Stromatolite Morphology and Depositional Characteristics of the Lower Ordovician Prairie Du Chien Group, Willow River Member

by
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A thesis submitted in partial fulfillment of the requirements for the degree of
Bachelor of Arts

Geology

at

Gustavus Adolphus College
1995

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under the supervision of Professor Keith J. Carlson

ABSTRACT

The Lower Ordovician Prairie Du Chien Group is a mixture of carbonate-siliciclastic sediments, extensively observable over much of southeastern Minnesota. The Willow River Member is the youngest division of the Prairie Du Chien Group, deposited between 485-490 m.y. ago.

In Fillmore Co., along highway 52, at the junction of the Root River, a quarter-mile exposure of Willow River Member reveals four distinct assemblages of stromatolite (i.e. sediment binding cyano-bacteria) growth. The first three layers of occurrence are primarily: Low-relief, continuous, stratiform to psuedocolumnar laminations, ranging in height from 4-7 inches vertically. The fourth assemblage consists of non-linked, discontinuous, dome to bulbous biostromes ranging spatially (in two dimensions) 8"X1'2" to 1'9"X2'6". Available morphologies and characteristics of the trapped sediment within the stromatolites imply upper and lower intertidal depositional conditions.

ACKNOWLEDGEMENTS

Significant expenses were compensated by Sigma Xi in order for me to continue with my research. I wish to thank Sigma Xi for their financial support throughout this project. Secondly, I wish to thank the faculty of the Gustavus Adolphus College Geology Department for their support and inspiration. I extend my utmost appreciation to K. Joe Carlson, who through his subtle gestures of encouragement, I present the paper you see before you.

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INTRODUCTION

In Fillmore Co., along highway 52, at the junction of the root river, there is a quarter-mile roadcut exposure of the Prairie Du Chien strata. Recent rerouting of Highway 52 (post-1974) has provided an exquisite outcrop ranging from 8-25 feet in height.

The Prairie Du Chien Group is located in the Lower Ordovician sequence of southeastern Minnesota (figure 1). These carbonate-siliciclastic sediments were largely deposited in a shallow marine sea commonly referred to as the Hollandale Embayment. The Prairie Du Chien is divided into two Formations :

- The Oneota and
- The Shakopee (in order of deposition)

Deposition between 485-490 m.y. ago. (Davis, 1984) The Shakopee Formation is thus divided further into: New Richmond and Willow River Members, respectively (figure 2).

Previous Work

The Prairie Du Chien has evolved a great deal as we comes to understand its place in the rock record. Originally taking its name from Owen in 1840, the Prairie Du Chien was first know as the Lower Magnesian Limestone. Bain renamed the group after a town in Wisconsin 1906. As mentioned, the Prairie Du Chien consists of the Oneota (McGee, 1891) and the Shakopee (Winchell, 1874) Formations. The Oneota Formation was further divided into the Stockton and Hager City Members by Davis (1970, 1972). The Shakopee Formation was also separated into two divisions - the New Richmond and Willow River Members - by Winchell (1874) and Wooster (1882).

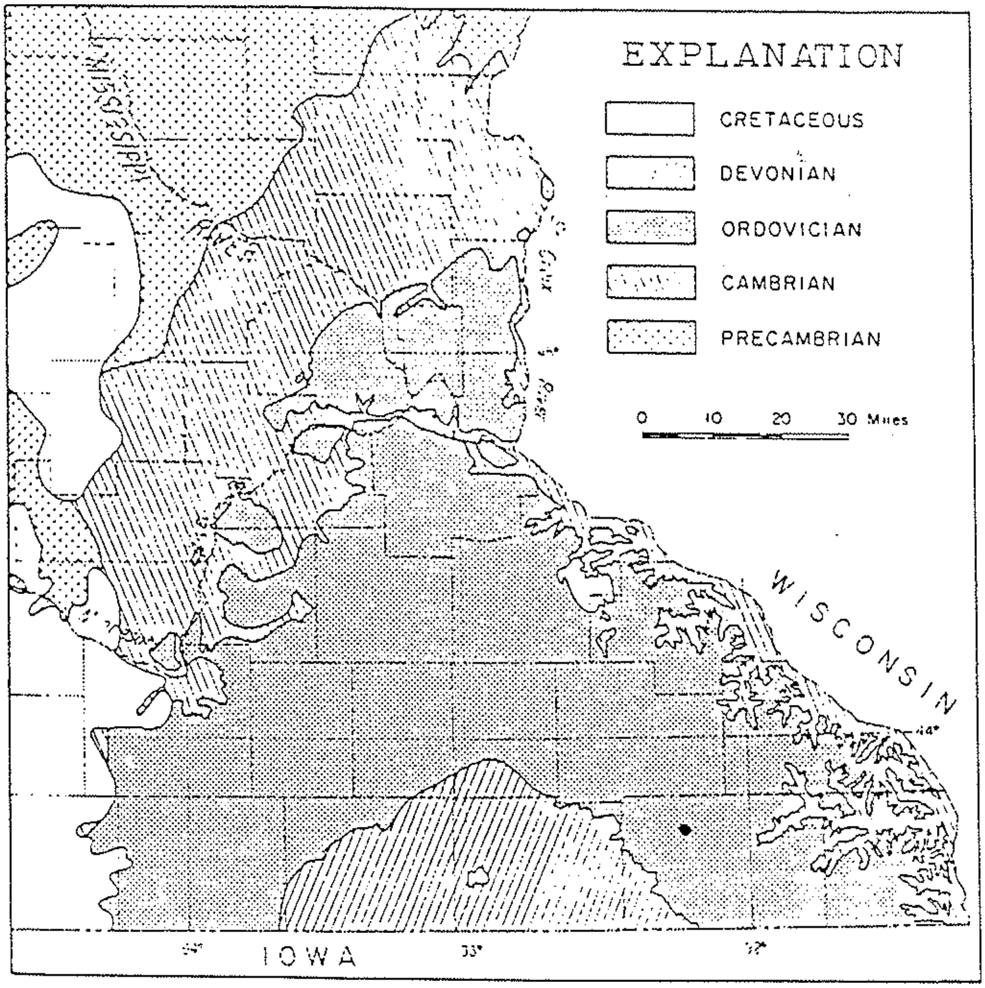


Figure 1: Generalized Bedrock map of southeastern Minnesota (Austin, 1972)

