CHAPTER 4

STROMATOLITES: ATTRIBUTES, CLASSIFICATION AND SYSTEMATICS
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4.1 ATTRIBUTES OF STROMATOLITES

The terminology used in description of stromatolites has evolved over the years and derived by a number of workers. The description given below has been used in the present thesis and is based on Hofmann (1969), Preiss (1972), Walter (1976) and Grey (1989). Many of the features commonly used in stromatolite description are:

4.1.1 Nature of outcrop

To study the nature of outcrop, observations such as the thickness, shape of the bed and its constituent units are studied. The latitude, longitude and a map showing the locations for the considered area are provided. The lateral and vertical extent of the bed and its constituent units are recorded. The lithology of the stromatolites and surrounding sediments and the state of preservation are studied.

4.1.2 Bed

The thickness, lithology and the nature of upper and lower boundaries are studied (i.e. the bed is well defined or lying over or under the sediments, the evidence of erosion or unconformity) (Figure 4.1).
4.1.3 Mode of occurrence

This section covers the gross morphology of the microbialite mass within the bed – the reef, carbonate build up or the lithoherm. The microbialite occurs in microbial lithoherm (bioherms) or lithostrome (biostromes) and/or as separate fascicles (Grey 1984), and/or as individual columns or oncolites.

4.1.3.1 Mode and shape – It describes the microbialite mass in a lithoherm or lithostrome:

i. Lithoherms (Bioherm) - Lithoherm is a circumscribed organo-sedimentary structure whose minimum width is less than or equal to one hundred times its maximum thickness embedded in rocks of different lithology (Figure 4.2 A).

Lithoherms (Bioherms) can be of following types:
a. Subspherical
b. Domed
c. Tabular
d. Intertonguing

ii. **Lithostromes (Biostromes)** - Lithostrome is a stratified organo-sedimentary structure whose minimum width is more than one hundred times its maximum thickness (Figure 4.2 B). Lithoherms can be:

a. Tabular
b. Domed

![Diagram of Lithoherms and Lithostromes](image)

Figure 4.2 - Mode of occurrence - A) Lithoherms (Bioherms), B) Lithostromes (Biostromes). (After Grey, 1989).

4.1.3.2 **Constituent of Lithoherms** - It describes the nature of microbialite constituents, lamination or non-lamination, linkage and spacing.
i. **Nature of Microbialite constituents** - It describes the shapes of the microbialites and their relationships within the bioherm or biostromes (Figure 4.3). They are of following types:

a. Stratiform
b. Simple columnar
c. Branching columnar
d. Simple conical
e. Linked conical
f. Branching conical
g. Spheroidal (oncolites)

![Figure 4.3 - Nature of microbialite constituents. (After Hofmann, 1965).](image)

ii. **Laminated or non-laminated** - The term “microbialite” (Burne and Moore 1987) was introduced to solve the problem which exists between stromatolite and thrombolite. If the microbialite is laminated then the structure is stromatolite and if non-laminated then the structure is thrombolite.
iii. **Linkage** – Linkage is the degree of connection between microbial lithoherms or fascicles (Figure 4.4 A). Linkages are of following types:

a. Linked

b. Partly-linked

c. Unlinked

![Diagram of Linkage and Spacing](image)

Figure 4.4 – Spacing of stromatolites – A) Linkage, B) Spacing. (After Hofmann, 1969).

iv. **Spacing** – Spacing is an important feature between lithoherms and fascicles (Figure 4.4 B). Sometimes lithoherms occur in clusters, or in an echelon arrangement. Spacing is of following types:

a. Contiguous

b. Very closely spaced

c. Closely spaced

d. Openly spaced

e. Isolated
4.1.4. Branching habit

4.1.4.1 Morphological types: Hofmann (1969) gave a detailed account of geometrical parameters which control stromatolites shape. A single fascicle consists of several morphological types. The morphological types can be categorized as:

(i) Stratiform (Figure 4.5)
   a. Flat-laminated
   b. Undulatory
   c. Pseudocolumnar
   d. Columnar-layered
   e. Cumulate

(ii) Simple columnar (Figure 4.6)
   a. Terete
   b. Cylindrical
   c. Turbinate
   d. Bulbous
   e. Nodular
   f. Hemispherical

Figure 4.5 – Types of non-columnar stromatolites (After Grey, 1989)

Figure 4.6 – Types of simple columnar stromatolites (After Hofmann, 1969)
(iii) Branching columnar

a. Style

1. Branching – Branching are of two types
   i. Bifurcate  
   ii. Multifurcate

   In Bifurcate branching the column divided into two daughter columns. In Multifurcate branching several daughter columns arise at the same horizon (Figure 4.7 A). Bifurcate branching is of two types dichotomous and lateral. In dichotomous branching the daughter column arise from the top of the parent column and in lateral branching the daughter column develops from the side of the parent column. Bifurcate daughter columns may form an equal division in which both columns are approximately of same width or an unequal division in which one is larger than the other.

2. Convergence – Some columns show reconvergence after branching (Figure 4.7 A). When two columns merge to form a larger column then branching is coalescent and the two columns are overgrown by a third larger column then branching is anastomosed.

b. Frequency of branching and spacing - The frequency of branching and its spacing along the column is observed. Branching may occur at regular interval or irregular interval.
**c. Angle of divergence** – The angle of divergence of daughter branches is noted (Figure 4.7 B). They can be

1. Parallel

2. Moderately divergent

3. Markedly divergent

d. **Method of branching** – Branching are of following types (Figure 4.7 C)

1. Alpha (α) - Branching in which the width of the individual remains constant.

2. Beta (β) - Branching in which the original column widens gradually before branching.
3. Gamma (γ) - Branching in which the original column widens abruptly before branching.

