

Morphological variability of stromatolites and their cyclicity: Examples from a Proterozoic carbonate platform of Vindhyan Supergroup, India

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Submitted towards the partial fulfillment of
BS-MS dual degree programme
by

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under the guidance of

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INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH PUNE

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“Somewhere, something incredible is waiting to be known.”
— Carl Sagan

This work is dedicated to my father.

Certificate

This is to certify that this dissertation entitled '**Morphological variability of stromatolites and their cyclicity : Examples from a Proterozoic carbonate platform of Vindhyan Supergroup, India**' submitted towards the partial fulfillment of the BS-MS degree at the Indian Institute of Science Education and Research, Pune represents original research carried out by **Devyani Jambhule** at **Birbal Sahni Institute of Palaeosciences, Lucknow**, under the supervision of **Dr. Adrita Choudhuri** during academic year January 2023 to December 2023.



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DEVYANI JAMBHULE
DECEMBER 2023

Declaration

I, hereby declare that the matter embodied in the report titled '**Morphological variability of stromatolites and their cyclicity: Examples from a Proterozoic carbonate platform of Vindhyan Supergroup, India**' is the results of the investigations carried out by me at the '**Birbal Sahni Institute of Palaeosciences, Lucknow**' from the period January 2023 - December 2023 under the supervision of **Dr. Adrita Choudhuri** and the same has not been submitted elsewhere for any other degree.

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Abstract

In the exploration of well-preserved Proterozoic stromatolites in the Bhandar Limestone Member and the basal horizon of the Sirbu Shale Member within the Vindhyan Supergroup of central India, various challenges arise due to the emergence of abiogenic features resembling their biogenic counterparts. This investigation utilized sedimentological, microscopic, and ultramicroscopic methods to unravel the origin of these intricate organo-sedimentary structures. Within the studied stratigraphic sections, six distinct stromatolite morphotypes were identified, including large-scale laterally linked domal stromatolites (S1), columnar stromatolites forming biostromes (S2) and bioherms (S3), small-headed stromatolites (S4), stratiform stromatolites (S5), and cabbage-shaped domal stromatolites (S6). Microscopic analysis revealed varied microfabrics, such as alternating dark-colored micritic and light-colored spar calcite-bearing laminae. Raman spectra analysis confirmed the presence of carbonaceous material within the darker micritic laminae. The diversity in macro-scale morphological variations and their cyclical patterns, coupled with in-depth microstructural investigations, strongly suggest a significant role of microbial communities in the formation of these stromatolites. The presence of different stromatolite morphotypes and their cyclical patterns further supports the hypothesis that microbial processes responded to changing energy conditions and subsidence-induced spatial alterations in a shallow marine environment, ultimately indicating a biogenic origin for these stromatolites.

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List of Acronyms

CCD	Charge Coupled Device
DLA	Diffusion limited aggregation
EPS	Extra polymeric Substances
KPZ	Kadar Parisi Zhang
WiRE	Windows-based Raman Environment

Chapter 1

Introduction

1.1 Introduction

When taking a stroll along the shoreline of a sea that undergoes carbonate deposition during the Precambrian times, one would anticipate the presence of stromatolites. These unique geological formations have captivated scientists and researchers for centuries, serving as invaluable indicators of the intricate interplay between microbial communities, water, and sediments throughout the Earth's ancient history. In fact, stromatolites have become one of the oldest and most enduring subjects in the field of geobiology. Stromatolites, according to [Kalkowsky \(1908\)](#) are laminated, benthic microbial structures which are essentially and originally carbonate in composition. These structures are the result of the complex interactions between microscopic organisms, particularly cyanobacteria, and their surrounding environment. Cyanobacteria are known for their photosynthetic capabilities, producing oxygen as a by-product. By means of sediment trapping, binding, and/or precipitation, the organisms secrete sticky biofilms that effectively capture sediments and minerals. This intricate process results in the development of layered structures, which exhibit vertical growth over extended timeframes spanning centuries or even millennia ([Golubic \(1991\)](#); [Noffke & Awramik \(2013\)](#); [Rp et al. \(2000\)](#)).

Stromatolites offer a remarkable glimpse into the Earth's distant past, dating back billions of years. By studying these ancient formations, scientists can gain insights into the environmental conditions, nutrient availability, and interactions between microbial communities that existed during these early epochs. Additionally, stromato-

lites have proven to be invaluable in understanding the processes of sedimentation and carbonate deposition. The genesis of these formations necessitates the presence of precise physical and chemical parameters, where optimal equilibrium is achieved through the delicate interplay of factors such as photic flux, thermal regimes, and hydro-chemical composition (Rp et al. (2000)). Their presence is a testament to the presence and resilience of microbial life during periods of our planet's history when oxygen levels were significantly lower than they are today and; hence serve as tangible reminders of the resilience and adaptability of microbial communities that have shaped our planet over billions of years (Burne & Moore (1987); Walter et al. (1980)). The shapes exhibited by stromatolites exhibit a fascinating diversity, comprising of flat to domical, branched, or conical structures (Fig. 1.1). Irrespective of their specific shape, every stromatolites share a common characteristic: they grow vertically by the accumulation of minuscule laminae, often measuring in the millimetre or micrometre scale. These individual laminae, distinguished by differences in colour, shape, thickness, continuity, and composition, serve as a record of the ever-changing local chemical, biological, or physical environment during the growth of each stromatolite (Park (1976); Seong-Joo et al. (2000)). These distinctive variations in laminae, as well as changes observed in the lamination, textures, and macroscopic shapes of stromatolites throughout geological history, present a captivating puzzle that demands explanation.

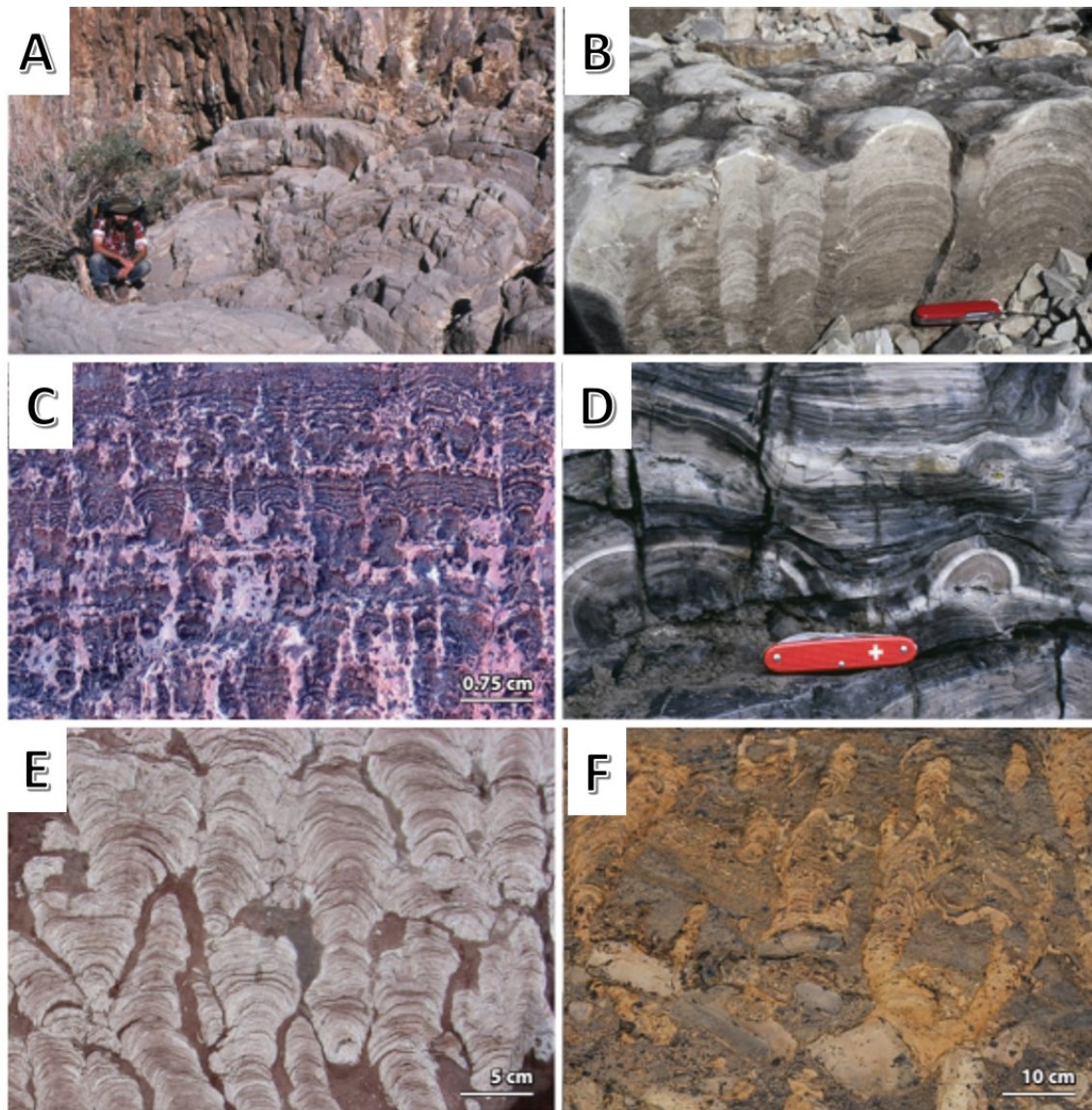


Figure 1.1: Archean and Proterozoic stromatolites. (A) Mesoproterozoic domal stromatolites, Bangemall Group, Australia. (B) Mesoproterozoic columnar stromatolites, Bil'yakh Group, Siberia. (C) Late Paleoproterozoic columnar precipitates, Duck Creek Formation, Australia. (D) Mesoproterozoic domal precipitated stromatolites, Narssarssuk Formation, Greenland. (E) Mesoproterozoic columnar stromatolites, Southern Ural Mountains, Russia. (F) Neoproterozoic stromatolites nucleated on cobbles, Upper Eleonore Bay Group, Greenland. Adapted from Bosak et al. 2013

Even in modern times, the extensive and remarkable record of stromatolite formation during the Archean and Proterozoic eons continues to pique scientific curiosity, giving rise to numerous questions about the patterns of carbonate precipitation, ancient biological processes and evolution, and the dynamic evolution of carbonate reefs

over time. Their morphology, when compared to modern analogues, gives idea about the paleogeography (Jahnert & Collins (2012, 2011)). The prevalence of stromatolites during these epochs is both conspicuous and widespread, with varying sizes ranging from mere millimetres to towering structures spanning meters in height and stretching laterally in small localized formations to massive aggregates spanning hundreds of kilometres in width. As scientists continue to explore and unravel the mysteries surrounding stromatolites, their importance in geobiology remains steadfast, providing a unique window into the early chapters of our planet's biography.

However, the utility of these testaments as unequivocal traces or signatures of life faces a multitude of compromises. One of the primary challenges in this quest lies in the occurrence of structures that are either formed or altered by abiotic processes (Grotzinger & Knoll (1999); Grotzinger & Reed (1983); Logan et al. (1964); Semikhatov et al. (1979)). Consequently, the confusion arising from the existence of structurally similar entities has led to an tendency for over-interpretation. Complicating matters further, abiotic processes have demonstrated the capacity to replicate the chemical fingerprints of life, such as carbon and nitrogen isotopes, as well as the production of carbonaceous material (Alexander et al. (2007); Thomazo et al. (2009); van Zuilen et al. (2002)).

Morphologically, there are abiotic processes capable of engendering structures resembling the laminated formations often associated with stromatolites. Indeed, laboratory experiments have successfully generated such laminated structures devoid of any biological influence (Bosak et al. (2013); Buick et al. (1995); Mcloughlin et al. (2008)). Additionally, folded structures (Fig. 1.2 (D),(E)) and mineral precipitates are frequently mistaken for their stromatolite counterparts (Mcloughlin et al. (2008)). Later, Semikhatov et al. (1979) gave the following definition of stromatolites as both biogenic and abiogenic deposits. Since then, there have been two schools of thought, those who support the biogenic definition of stromatolites (Awramik et al. (1976); Burne & Moore (1987); Walter & Awramik (1979)) and the proponents of both biogenic and abiogenic origin for stromatolites (Grotzinger & Knoll (1999); Logan et al. (1964); Mcloughlin et al. (2008); Semikhatov et al. (1979)). These revelations have instilled doubt regarding the presumed biogenic nature of stromatolites, necessitating a critical evaluation of the extent to which the laminated structures termed as stromatolites can genuinely be attributed to biological origins.

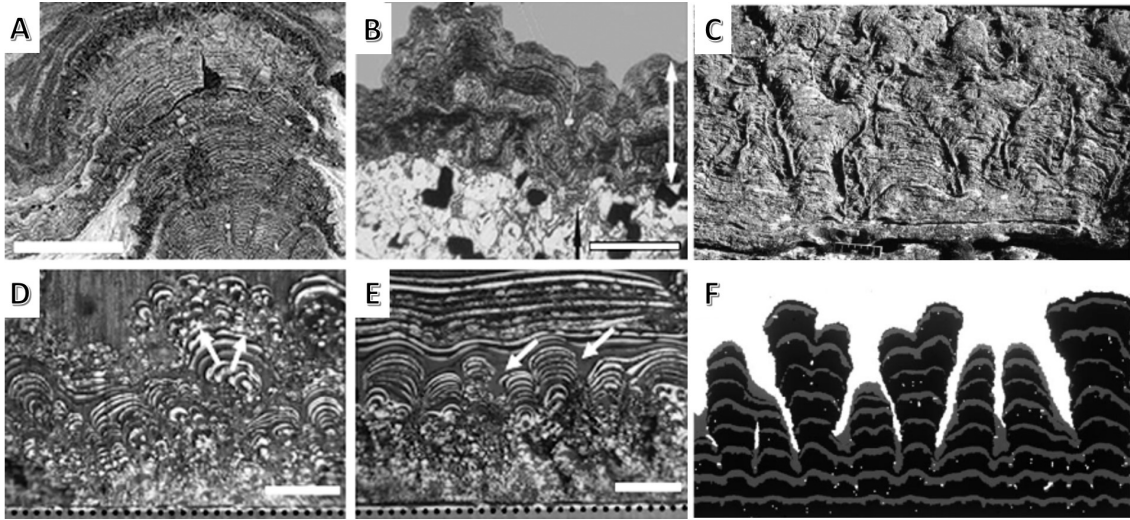


Figure 1.2: (A) Depicts branched, Mini columnar silica sinter formations observed in a New Zealand hot spring. (B) Illustrates microlaminated desert varnish featuring Mini columnar morphologies. (C) Showcases branching columnar stromatolites from the Paleoproterozoic Taltalei Formation in northwest Canada, revealing notable similarities with our model results (F). (C), (D) Displays our synthetic stromatolites, characterized by unbranched, columnar structures, and overlain by stratiform laminae, providing a comparison with the panel above. (F) Represents a growth model based on diffusion-limited aggregation and episodic sedimentation. Observed the similarities between the top panel and bottom panel. Adapted from (Grotzinger Knoll, 1999; McLoughlin et al., 2008)

Consequently, the concept of biogenicity (McLoughlin (2011a)) has emerged, highlighting the formidable challenge of discerning the biogenic nature of any biosignature, given the striking resemblances between biotic and abiotic formations (Buick et al. (1995)). Such challenges will inevitably manifest when endeavouring to identify unequivocal traces of life on other terrestrial sites without the physical analysis of samples. Resolving these obstacles will assume pivotal significance in the formulation of future life-detection strategies and extraterrestrial missions aimed at discerning the existence of life beyond Earth. The solution to these conundrums lies in the amalgamation of diverse lines of evidence that collectively give proof of the biogenic hypothesis. The establishment of stringent criteria for assessing the biogenicity of stromatolite structures on Earth will facilitate the formulation of testable hypotheses pertaining to layered carbonate formations encountered elsewhere. Consequently, a meticulous examination of each stromatolite structure is imperative to identify discerning features that validate and reinforce the biogenic hypothesis. Strikingly, stromatolites exhibiting robust signatures of biogenicity can serve as invaluable analogue sites for investigating early manifestations of life on ancient Earth, as well as in extraterrestrial environments.

1.2 Hypothesis

Our scientific hypothesis posits that the stromatolites originating from the Upper Vindhyan Group exhibit a biogenic origin.

1.3 Objectives

To support the hypothesis, the work centres around the meticulous examination of stromatolites present within the Bhander Formation, a constituent of the Upper Vindhyan Group, Vindhyan Basin in central India. To date, only a little number of studies have explored the ancient stromatolite. But the biogenicity by leveraging morphological variations and cyclicity, as well as microfabric analysis has not been conducted yet. Hence the following mentioned point are the major objectives of our study:

- **Paleoenvironment reconstruction**

- Our focus is on understanding depositional processes and environments derived from primary sedimentological features. This comprehensive approach enhances our understanding of the geological history and sedimentary dynamics within these formations.

- **Morphological variability and cyclicity**

- The investigation entails the systematic classification of different morphotypes and cyclicities exhibited by the stromatolites, as well as a detailed analysis of their microfabrics.

- **Biogenicity Assessment of the Stromatolites**

- The research will culminate in an assessment of the biogenicity of the stromatolite facies. This assessment involves evaluating various criteria to determine the extent to which stromatolites are a product of biological activity. Also, the stromatolites are compared with other stromatolite occurrences for a comprehensive understanding.

Chapter 2

Materials and Methods

2.1 Geological Setting

The Vindhyan Supergroup is one of the thickest Precambrian sedimentary succession among the Purana basins of India and the second largest Proterozoic succession in the world. Deposited in an intra-cratonic basin, it is considered to be composed mainly of shallow marine deposits. Since the earliest descriptions by ([Auden \(1933\)](#); [Oldham \(1856\)](#)), the Supergroup has received much attention, and volumes of geological and geophysical data have been gathered. The strata are unmetamorphosed, well-exposed and broadly accessible and have been studied for decades ([Auden \(1933\)](#); [Bose et al. \(2015\)](#); [Oldham \(1856\)](#)).

The Vindhyan Supergroup, which spans about 4,500 meters in thickness, primarily comprises slightly deformed and un-metamorphosed siliciclastic and carbonate rocks found across central India. The region is divided into basins, with the Rajasthan sector and Son Valley section being the most prominent. Over time, this vast basin has undergone multiple supercontinental cycles, volcanic and tectonic activity, and witnessed the evolution of various life forms.