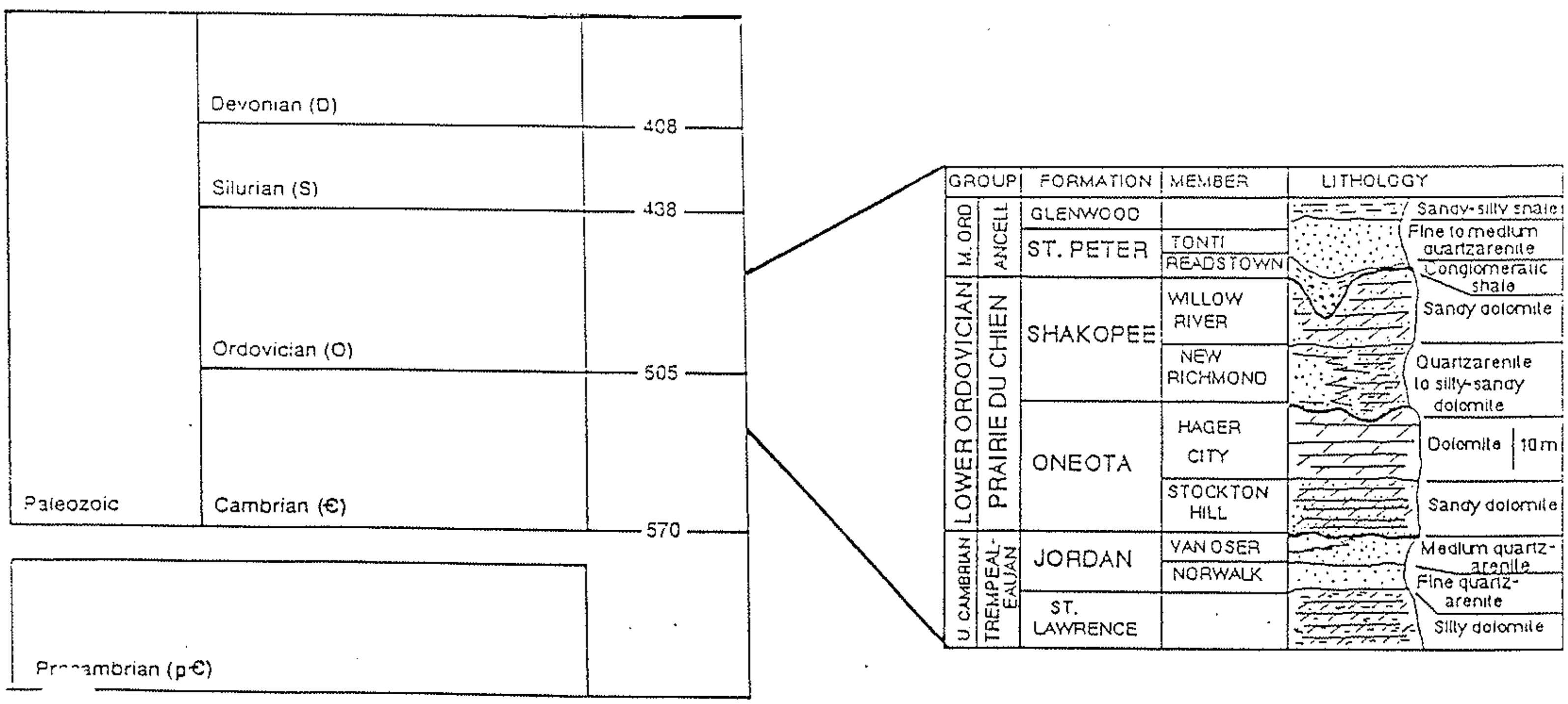


Figure 2: Geologic time scale with age relationships of the Prairie Du Chien (Smith, 1993)

The Willow River Member is mainly considered to be made up of sandy dolomite, showing laminations and crossbedding of varying degree (Smith, 1993). Yet in comparison to the New Richmond Member, less sand is present, and the Willow River Member exhibits an increase in stromatolite propagation (Davis, 1966, 1970, 1972; Austin, 1971). Smith (1993) described the stromatolites' sizes and types ranging from: laterally linked 2-cm-wide hemispheroids to 1.5-m-tall, 3-m-wide flattened spheroids. Two basic types of stromatolites have been observed at the Root River outcrop. This study focuses on those stromatolite assemblages in an attempt to describe the stromatolite depositional characteristics and habit of the Willow River Member.

Range and Development

Stromatolites are organic-sedimentary structures composed of flat, undulated, or cabbage-like laminations (figure 3). These are built up by dense mats consisting primarily of blue-green algae, which selectively trap and bind sediment particles among their mucilaginous filaments.

Stromatolites range in age from early Precambrian to Recent, however they are most abundant during the Precambrian and Lower Paleozoic (400-570 m. y. ago) with a marked decline in the Middle Ordovician. (see figure 2) The extent of stromatolite propagation range diversely, for example: stromatolites are found in the Gunflint Chert of northern Minnesota (Awramik, 1976) , the Swaziland Supergroup of South Africa (Byerly *et al*, 1986), and are also found in the Strelley Pool Chert of Western Australia (Lowe, 1983), (figure 4). Modern stromatolite growth, however appears to fall between 30° either side of the equator and is restricted to environments which are:

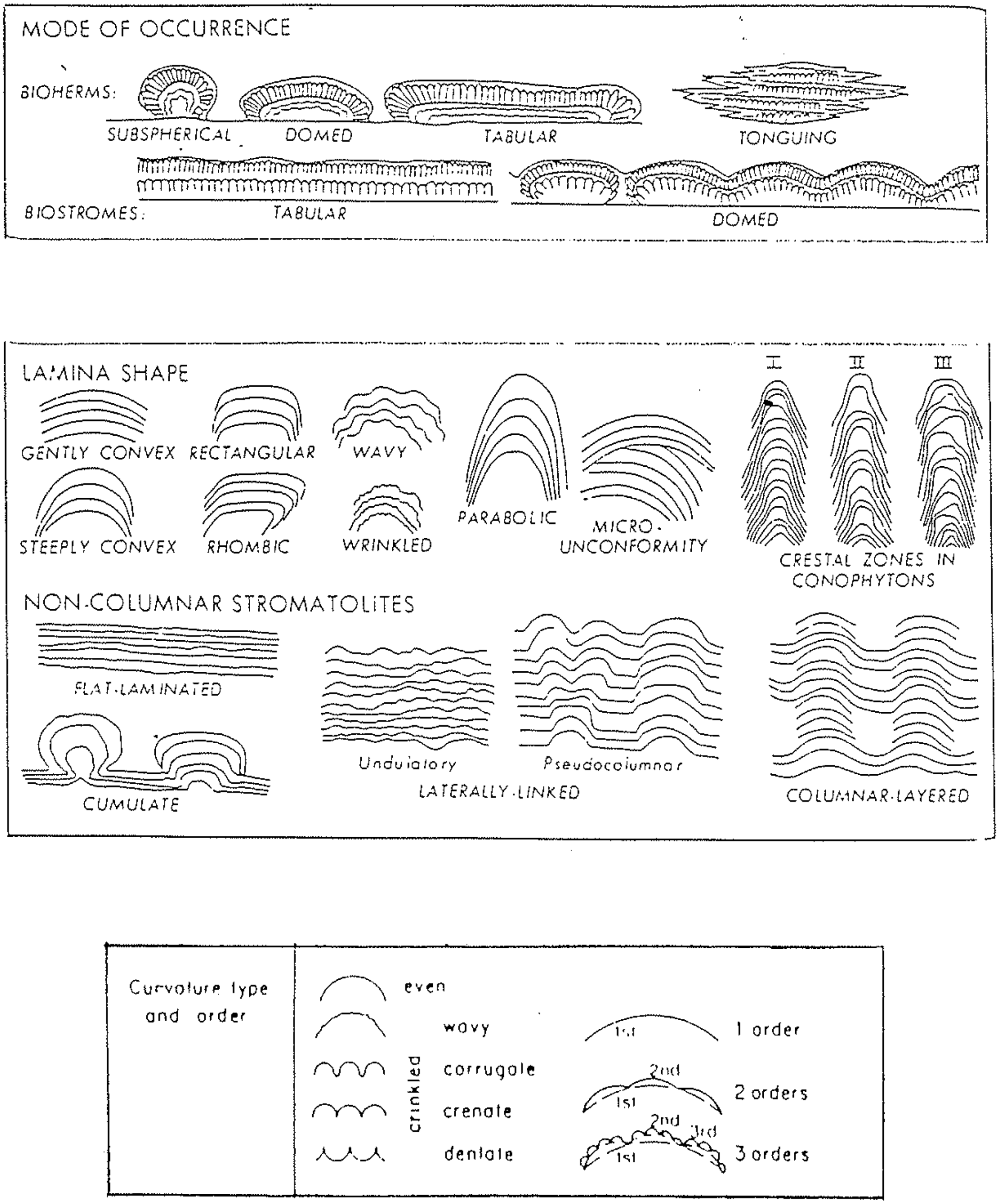


Figure 3: Stromatolite morphologies. Reproduced from *Trans. Royal Society of South Australia* (Walter, 1976)

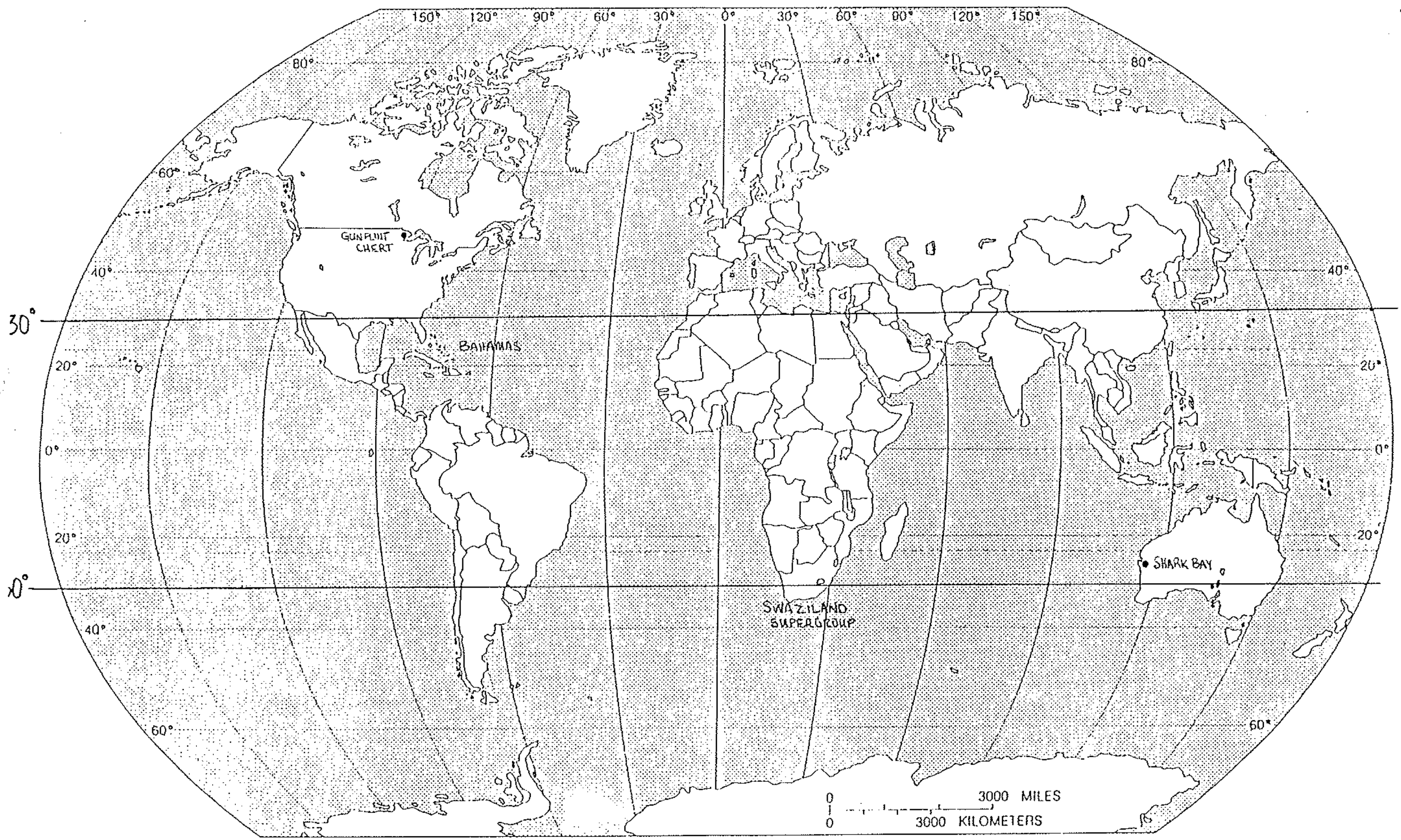


Figure 4: World map showing stromatolite distributions. World map reproduced from BYU Geography Department (1991)

1) hypersaline, and/or

2) supratidal and intertidal flats

where algal consuming metazoan fauna, such as mollusks and gastropods, are restricted and algal growth is permitted relatively undisturbed.