(iv) **Simple conical** – The microbialites form simple, unlinked or rarely-linked cones (Figure 4.8 A)

(v) **Linked conical** – Microbialites form conical structures they may be ridged and there is considerable linkage between columns (Figure 4.8 A)

(vi) **Branching conical** – Some conical stromatolites give rise to highly complex structures (Figure 4.8 A) which consist of a central cone, surrounded by lateral branches

(vii) **Spheroidal** – This morphology includes the structure oncolites (Figure 4.8 B). They are completely detached from the surrounding substrate and are usually laminated, non-laminated fabrics may also occur.

*Figure 4.8 – Types of conical and spheroidal stromatolites – A) Conical forms, B) Spheroidal forms (After Grey, 1989)*
4.1.5 Column Shape

4.1.5.1 Plan outline - This is the horizontal cross section i.e. the shape of the column when viewed in a plane at right angles to the direction of the growth vector (Figure 4.9). Hofmann (1969) defined the following shapes:

a. Rounded
b. Oblong
c. Scutate
d. Crescentric
e. Laxilobate
f. Densilobate
g. Brevilobate
h. Polygonal
i. Lanceolate

Figure 4.9 – Plan outline of microbialites. (After Hofmann, 1969)
4.1.5.2 Vertical profile - The shape of a column is one of its most distinctive features (Figure 4.10). In this, size of the column, elongation and attitude of the column are studied.

i. **Column size** – The average length (i.e. vertical height) of the column and average diameter is noted.

ii. **Elongation** – Elongation is defined as the ratio of height to width of the column (Figure 4.10 A). Hofmann (1969) described them as
   a. Crustose \( H << 2r \)
   b. Stubby \( H - 2r \)
   c. Slender \( H >> 2r \)

iii. **Variability of growth** - Diameter of column remains constant or it vary (Figure 4.10 B). Hofmann (1969) described the degree of variability as
    a. Uniform- The diameter of the column is fairly constant in width.
    b. Constringed – The diameter of the column is of variable width.
    c. Ragged – The diameter of the column is very variable

iv. **Attitude** – Attitude is defined as the inclination of the column to the bedding plane, is the column straight or curved. Hofmann (1969) recognized the following types (Figure 4.10 C)

1. Erect Straight and vertical
2. Inclined Straight but an angle to the vertical
3. Recumbent Inclined with convex curvature
4. Decumbent Inclined with concave curvature
5. Sinuous Alternately convex and concave
6. Centrifugal Growing outwards from a central point
4.1.6 Features of Stromatolites

4.1.6.1 Margin structure - Margin structures are commonly formed by modification of the laminae.

i. Walls - Structure at the margin of a column formed by one or more laminae from within the column bending down and coating the column margin for at least a short distance is called a wall. Walls are described as present, patchy or absent. A wall may be simple in which overlapping are more or less parallel to each other along the sides of the column and gradually taper out, or complex in which one or more laminae overlap the edges of several underlying laminae.

ii. Surface ornamentation - The nature of the outer wall determines the longitudinal profile (Figure 4.11). This is best observed in three dimensional reconstruction.
The ornamentation can be

1. Smooth
2. Bumpy
3. Tuberous
4. Lobate
5. Rugate
6. Ragged
7. Projections
8. Nitched

Figure 4.11 - Types of column ornamentation, (After Grey, 1989).

iii. **Linkage** – Many columns show interconnections. Two columns are connected by bridge. Bridging may be slender or massive depending on the number of laminae involved.

4.1.6.2 Laminae - Lamina is defined as the smallest unit of layering. The nature of laminae is an extremely significant characteristic of laminated stromatolites.
i. **Lamina profile** – Lamina profile is an important characteristic of all laminated stromatolites and it varies throughout the column or fascicle, but they are diagnostic. Laminae profile can be of following types (Figure 4.12 A)

1. Flat
2. Gently convex
3. Steeply convex
4. Parabolic
5. Inflated
6. Concave
7. Conical
8. Cuspate
9. Obscure
10. Rectangular
11. Rhombic
12. Penecinct
13. Plenicinct

![Diagram of lamina profile and type](image_url)

Figure 4.12 – Types of laminae - A) Profile, B) Laminar type. (After Hofmann, 1969).
ii. **Lamina Type** – Hofmann (1969) characterized laminae according to the order of curvature and degree of evenness as even, corrugate, crenulate and dentate. Basically, nature of laminae can be (Figure 4.12 B)

1. Smooth  
2. Wavy  
3. Wrinkled

iii. **Synoptic Relief** – The nature of successive growth interfaces of the stromatolites (Figure 4.13 A). Hofmann characterized them as

1. Low – 2r >> h  
2. Moderate – 2r = h  
3. High – 2r << h

iv. **Degree of inheritance (serial development)** - It describes how closely the shapes of successive laminae conform to preceding laminar shapes (Figure 4.13 B). It is of following types.

![Diagram](image)

Figure 4.13 – Superposition of laminae – A) Synoptic relief, B) Degree of inheritance.

(After Hofmann, 1969)
1. Low
   Successive laminae rarely conform to the shape of the preceding laminae.