Our study focuses on the Son Valley sector, particularly around Maihar town in Madhya Pradesh. The Upper Vindhyan Group is characterized by clastic rocks, and the sole carbonate unit, the Bhandar Limestone, is located near the top of the sequence ([Sarkar et al. \(1996\)](#)). The Bhandar Formation has five distinct members: Ganurgarh Shale, Lower Bhandar Sandstone, Upper Bhandar Sandstone, Sirbu and Bhandar Limestone. The Bhandar Limestone stands out as a carbonate platform,

which display sedimentary features indicative of emergence and salt pseudomorphs (Bose & Chaudhuri (1990)).

The Bhandar Limestone itself comprises micritic, stromatolitic, intraclastic, and oolitic facies, representing a unique carbonate platform in the Upper Vindhyan region (Sarkar et al. (2014)). Sirbu Shale is situated above the Lower Bhandar Sandstone and gradually progrades to the Upper Bhandar Sandstone with which the Vindhyan sedimentation is terminated (Bose et al. (2001) and references therein).

Determining the absolute ages of the Upper Vindhyan Group poses challenges due to the absence of volcanic sequences, typically used in dating techniques. Various attempts to date the Bhandar Limestone formation have yielded approximate ages, with one method suggesting around 650 million years (Ray et al. (2003)). Another study using Pb-Pb isochron ages estimated a depositional age of 908 ± 72 million years for the Son Valley Bhandar Limestone (Gopalan et al. (2013)). Strontium (Sr) isotope stratigraphy has also played a crucial role in assessing the age of the Bhandar Formation within the Upper Vindhyan, suggesting a Neoproterozoic age based on investigations by different researchers (Kumar et al. (2002); Ray et al. (2003)).

2.2 Study Area

The Son Valley region some of the excellent outcrops of stromatolite belonging to the Bhandar Formation, Upper Vindhyan Group (Fig. 2.1). Field investigations for the present study were centred in and around Maihar town ($24^{\circ}16'9.89''$ N; $80^{\circ}45'23.94''$ E) of Satna district, Madhya Pradesh, India. The study area features well-exposed outcrops along the banks of the Thomas River, as well as in the quarry sections surrounding the river at Dolni, Emilia, and Patna Nala near Maihar (Fig. 2.1).

2.3 Methods

2.3.1 Field Techniques and Optical Microscopy

In our study, we conducted detailed measured transects to map both stromatolitic and non-stromatolitic facies within the Bhandar Limestone and the basal part of the Sirbu Shale. We identified better exposures of these formations in quarry sections throughout the study area, as well as in the Thomas River , which provided valuable

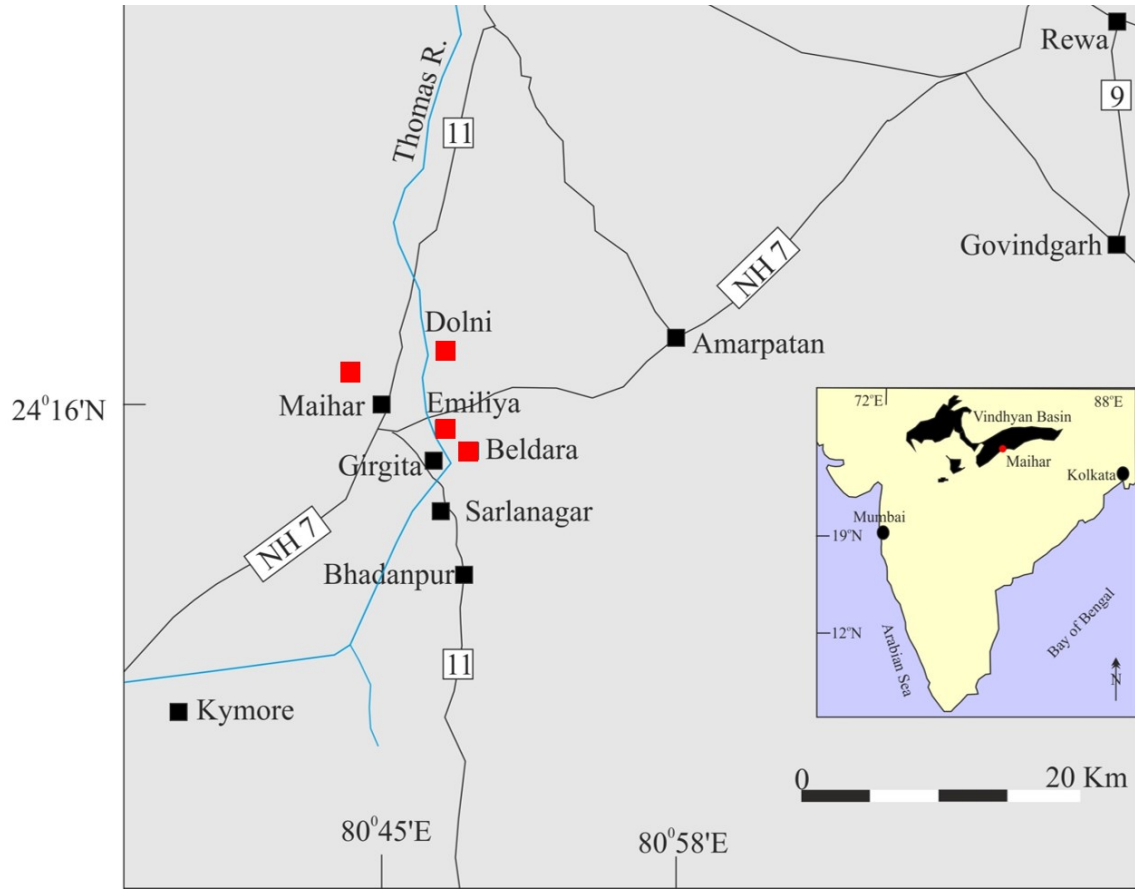


Figure 2.1: Geological map of Vindhyan basin in Son valley, showing study area Bhandar Limestone and basal part of Sirbu Shale. Coordinates of the four locations: Emilia River Section at Beldara ($24^{\circ}15'28.89''\text{N}$; $80^{\circ}48'18.29''\text{E}$), Dolni section ($24^{\circ}18'10.72''\text{N}$; $80^{\circ}48'11.49''\text{E}$) and Patla Nala Section ($24^{\circ}18'35.45''\text{N}$; $80^{\circ}46'9.42''\text{E}$), denoted with red squares.

opportunities for our research.

We examined a total of three specific locations and carefully documented the vertical variations in the stacking pattern of strata, as well as variations in texture and physical structure. To gain deeper insights, we analyzed thin sections of selected samples. Total 19 thin sections were studied under polarizing microscope Leica 750P and photos were captured with Leica ICC50E attached with the microscope and with the help of LAS X image analyzer.

2.3.2 Raman Spectroscopy

Thin parts that were polished were subjected to Raman spectroscopy. An inVia™ confocal Raman microscope system (Renishaw) at BSIP, Lucknow was utilized, which is equipped with red laser (785nm) that passes through an optical microscope and employs a 20x and 100 x objective. The Raman spectrum was obtained for every analysis using a single spectrometer that had a CCD detector. Every analysis's acquisition time was 10 s.

An extensive scan was used to collect Raman data, covering around 200–2000 cm^{-1} . The data processing involved peak selecting and baseline correction to take into consideration the spectrum fluorescence in carbonate samples using Renishaw's WiRE (Windows-based Raman Environment) software.

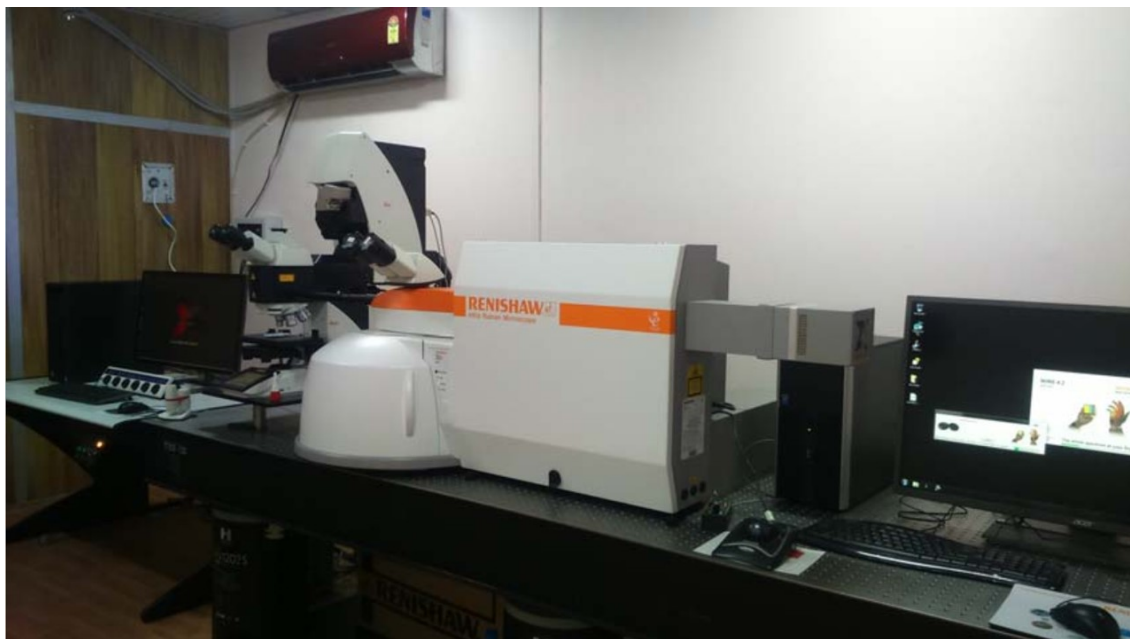


Figure 2.2: Raman Spectrometer at BSIP Lucknow

Chapter 3

Reevaluating Biogenicity Criteria and Challenges in Stromatolite Research - A review

3.1 Purpose of the Review

The search for potentially habitable environments on extraterrestrial worlds has intensified the need to understand biosignature preservation and analogous environments on Earth ([Brown et al. \(2020\)](#); [McMahon et al. \(2018\)](#); [Bosak et al. \(2021\)](#)). Ancient underwater sedimentary rocks hold crucial information about past climates, mineralogical conditions, and chemical processes, offering insights into prebiotic reactions and microbial life. This understanding helps in comparing Earth's habitability over time with other celestial bodies. Distinctive structures like stromatolites and microbialites serve as indicators of ancient life but require comprehensive analysis ([Allwood et al. \(2018\)](#); [Batchelor et al. \(2004\)](#); [Bosak et al. \(2013\)](#); [Grotzinger & Rothman \(1996\)](#); [Nutman et al. \(2019\)](#)).

The question of life's origin has evolved from philosophy to empirical investigation. Astrobiology aims to explore the possibility of life beyond Earth, requiring a profound understanding of life's emergence and its detectable signs. Stromatolites, structures formed by microbial activities, provide a fossil record spanning billions of years and serve as model ecosystems to study biosignature formation under various conditions, enriching astrobiology knowledge ([Bosak et al. \(2013\)](#); [Nutman et al. \(2016\)](#)).

Stromatolites, a type of microbialites found in Precambrian carbonate platforms, have a deep geological history. Recent discoveries suggest their presence around 3.7 billion years ago, reinforcing their importance as repositories of biosignatures (Nutman et al. (2019, 2016)). Despite debates about their biogenicity, stromatolites offer critical insights into Earth's microbial history. This comprehensive review focuses on detecting and interpreting biosignatures in carbonate-rich deposits, addressing challenges in distinguishing them from abiotic processes or contamination. It also explores stromatolites, emphasizing their dual role as geological formations and evidence of ancient microbial life. The review examines their formation processes, microbial contributions, evidence supporting their biogenicity, and recent analytical advancements. Ultimately, it highlights the significance of stromatolites in unravelling Earth's history and their relevance in astrobiology, aiming to stimulate further research in this field.

3.2 Stromatolite morphogenesis

Stromatolite morphogenesis, particularly the transformation of tiny laminae into substantial macroscopic structures over prolonged periods, presents a profound enigma in scientific inquiry. Currently, determining a specific origin mechanism for stromatolite formation is challenging, as it likely involves a combination of various processes, such as sediment trapping and binding, mineral precipitation (Riding (2000)). Thus, the precise origin remains enigmatic. In this section, we aim to explore various processes and explanations for the formation of stromatolite structures, encompassing both abiotic and biotic processes. With an emphasis on the Precambrian stromatolite record and modern stromatolites, we will examine observational and experimental models of stromatolite morphogenesis.

3.2.1 Theories of Stromatolite Accretionary Mechanisms

This discussion outlines the processes governing stromatolite accretion, as well as the associated laminar structures and micro textures. Microbial involvement in stromatolite formation revolves around two principal mechanisms: the entrapment and binding of sediments through microbial filaments and the mineral precipitation processes (Gebelein (1969); Golubic (1976); Riding (2000)). Furthermore, abiotic precipitation of carbonate minerals has a crucial function in the construction of stromatolites.

Sediment Trapping-and-Binding

Sediment trapping and binding involve sediment particles settling onto microbial mats, where they become immobilized through adhesion to the mat's surface or obstruction by its rough structure (Golubic (1976); Golubic et al. (2000); McLoughlin (2011b); Riding (2000)). EPS, produced by microbes, enhances sediment adhesion and entrapment. Microbial growth then leads to the permanent incorporation of these sediment particles into the mat. Two categories of agglutinated stromatolites exist: coarse-agglutinated stromatolites, which infrequently trap and bind coarse sediments like ooids, and fine-agglutinated stromatolites, typically found within surrounding micritic sediments (Riding (2000); Rp et al. (2000); Riding (2008)). Petrographic analysis often reveals these preserved sediment grains within stromatolite structures, sometimes surrounded by remnants of organic laminae formed during quiescent periods (Frantz et al. (2015)).

Sediment trapping and binding in stromatolites are closely tied to microbially induced carbonate precipitation, forming "Fine-Grained Crusts" with diverse microstructures (Frantz et al. (2015); Riding (2000, 2008)). Microbial involvement is further supported by microfossil remains (Awramik et al. (1979)), micropores resembling decayed microbial molds (Bosak et al. (2004)), and layered structures alternating between dark, microbially influenced layers and light layers, possibly formed abiotically (as seen in *Conophyton*) (Grotzinger & Knoll (1999))

Mineral Precipitation

Mineral precipitation plays a pivotal role in the formation and long-time preservation of stromatolite structures. Stromatolites, which are frequently found in Archean and Proterozoic geological records, frequently include textures that have been preserved due to early lithification of pore spaces and the micritization of main mat builders (Decho (2010); Dupraz & Visscher (2005)). Similar textures can be observed in modern nonmarine stromatolites and are typically associated with the micritization of cyanobacterial sheaths (Bontognali et al. (2010); Dupraz et al. (2004)).

The uneven distribution of these fabrics suggests that there have been variations in mineral precipitation patterns occurring simultaneously throughout different geological time periods. The focus of recent studies has changed from cyanobacterial filament encrustation to micritization processes fueled by organic decomposition in

the extracellular matrix. (Decho (2010)). This type of micritization leads to the preservation of finer micritic laminae, especially in zones rich in sulfate where photosynthetic laminae have been degraded or are absent. Differences in environmental conditions, such as the availability of sulfate, oxygen, and carbon dioxide, during different geological eras have had a significant impact on mineral precipitation dynamics and the preservation of stromatolite textures. These changes are likely linked to global shifts in redox conditions, a phenomenon observed in various geological formations.

Biologically Induced precipitation

The thickening of stromatolite laminae at their crests, especially conical stromatolites, is often attributed to microbial chemo- or phototaxis (Batchelor et al. (2004)). Phototaxis suggests that microbial biofilms grow upwards to access more light for photosynthesis, while chemotaxis implies upward growth to reach additional nutrients. Microbial motility drives this enhanced upward growth, known as "upslope diffusion," influenced by factors like light availability, boundary layer thickness, and diffusive gradients.

Recent research, however, challenges the role of phototaxis as the primary driver. Laboratory experiments with microbial mats suggest that microbial motility, not phototaxis, largely shapes mat growth (?). Microscopic features like contorted laminae and preserved oxygen bubbles serve as indicators of phototactic stromatolite growth. These characteristics have been found in well-preserved Proterozoic stromatolites, hinting at the emergence of oxygenic photosynthesis during that era.

In certain formations, sinuous growth patterns observed in stromatolites, such as those from the Bitter Springs Formation (around 850 million years old), suggest heliotropism—growth tracking the sun's changing position (?). This implies that these stromatolites solidified rapidly enough to record annual variations in sunlight exposure, highlighting environmental influences on their growth.

3.2.2 Theoretical models of Morphogenesis

Stromatolites, which are macroscopic microbial structures characterized by slow growth over extended periods of years to millennia, present significant challenges for scientific investigation due to their extended lifespans. To address these challenges, researchers employ mathematical models to quantitatively reconstruct the processes

governing stromatolite growth based on the analysis of rock samples (Bosak et al. (2013); Grotzinger & Knoll (1999)). These mathematical models are firmly grounded in the principles of physics, biology, and chemistry, offering valuable insights that surpass what can be gleaned from direct field observations. These models can be broadly categorized into two main types: local and non-local. Local models delve into the immediate dynamics of stromatolite growth, focusing on processes such as vertical expansion and random perturbations. Many of these models are based on the Kardar-Parisi-Zhang (KPZ) equation and are capable of predicting the shapes of stromatolites and variations in the thickness of their laminae (Batchelor et al. (2000, 2004); Kardar et al. (1986); Grotzinger & Knoll (1999)).

Non-local models, on the other hand, consider stromatolite growth influenced by external factors, such as the impact of sediment grains. Models like diffusion-limited aggregation (DLA) simulate the development of branching morphologies in stromatolites. These non-local models require careful consideration of scale-dependent comparisons with real-world observations.(Bosak et al. (2013); Dupraz et al. (2006); Grotzinger & Knoll (1999)).

Future research in this field should aim to integrate sedimentological parameters to gain a deeper understanding of the spacing between stromatolite columns, their dimensions, and the frequency of branching. It is also crucial to investigate the mechanisms that stabilize the forms of stromatolites, particularly those that do not exhibit branching, despite predictions from DLA models. Factors like oscillatory flows and the dynamics of precipitation contribute significantly to the morphologies of stromatolites. Unravelling these complexities promises to enhance our comprehension of Earth's ancient history and the evolution of life on our planet

3.3 Patterns in Stromatolites characteristics over time

3.3.1 Abundance of stromatolites through time

Collectively, various investigations (Bosak et al. (2013); Semikhatov & Raaben (2000)) indicate that stromatolites were prominent components of carbonate formations throughout the Proterozoic era. However, their occurrence declined notably in later Neoproterozoic successions, particularly after the initial proliferation of macroscopic animals (Fig.2.3) (Awramik (1991); Bosak et al. (2013); McLoughlin (2011a); Grotzinger &

Knoll (1999)). This initial drop in stromatolite abundance aligns temporally with the diversification of seaweeds capable of outcompeting microbial mats for seafloor space (Awramik (1991); Bosak et al. (2013); McLoughlin (2011b); Grotzinger & Knoll (1999)). Additionally, this decline coincides with changes in seawater chemistry and carbonate production dynamics (Grotzinger & Knoll (1999)). Most scholars concur that the decline in stromatolites at the end of the Proterozoic era can be attributed to grazing and competition for space by metazoans (Bosak et al. (2013); Garrett (1970); Grotzinger & Knoll (1999)).