Stromatolite limitations are also a product of calcium carbonate and carbon dioxide saturation levels. Surface marine waters are usually saturated with $CaCO_3$, so calcareous materials are not dissolved. Saturation is a function of temperature and pressure associated with depth; therefore, at greater depths, $CaCO_3$ begins to dissolve as $CaCO_3$ solubility increases. Likewise, CO_2 levels rise, as CO_2 solubility decreases. Thus, marine carbonate precipitation is restricted to shallow water conditions (down to a depth of 4500 meters) and where water temperatures favor CO_2 solubility. The basic chemistry involved is a reaction of $CaCO_3$ and CO_2 :

$$\underset{\substack{\text{carbon}\\\text{dioxide}}}{CO_2} + \underset{\text{water}}{H_2O} \Leftrightarrow \underset{\substack{\text{carbonic}\\\text{acid}}}{H_2CO_3} \Leftrightarrow \underset{\substack{\text{hydrogen}\\\text{ion}}}{H^+} + HCO_3^-$$

$$H_2CO_3 + \underset{\substack{\text{calcium}\\\text{carbonate}}}{CaCO_3} \Leftrightarrow \underset{\substack{\text{calcium}\\\text{ion}}}{Ca^+} + \underset{\substack{\text{bicarbonate}\\\text{ion}}}{2HCO_3^-}$$

These Recent occurrences of marine stromatolites are most notably found in Shark Bay, Western Australia and the tidal flats of the Great Bahama Bank (figure 4).

Methodology

As mentioned, the field area consists of a quarter-mile exposure of Willow River Member strata along highway 52. The layout of the study area provided a unique look into the dynamics and extent of the stromatolite growth, due to the occurrence of perpendicularly intersecting roads. As a result, spatial differences were directly observable - both latitudinally and longitudinally - allowing for a more representative look into the character of stromatolite growth and sediment binding.

The study area was divided into four sites (figure 5), in order to log and describe the sediments in detail - namely the stromatolite assemblages.

- Site one is an East-West cut across the study area.
- Site two is an Northwest - Southeast cut across the study area which was created by the old highway. Due to diagenetic effects - effects associated with burial - much of the stromatolite structure was removed, thus proving to be a poor candidate for description.
- Sites three & four cut across the study area North to South, and correlated nearly exactly with measurements taken at Site 1 (+/- 5 inches variability associated with the surface on which growth occurred).

In detailing the character of the sediments, four distinct layers of stromatolite propagation were discovered. It should be noted that diagenesis has altered much of the rock in the area; however in sites 1, 3, and 4 much of the alteration was localized. Therefore, stromatolite integrity and continuity was maintained in most circumstances.

Select samples were taken from each site and brought back to be analyzed in detail. 2X3 inch thinsections were made in order to examine and describe the individual laminations. Using a slide projector, each thinsection was projected onto a wall where detailed tracings were made of select structures. Descriptions were also produced, corresponding to each slide. (see Appendix 1)

Outcrop Morphology

Overall, the stromatolites occur at four distinct layers (figure 6 and 7). Starting from the base of the outcrop, which I signify as zero, these layers occur at:

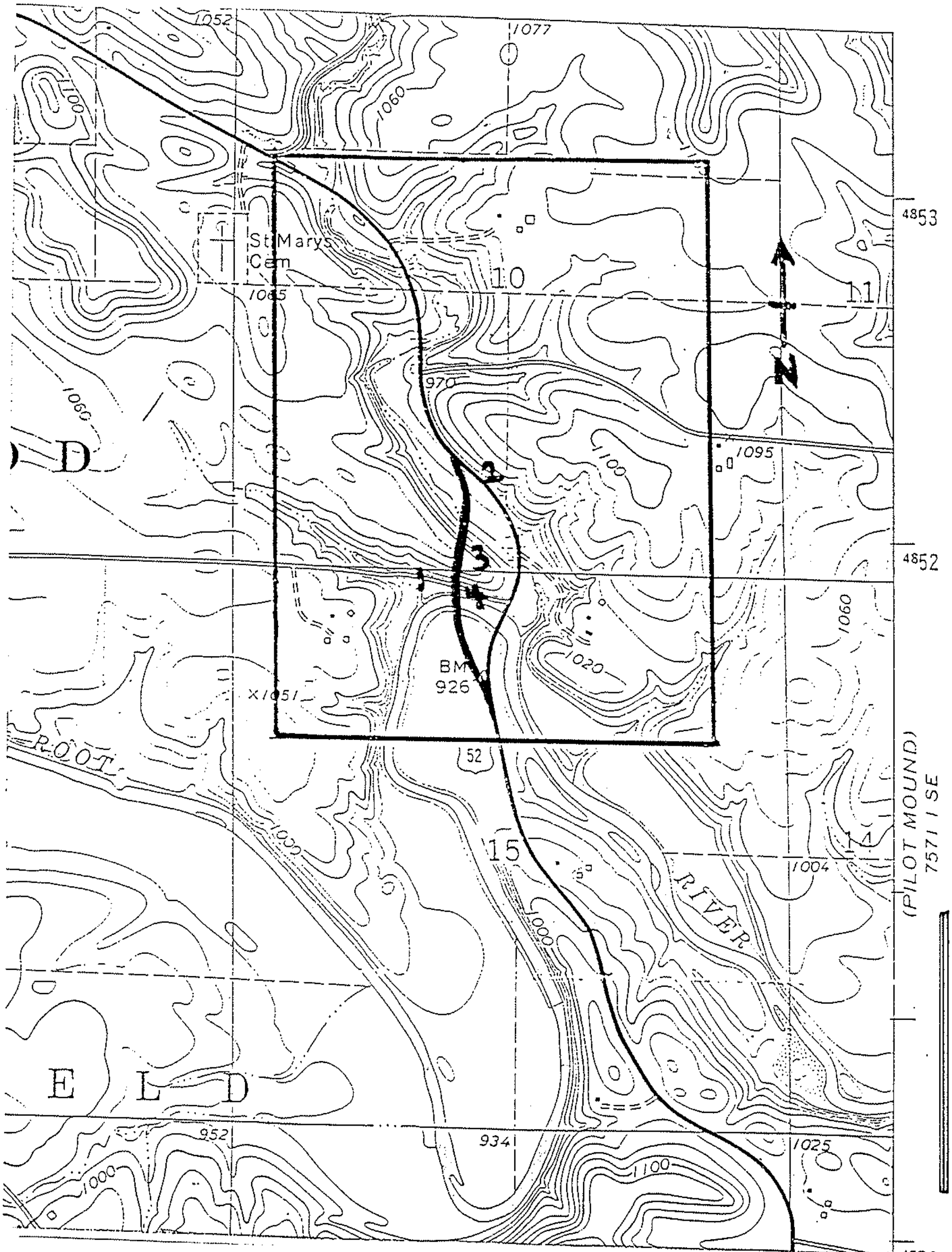
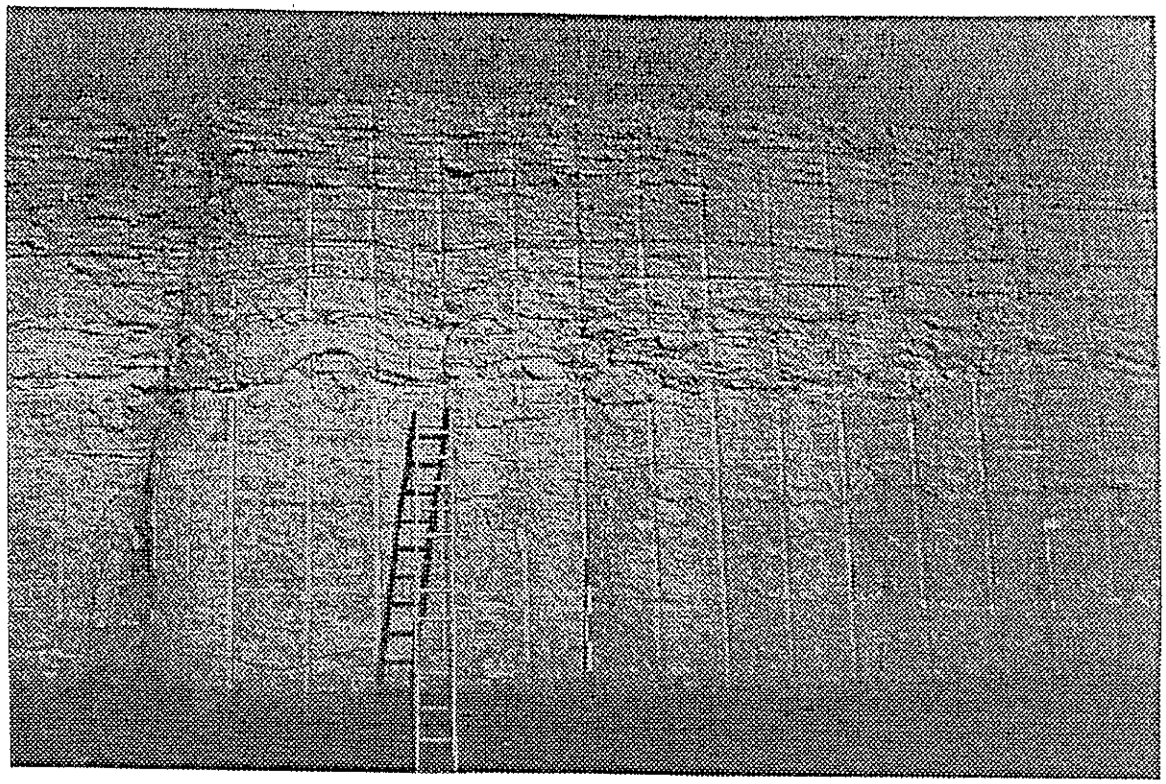


Figure 5: Study area. Reproduced from the 7.5 minute Chatfield Quadrangle (1974).