2. Moderate
   Some but not all laminae are conformable

3. High
   Most laminae are conformable

v. Lateral continuity – It describes the continuity of laminae across the column and their variability across the column (Figure 4.14). Laminae can be

1. Consistent – Lamination is continuous from one side of the column to other, lithology is consistent and thickness changes slightly.

2. Regularly variable in thickness – Lamination is continuous from one side of the column to other, lithology is consistent but thickness varies considerably but regularly, thick at center to thin at margin.

3. Irregularly variable in thickness – Lamination is continuous from one side of the column to other, lithology is consistent but thickness varies considerably but irregularly, across the column.

4. Lenticular – Lamination extends from one side of the column to other but form a series of discontinuous but aligned lenses, lithology within the lenses is consistent.

5. Discontinuous – Lamination does not extend from one side of the column to the other, but form a series of discontinuous and offset lenses, Lithology is consistent.

6. Heterogeneous – The lithology is different from margin to center of the column, thickness is variable. The variation may result from either the nature of the original fabric, or from diagenesis.
vi. **Types of accretion** – It describes how laminae are stacked on top of each other. Laminae may be parallel or overlap the margin of the other, type of laminae, their involvement in the formation of each pattern, and how dark and light laminae overlap (Figure 4.15 A).

Stromatolite lamination consists of alternate light and dark fabrics related to diurnal or seasonal changes and most sets of laminae reflect complex sedimentological, biological and diagenetic processes.
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Stromatolite lamination consists of alternate light and dark fabrics related to diurnal or seasonal changes and most sets of laminae reflect complex sedimentological, biological and diagenetic processes.
Some stromatolites have uniform fabrics (Figure 4.15 B) or non-uniform.

![Diagram of Type and Pattern of Accretion](image)

Figure 4.15 – Type and pattern of accretion – A) Type of accretion, B) Pattern. (After Grey, 1989).

Lamina form couplets – i.e. a simple alteration of light and dark laminae or non-couplets (Figure 4.15 B). Non-couplets can be described as having (Figure 4.16 A):

a. Even fabric – All laminae have the same fabric and boundaries probably represent micro-uniformities.
b. Void intercalated – In which either couplets or non-couplets are separated by different types of lamination usually by an infill of sparite.


d. Film-bounded fabric – The uppermost limit of the laminae is a film, usually of dark material.

vii. Macrolaminae – A macrolaminae (Figure 4.16 B) usually consist of a band formed by laminae of uniform thickness, juxtaposed against a second band containing laminae of different thickness. The laminae forming the macrolaminae may be couplets or non-couplets. Macrolaminae can also be formed by the repeated occurrence of a lamina with a different fabric in a set of fairly uniform laminae e.g. void-filling laminae may occur at intervals and form boundaries to sets of light and dark laminae.

![Figure 4.16 - Fabric and Macrolaminae (After Grey, 1989)](image-url)
4.1.6.3 Fabric and microstructure – Fabric "refers to internal spatial properties such as the development of a lamination". Microstructure refers to the microscopic characteristic of the internal properties (Monty 1976). These are studied by the shape of the lamina.

Fabric plays an important role in stromatolite classification. Fabrics, which can be recognized, are:

i. Banded – Continuous laminae and abrupt, distinct, more or less parallel boundaries (Walter 1972, p.12).

ii. Catagraph-Bearing – Regular spheroids with a dark envelope in a clear calcite infilling in a microsparite matrix (Bertrand - Sarfati, 1976, p.256).

iii. Film – Regularly banded, dark, thin Micritic films, alternating with clear sparite or microsparite (Bertrand - Sarfati, 1976, p.253).

iv. Frutexities – A microstructure consisting of millimeter-sized, iron rich shrubs, in which some trace of the original constructing organism remains. (Playford et al. 1976, Walter and Awramik 1979).

v. Granular – Laminae poorly defined and large grains are usually concentrated in dark layers.


vii. Micritic mat - "Basically the laminae are thick darkish in colour and composed of micrite, their upper boundary may be straight, crinkled or scalloped. The laminae are formed by two different layers, the upper one (micritic) is darker than the lower one (microsparitic)" (Bertrand - Sarfati, 1976, p.257).
viii. Pelletal – Laminae, which are well defined, are formed from pelloidal structure (Preiss, 1974).

ix. Porostromate – It is defined by the growth of loose or tangled, vertical, flabellate or flat lying straight or sinuous calcified filaments or threads, or even of calcified unicells (Monty, 1981).

x. Streaky – The laminae are moderately distinct and continuous, the darker are usually the most distinct and are set in a pale matrix into which they frequently grade vertically (Walter 1972, pp. 11 & 14).


xii. Tussocky – Irregular lamination defined by juxtaposition of separate hemispheric tussocks of different size (Bertrand-Sarfati, 1976, p.253).

xiii. Vermiform – Narrow, sinuous, pale coloured areas (usually of sparry carbonate) are surrounded by darker, fine-grained areas (usually carbonate) (Walter, 1972, p.14; Bertrand-Sarfati, 1976, p.255).

4.1.7. Interspace Filling

Interspace is the space between two columns. A study of stromatolite interspaces provides valuable information on lithofacies relationships and palaeoecology. The feature such as the nature of the interspace filling and relationships between the interspace and column margin is noted.