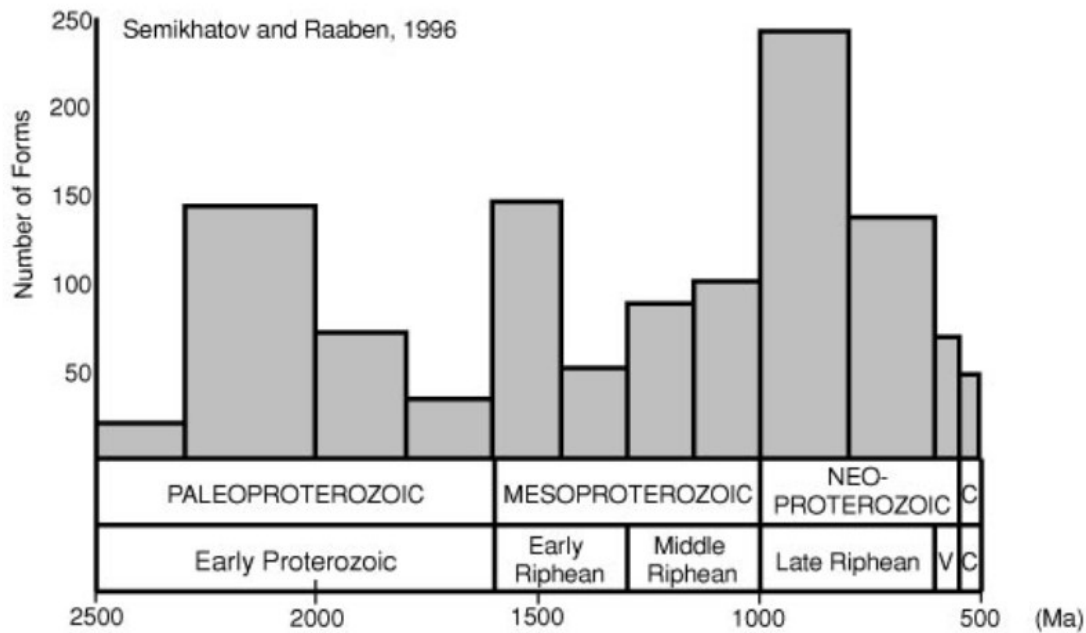


Figure 3.1: Abundance patterns of Stromatolites over time. Adapted from (Grotzinger & Knoll, 1999)

3.3.2 Microfabrics of stromatolites through time

A substantial transition in stromatolite characteristics is evident in the Precambrian. During the Archaean era, stromatolites primarily formed through chemical precipitation, displaying sparry microfabrics (Riding (2000)). However, in the Neoproterozoic era, stromatolites exhibited finer-grained microfabrics, showcasing a greater influence of microbial activity (Frantz et al. (2015); Riding (2008)). In the intermediary Palaeo and Mesoproterozoic periods, stromatolites with hybrid fabrics were predom-

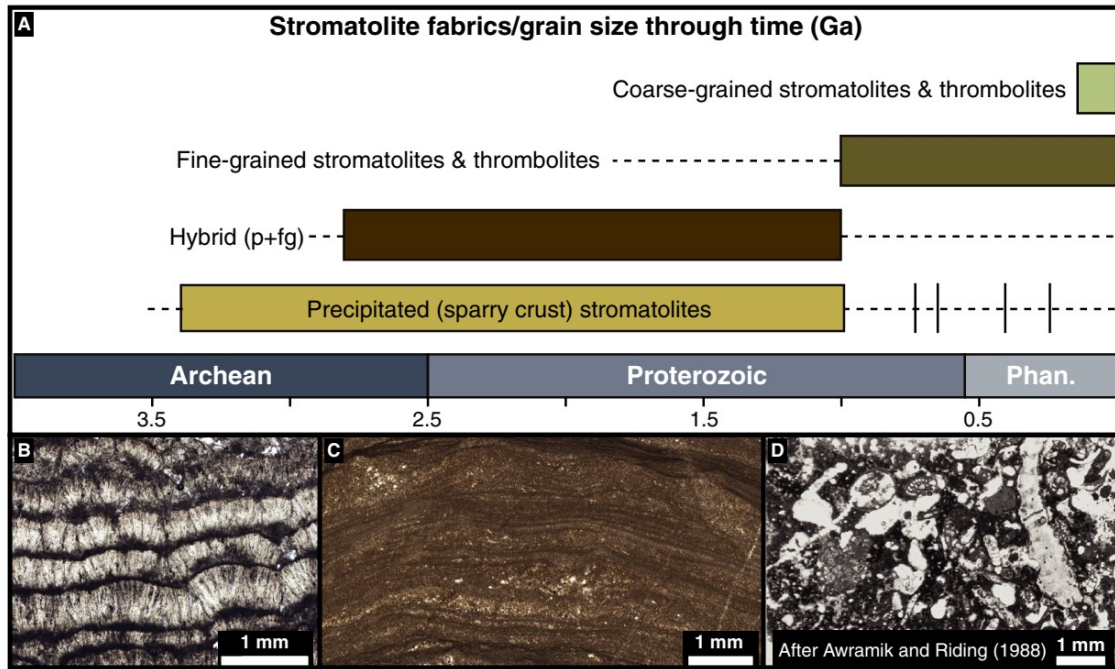


Figure 3.2: Evolution of Stromatolite Microfabrics Over Time. (A) Chronological distribution of stromatolite and thrombolite fabrics, categorized as precipitated (sparry crust, tan), fine-grained stromatolites and/or thrombolites (olive), hybrid (precipitated plus fine-grained, brown), and coarse-grained stromatolites and/or thrombolites (sage), adapted from Riding (2011). Thick bars indicate periods of high fabric prevalence, while dashed lines represent times when these fabrics were present but not predominant. (B) Photomicrograph illustrating a typical precipitated/hybrid fabric found in the Barstow Formation during the Miocene epoch, characterized by alternating precipitated layers and fine-grained layers. (C) Photomicrograph showcasing a typical fine-grained fabric observed in the Belt Supergroup, dating back to approximately 1.4 billion years ago. (D) Photomicrograph displaying a coarse-grained fabric found in a modern marine thrombolitic stromatolite from Shark Bay, Australia, modified from Awramik Riding (1988). Figure adapted from Frantz et al. (2015).

inant (Frantz et al. (2015)). These hybrids are believed to have grown through a combination of chemical precipitation and sediment trapping-and-binding processes (Riding (2008)). This transition has been linked to a protracted decline in seawater carbonate supersaturation during the Precambrian, prompting a shift from chemical precipitation to microbial trapping-and-binding as the primary mechanisms driving stromatolite growth (Frantz et al. (2015); Grotzinger & Kasting (1993)).

Distinctive stromatolite characteristics have the potential to preserve evidence of significant evolutionary events. For instance, the lower Cambrian period saw the emergence of dendrolites and skeletal stromatolites due to cyanobacterial biomineralization (Riding & Voronova (1984)). These forms were most abundant during the Cambrian and Lower Ordovician periods. Additionally, in the Phanerozoic era, the

abundance of microbial carbonates generally exhibited an inverse relationship with marine metazoan taxonomic diversity, suggesting that metazoan competition progressively limited microbial carbonate formation ([Riding & Liang \(2005\)](#)). Other stromatolite forms indicative of specific geological periods has been identified, although their precise environmental and evolutionary significance remains incompletely understood. For instance, late Archaean carbonate sequences contain fenestrate microbialites, characterized by irregular columns or tent-like structures composed of dark organic layers enclosed in irregular calcite cements ([McLoughlin \(2011a\)](#)). The limited temporal distribution of these forms has yet to be fully explained.

3.4 Evaluating stromatolite biogenicity: Criteria and Challenges

This section delves into the concept of biogenicity and its application in the context of stromatolites. We will explore the rigorous criteria employed to assess biogenicity, address the complexities of distinguishing biogenic from abiotic features in stromatolites, and emphasize the significance of integrating both modern and ancient stromatolite data into our analysis.

3.4.1 The Definition of Biogenicity

Biogenicity refers to the identification of specific chemical and morphological attributes within geological materials that suggest the past or present presence of life forms. These attributes encompass elemental and isotopic signatures, often accompanied by distinct textural characteristics arising from biological activities ([McLoughlin \(2011a\)](#)). To systematically evaluate biogenicity, we consider three fundamental dimensions:

- Morphological Complexity and Size Distribution
- Elemental Composition, Bonding, Symmetry, and Isotopic Composition
- Environmental Distribution or Geological Context

3.4.2 Challenges in Biogenicity Assessment of Stromatolites

Unearthing definitive evidence of ancient life within stromatolites presents formidable challenges owing to the different challenges that have engendered persistent ambiguities within scientific discourse. Several complications merit attention:

Abiotic Mimicry

Abiotic processes have the capability to yield structures resembling stromatolites, potentially leading to erroneous interpretations. Folded layered rocks and mineral precipitates, for instance, can closely emulate biogenic stromatolites, and laboratory experiments, along with numerical simulations, can replicate these abiotic formations. Furthermore, the integration of both abiotic and biogenic organic matter into geological matrices can give rise to pseudo-fossils remarkably similar to microfossils (McCloughlin et al. (2008); Grotzinger & Knoll (1999); Logan et al. (1964); Grotzinger & Reed (1983); Awramik et al. (1979)).

Disparity between Modern and Ancient Stromatolites

One significant setback in defining stromatolites lies in the scarcity of information obtained from present-day analogues. Comparisons between ancient and modern stromatolites drive the hypothesis of their biogenic origin of stromatolites. However, despite extensive studies on modern stromatolites, the interpretation remains elusive due to the disparity between features and characteristics observed in ancient stromatolites and modern stromatolites (Bosak et al. (2013); Frantz et al. (2015); Riding (2000); Riding & Liang (2005)). Therefore, the goal is to establish an understanding of stromatolite development through rigorous, quantitative analyses of their form and lamina texture, including the deconvolution of diagenetic overprints, revealing primary textures indicative of specific microbial and sedimentary processes.

Nevertheless, substantial disparities exist between modern and ancient stromatolites, mandating a nonuniformitarian approach:

- **Environmental Disparities**

- Archean and Proterozoic stromatolites evolved within marine environments distinct from those observed in the present era. Dissimilarities in major

elemental chemistry and redox profiles characterize ancient seawater in contrast to contemporary oceanic conditions ([Bosak et al. \(2013\)](#); [Frantz et al. \(2015\)](#); [Bosak et al. \(2021\)](#)).

- **Evolution of Microbial Communities**

- The evolution of microbial communities responsible for stromatolite formation may have unfolded over geological epochs, shaping the distinctive characteristics exhibited by these structures.

3.4.3 Evaluating stromatolite biogenicity: Criterion

In the realm of astrobiology, our understanding is impeded by the singular representative biosphere we possess, which shapes our tools and hypotheses about extraterrestrial life. This situation introduces substantial cognitive biases that can hinder our ability to detect and recognize life beyond Earth. It's conceivable that all forms of life produce residual biosignatures, and stromatolites emerge as an invaluable ecosystem to investigate how these biosignatures materialize in the face of a dynamically changing environment. In this context, we delve into the patterns (such as morphology and fabrics) and products (including minerals and molecules) exhibited by stromatolites. This examination is crucial for elucidating the study of biosignatures across various spatial scales and for elucidating the role of stromatolite research in determining the boundaries of habitability beyond our planet. The geological record serves as a testing platform for formulating stromatolite biogenicity criteria, which could eventually find application in scrutinizing laminated sedimentary structures on other celestial bodies. A concise overview of extensively employed stromatolite biogenicity criteria is presented here, drawing from the seminal work of ([Buick et al. \(1981\)](#)), supplemented by additional points introduced by ([Hofmann \(2000\)](#)):

- **Sedimentary or Metasedimentary Rocks**

- An imperative initial condition mandates that the structures exist in unambiguous sedimentary or metasedimentary rocks. This stipulation is essential for establishing the potential biogenicity of a stromatolite.

- **Synsedimentary Nature**

- Demonstrating that the structures originated in tandem with sediment deposition is vital. This requirement serves to rule out contributions from soft sediment deformation or subsequent structural alterations to the final stromatolite morphology.

- **Convex-Upward Structures**

- While a prevalence of convex-upward structures can offer insights, it is a qualitative guideline that neither guarantees nor solely defines biogenicity. Such morphologies can also emerge from abiotic processes, like the self-organization of structures such as stalagmites or agate crusts.

- **Laminae Thickness over Crests**

- This qualitative criterion aims to distinguish abiotic chemical crusts from biogenic stromatolites by highlighting changes in laminae thickness. However, exceptions exist, as freshwater *Phormidium* stromatolites demonstrate isopachous growth, revealing that crusts need not thicken uniformly.

- **Wavy, Wrinkled Laminations**

- This qualitative stipulation excludes uniform, abiogenic precipitated crusts. Nonetheless, it lacks defined parameters and can be influenced by sedimentary rheology and diagenetic alterations.

- **Presence of Microfossils or Trace Fossils**

- The rigid requirement for microfossils or trace fossils is challenged by the low preservation potential of microbial remains. This stipulation excludes a significant percentage of known fossil stromatolites.

- **Correlation of Microfossil Composition with Morphological Changes**

- This highly restrictive criterion necessitates changes in microfossil assemblages to align with corresponding morphological alterations in the stromatolite, an infrequent occurrence in practice.

- **Organization Indicating Microbial Sediment Precipitation**

- The expectation that fossils or trace fossils should indicate sediment trapping, binding, or precipitation by living microorganisms is ambitious. These features are typically observed under minimal diagenesis conditions.
- **Brecciated Mat Chips in Depressions**
 - Occasionally visible, these chips gain significance if exhibiting distinct laminated internal fabrics or micro textures, differentiating them from fragments of fractured seafloor crusts.
- **Thin, Rolled-Up Fragments Indicative of Microbial Mats**
 - While desirable and sporadically observed, these indications require exceptional organic preservation and are not widespread.
- **Spatial Self-Organization**
 - : Stromatolites exhibit regular spatial patterns due to self-organization of ecological communities. This self-organization allows communities to concentrate local resources and create a more resilient ecosystem that can withstand environmental disturbances.
- **Microfabric Characteristics**
 - : Microfabrics within stromatolites, including features like laminae and micrite, offer insights into the type of microbial community involved in stromatolite formation. - Different microbial processes result in distinct microfabric characteristics.
- **Compositional Differences in Laminated Growth Structures**
 - : While helpful, this criterion has exceptions, especially in carbonate settings where similar compositions can be found in both stromatolite and surrounding matrix.

Chapter 4

Observations and Results

4.1 Introduction

The objective of this chapter is to describe different facies of the studied Bhandar Formation i.e., Bhandar Limestone Member as well as the basal part of the Sirbu Shale Member. Systematic study of the lithology, sedimentary structures, and body geometry have been considered for the facies analysis of the Bhandar Limestone Member and the basal part of the Sirbu Shale member of the Bhandar Formation.

4.2 Lithostratigraphy and Facies associations

4.2.1 Facies analysis from Bhandar Limestone

The study of the various facies within the Bhandar Limestone was carried out along the Thomas River section near Emilia and Dolni villages and near Beldara village close to Maihar town (Fig 1.3). The maximum thickness of the Bhandar Limestone in these areas is ca.18 m and the exposure is well enough to carry out detailed facies analysis. Considering the lithology and sedimentary structures present therein, following five facies are identified within the Bhandar Limestone.

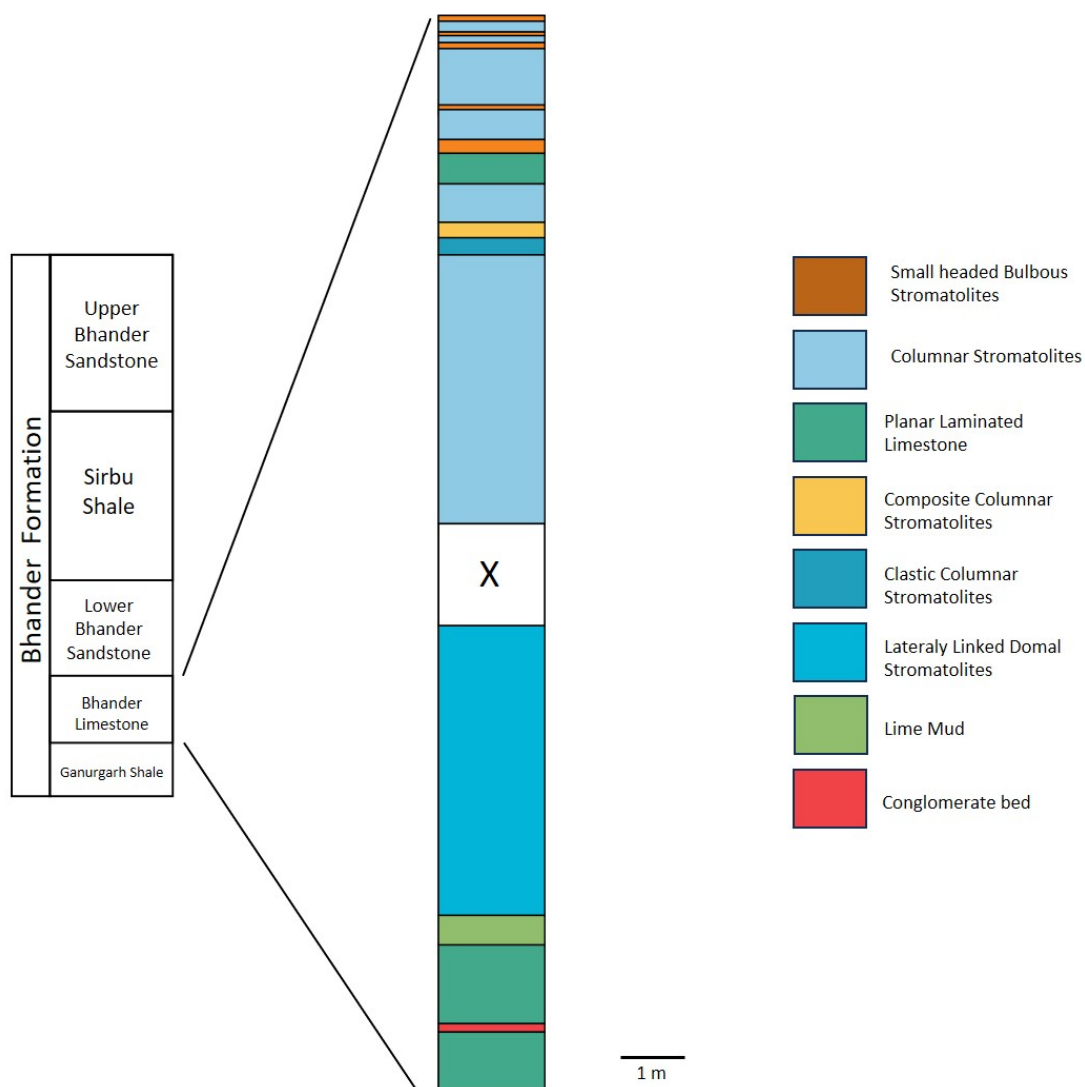


Figure 4.1: Stratigraphic lithology of (A) Bhandar Formation and (B) Emilia River Section representing Bhandar Limestone. The Bhandar Limestone, which is the sole only carbonate platform in Upper Vindhyan, is depicted. The cyclicity observed is represented by alternating brown and blue sections and further discussed in the report. Scale is 100 cm.