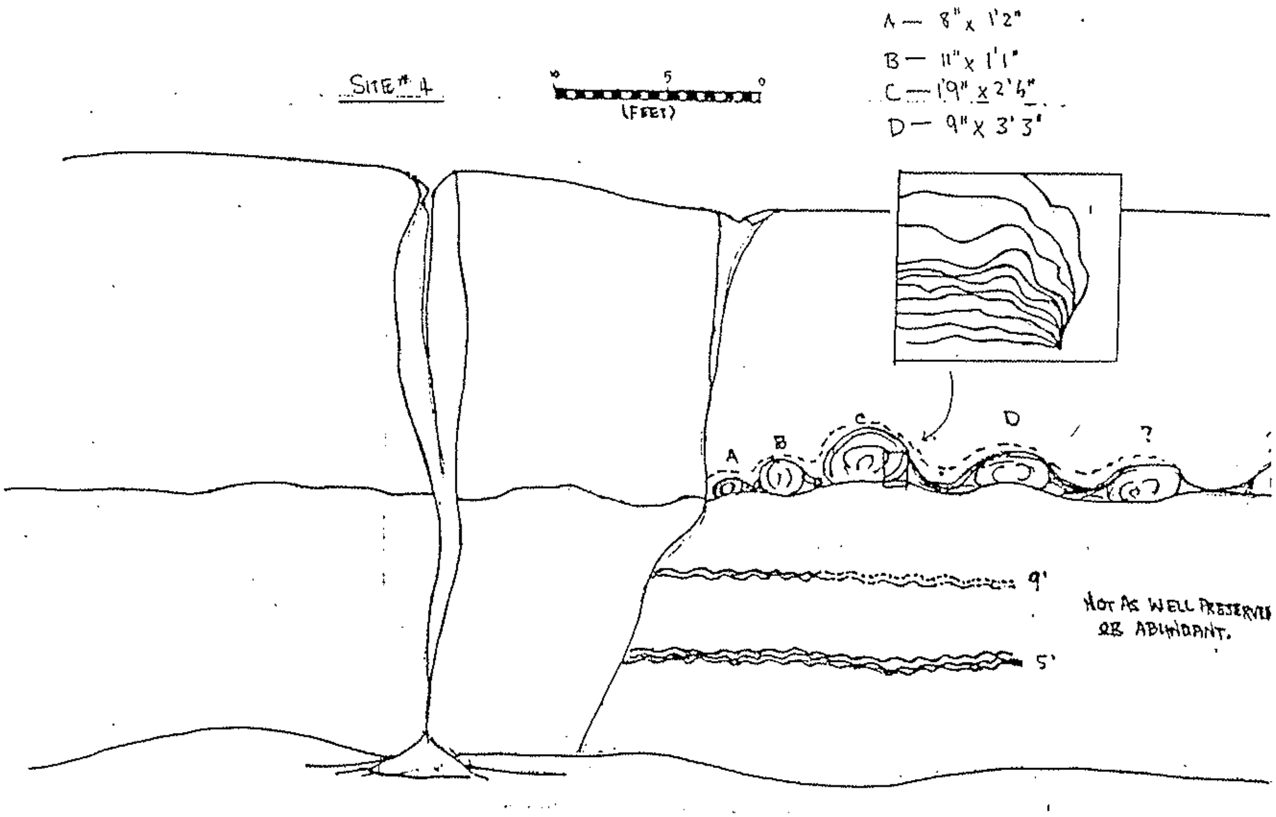
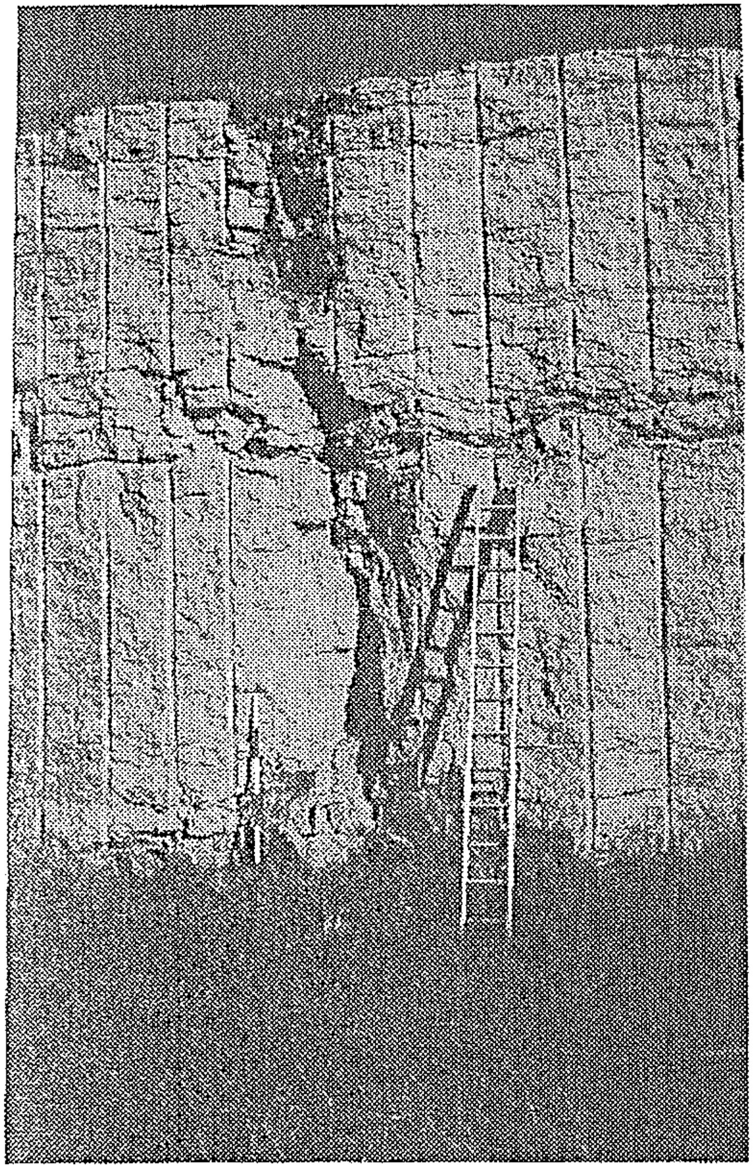


Figure 7: Site 4, outcrop schematic



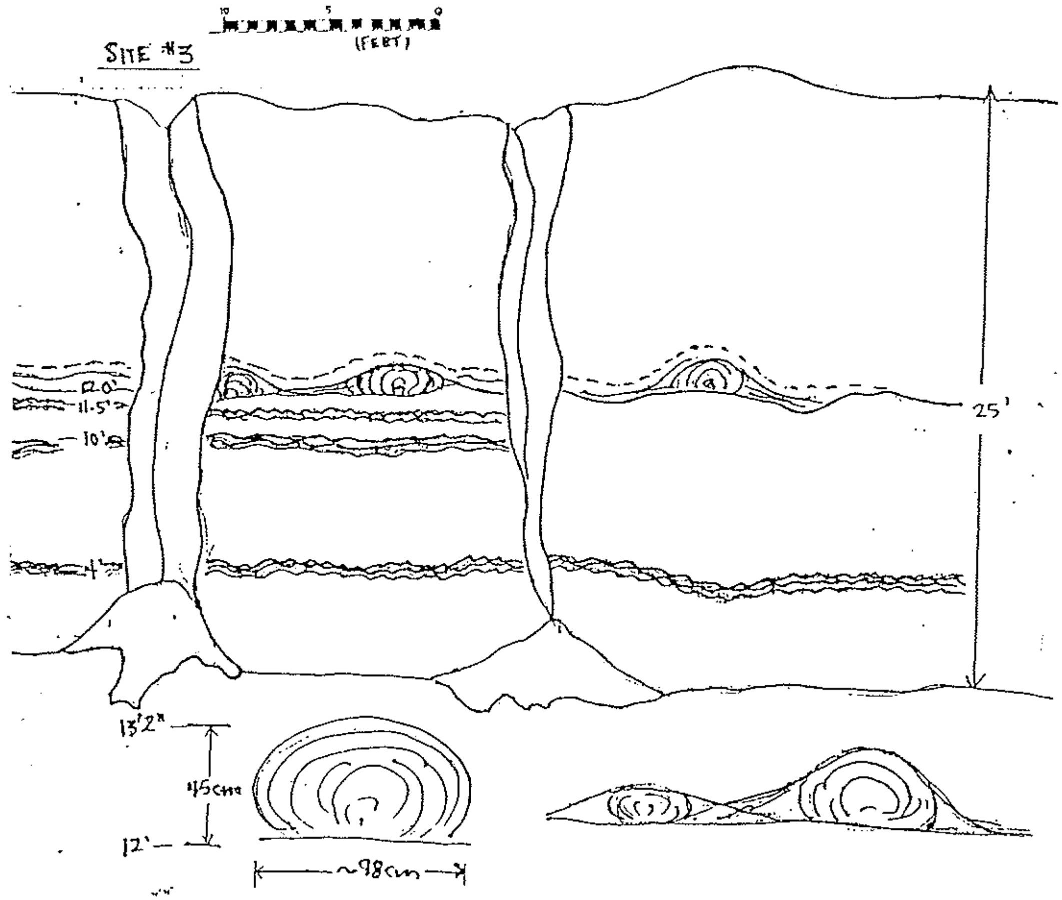


Figure 6: Site 3, outcrop schematic

Layer 1 → 4'0"	Layer 2 → 10'0"
Thickness: 5 inches	Thickness: 7 inches
Layer 3 → 11'5"	Layer 4 → 12'0"
Thickness: 4 inches	Thickness: 1'9"