4.1.8. Secondary Alteration

Secondary alteration is the alteration of any other mineral in stromatolite structure. There is any evidence of diagenesis, recrystallization, and secondary silicification. Stylolites or veins may be observed.
4.2 CLASSIFICATION OF STROMATOLITES

In spite of about a century of study of stromatolites their classification is still a matter of debate. The first attempt of classification of Precambrian stromatolite was made by Walcott (1914, p.104) on the basis of external form. He divided Beltian algal structures into four categories: Massive cellular, Semispherical, Flabelliform and Tubiform. Pia (1927, pp. 36-37; 1928, p. 212) made classification based on growth form. He included in thallophyte Class Schizophyceae into 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]). Maslov (1937a, 1937b, 1938, 1939a, 1939b, 1939c) recognized two major types of stromatolites: Collenia with convex laminae and Conophyton with conical laminae. Krasnopeeva (1946) classified stromatolites into four genera: Newlandiella, Algostroma, Kabyrsina and Sibirephycus. 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. Anderson (1950, p.7) found existing classification unsatisfactory. He referred carboniferous stromatolites into 12 formalized growth forms. They include flat, nodular, bulbous, turbinate, cylindrical, branching and coalescent forms. Rezak (1957, p.131) used a simple classification using ‘genera’ on the mode of growth and ‘species’ on gross form of colony and nature of laminae. He classified stromatolites into Cryptozoan, Collenia, Newlandia & Conophyton. Maslov (1953, 1960) suggested a formal, non-biological classification of phytolites (stromatolites and oncolites). 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 peculiarities.

Korolyuk's (1960) classification of stromatolites was based on newly recognized morphological features of buildups as type, subtype, group and form. Vologdin (1962) 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. Logan et al. (1960, 1964) proposed a new concept of stromatolite classification based upon the geometric forms and related these forms to their sites of growth relative to sea-level environment. The classification used the arrangement of basic geometric units (hemispheroids and spheroids) from which common stromatolites and oncolites were formed. Such arrangements were a reaction of algal mat to environmental factor and it was therefore possible to describe form arrangement to environment processes. Three main types of arrangements proposed were

1. Laterally linked hemispheroids (LLH)

2. Discrete, vertically hemispheroids (SH)

3. Spheroidal structure (SS).

It is argued that majority of algal stromatolite structure are compounded of LLH and SH arrangements. As the growth is possible and the structure arrangement alternate then the stromatolite may be designated as LLH > SH > LLH and so on.
Raaben (1964, 1969) classified columnar stromatolites into four main supergroups based on the mode of ramification and shape of the column. These supergroups are

1. Conophytonida (non-ramified with cylindrical column).
2. Kussiellida (ramifying actively, cylindrical column).
3. Tungussida (ramifying actively, column widening upward, cup like, with axes divergent).
4. Gymnosolenida (ramifying actively, pseudocylindrical columns, axes running roughly parallel).

Komar (1966, p. 50) classified stromatolites on the basis of

1. Type of branching
2. General form of column
3. Characters of lateral boundaries
4. Textural features.

Based on these features stromatolites are grouped into a hierarchy of types, subtypes, groups and forms.

Aitken (1967) used a new terminology for algal carbonates. Those with organic microstructure he termed them as skeletal calcareous algae and those without cellular structure are termed as noncalcareous algae. Walter (1972) gave an elaborate review on the classification of stromatolites and summarized that among Russians there were two school of thoughts. One school of thought (Semikhatov, Krylov, Raaben, Komar, Nuzhnov, Shapovalova) holds that reconstruction of stromatolites by the methods applied by Krylov (1959, 1963) provides much taxonomically useful data. Other school of thought (Korulyuk and Sidirov) classify taxa only on the basis
of slabs and thin sections without considering reconstruction. In the first school of thoughts Krylov classified the columns on the basis of very minute and consistent differences in column shape and arrangement. He did not consider microstructure arguing that they were due to secondary alterations, on the other hand others used differences in column shape and arrangement for defining (form genera) microstructure for the separation of forms. Preiss (1972) suggested that retention of the term 'group' based on gross morphology, column shape, branching and margin structure and 'form' should be deferred on the basis of lamina shape and microstructure.

Krylov (1976) in ‘Approaches to the classification of stromatolites’ summarized the 12 classifications prevalent at that time. These were based on different features or the combination of features depending upon what was being classified whether a sample, column or bioherm, he suggested that morphologically different constructions from different parts of the same bioherm could have different names in accordance with diagnosis of the taxa described in the literature and the use of linean nomenclature is meaningful only when the strictest rules are observed to maintain its stability. The classification is as follows:

Classification applicable to any stromatolite

For stromatolite classification single vertical section is sufficient to study its features. The group distinguished in this way is again subdivided on the basis of: -

1. Branching :- Stromtollites with branching columns are termed as Gymnosolen (Pia 1927, Cloud 1942, Raaben 1960) and stromatolites
whose columns widened upwards belong to group Cryptozoon (Pia 1927, Rezak 1957).

2. Shape of Lamination: Stromatolite with domal shape lamination belong to group Collenia (Maslov 1914) and with conical shape laminae with an “axial zone” belong to group Conophyton. Maslov (1960) introduced an intermediate group Conocollenia.

Other classification of stromatolites is based on its types and subtypes. On these basis five types are identified:

i. Columnar
ii. Stratiform
iii. Nodular (Korolyuk 1960c)
iv. Columnar stratiform
v. Columnar nodular (Krylov 1963)

Classification of stratiform stromatolites

4. Stromatolites are classified on the basis of layers. For the identification of this group adjacent tubercles and hollows should be present in sample which are observed in vertical sections. Group with regular alteration of convex tubercle and concave hollows termed as Stratigera and group with non-inherited morphology of layers are termed as Irregularia (Korolyuk 1960c).