Facies A – Stromatolite facies

The following facies is distinguished by the existence of a diverse variety of stromatolites. These facies are best exposed in the Thomas River section near Emilia village. Large laterally-linked domal stromatolites (S1), columnar stromatolites (both bio-herm (S2) and biostrome (S3) type), small-headed stromatolites (S4), and stratiform stromatolites (S5) are among the five distinct stromatolite morphotypes found in the

Bhander Limestone. The Emilia section primarily hosted S1, S2, S3, S4 stromatolites morphotypes and the Dolni section hosts S5 morphotypes (discussed later; Fig. 4.2). The diameters of all morphologies of stromatolites vary from 0.1 cm to 440 cm. The stromatolites' each lamina has a wavy appearance. The heads of some of the domal forms are inclined and show a preferred orientation (Fig. 4.2 (B)). Some minor, local-scale faults are observed disrupting the stromatolite laminae (Fig. 4.2 (B)). On occasion, the top surface of the stromatolites also exhibits wave ripples. These stromatolites are also associated with some cracks which are present on the bedding surface. Overlying S1 morphotype, columnar stromatolite (both S2 and S3 morphotypes) are present in the same section. All stromatolite morphologies have column heights ranging from 1 to 100 cm. These stromatolites are frequently characterised by branching (Fig. 4.12). There are incline shapes among the columnar forms (Fig. 4.2). Small-headed stromatolites (S4 morphotype) are present above these columnar forms. Large chunks of stromatolites are present in the intercolumnar area of the columnar forms, along with a lot of debris from stromatolites. Between various morphotypes, particularly between columnar and small-headed stromatolites, several cycles are present. The detailed descriptions of these morphotypes and their cyclic variations are discussed in detail in Chapter 4.

- *Interpretation*

- A dense microbial mat growth within the photic zone is indicated by the presence of stromatolites [Awramik et al. \(1976\)](#); [Noffke & Awramik \(2013\)](#); [Riding et al. \(2011\)](#). Compared to the columnar and stratiform forms, the massive laterally-linked domal stromatolites evolved at comparatively deeper water [Beukes & Lowe \(1989\)](#). The occasional presence of wave ripples over the surface of the large domal forms and small-headed stromatolites also supports the wave activity. Possible storm intervention is indicated by the presence of fractured stromatolite debris in the columnar stromatolites' intercolumnar region. The inclined nature of the columnar stromatolites indicates the presence of strong currents in the depositional area [Tosti & Riding \(2017\)](#). Also, frequent branching of the columnar stromatolites indicates strong current or wave influence and an impact of the sedimentation rate. Within the depositional basin, the water depth decreases as morphotypes change from huge domal forms to columnar forms and ultimately small headed morphotypes.

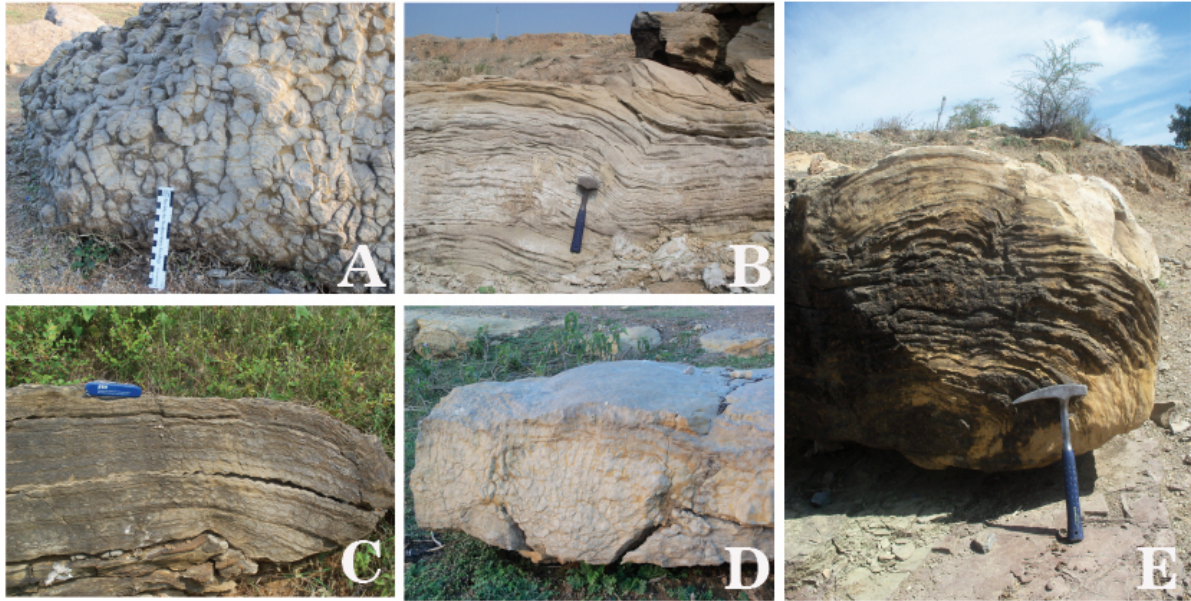


Figure 4.2: Facies A – Different morphologies of stromatolites. (A) . A) Laterally linked domal stromatolites. B) Small- headed bulbous stromatolite. Region highlighted with red box are the facies. Scale length – 14cm C) Columnar stromatolite (Bioherm type) ,D) Columnar stromatolite (Bioherm type) ,D) Columnar Stromatolites (Biostrome type), E) Stratiform stromatolites. A-E are observed at the Bhandar limestone. (F) Cracks on the bedding surface.

Facies B – Planar laminated lime mudstone facies

These facies, made of lime mudstone, is characterised by mm-thick plane laminations which are laterally persistent (Fig.4.3). Occasionally thin veneer of argillaceous material drapes the carbonate laminae. The carbonate laminae show rhythmic alternation of thick-thin laminae (Fig.4.3) and in places, show normal grading. These facies are occasionally intercalated with thicker and coarser (sand/granule grade) intraformational conglomerate facies beds (Fig.4.3) Small-scale soft-sediment deformation structures are also observed in minor occurrence. Molar Tooth Structures, a unique type of carbonate cement-filled cracks are also present within these facies (Fig.4.3). Contact between these facies and the stromatolite facies is sharp and erosional (Fig.4.3). It

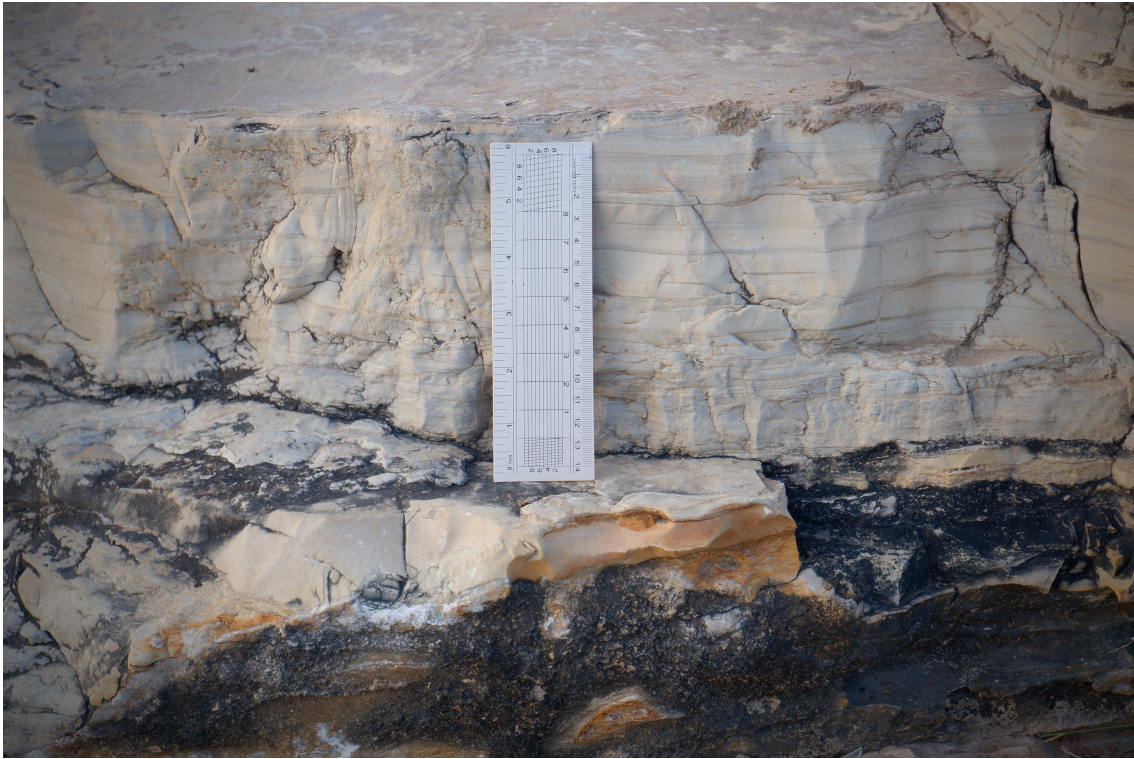


Figure 4.3: Facies B – Planar laminated Lime Mudstone. (A) mm-thick plane laminations. Observe the alteration of thick and thin laminae

rarely grades into cross-stratified calcarenite facies.

- *Interpretation*

- Fine grain size, planar nature of laminae, lateral persistency, rhythmic alternation of thick-thin laminae indicates tidal influence (De Boer et al., 1989) and low-energy depositional setting. The normal grading found in the carbonate laminae indicates that carbonate sediments were delivered and plume deposition occurred beneath the wave base [Chakraborty \(2004\)](#). These facies may be located lower on the slope than the stromatolite facies based on their association with the intraformational conglomerate facies. Presence of small-scale soft sediment deformation features, Molar tooth structures indicates presence of tectonic disturbances. However, microbial influence is also interpreted for generation of these kinds of cracks as well [Pollock et al. \(2006\)](#); [Shen et al. \(2016\)](#).



Figure 4.4: Facies C – Intraformational Conglomerate. Closer view of transition between planar laminated limestone and Conglomerate bed

Facies C- Intraformational Conglomerate Facies

This facies are frequently found in association with the preceding Facies B. These conglomerate beds contain tabular, rounded to sub-rounded limestone clasts, size ranging from approximately 0.1 cm to 7 cm. Both clast-supported and matrix-supported conglomerates are observed (Fig.4.4). The transition between the clast-supported conglomerate and matrix supported conglomerate is very sharp (Fig.4.4) The clasts show long-axis imbrication and some of them are crudely cross-stratification (Fig.4.4). Overall, the clasts show normal gradation.

- *Interpretation*

- The facies are likely to be deposited from a mass flow [Chakraborty \(2004\)](#). Normal gradation within the clasts corroborates the interpretation. From the association with plane laminated limestone facies, it is likely that these facies were deposited in the slightly deeper part of the shelf.

Facies D- Cross-stratified limestone facies

These facies are characterized by tabular body geometry with flat base and convex-up top. Internally, the limestone shows large-scale (maximum average set thickness is 30 cm) cross-stratification which are planar in nature (Fig.4.5). These facies are observed in Dolni section and it laterally terminates against the stromatolite facies. The cross-stratification shows bi-directional current pattern. The top of the bed occasionally shows the presence of ripples (Fig.4.5). Chertification is common within the facies (Fig.4.5). This facies alternates with ripple-laminated limestone facies both laterally and vertically.

- *Interpretation*

- The tabular body geometry, flat base and convex-up body geometry, bi-directional current pattern imply these facies to be a bar on the marine shelf under wave agitation. The large cross-stratification indicates the dominance of oscillatory flow. The existence of wave action at the depositional location is further confirmed by the presence of ripples on top of the bed [Sarkar et al. \(2014\)](#).

Facies E- Calcarenite-shale facies

These facies are heterolithic in nature and observed in Dolni section. It is characterised by repetitive alternations between lime shale beds with plane lamination or small-scale ripple lamination and occasional calcarenite sheets (Fig.4.6 (A), (B), (H)). The calcarenite sheets are internally characterised by convolute laminations, wave-ripple lamination, hummocky cross-stratification. The base of the calcarenite sheets is sharp and tops are relatively gradational in nature. On bedding plane, they exhibit wave-ripple having straight or broadly curved crests, locally bifurcating (Fig.4.6 (E), (G)). These calcarenite sheets frequently contain chert nodules (Fig.4.6 (D)). The average height and spacing of the waves are 5 and 25 cm, respectively. This facies alternates vertically and laterally with the preceding facies.

- *Interpretation*

- Repeated alternation between lime shale and calcarenite sheets suggests frequent energy fluctuations within the depositional site. Lateral and vertical



Figure 4.5: Facies D and B1 - Cross Stratified Facies. Alterations with the ripple-laminated limestone. Red ellipses represent the draped chert nodules.

alteration with the preceding Facies D indicates that Facies D was deposited within interbar setting [Sarkar et al. \(2014\)](#). Presence of plane lamination within lime shale beds indicates they were deposited in low energy condition while calcarenite sheets interbedded with shale showing frequent wave features must be deposited during high energy condition possibly storm. Hummocky cross-stratification within calcarenite sheets corroborates this interpretation. Wave ripples on the bed top indicates waning nature of the storm ?. Therefore, lime shale is indigenous in origin, deposited in an interbar region during the fair-weather condition while calcarenite sheets are extraneous origin, deposited only when high-energy storm could cross the bar top and reach up to interbar region.

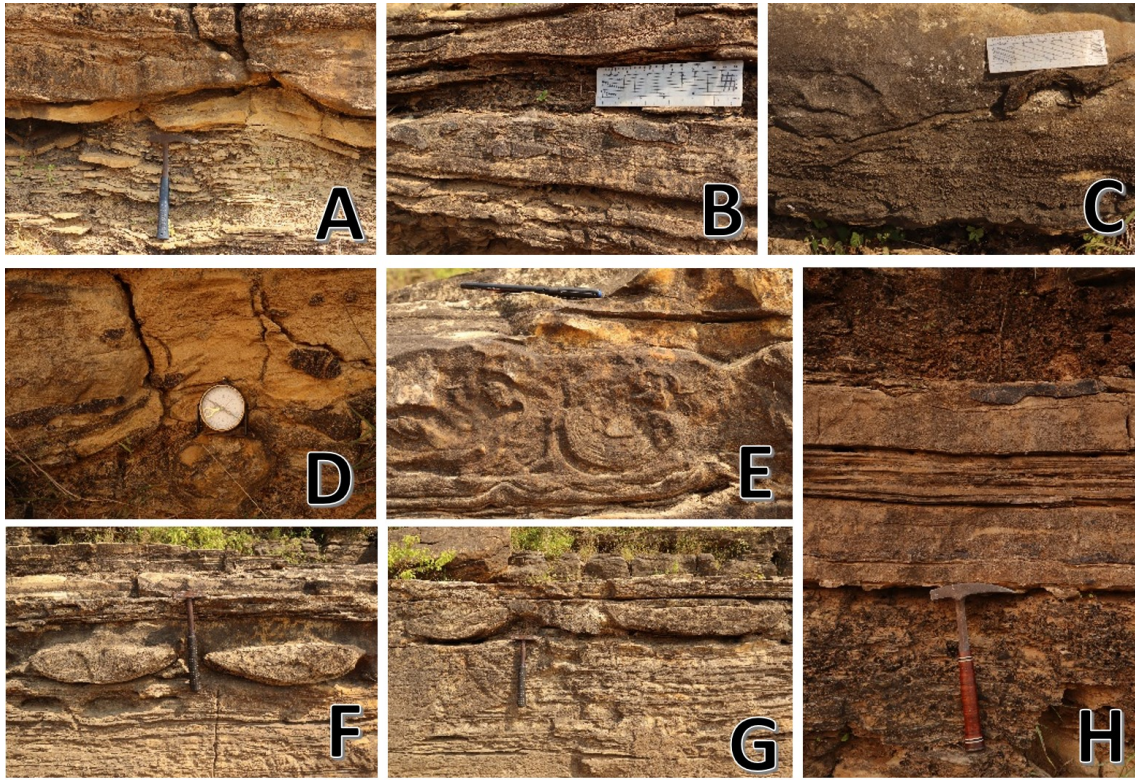


Figure 4.6: Various sedimentary features within Facies E, which primarily consists of calcarenite-shale sequences. (A) and (B) showcase modifications observed in certified arenite and calcareous shale. (C) highlights a coarse-grained calcarenite layer. (D) depicts Chertification occurring within the calcarenite. (E), (F), and (G) display composite convolute laminations, with (E) specifically demonstrating convolute lamination in conjunction with wave-ripple lamination. (H) illustrates alternating layers of calcareous shale beds interspersed with planar laminations of calcarenite sheets.