respectively - measured from the base of growth, (note: thicknesses represent maximums). The occurrence of each stromatolite layer was surprisingly consistent throughout the exposure. Such consistency enabled a collective evaluation of the study area. Thus, in the discussion which follows, specific examples have been chosen that best represent the stratigraphy and depositional habit.

Layers 1-3 are consistently planar, low relief structures possessing a stratiform to psuedocolumnar morphology. Each was best observed on a weathered surface for detail of laminae.

Layer 4 is most striking. The stromatolites take on a bulbous, discontinuous morphology, displaying a second order crenate exterior (see figure 3); and are overlain with a thin layer of clay.

Conclusions

Detailed analysis of the individual stromatolite layers suggested two environments of deposition:

1) Lower intertidal environment, where periodic exposure and submersion by tides is normal.
2) Upper intertidal, where periodic exposure exceeds that of submersion by tidal waters.

Evidence

Upper Intertidal Environment is characteristic of the morphology and depositional habit found in layers 1-3. This conclusion is supported by the following observations:

•Thicknesses of individual layers of low relief, continuous laminations, characterized by a planar, stratiform to psuedocolumnar (1st order) structure (see figure 3).

•Figure 8 shows the possibility of aerial erosion features, showing areas where the stromatolite continuity has been disrupted by external forces. Note the large areas of massive sediment (sp), and the apparent sequential pairing between disturbed laminations.

•Figure 9 is taken from the same site and layer as figure 8. Note the areas of disruption to the left of center and greater spacings between individual laminae. Figure 10 illustrates the occurrence of several areas of very fine grained (micritic) sediment trapping (sp); however, figure 11 may be the best example of this type of sedimentation. Note the large areas of sediment (micrite) followed by continued growth of the algal layers.

Large sediment pools and the discongruent nature of the laminations suggests an environment of high fluvial/sediment interplay, indicative of a shallower fluvial environment. These sediment pockets also suggest deposition was rapid and in relatively large amounts. This type of sedimentation would not be uncommon in a upper intertidal setting where submersion by tidal waters were limited (Lowe, 1983; Hoffman, 1973).

The observed pockets of sediment and the stratiform morphology is suggestive of a low-energy, protected embayment (Hoffman, 1973). The relatively undisturbed waters would allow sediments to accumulate, considering circulation would be limited. However, the observed areas of disruption would suggest occasional exposure to high-energy situations (i.e. storms) and/or aerial exposure.

Figure 8: Stromatolite tracing (vertical cut - 10'0" site 1), lamination indicate a disruption by external forces.

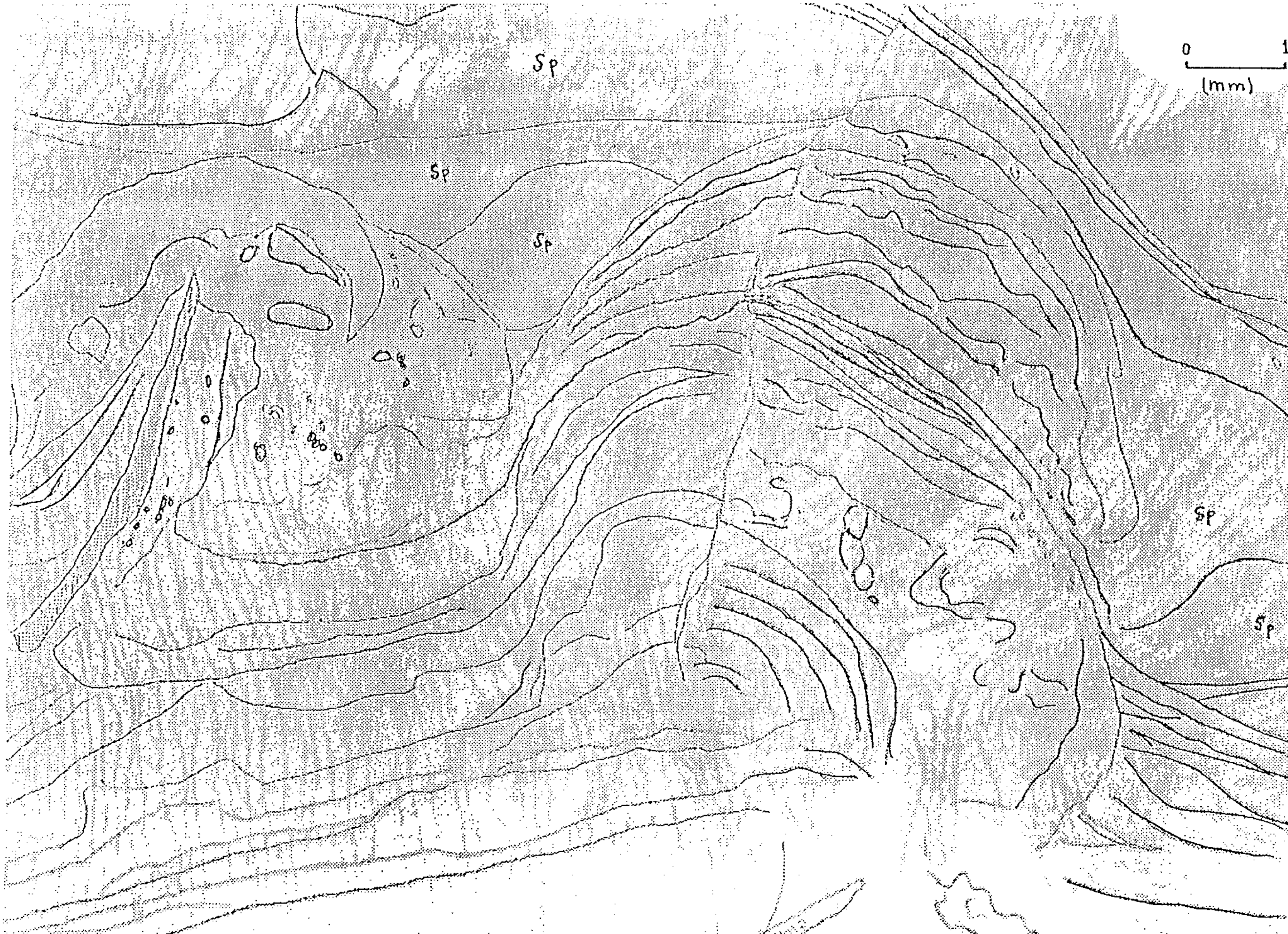


Figure 9: Stromatolite tracing (vertical cut - 10'0" site 1), laminations indicate some disruption has occurred and large pockets of sediment are visible (sp).