5. Stromatolite classification is based on two criteria: lamination morphology and microstructure. Group Gongylina (Komar 1960) is similar to Irregularia in morphology but differs in microstructure.
Classification of columnar-stratiform stromatolites

5. Groups are classified by the morphology of the columns and the shape of the laminae. For this group study sample should include 2-3 columns in single vertical section. In this way following groups are distinguished. Schancharia and Columnnaefacta (Korolyuk 1960c), Parmites (Raaben 1964b), Omachtenia (Nuzhnov 1967), Gruneria (Cloud and Semikhatov 1969b), Dgerbia (Dolnik 1969 in Dolnik and Vorontsova 1971) & Tarioufetia (Bertrand-Sarfati 1972c).

Classification of nodular stromatolites

6. Nodular stromatolite are classified by study of the central part of the nodule in vertical section. Two groups Colleniella and Paniscollenia are distinguished (Korolyuk 1960c). The difference between these two groups is the morphology of the laminae.

7. Group Nucleella (Komar 1966) is classified on the basis of morphology and also studying the microstructure of the laminae. The group is identified by microscopic study of thin section.

Classification of columnar - nodular stromatolites

The group Tinnia (Dolnik 1969 in Dolnik and Vorontsova 1971) and Gaia (Krylov 1971) are identified by studying a large sample that shows a substantial part of the nodule. Vertical section is studied and it is desirable to have a complete photograph or drawing of the outcrop.

Classification of columnar stromatolites

There are five independent classification of columnar stromatolites:
8. Columnar stromatolite are identified by studying the vertical section that passes across the middle of the column. Groups are distinguished according to the shape of laminae and nature of column margins (Korolyuk 1960a). The classification includes the following groups: *Collumnacollenia*, *Planocollenia*, *Linocollenia*, *Sacculia* (Korolyuk 1960a), *Boxonia* (Korolyuk 1960c non Komar 1964), *Conophyton* (Maslov 1938), *Illicita* (Sidorov 1960), *Tunicata* (Sidorov in Korolyuk 1968), *Katernia* (Cloud and Semikhatov 1969b) and *Kasaia* (Bertrand-Sarfati 1972c).

9. These group are distinguished on the basis of three morphological features:
   a). General shape of the columns (tuberous, sub-cylindrical)
   b). Types of column margins (smooth, bumpy, ribbed, walled or naked)
   c). Character of branching

1971), *Boxonia* (Komar 1964, non Korolyuk 1960c), *Tilemsina, Serizia, Mouatila, Tifounkera* (Bertrand – Sarfati 1972) can be identified.

10. These groups include the three features mentioned above with fourth i. e. the microstructure of the layers. For this group identification graphical reconstruction as well as thin section (Komar 1961) studies are necessary. In this way groups *Microstylus* (Komar 1966) and *Glebulella* (Dolnik 1969) have been identified and new diagnosis for the previously described stromatolite groups have been provided: *Kussiella* (Komar 1966, non Krylov 1962), *Boxonia* (Komar 1966, non Korolyuk 1960c, non Komar 1964) and *Kotuikania* (Komar 1966, non Komar 1964).

11. Under this classification the groups are distinguished as regular combinations of morphologically different constructions. For identification of these groups in laboratory, a large hand specimen in combination with field photographs and drawings and sometimes a "graphical reconstruction" is used. It is easiest to identify in the field. This group include *Compactocollenia* (Korolyuk 1960) which is a combination of a nodule with a branching column, *Tungussia* (Semikhatov 1962) which is the combination of inclined columns with vertical tuberous branches and *Jacutophyton* (Shapovalova 1968) which is the combination of an axial column corresponding to the diagnosis of the *Conophyton* group with branches of definite morphology.
12. This classification for defining group includes the study of mode of occurrence (i.e. shape of the bioherm), column shape, branching style, laminae shape and microstructure.

Hofmann (1969) and Bhattacharya (1980) attempted ‘Mathematical approach’ a new method for stromatolite classification. Both suggested that a particular form of a stromatolite can be represented by mathematical equation, which will remain unchanged when the same form with minor variations of less important parameters is described. Bhattacharya (1980) proposed that quantitative aspects of stromatolites should be given due emphasis in the identification of forms instead of the classical qualitative aspects.

Banerjee and Chopra (1986) used morphometric analysis technique involving the technique of tracing of the upper laminae boundary of each stromatolite columns which permits measurement of different profile shape attributes such as area, length, width, vertical & horizontal intercepts and profile inclination. By statistical analysis different groups of lamina are categorized for the correlation of stromatolites.

Raaben and Sinha (1989) proposed a scheme of classification of stromatolites with a larger amount of data in order to establish new superior taxa at every rank level. They introduced a new taxon ‘Microstromatithi’ to incorporate small columnar and non-columnar stromatolites (see table 4.1).

Komar (1989) proposed a classification of the microstructure of the Neoproterozoic stromatolites.
Grotzinger and Rothman (1996) presented an abiotic model for stromatolite morphogenesis. Discarding all classifications, on the basis of mathematical equation derived by digitizing height of lamina. They tried to prove that morphology is the result of a physical & chemical processes.

Recently, Semikhatov and Raaben (2000), Raaben et al., (2001) presented a comprehensive classification scheme of stromatolites incorporating different aspects (see table 4.1).