4.2.2 Facies Analysis of the basal Part of the Sirbu Shale Member

The study of the various facies within the basal part of the Sirbu Shale Member was carried out along Patna Nala section close to Maihar town (Fig. 1.3). The underlying Lower Bhandar Sandstone Member is reddish in colour, bear emergence features like desiccation cracks, salt-pseudomorph crystals. The Lower Bhandar Sandstone Member is interpreted as of coastal origin [Bose & Chaudhuri \(1990\)](#). The maximum thickness of the outcrop of the Sirbu Shale is ca. 7m and the exposure is well enough to carry out detailed facies analysis. Within the Sirbu Shale, the following three facies are recognised based on the lithology and sedimentary structures found therein.

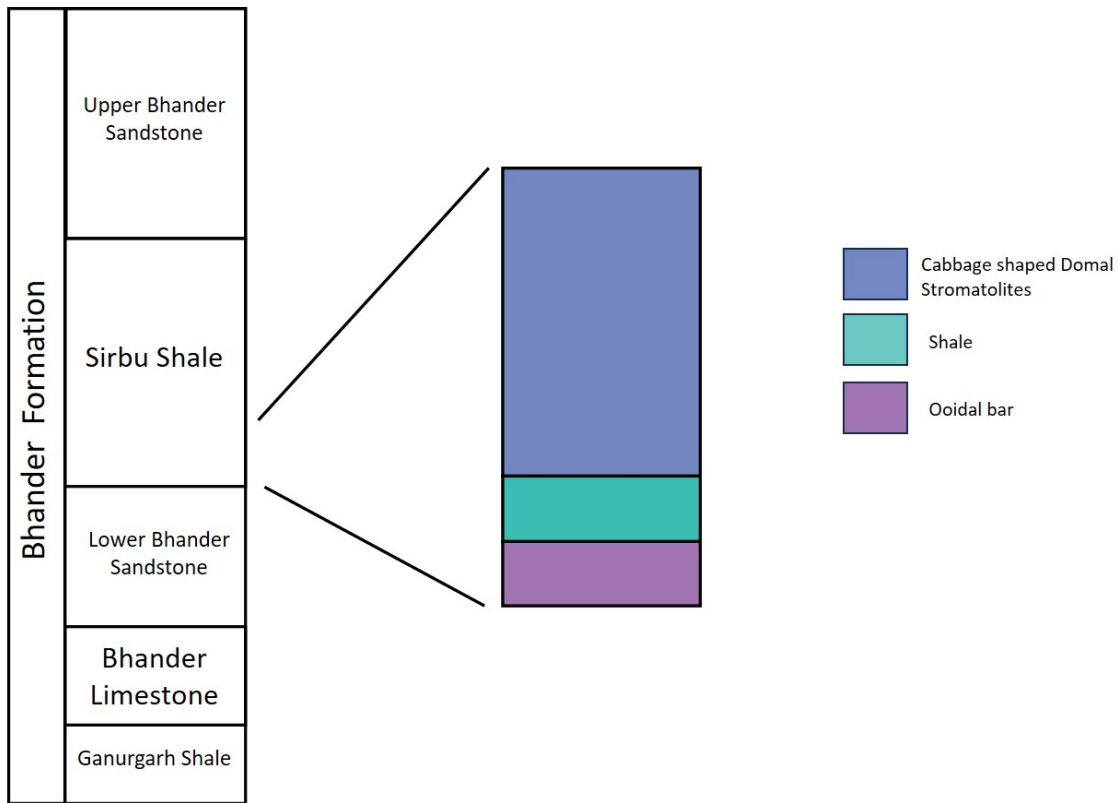


Figure 4.7: Stratigraphic lithology of (A) Bhandar Formation and (B) Patla Nala Section representing Basal Part of Sirbu Shale, highlighting one of the studied areas. The Sirbu shale is a mixed siliciclastic and carbonate platform with presence of ooids, supporting the presence of a interbar settings.

Facies A1- Stromatolite facies

These facies, which are only found in the base of the Sirbu Shale, are primarily cabbage-shaped domal stromatolites (S6), with average column height and diameter of 27.11 cm and 20.75 cm, respectively (Fig. 4.2 (E)). The Lower Bhandar sandstone Member's emerging features can be seen in the alternating sand-shale sequence above these domal stromatolites. These create bioherms.

● *Interpretation*

- Stromatolite indicates microbial growth and deposition took place within the photic zone. However, these large cabbage –headed stromatolites possibly deposited within deeper water in comparison to the stromatolites observed in the Bhandar Limestone Member.

Facies B1- Cross-stratified limestone facies

It is characterised by, oolitic or peloidal light-coloured calcarenite with tabular bed geometry. This facies vertically grades to the next Facies C1. Internally these facies are cross-stratified with chevron and herringbone geometry (Fig. 4.5). Wave cum current ripples and desiccation cracks are occasionally preserved on the bedding (Fig.4.5) surface. The contact between facies B1 and the preceding Facies A1 is sharp.

- *Interpretation*

- The tabular body geometry with cross-stratification pattern implies these facies to be a bar. Both the chevron and herringbone cross-stratification indicates the dominance of oscillatory flow. Presence of ooids within the calcarenite beds indicate presence of wave agitation within the depositional site.

Facies C1- Ripple laminated facies

With intact ripple forms on the bed surfaces (Fig. 4.8 (A)), the facies is characterised by ripple laminae inside fine-grained silty limestone (Fig. 4.8 (B)). These waves are 5 mm tall and spaced 10 cm apart on average. The ripples' crests can be locally bifurcated and straight or broadly sinuous.

- *Interpretation*

- Deposition occurred in the interbar area, which is a lower flow regime that may have been behind the bar (Facies B1).

4.2.3 Morphological variability and cyclicity within the stromatolites of the Bhander Formation

Morphology is an important criterion for classifying stromatolites, taxonomy and biostratigraphy, and also used to interpret about the depositional environment. Even though we use modern stromatolites as an analogy to study the ancient fossilized stromatolite, we cannot ignore the fact that they are very different from each other in multiple aspects. One of the aspects which sets apart Phanerozoic stromatolites



Figure 4.8: Ripple laminated facies. (A) Preserved ripple forms on the bed surface. (B) Ripple laminae within limestone.

from Precambrian one is the occurrence of vast range of shapes and sizes in Precambrian Sedimentary carbonates. Here the stromatolite facies concerned are found in two stratigraphic levels within the Bhander Formation viz. the Bhander Limestone Member and the basal part of the Sirbu Shale and have diverse forms.

Along with the morphological variations, cyclicity between several morphotypes are also observed in the field exposures. Our goal in this section is to document the morphological variation of the stromatolites and their cyclicity. The stromatolites exposed along the Thomas River near Emiliya, Beldara, Dolni and Patna nala (Fig.1.3) in and around Maihar, M.P. are studied for the present endeavor.

Following are the detailed descriptions of different stromatolite morphotypes-

Laterally linked domal stromatolites (S1)

This form is present in the Thomas River section near Emilia village. They occur above planar laminated lime mudstone facies (Facies B) and below the columnar stromatolite morphotype (Fig. 4.10(A)). These forms have a diameter ranging from 90 to 440 cm and a maximum height of 1 m. The upper surface of these stromatolites is covered by wave ripples (Fig.4.10 (C), (D)). Internally, they are composed of laterally-linked laminae which are undulatory and continuous in nature. The average width between the two domal forms is about 0.5 m. Many local-scale faults are present which disrupt the laminae of the stromatolites. The stromatolite laminae seem to accrete over these faults resulting in a change in their orientation (Fig.4.10 (B)).



Figure 4.10: Laterally Linked Domal Stromatolite. (A) Contact between Laterally linked Stromatolites and Columnar stromatolites. (B) Closer view of Laterally Linked Domal Stromatolites. (C) and (D) show Ripple marks form the surface of stromatolites. (D) shows the ripples from top view.

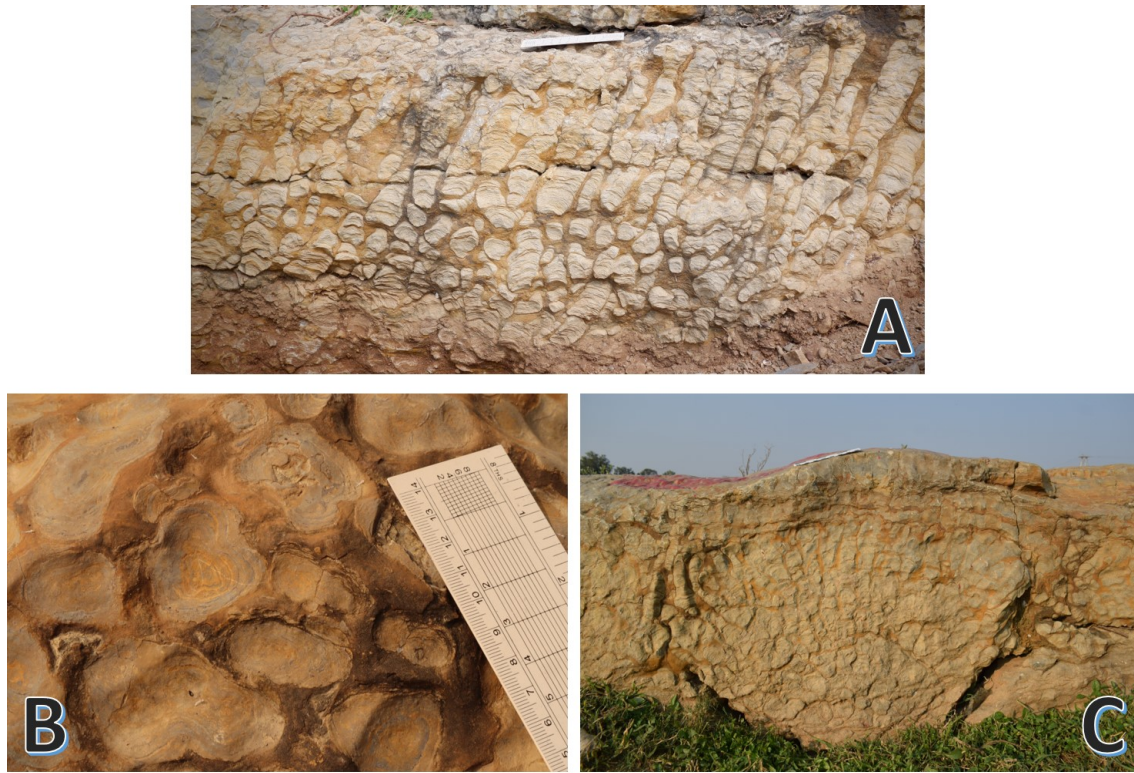


Figure 4.11: Columnar stromatolites (Biostromal (S2) and Biohermal(S3))

Columnar stromatolites (Biostromal (S2) and Biohermal(S3))

This columnar stromatolite morphotype is found along the Thomas River section near Emiliya village and present above the laterally-linked domal stromatolite morphotype (S1) (Fig. 4.11). Average height of 7.39 cm and average width of 3.38 cm, the individual columns are inclined or vertical in form and frequently parallel to one another (Fig. 4.11). While the inclined and branching columnar morphotypes tend to create bioherm (S3), the vertically oriented, parallel-natured columnar stromatolites form the biostrome (S2) (Fig. 4.11 (B),(C)). For both S2 and S3 morphotypes, the columns are cylindrical in nature. The diameter of the base is less compared to their head; gradually the column width increased upward giving rise to wider head. When the stromatolites heads are exposed in bedding plane, they are circular to elliptical in outline. Intercolumnar area with variable width are observed in between the columns- some of the stromatolite columns are tightly packed while others have wide intercolumnar space filled-up by stromatolite debris, micrite and carbonate cement (Fig. 4.11 (A)). Branching is also observed within the columns, with most bifurcating

and some exhibiting dendroid and lateral branching (Fig. 4.11). The branching pattern is divergent dominantly, with some coalesced types of branching also observed. Many columns showed significant inclination, varying from 50 to 130 degrees in N-E direction. This inclination could be indicative of the influence of current action. In some cases, the inclination was consistent throughout the column, while in others, initially vertical columns exhibited inclination (Fig. 4.11). The internal laminae are steeply convex, and individual laminae were either smooth or wrinkled.

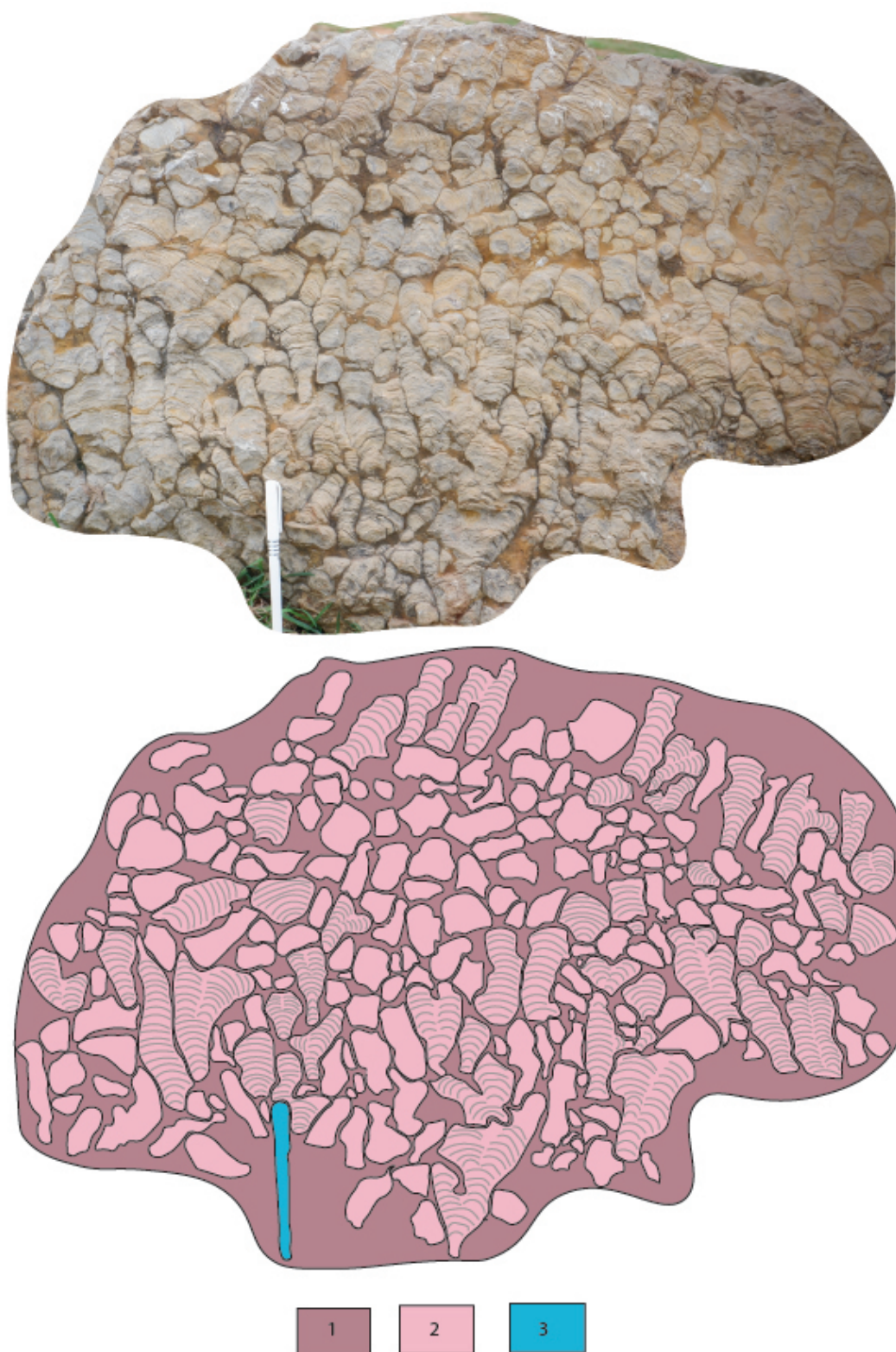


Figure 4.12: Different Branching patterns within columnar stromatolites. 1 - Micrite and carbonate Cement, 2 - Stromatolite columns and 3- Reference (Pen) Length - 13cm. Note the irregular branching in different directions.

Small-headed stromatolites (S4)

These S4 morphotypes are the smallest among all the other morphotypes (Fig.4.13). They occur above the columnar stromatolite morphotypes (S2 and S3). They are characterized by their small size and simple morphology, with the smallest height among all the observed morphotypes ranging from 1cm to 3 cm (Fig. 4.13). They have bulbous shape with widths ranging from 1cm to 4 cm. The columns show no preferred orientation. hence, we can say that they have wider intercolumnar areas compared to those present in S2 and S3 morphotypes. The width of the intercolumnar area varies from 2 cm to 5 cm and it is filled-up by micrite and stromatolite debris.



Figure 4.13: Small-headed stromatolites (S4). The red box highlights the stromatolite facies

Stratiform stromatolites (S5)

This morphotype is present along the Thomas River section near Dolni village. It is characterised by micro-scale stromatolite columns (Fig.4.14). Unlike the small-headed stromatolite (S5), these micro-scale stromatolites columns are laterally linked. The columns have very constricted troughs and wider crests (Fig. 4.14). Together,

the micro-scale stromatolite columns form stratiform column (Fig.4.14). Internally their laminae resembles to crinkly-laminated microbial mats. Internally, the laminae exhibit a gentle convex-up curvature and remain continuous across the columns. The thickness of the laminae remains consistent within the columns. On average, the height and width of the micro-scale stromatolite columns measure 6 cm and 2 cm, respectively. Inter-columnar areas are not observed for this morphotype.



Figure 4.14: Stratiform stromatolites (S5)

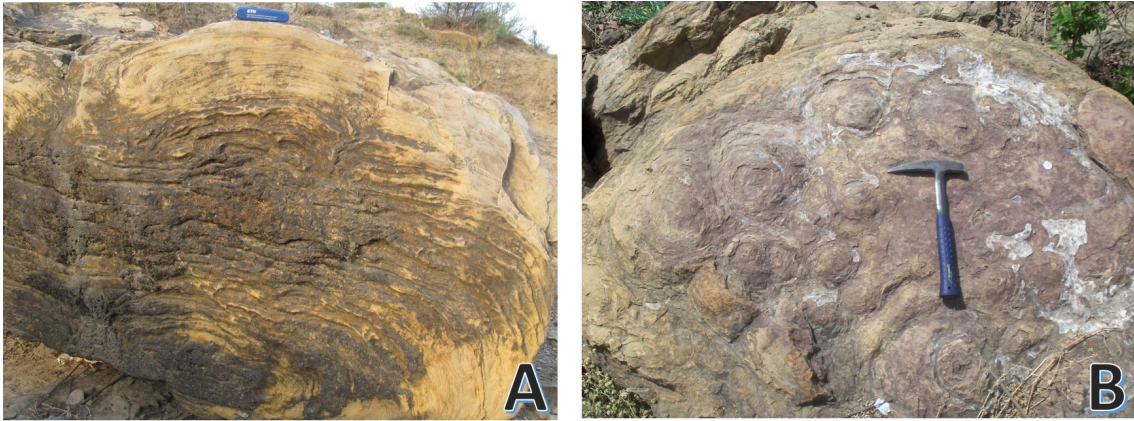


Figure 4.15: Cabbage-shaped stromatolites (S6). (A) depicts one dome with composite morphology. (B) depicts the head region of the stromatolite domes.

