed by Kalkowsky, 1908. Certain curious layered, banded structures in the Buntersandstein associated with ooliths, and supposed to be organic (Cummings, E.R., p. 334, 1932).
2. A term applied to a large mass of mixed rock which consists of alternating layers of igneous and schistose rocks in sill relationship. A large mass of stromatite, q.v."

12. *Oncolite* (Am. Geol. Inst., 1960, p. 46)
"Small body of varied shape consisting of a central object enclosed by laminae like an oolite except that the individual laminae generally are not concentric but overlap; occurs in Precambrian of South Africa, presumed to be algal; Young, 1941 ..."

13. *Stromatolite*; *oncolite* (Maslov, 1960, p. 20)
(In translation): By the name stromatolite are meant fossil concretions, calcareous or dolomitic, formed by primitive organisms on a basin floor. They are attached directly to the bottom (stromatolites proper), or they are freely moved about by the waters (oncolites).

14. *Stromatolite* (Challinor, 1961, p. 191)
"Stromatolite (Stromatolith). A rock having a banded structure suggesting an organic, particularly an algal, origin."

15. *Stromatolite* (Häntzschel, 1962, p. W226)
"General name for variously shaped, finely stratified calcareous crusts and calcareous bodies (also called stromatoliths); obviously formed by lime-precipitating algae; commonly associated with oolites or ooid-grains ..."

16. *Stromatolite* (Krylov, 1963, p. 21 and 127)
(In translation): Lamellar formations attached to the substrate and found mainly in carbonate rocks are called stromatolites. ... Such structures show a regular repetition of similarly bent laminae ... They are the result of the life activity of algal and perhaps bacterial colonies. The composition of algae and bacteria determines the shape of colonies, and this shape is shown in the configuration of the stromatolitic structures. ... Facies conditions determine the composition of the algae in a colony, and this composition in turn determines the shape of the colony. Under similar facies conditions there occur closely related types of stromatolites (columnar, etc.).

17. *Stromatolite* (Donaldson, 1963, p. 6)
"The term stromatolite is used here to signify any laminated sedimentary structure possibly formed as a result of algal activity."

18. *Stromatolite* (Pettijohn and Potter, 1964, p. 345)
"The term stromatolite has been generally applied to laminated structures attributed to the work of blue-green algae. Commonly called 'algal structures'. Characteristically laminated with varied gross forms, from near-horizontal, to markedly convex, columnar and subspherical (Cloud, 1942)".

19. *Stromatolite* (Logan, Rezak, and Ginsburg, 1964, pp. 68-69)
"... the term has been used to designate both organic and inorganic laminated structures. ... To be useful, the term stromatolite should be preceded whenever possible by an adjective signifying the kind of stromatolite under consideration, for example, algal stromatolite, foraminiferal stromatolite, inorganic stromatolite, and so forth. ... Algal stromatolites are laminated structures composed of particulate sand, silt, and clay-size sediment, which have been formed by the trapping and binding of detrital sediment particles by an algal film. ... Oncolites are ... a category of stromatolite structure."

20. *Algal stromatolite* (Aitken, 1967, p. 1163)
"The term *algal stromatolite* (Pia, 1927; Logan and others, 1964; Johnson, 1966) is restricted in this paper to fixed bodies of cryptalgal origin, characterized by non-planar lamination and possessing definable boundaries or contact with other stromatolites."

21. *Thrombolite* (Aitken, 1967, p. 1164)
"The term *thrombolite* (from the Greek thrombos, bloodclot) is proposed for cryptalgal structures related to stromatolites, but lacking lamination and characterized by a macroscopic clotted fabric."

22. *Cryptalgal* (Aitken, 1967, p. 1163)
"Cryptalgal sedimentary rocks or rock structures may be defined as those believed to originate through the sediment-binding and/or carbonate-precipitating activities of nonskeletal algae. The presence of filamentous or unicellular structures due to nonskeletal algae should not be considered to exclude a carbonate rock from the cryptalgal group."

23. *Stromatolite* (Hofmann, present usage)

A millimetre- to dekametre-sized organosedimentary structure whose growth is recorded by a succession of laminae. These laminae represent intervals of accumulation of fine sediment on surfaces presumed to have been populated by a community of micro-organisms. The sedimentary material is accumulated by trapping or agglutination on the organic plexus, or by nonskeletal precipitation resulting from the metabolic activity of the micro-organisms.

24. *Oncolite* (Hofmann, present usage)

An oncolite is a stromatolite with centrifugal growth vectors, and encapsulating laminae formed around an intermittently mobile nucleus.