Batchelor et al., (2004, 2005) proposed a mathematical model for stromatolite morphogenesis. The model considers the relationship between upward growth of a phototropic or phototactic biofilm and mineral accretion normal to the surface of the mat. Domical structures are formed when mineral accretion dominates. When vertical growth dominates Coniform structures evolve that reproduce the features of Conophyton a stromatolite that flourished in certain low-sedimentation environments for much of the Proterozoic. The proposed model for stromatolite morphogenesis involves two process.

a. Upward growth of a phototactic BMC (benthic microbial community).

b. Mineral accretion normal to the surface.
Table 4.1: Successive stages in the development of the traditional stromatolite classification system (after Raaben, Sinha & Sharma, 2001)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Phenotype</th>
<th>Family</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>Superotype Conophyton Collenia 1960</td>
<td>Stratiform Columnar Nodular</td>
<td></td>
</tr>
<tr>
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Note: Table continues with additional stages and descriptions.
4.3 SYSTEMATICS

Columnar and branching stromatolites are recognized in the present study on the basis of vertical profiles in the outcrop, samples and serially cut slabs. Morphological features such as shape of columns, type of branching, lamina shape, nature of laterd surface etc. are based on Grey (1989).

GROUP COLONNELLA KOMAR 1964

Type Formation: Colonnella cormosa Komar

Diagnosis

Columns are straight, narrow, cylindrical, mostly linked with less or narrow intercolumnar space. Commonly uniform in width. Laminae gently convex. The microstructure is smooth.

Content

Colonnella laminata Komar
(Plate III, IV Figure 4.17)

Material

Seven specimens. This variety is known from three outcrops. The material described has been collected from NW of Koliapara, Kerlakonta, Machkot and Mundapal localities.

Description

Regular subcylindrical parallel columns with rounded ovate cross profile. The diameter ranges from 5 to 15 cm height up to a meter. The stromatolite outcrop from deeply convex bell shaped and lensoid morphology. Columns are semispheric and when approaching the margins they are sometime sharply conical.

Outcrop

This stromatolite form is well developed in the Middle part of the Jagdalpur shale Formation. The stromatolitic bioherms are well exposed near the Bastar village NW of Koliapara, Kerlakonta, in the Ganeshbahar Creek of Machkot area and in the East of Mundapal village. All the stromatolitic outcrops are red coloured dolomitic limestone. The carbonate units are surrounded by shales. In the Mundapal exposure are present several calcite veins and stylolites.

Mode of occurrence

Stromatolitic bioherms occur an isolated outcrop in between the shales. In some of the outcrops, stromatolites are large, complete and compact while in others the stromatolites are broken on the margin.
Figure 1-3 Field occurrences of *Colonnella laminata* Komar in Jagdalpur Limestone, Chhattisgarh.

Figure 1- Polished slab of *Colonnella laminata*, Koliapara.

Figure 2- Polished slab of *Colonnella laminata* Koliapara.

Figure 3- Field exposure of Jagdalpur Limestone showing small columns and branching is absent.
Figure 4.17 – 3-D reconstruction of *Colonnella laminata*.
Fascicle morphology

Fascicles are made up of columns without any branching. Fine laminae alternate with mud and limestone. Laminae profiles is hemispherical and convex overlapping of laminae form a clear wall structure.

Branching habit

Branching is absent.

Column shape and margin structure

Columns are cylindrical in shape and ovate to semicircular in transverse section. Mostly formed by flexous, dome shaped / hemispherical laminae which are convex, stacked one above the other margin is compact and thin.

Microstructure and Texture

Laminae of stromatolites occur in pair of light and dark colours in which the light and dark laminae are thicker towards the margins of the column where in central portion the light and dark laminae are equally thick. Dark laminae produce streaky to uniform texture. Light laminae range in thickness from 400-250 μm and dark laminae range in size from 80-120 μm and made up of equigranular dolomites. Both the dark and light laminae range in size have well defined boundary. This boundary can be marked on the stromatolitic columns owing to very thin admixture of dark argillaceous material accumulated / trapped on the microcrystalline surface.
1. Slit grain in intercolumnar space.
2. Intercolumnar space and part of column with dolomite.
3. Column with shale and dolomite.
4. Dolomite.
5. Colonnella laminata layer.
Interspace filling

Interspace between the columns are very narrow and contain a mixture of clay and dolomite. The grain size is almost identical to those clay particles within the laminae of the stromatolite column.

Secondary alteration

Stromatolites are present in the red coloured dolomites which are part of red coloured Jagdalpur shale Formation. Presence of ghost rhombs and equigranular dolomite in the laminae suggest the primary trapping and binding of the carbonate grains. Stylolites are noted in few places.

Comparison

The present stromatolite form differs from other forms of *colonnella* group by a very simple microstructure of the microbial strata and their deeply convex laminae.

Distribution

These stromatolites have been identified in Jagdalpur Shale Formation. They are noticed at the middle level of this Formation.

Age

Meso to Neoproterozoic.
GROUP *GYMNOSELEN* STEINMANN 1911

**Type form:** *Gymnosolen ramsayi* Steinmann 1911

**Diagnosis**

Smooth, straight, subcylindrical, actively branching columns which expended or swollen before branching subparallel to slightly divergent. Sometimes bridging and coalescing of columns at few places. Laminae are convex. Transverse section of the column subcircular oval to polygonal.

**Content**

**Gymnosolen furcatus Komar**

(Plate V, VI, VII  Figure 4.18, 4.19)

**Description**

The structure of stromatolite consists of vertical subcylindrical columns of 10-15 cm long cross profile rounded or ovate of 2-5 cm diameter. Repeated branching observed. Columns swollen before branching. Intervals between the section of branching at 6-9 cm and up.