Cabbage-shaped stromatolites (S6)

This morphotype is only present at the basal part of the Sirbu Shale Member exposed along Patna nala. The exposures of S6 morphotype directly overlie the Lower Bhandar Sandstone Member characterized by alternating sand-shale succession showing emergence features (Fig.4.15). This distinct morphotype is characterized by dome-shaped columns resembling the turbinate or bulbous morphology (Fig.4.15). These structures are typically large, with an average height of approximately 27.11 cm and an average width of around 20.75 cm. The individual domes mostly stand erect or are slightly inclined. Unlike the columnar morphotype (S2 and S3), this morphotype shows less branching, although we observed some coalesced convergence within the domes. Inter-columnar spaces are scarce. The laminae were not visible to the naked eye, but we observed steeply convex and smooth to wrinkled nature in them. In bedding plane section, stromatolite heads with circular to elliptical outline is observed (Fig.4.15).

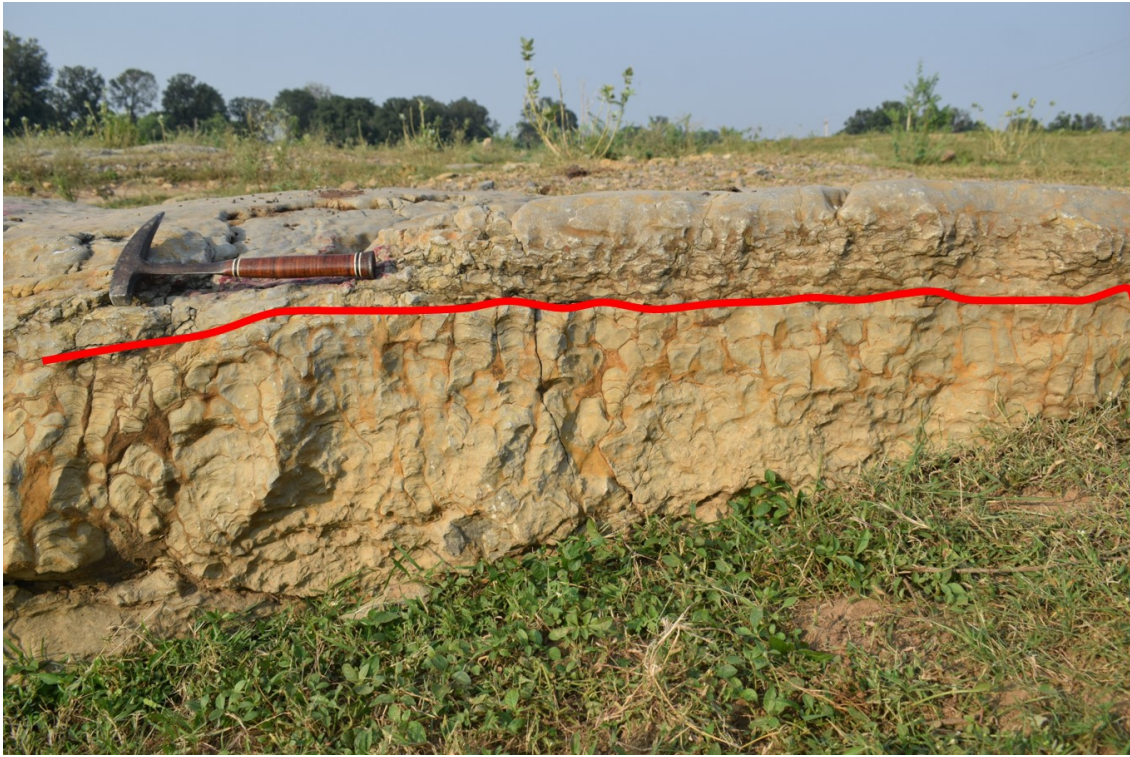


Figure 4.16: Cyclicity within different stromatolite morphotypes

Cyclicity within different stromatolite morphotypes

The Bhandar Formation in the Upper Vindhyan is characterized by a continuous and cyclic limestone sequence dominated by stromatolites, biostromes, and bioherms. These formations display alternating patterns and diverse morphologies (Fig. 4.9). The cycles exhibit a gradual increase in thickness, ranging from 32 cm to 162 cm within each cycle (Fig. 4.18). The majority of cycles consist of columnar and small-headed, bulbous stromatolites, while occasional microbial laminites mark the cycle terminations. The cycles follow a pattern starting with columnar stromatolites, transitioning to small-headed stromatolites, and concluding with small-headed stromatolites, resulting in vertical stacking of the cycles (Fig. 4.17). The transitions between different stromatolite types are distinct, leading to vertical accumulation of morphologies. The larger columnar stromatolites within each cycle are generally thicker, with dimensions ranging from 25 cm to 152 cm, while the smaller small-headed stromatolites are thinner, ranging from 7 cm to 32 cm. The stromatolite-dominant unit exhibits localised variations in cycle thickness.

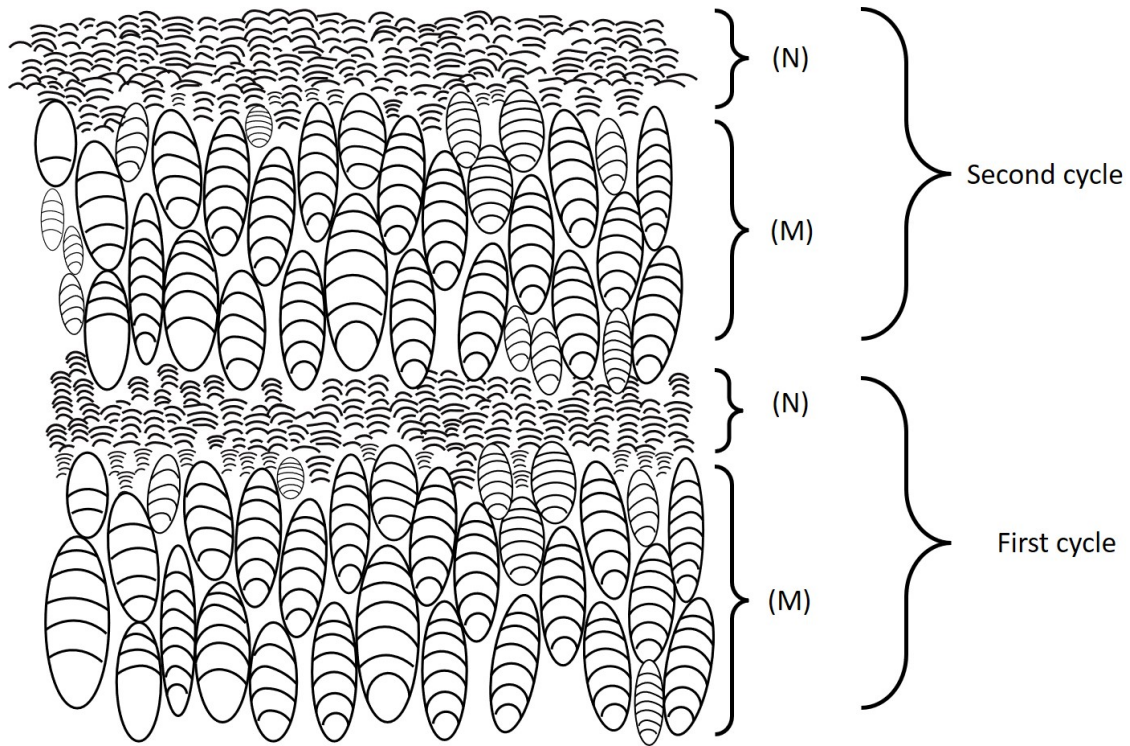


Figure 4.17: Schematic diagram of the cyclicity of Columnar stromatolite and Small headed bulbous stromatolite. The diagram shows two complete cycles. (M) represents columnar morphotype, (N) represents small-headed morphotype.

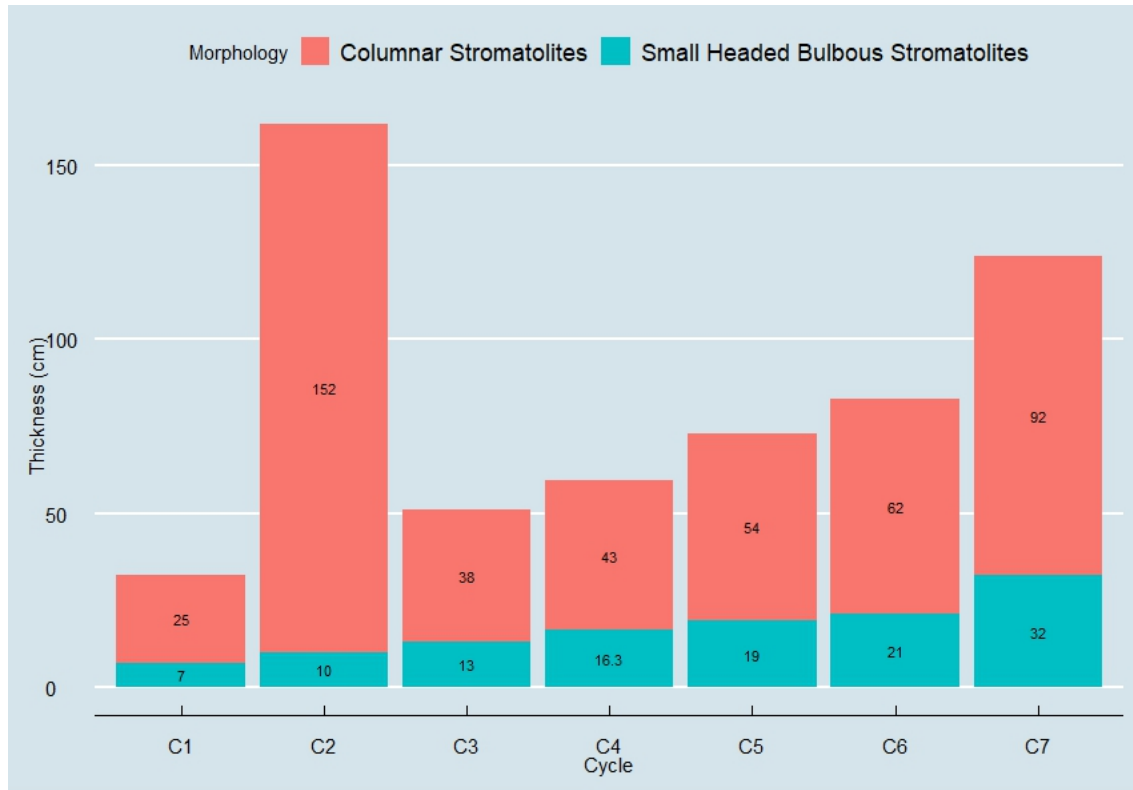


Figure 4.18: Thickness variation for each cycle, and of each morphotype respectively. Note the overall increase in the overall thickness of each cycle, suggesting a swallowing upward trend.

4.3 Petrographical and Spectroscopical observations

4.3.1 Petrographic Observations

Petrographic studies of the stromatolite facies have revealed various sedimentary microfabrics. These stromatolites are characterized by alternating dark micritic and sparry calcite-bearing light laminae (Fig. 4.19). The light laminae have undergone varying degrees of recrystallization. The transition from the dark laminae to lighter laminae is always sharp in nature, but the contact between the lighter laminae to dark laminae is always gradational in nature (Fig. 4.19).

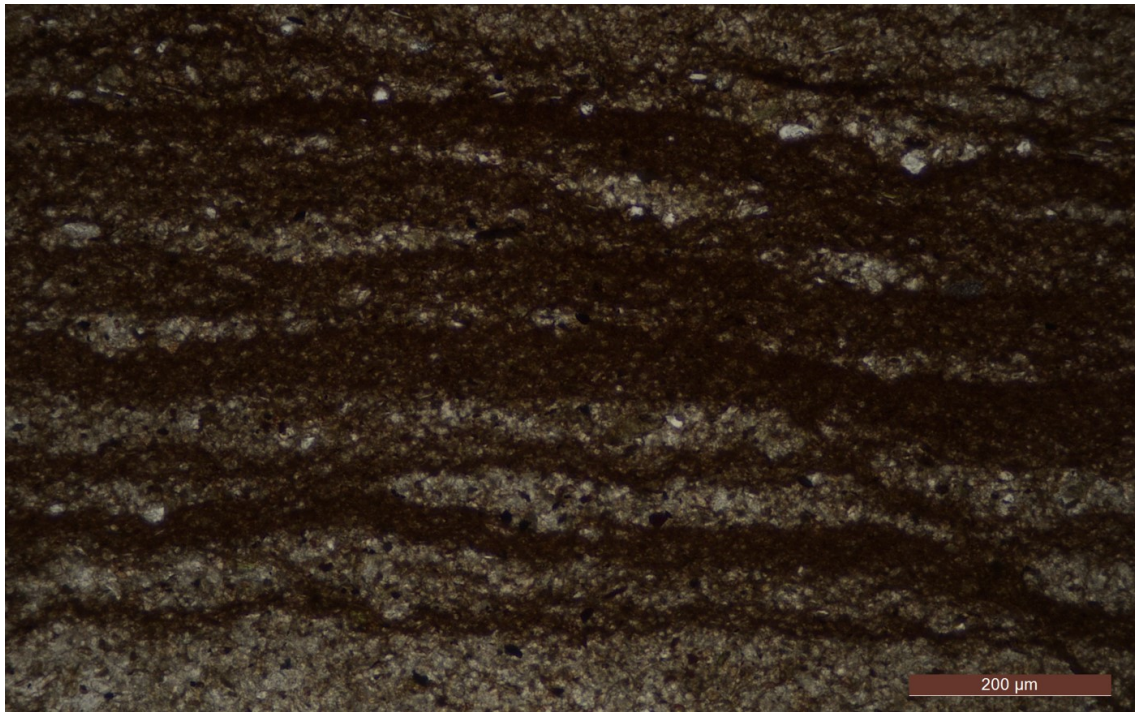


Figure 4.19: Alternating dark micritic and light, sparry calcite laminae. The figure shows sharp transition from dark to light laminae, with a gradational shift from light to dark laminae. Note that most of the material is heavily recrystallized.

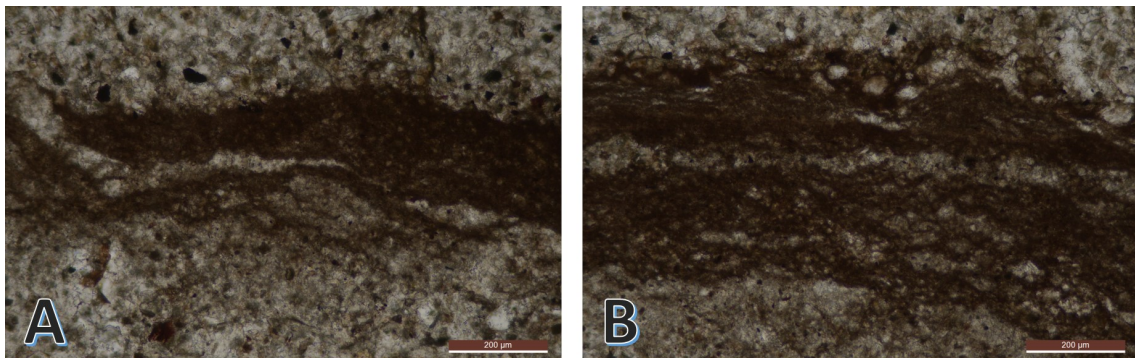


Figure 4.20: Crinkly laminae. It resembles a mesh-like network.

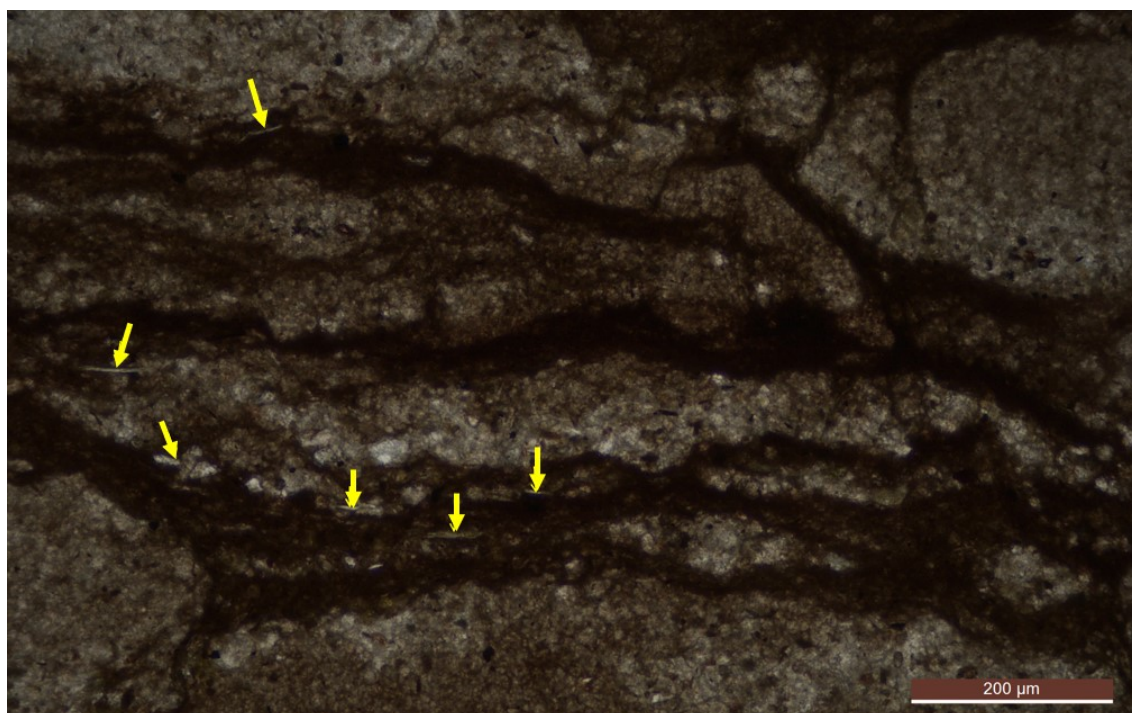


Figure 4.21: Silica and Mica grains trapped by dark micritic laminae. This shows evidence of trapping and binding of sediments.

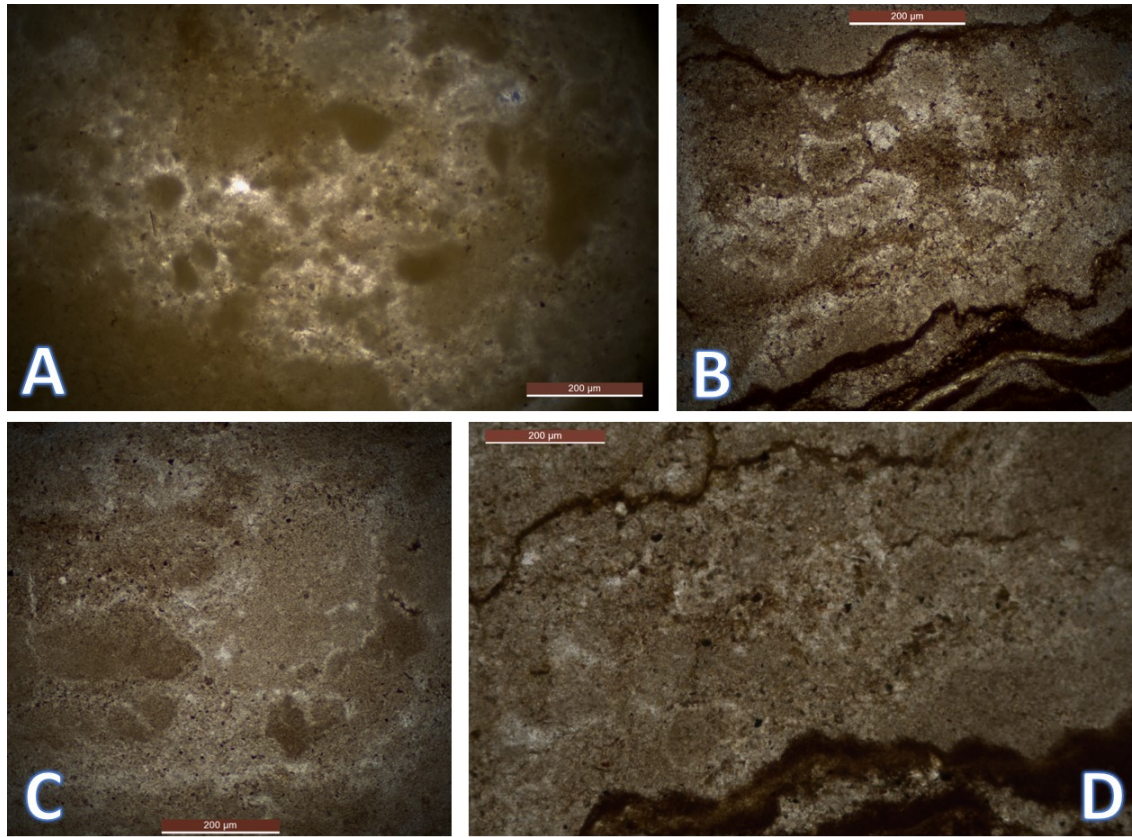


Figure 4.22: Stromatolite fabric mesostructure. (A), (B), (C) and (D) – Clotted texture in the fabric.

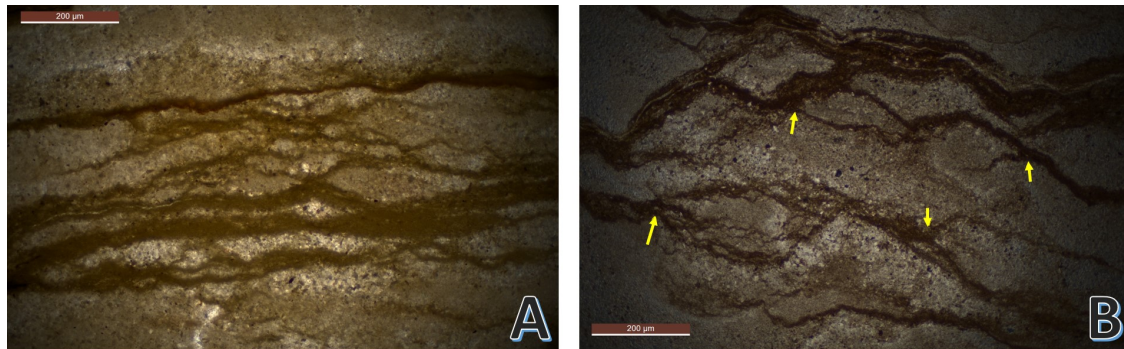


Figure 4.23: Frayed edges of the darker laminae. Note the bifurcating nature of the frayed edges, shown by yellow arrows in (B)

The darker are laminae are crinkly in nature (Fig. 4.20 (A), (B), often shows frayed edges with bifurcating nature (Fig.4.23 (C),(D)). In some thin sections, silica

grains are observed to be trapped in between the frayed dark laminae (Fig. 4.21). In some thin sections, along with the detrital silica particles, ooids and peloids grains are also present in between the dark and light laminae. Thickness of the dark and light laminae is variable in nature but they are laterally continuous.

In some of the thin sections clotted fabric is observed within the darker laminae (Fig. 4.22). This feature is characterized by light grey patches, which are lighter in color at the edges bearing a clotted texture (Fig. 4.22 (B)). The clot fabric is composed of micrite. The space between the clots is filled by recrystallized spar which represents drusy growth. The shape and size of these clots are highly variable and irregular, ranging 50-200 μm in length and 20-150 μm in width. The boundary of the clots is not very well defined, in few places the boundary consists of silicate crystals.

Fenestrae are also often found in association with the dark-light laminae couplets. Fenestrae are filled with sparry calcite showing drusy growth. In our observations, we have identified laminae composed of palisade crystals within the thin sections. The thickness of these palisade laminae exhibits variability, but they demonstrate lateral persistence.

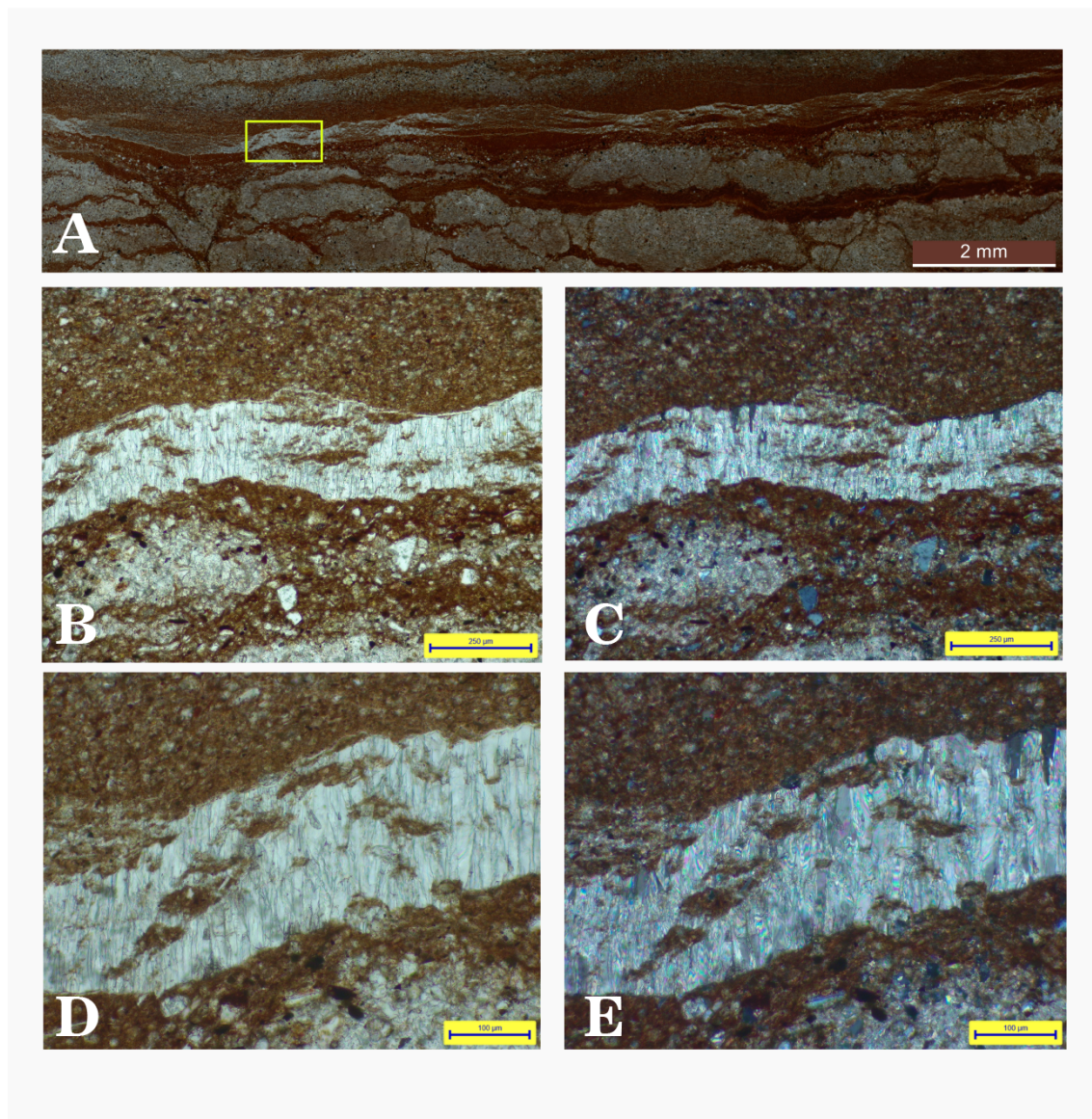


Figure 4.24: Plaisade Texture

4.3.2 Raman Spectroscopy observations

Raman spectra of the different materials in the Bhandar Formation stromatolite samples are presented in the fig.

Kerogen, or leftover organic material, was identified by optical microscopic examination of petrographic thin section samples of stromatolite samples from the Bhandar Formation [Summons & Hallmann \(2014\)](#). Under transmitted light, the kerogen in these samples appears as very fine, spherical, amorphous particles with a medium to dark colour. Raman spectroscopy has shown to be an effective method for determining the biogenicity of samples and verifying the existence of kerogen [Marshall et al. \(2012\)](#); [Schopf & Kudryavtsev \(2005\)](#); ?. For this reason, Raman spectra of the dark matter was obtained on representative thin sections of stromatolites. The disordered band, sometimes referred to as the "D" band [Castiglioni et al. \(2001\)](#), and the graphitic band, also referred to as the "G" band [Tuinstra & Koenig \(2003\)](#), are the two main kerogen peaks that should be visible in the kerogen spectrum.

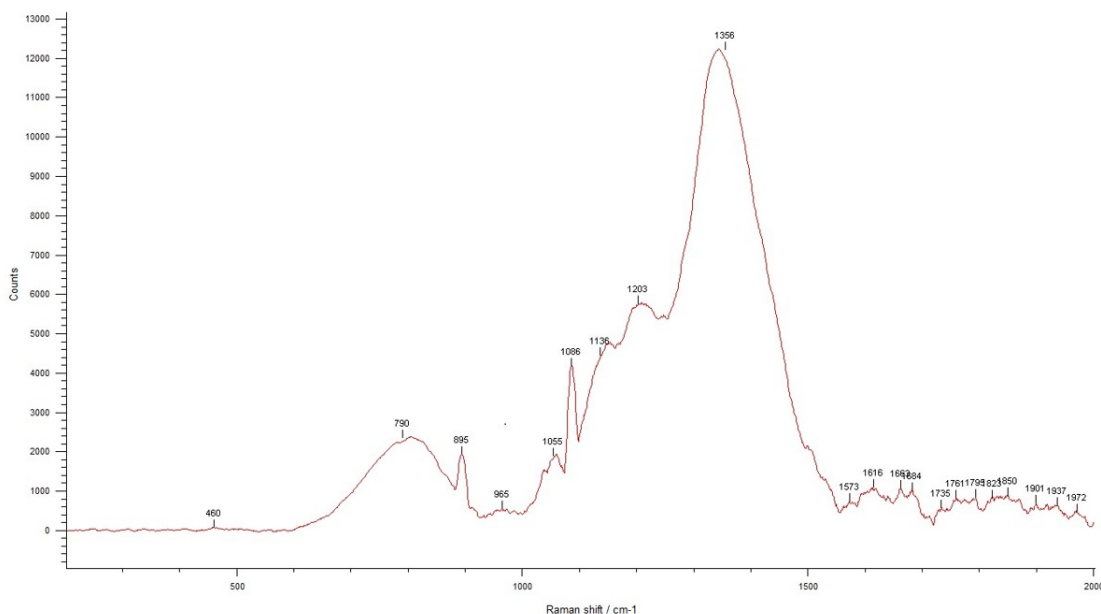


Figure 4.25: Raman spectrum displaying distinctive kerogen features: the 'D' band (centred at approximately 1356 cm^{-1}) indicating disorder ([Castiglioni et al., 2001](#)), and the 'G' band (centred at around 1616 cm^{-1}) signifying graphitic carbon ([Tuinstra & Koenig, 1970](#)). Noteworthy is the carbonate peak at approximately 1086 cm^{-1} .

The high fluorescence may have made it challenging to acquire completely well-

resolved peaks. With the D band centred at around 1356 cm^{-1} and the G band centred at approximately 1616 cm^{-1} , the stromatolite spectrum still shows results that are comparable to the Kerogen spectrum and can be easily identified. (Fig. 5.5). All the spectra show similar peak wave numbers for D and G band and also display a prominent carbonate peak at 1086 cm^{-1} (Fig. 5.5). A prominent characteristic observed in most Raman spectra is that the intensity of the D band is higher than that of the G band.

The presence of microbially induced laminae, lighter precipitated laminae, clots, ragged edges, and kerogen in thin sections and Raman spectra, thus, all further indicate or support a biogenic origin of the kerogen material, so verifying the biogenicity of the stromatolite.

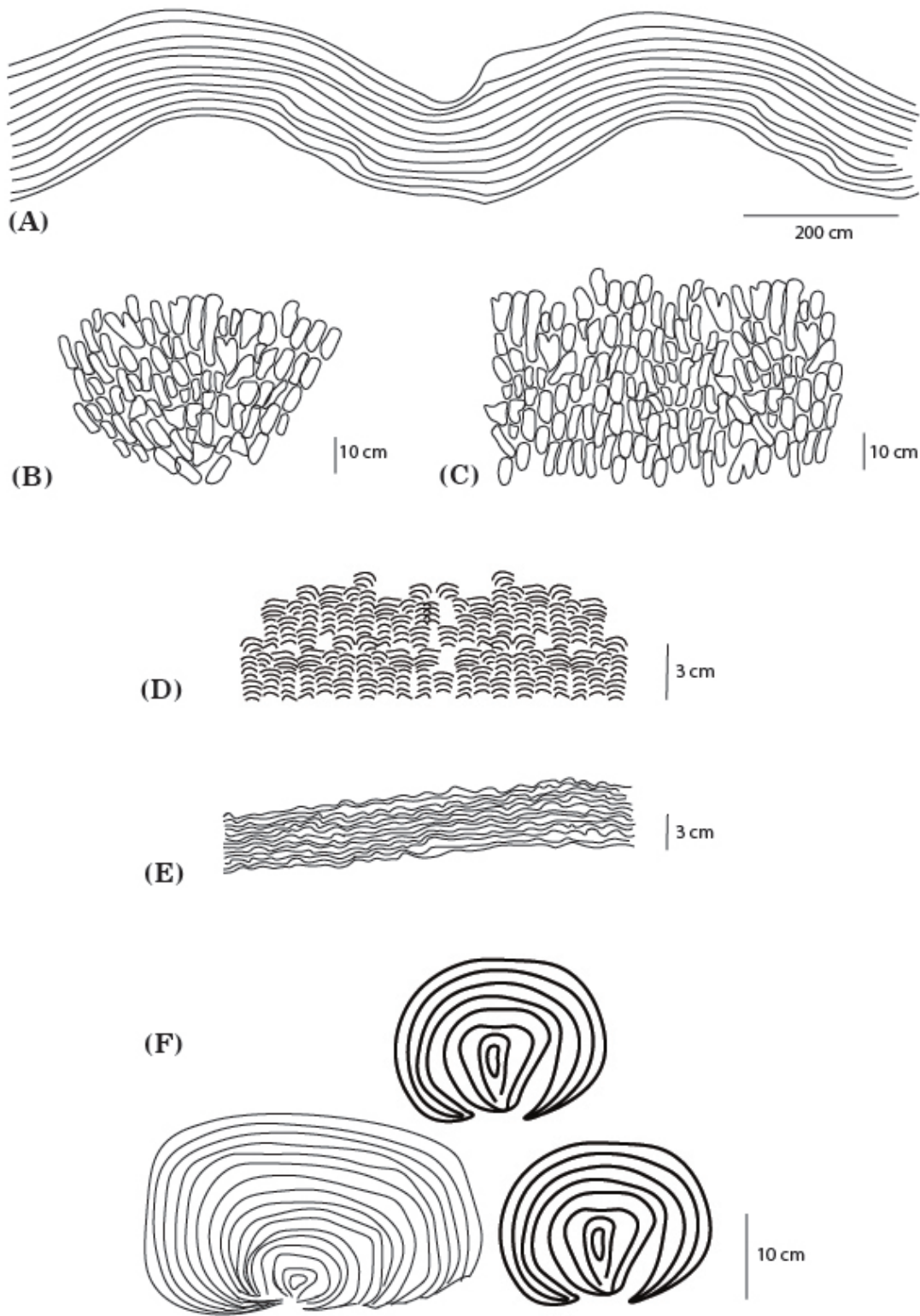


Figure 4.9: Schematic of different morphologies

Chapter 5

Discussion

5.1 Depositional Paleoenvironment

The stromatolites of the Bhandar Formation are present within the Bhandar Limestone Member and in the basal part of the Sirbu Shale Member. Both the studied limestone intervals preserve well-developed primary sedimentary structures and lithofacies variations. Thus the lithofacies analysis provides the fair notion about the depositional paleoenvironment. Our study inferred the depositional environment to be a carbonate ramp environment, which can be distinguished into four distinct depositional environments within the ramp platform: deeper part of shelf settings, shallower part of shelf settings, barrier or bar settings, and inter-bar/lagoonal settings. The stromatolite facies (facies A) was deposited within the photic zone. However, the variations in water depth within the depositional realm are reflected through the different morphotypes observed within this stromatolite facies (facies A). Based on the column height and column diameter, the S1 and S5 morphotypes were probably deposited at a greater water depth and S4 morphotype might have been deposited in shallower part of the shelf. S2 and S3 morphotypes possibly occupy the intermediate water depth region and therefore possibly affected by both increasing and decreasing water depth condition. Different branching patterns of the columns, variable inter-columnar area, and inclined as well as vertical orientation of the columns corroborate this changing water depth condition faced by S2 and S3 morphotypes. The S4 morphotype on the other hand shows smallest column height and desiccation cracks are also associated with them, implying shallow water depth and occasional sub-aerial exposure of the stromatolite columns. Though, S1 morphotype was deposited in the

deeper part of the photic zone, but it also faced decreasing water depth condition. Presence of small-scale wave ripple laminations and synaeresis cracks on the bedding plane of S1 morphotype corroborates this interpretation. The planar laminated mud limestone (facies B) with their lateral persistency and mm-scale thin laminations, mud-sized particles indicate that it was deposited in tranquil environment, possibly to the deeper part of the shelf. The associated intraformational conglomerates (facies C) are likely to be the product of external triggering mechanisms such as tectonic subsidence or storm pounding within the same depositional environment. The cross-stratified limestone (facies D) is possibly deposited within the fair weather wave-base with occasional storm intervention. Presence of ooids within the calcarenite facies indicates high-energy nature of the depositional setting. Hummocky cross-stratification with ripple on top implies storm events. Large scale cross-stratification within this facies indicates possibly it was a barrier-bar within the carbonate depositing shelf environment. Facies E i.e. alternation between shale and minor calcarenite sheets might have been deposited in a quieter environment e.g. lagoonal/interbar region. Plane lamination within shale indicates deposition from suspension mode; in between shale occasional calcarenite sheets indicate minor fluctuations in flow regime condition within the interbar/lagoonal setting during storms. A schematic diagram shows different facies in different paleogeographic position of the inferred carbonate depositing shallow marine shelf (Fig.5.1). Cabbage shaped stromatolite (S6 morphotype) directly overlies the facies E and therefore implies that this morphotype was deposited in the lagoonal environment, behind the barrier-bar where there was little accommodation space available. Ooids and peloids in between the stromatolite laminae confirms that ooids were derived from the barrier-bar and later trapped by the microbial community of the cabbage shaped stromatolite (S6).