**Materials**

Six specimens were collected from Machkot, Koliapara, Mundapal, Bharni, Ghatlohangha, Raykera Nala area.

**Outcrop**

The dolomitic hummocks containing this stromatolite are present in Machkot Reserve Forest. The specimens are collected from the Machkot-Tiria forest roadside cuttings. Nearly all the hummock has similar type of stromatolites. In between two hummocks are red colours shales. Which terminates by the side of the hummocks.

**Mode of occurrence**

Columnar branching stromatolites make the fascicle. Columns are made up of hemispherical convex lamina stocked one over the other. Fascicle broadens before branching.
PLATE V

Figure 1-6, Field occurrences of stromatolite Gymnosolen furcatus Komar, in Jagdalpur Limestone Formation, District Jagdalpur, Chhattisgarh.

Figure 1 - A biostrme of Gymnosolen furcatus exposed in village Junaguda, commonly described by previous workers as 'Crocodile skin structure' in geological literature.

Figure 2 - An occurrence of stromatolite in village Mundapal.

Figure 3 - An outcrop of agglutinated broken pieces of Gymnosolen furcatus exposed in village Bharni, such pieces are found on the slope where they got broken and redeposited at the same place, unoriented columnar pieces are testimony of this fact.

Figure 4 - Field exposure of stromatolite in Ghatlohanga area.

Figure 5 - An exposure of stromatolites in Raykera Nala, this exposure also show recent weathering features.

Figure 6 - In Gupteshwar area, these stromatolites show characteristic walled structure.
**Fascicle morphology**

Fascicles are made up of columns with frequent branching. Fine lamina alternate with shale and limestone. Lamina profile is hemispherical and where branching is present concavity and convexity of the laminae can be seen to continue. Wall structure is clear and rarely some of the part of the stromatolites does not form clear wall structure.

**Branching habit**

Branching frequent and divergent, columns are bulbous before the branching.

**Column shape and margin structure**

Columns are subcylindrical in shape and ovoidal in transverse section. They are formed by flexous, dome shaped/hemispherical laminae which are convex, stocked one above the other. Overlapping of the laminae form a wall structure.

**Lamina**

Lamina profile varies from gently to flexous, convex, dome shaped/hemispherical set of dark and light laminae. Laminae at the junction of branching are continuous and convex and concave thin at the margin. Some time the laminae are found disrupted because of the secondary alteration.
Figure 4.18 - 3-D reconstruction of Gymnosolen furcatus.
Microstructure and Texture

Laminae of the stromatolites occur in light and dark pairs in which the lighter laminae are thicker in middle and dark laminae are equally thick and produce streaky texture. Light laminae usually range in thickness from 200-300 μm and dark and light laminae range in size from 50-100 μm. Both the dark and light laminae have well defined boundary. Dark laminae are composed of brownish grey non oriented rounded lumps of kerogen. Lighter laminae made up of finely granular dolomite. Some time streak of shale is noticed in the lighter laminae.

Interspace fillings

Interspaces between columns vary and filled with shale and carbonate that are very fine grained almost equal to those adjacent shales.

Secondary alteration

Stromatolites are present in light red coloured dolomite. Suggesting their secondary alterations.

Comparison

Markedly subcylindrical column with divergent branching and typical laminae profile permit its assignment to Gymnosolen furcatus Komar which is different from other known Gymnosolen varieties.
1. Single column of *Gymnosolen furcatus*, showing bulbous nature.
2. *Gymnosolen furcatus* column with alternating light and dark laminae.
3. *Gymnosolen furcatus* margin of the column.
4. *Gymnosolen furcatus* enlargement of column with dolomite.
5. Column of *Gymnosolen furcatus* further enlarged.
6. Intercolumnar space of *Gymnosolen furcatus* (Scale same as 5).
Figure 1 - Polished slab of *Gymnosolen furcatus*, Koliapara.

Figure 2 - Polished slab of *Gymnosolen furcatus*, Koliapara.
Distribution

These stromatolites have been identified in Jagdaipur Shale Formation in Machkot, Koliapara, Mundapal, Bharni, Ghatlohang, Raykera Nala area.

Age

Neoproterozoic.
PLATE VIII

Figure. 1-5 Field occurrences of stromatolites *Kussiella enigmatica* Raaben, in Jagdalpur Limestone, Chhattisgarh.

Figure.1 - Stromatolitic biostrome of *Kussiella enigmatica* exposed in Mongrapal locality, Jagdalpur.

Figure.2 - Longitudinal section of *Kussiella enigmatica* in freshly cut exposure of an outcrop in Mongrapal area, Jagdalpur. It shows column morphology, bridging and intercolumnar space. This outcrop has undergone extensive dolomitization.

Figure.3 - Note fine, freely hanging laminae not forming any wall structure in Mundapal locality.

Figure.4 - Field exposure of *Kussiella enigmatica* in Kolab River section, Gupteshwar locality of District Jagdalpur showing columns and branching.

Figure.5 - Close-up view of columns of *Kussiella enigmatica* noted in Junaguda village, District Jagdalpur, Chhattisgarh.
Outcrop

*Kussiella enigmatia* occurs in Machkot area and NW of Mundapal locality where Jagdalpur Shale Formation is exposed. The stromatolites are present in the red coloured dolomite. The outcrop is lensoid 10x2.5 meter bioherms. The strata containing stromatolites is 2-3 meters thick and may be traced over 2 kilometers.