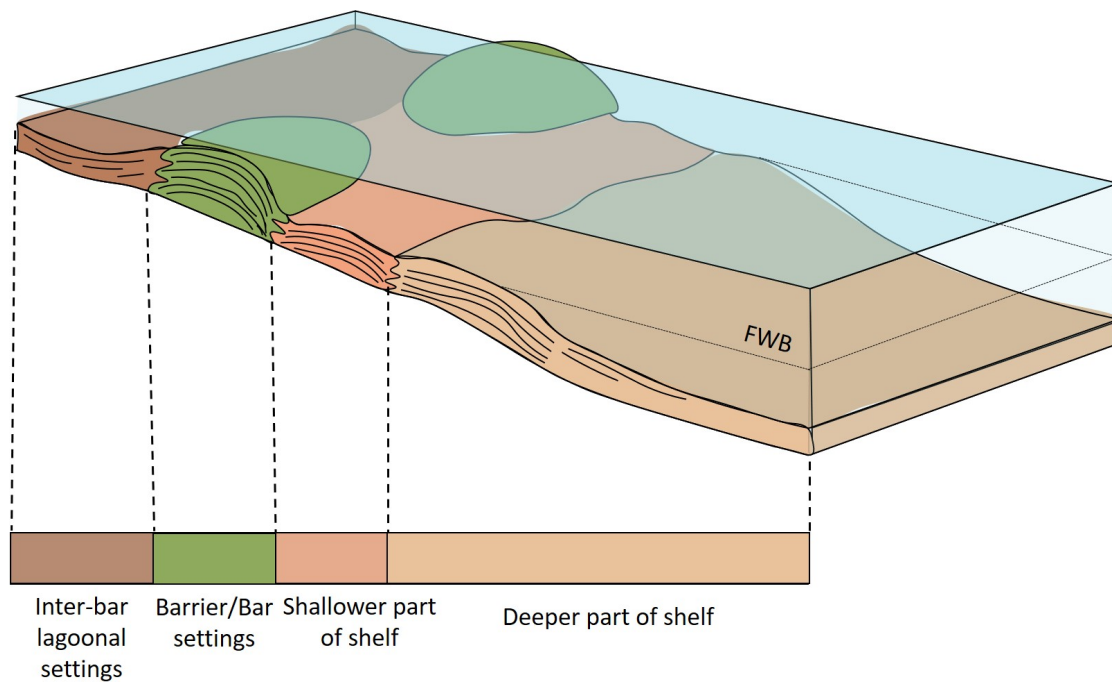


Figure 5.1: Model for the rimmed platform development of carbonate platform with the distinguished environments

5.2 Cyclicity

Apart from the lithofacies analysis, transition from one stromatolite morphotypes to other morphotypes are also observed (Fig.4.16). In addition, a cyclicity between different stromatolite morphotypes specially between S2, S3 and S4 morphotypes are recorded during the fieldwork. The individual cycle begins with S2/S3 morphotypes overlain by S4 morphotypes and occasionally with microbial laminites (Fig. 4.16). Overall thickness of S4 morphotypes within each cycle gradually increases upward (Fig. 4.18). This indicates creation of accommodation space/increasing water depth and then gradually filling up of that accommodation space in a repetitive manner. Whenever the accommodation space/increasing water depth, the larger stromatolite columns i.e. S2 or S3 morphotypes are developed; then gradually as the accommodation space is getting filled-up by the larger stromatolites and the water depth is reducing, the microbial community responded to the changing environmental condition by reducing its column height and therefore S4 morphotypes are appearing on top of each cycles. Polygonal cracks on top of the bedding planes of small scale stro-

matolite (S4 morphotype) also corroborate this repetitive wetting and drying phases of the depositional setting. As a whole, the cyclicity between different morphotypes indicate overall shallowing upward trend of the Bhander Formation. Even though, S1 morphotype is correlated with the greater water depth within the photic zone, small-scale ripple lamination and syneresis cracks on bedding plane of the S1 morphotype indicates that these were also influenced by decreasing water-column height. The repetitive creation of accommodation space for development of cyclic pattern can be correlated with the local tectonics affecting the present depositional setting. Presence of small scale faults associated with S1 morphotype, intraformational conglomerates in association with planar laminated mudstone facies corroborates the local-scale tectonic activity. In addition to that, convolute laminations are also observed within the Bhander Limestone in and around Dolni section near Maihar town, which provides evidence of sediment reworking due to tectonic activity.

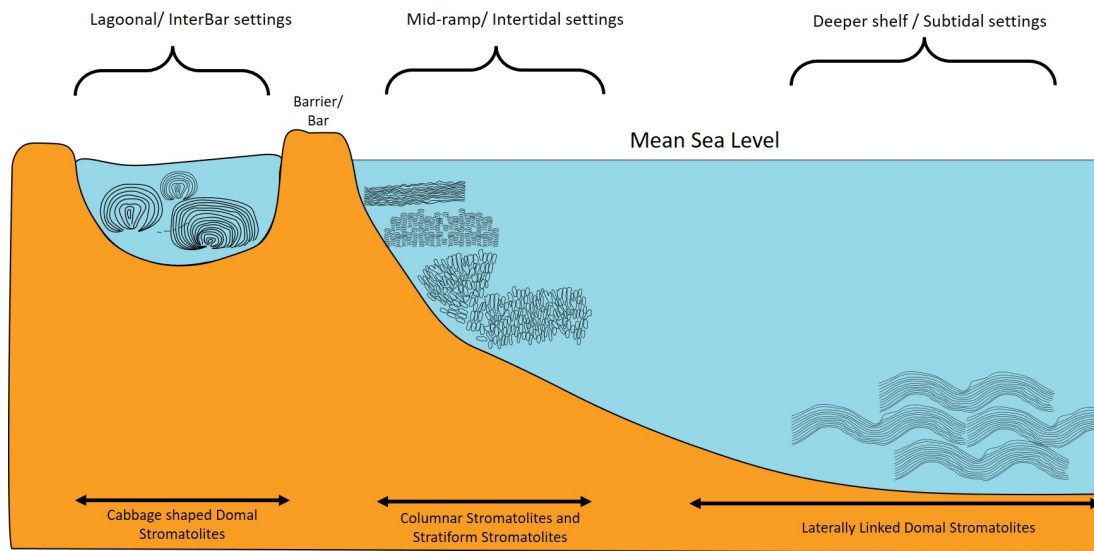


Figure 5.2: Model for the development of stromatolites in different water depth settings. Cross-section of the platform representing the different morphologies of the stromatolites. Note the depth controlled growth pattern of the stromatolites along the profile.

Our observations indicate pronounced hydrodynamic forces, including wave activity and storm events, exert a significant influence on the stromatolitic carbonate succession within the Bhander Limestone member. This influence is evident through the inclined orientation of columns, and the presence of shale deposited with alternating thin sheets of calcarenite.

The recurrent occurrences of columnar stromatolites and small-headed bulbous

stromatolites within the geological record are indicative of a cyclical fluctuation in local water depth. The initial sedimentary layer, featuring columnar stromatolites, suggests an increase in water depth, which may have resulted from an increase in accommodation space. This creation of accommodation space could have been a consequence of subsidence resulting from tectonic activity or intense storm events. Notably, minor-scale local faults are observed in the laterally connected domal stromatolites, along with the presence of a clastic stromatolite horizon.

However, it is noteworthy that the thickness of the small-headed bulbous stromatolites increases with each successive cycle. This indicates that, despite the presence of accommodation space being created, the stromatolite columns are forming in progressively shallower settings. This interpretation is supported by various sedimentary features found at the top of the bedding surface, including synaeresis cracks, polygonal cracks, and ripple marks. These sedimentary facies collectively provide evidence of recurrent subaerial exposure or the alternation between wet and dry conditions on the bedding surface due to subaerial exposure events.

5.3 Biogenicity of the Stromatolite facies

To assess the potential biogenicity of the Stromatolites within the Bhander Formation using commonly accepted criteria, we employed the criteria established by Buick et al. (1981) and Hofmann (2000), which have been thoroughly scrutinized in our review. It is crucial to note that the Bhander Limestone stromatolites are believed to have formed in a shallow marine environment, while the Sirbu Shale stromatolites are interpreted as originating in tidal flat and interbar settings. This inference proves the syngenecity of the stromatolite facies.

The first set of biogenicity criteria pertains to the contextual aspects of lamination. The microfabric of the Stromatolite facies strongly suggests a biogenic origin. The presence of alternating layers of micrite, microspar, and carbonate material aligns with microbial trapping and binding activity, resulting in episodic depositions. The fenestrae observed within the stromatolites conform closely to the overlying and underlying laminar structures, exhibiting inward-growing calcite cement fill. This provides compelling evidence for the primary nature of the fenestral fabrics. Fenestral fabrics elongated along stromatolite laminations are indicative of desiccation, which causes microbial mats to contract and create primary voids along laminae.

Furthermore, the occurrence of millimeter-scale oxygen-rich bubbles, formed during photosynthesis, can persist within a mat for an extended period before being preserved by the early lithification of stromatolite laminae, as demonstrated in laboratory experiments. Although some fenestrae exhibit spherical to subspherical morphologies while others extend horizontally along the laminae, this diversity suggests that both desiccation and gas bubble formation within a microbial mat contribute to fenestrae formation. The predominantly subtidal to supratidal setting offers ideal conditions for the development of complex layered microbial mats, akin to those preserved in the Bhandar Limestone and Sirbu Shale localities.

The second set of biogenicity criteria pertains to the morphology of lamination. A biogenic stromatolite should exhibit convex-upward structures, laminae thickening over crest flexures, wavy or crinkled laminations with multiple orders of curvature, and may be associated with thin, rolled-up fragments possessing coherent, flexible laminae that can reasonably be interpreted as microbial mats. One of the criteria specified by Buick et al. (1981) for establishing the biogenicity of a putative stromatolite is the presence of wavy or crinkly laminae with multiple orders of curvature. Importantly, our stromatolite facies prominently features such crinkly laminae, accompanied by a mesh-like network characterized by abundant frayed edges. Additionally, all stromatolite columns consistently exhibit convex upward morphology throughout the outcrop. However, we did observe the absence of thin, rolled-up fragments and brecciated mat chips in depressions, although their absence could potentially be attributed to preservation potential factors.

The third set of biogenicity criteria involves the presence of microfossils and trace fossils within the lamination. Nevertheless, there is no direct evidence of microbes causing the lamination, and microfossils are conspicuously absent in all examined sections. Here the absence could be an artefact of preservation.

Raman spectroscopic analysis of the material revealed the presence of kerogen, albeit with indications of thermal maturity. The Raman spectra reveal a pronounced D peak relative to the G peak, and both peaks are not well resolved. These observations suggest that, rather than consisting of crystalline graphite, which is the end-product of maturation, the stromatolites are composed of geochemically moderately altered amorphous carbonaceous matter, characterized by interlinked polycyclic aromatic hydrocarbons. Notably, the chemical markers of biogenicity become less discernible during geochemical maturation, as these functional groups are chemically labile and

are no longer detectable in Precambrian organic matter, except in exceptionally well-preserved microbes and associated organics. Raman spectra provide clear insights into the maturation state of such carbonaceous matter, distinguishing between amorphous and crystalline graphite. Specifically, our interpretation of the Raman data suggests that geochemically altered fossils, such as the ones studied here, are comprised of kerogens with a relatively ordered overall structure, primarily composed of fairly large and hydrogen-poor polycyclic aromatic hydrocarbons (PAHs). The presence of a shoulder peak on the D band further supports the presence of biogenic disordered kerogen, rather than plausible abiogenic graphitic kerogen.

Morphological Variability - as a biogenicity criteria

The distribution, height, and morphology of stromatolites are significantly influenced by hydrodynamics, sedimentation, and accommodation space. Large columnar stromatolites suggest the presence of substantial accommodation space, which essentially acts as a passive boundary condition. Meanwhile, sediment dynamics and hydrodynamics play active roles in regulating the form and distribution of stromatolites. The Thomas River bank region exhibits notable lateral heterogeneity within relatively short sections, especially in the Emilia portion, which must be duly considered when studying two-dimensional outcrop profiles.

The biogenic origin of stromatolites in the Bhander Limestone layer is strongly supported by the presence of five distinct stromatolite facies, which closely resemble established microbialites found in the geological record. It is crucial to acknowledge that the morphological variations observed in the Bhander Formation stromatolites are linked to changes in environmental processes. While shifts in microbial mat formation affect stromatolite initiation, dispersion, and morphogenesis, this doesn't necessarily imply diversification within the stromatolite assemblage, as noted by Allwood et al. (2009). The data does not directly reveal biodiversity, and the absence of microfossils makes it challenging to ascertain whether a single type of microorganism was responsible for the entire stromatolite assemblage. Nevertheless, the structural changes in stromatolites, coupled with shifts in the depositional environment, imply that microbial communities on the stromatolite surfaces had to adapt to these changing conditions. Given the diverse responses of microbial mat populations to changing environmental conditions, it is likely that a range of stromatolite shapes and textures emerged during the deposition of the Bhander Formation.

For the purposes of comparative analysis, we deliberately selected stromatolitic carbonate sequences within the Strelley Pool Formation (dating back to approximately 3.43 to 3.35 billion years ago) and the Dresser Formation (around 3.48 billion years old). These formations are distinctive in both macroscopic appearance and microfabric texture and are well-documented references for evaluating the physical attributes and biogenic origins of stromatolites. Notably, they represent some of the earliest known occurrences of stromatolites, rendering them invaluable for meaningful comparisons.

Numerous independent studies, as referenced in the table, have collectively corroborated the biogenic nature of these ancient stromatolite communities. Furthermore, the criteria outlined in the table closely align with the observed stromatolite facies in our current investigation. Therefore, we can confidently infer the biogenic origin of the observed facies. To enhance the comprehensiveness of the assessment framework, we propose introducing morphological diversity as a new criterion.

Table 5.1: Comparison of Biogenicity criteria and additional features between the Stromatolite facies from Dresser Formation and Strelley pool formation. See Below.

Criteria	Dresser Formation stromatolites	Strelley Pool Chert Stromatolites	Bhander Limestone
Sedimentary or Metasedimentary context	+	+	+
Syn- sedimentary nature	+	+	+
Dominance of Convex upward structures	+	+	+
Laminae thicken over Crests or Non- isopachous layering	+	+	+
Wavy or Crinkly laminations	+		+
Presence of microfossils or trace fossils	-	-	-
Presence of trapping and binding or precipitation of sediments	+	+	+
Brecciated mat chips in the depressions	NA	NA	-
Thin, rolled-up fragments	NA	NA	-
Presence of Organic matter	-	+	+
Morphological Diversity	Low: two morphotypes	High: seven morphotypes	High; Six morphotypes
Fenestrae	+	+	+
References	(Hickman-Lewis et al., 2022; Van Kranendonk et al., 2008)	(Allwood et al., 2007, 2009; Wacey, 2010)	This study

Chapter 6

Conclusions

Based on a meticulous examination of the exposed rock formations, polished rock samples, and thin slides of the Bhandar Formation Stromatolites, and considering the known processes governing the formation of Precambrian Stromatolites, the following conclusions are deduced:

1. Six distinct morphological types of stromatolites are identified within the stromatolite facies. These stromatolites were deposited in a shallow marine carbonate ramp environment, affirming the synchronous origin of the stromatolite facies.
2. The presence of various stromatolite morphotypes suggests that the behavior of the microbial community responsible for stromatolite formation is influenced by the specific environmental conditions in which they develop.
3. A consistent increase in thickness observed in the smallest stromatolite morphotype and the presence of microbial laminae provide evidence of an overall shallowing upward trend within the Bhandar Formation.
4. The recurring alternation between different stromatolite morphotypes suggests fluctuations in water depth attributable to local tectonic processes.
5. The environmental characteristics, morphological features, microfabric structures, and laminations found within the Bhandar Formation stromatolites closely resemble those observed in Precambrian stromatolites. This alignment implies a similar mechanism of genesis, possibly involving biomineralization and microbial metabolic activities, in the stromatolites within the study area. These findings further substantiate the notion of a biogenic origin for the stromatolites under investigation.

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