Mode of occurrence

*Kussiella enigmatia* occurs in the mode of bioherm in the Machkot and NW of Mundapal areas.

Fascicle morphology

Fascicles are made up of columns with frequent branching. Fine laminae-alternate with shale and limestone. Laminae freely hang and do not form clear wall structure.

Branching habit

Branching is frequent passive and parallel.

Column shape and margin structure

Columns are rounded in cross section and cylindrical in shape. Margin formed by laminae which have peaks and cornices falling freely with almost straight, subparallel columns; constrictions at the base are in frequent. Bridging between the columns noticed.
Figure 4.20 – 3-D reconstruction of *Kussiella enigmatica*
Lamina profile

Lamina profile varies from gentle to flexous, convex, dome shaped/hemispherical set of dark and white carbonate laminae. Towards the top laminae are sometime straight and thickened at the centre and thin at the margin.

Microstructure and Texture

Laminae of the stromatolite occur in dark and light pairs in which lighter laminae are 100-1000 μm thick whereas the dark carbonate laminae 40-200 μm. The carbonate grains are of 3-5 μm grain size xenotopic to hypidiotopic equidimensional and polygonal. Lighter pale laminae vary from 90 percent carbonate to 90 percent clay. The carbonate has the same texture as in the dark laminae except the grain size is large.

Interspace filling

Interspaces between the columns are narrow and contain a mixture of clay and carbonate with same micro structure and texture. Nature of the most of the filling is dust form.

Secondary alteration

Carbonate at NW of Mundapal is cleaved and stromatolites are deformed; those reconstructed are from Machkot area. Mundapal stromatolites are well exposed due to joints making possible the observations in the field. This joint pattern may be due to crystallization of silicic component present in the interspaces.
Comparison

Markedly cylindrical columns with rounded to ovate cross section and convex hemispherical laminae profile with cornices and peaks along with bridging phenomenon permits that stromatolite is properly classified as *Kussiella enigmatica*.

Distribution

Jagdalpur Formation, in the Machkot area and NW of Mundapal, Mongrapal, Junaguda, Gupteshwar areas of Indravati Group in Jagdalpur district, Chhattisgarh.

Age

Neoproterozoic.
GROUP BOXONIA KOROLYUK 1960

Type form

Boxonia gracilis Korolyuk

Diagnosis

Stromatolites with subparallel, subcylindrical columns which are walled with few bumps and bridges. Branching α-β parallel and frequent.

Content

B. gracilis Korolyuk, B. grumulosa Komar, B. iissa Komar, B. krasivica Golovanov, B. bianca Raaben, B.bacillia Zhu, Yu & Gao, B.dontata Cao, Zhao & Xia, B. divertata Sidorov, B. grumulosa Komar, B. jinshanzhaiensis Cao, Zhao & Xia, B.kunlunensis Cao, B. pertaknurra Walter, B. songjiensis Cao, Zhao & Xia, B. xifengensis Zhu & Wang, and B. fuxiensis Rong.

Age

Neoproterozoic.

Boxonia pertaknurra Walter

(Plate IX, X Figure 4.21)

Material

One specimen from Koliapara.
Figure. 1-2. Field occurrences of stromatolite *Boxonia pertaknurra* Walter, in Jagdalpur limestone, Chhattisgarh.

Figure. 1 - Field exposure of Jagdalpur limestone showing *Boxonia pertaknurra* in a weathered outcrop showing long unbranched columns, interspaces between the columns are filled with fine grained clay in Koliapara locality of Bastar village, District Jagdalpur.

Figure. 2 - Note the plan view of columns of *Boxonia pertaknurra*, the cross section of the columns are oval to elliptical in shape. Scale in figure 2 is 14 cm and same for the figure 1.
1. Column of *Boxonia pertaknurra*.
2. Intercolumnar space of *Boxonia pertaknurra*.
3. *Boxonia pertaknurra*-Details of the intercolumnar part with floating kergen.
4. Microstructure of *Boxonia pertaknurra*. 
Description

Columns erect, branching predominantly and parallel continuous wall except in the lower region. Laminae rhombic or rectangular with streaky and clotty microstructure.

Outcrop

The B. pertaknurra are exposed in Mundapal immediately below the K. enigmatica bioherms, mound size range between 2.3 x 10 meters. The two adjacent mounds are filled with shale.

Mode of occurrence

B. pertaknurra occurs in the mode of bioherms extending for one kilometer in the Mundapal locality.

Fascicle morphology

Fascicle is made up of an elongated columns and infrequent branches. Fine laminae show admixture of clay and limestone. Branches are mostly parallel and divide at angle which is less than 5° seldom 1 cm apart.

Branching habit

Branching frequent, dichotomous, predominantly α-parallel with moderate β parallel. Bridging between narrow column occurs infrequently.

Column shape and margin structure

The columns are 2-4 cm wide and 14-30 cm long with irregular transverse section, bridging and coalescing noticed. Small columns are straight and subcylindrical. In transverse section these are rounded or oblong. The columns are smooth with short thin transverse ribs. Walls are noted.
Comparison

In gross morphology the *B. pertaknurra* resembles *Acaciella, Kussiella, Boxonia* but the presence of clear wall structure differentiate it from other forms and justify its consideration as *Boxonia*. Microstructure and texture make it a clear identification in *pertaknurra*.

Distribution

Jagdalpur Limestone Formation at Mundapal bears the bioherms.

Age

Neoproterozoic.
Figure 4.21 – 3-D reconstruction of Boxonia pertaknura