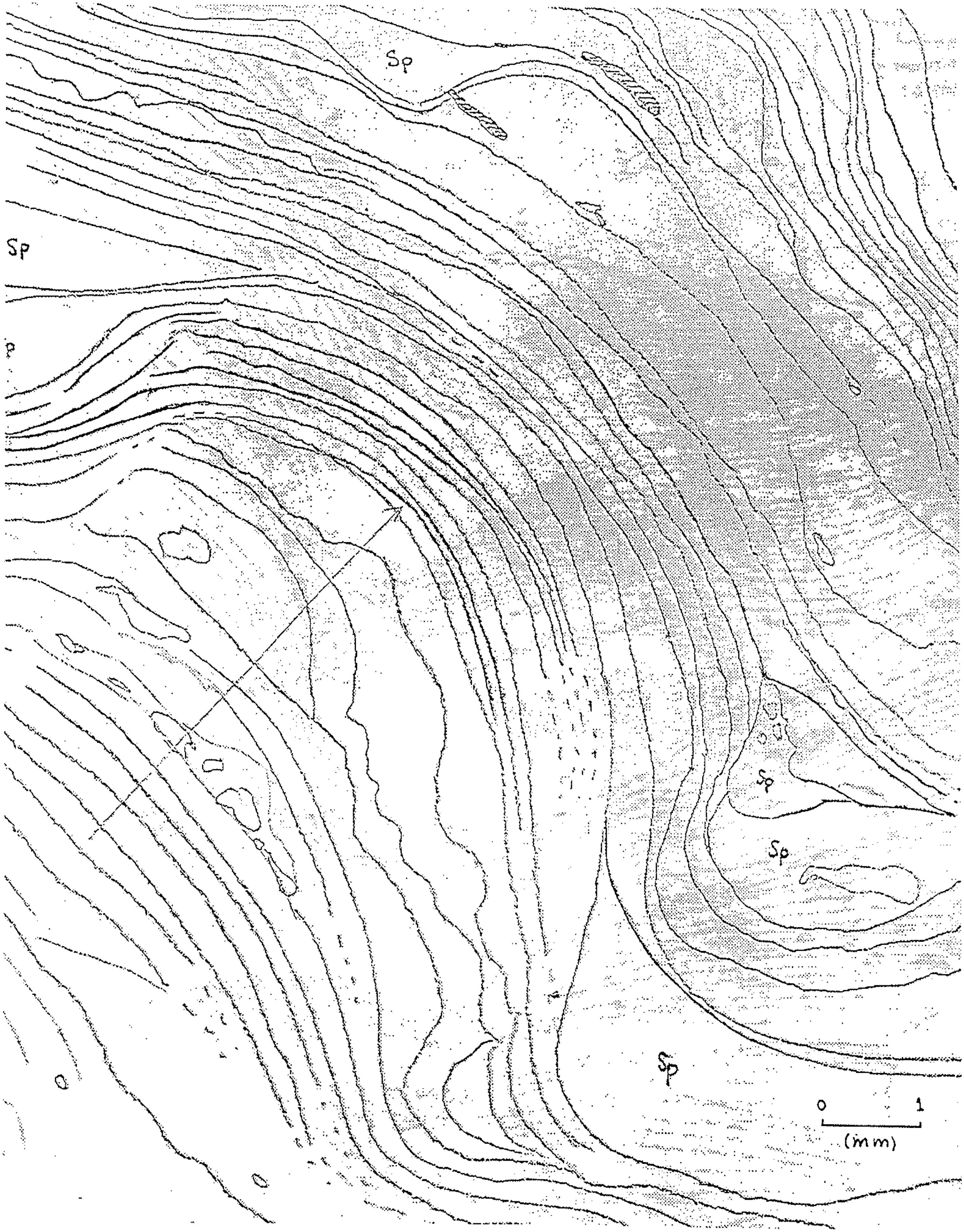


Figure 10: Stromatolite tracing (vertical cut - 4'0" site 3), large pockets of sediment prevalent (sp).

Figure 11: Stromatolite tracing (vertical cut - 11'6" site 3), excellent example of sediment accumulation within stromatolite laminations (sp).

The evidence which supports an upper intertidal setting has been observed by a number of workers sighting modern day examples (Playford and Cockbain, 1976; Banerjee 1980; Hoffman, 1973, 1976).

A Lower Intertidal Environment, characteristic of layer 4 of the sequence, is deduced from observations and characteristics of trapped sediment. These observations are as follows:

- Stromatolites take on a bulbous, discontinuous morphology, varying spatially (in 2-dimensions) from: 8"X1'2" to 1'9"X 2'6". The laminations assume a (2nd order) psuedocolumnar morphology within individual bioliths (see figure 3). The height can indicate the upper limit of tidal waters (Playford and Cockbain, 1976). The increased size suggests an influx in water depth.
- Sediment trapping is confined to individual laminae and larger pockets of sediment are absent. Any "large" scale trapping (large referring to sand grain size particles) in restricted to psuedocolumnar depressions. Figures 12 is a detailed tracing of what I refer to as a *growth suture*, an area between psuedocolumnar structure where sediment is often confined. Note the lack of sediment pools as seen in layers 1-3. Figure 13 also shows the increase of coarse materials (i.e. sand size particles) and the absence of sediment pockets. Such features indicate a greater circulation of water associated with greater depth.

Workers, such as, Playford and Cockbain (1976) support these finding with observations of modern stromatolites in a hypersaline barred basin at Hamelin Pool, in Shark Bay, Western Australia. They have observed intertidal stromatolites with morphologies ranging from club-shaped to cyndricular columns. The vertical

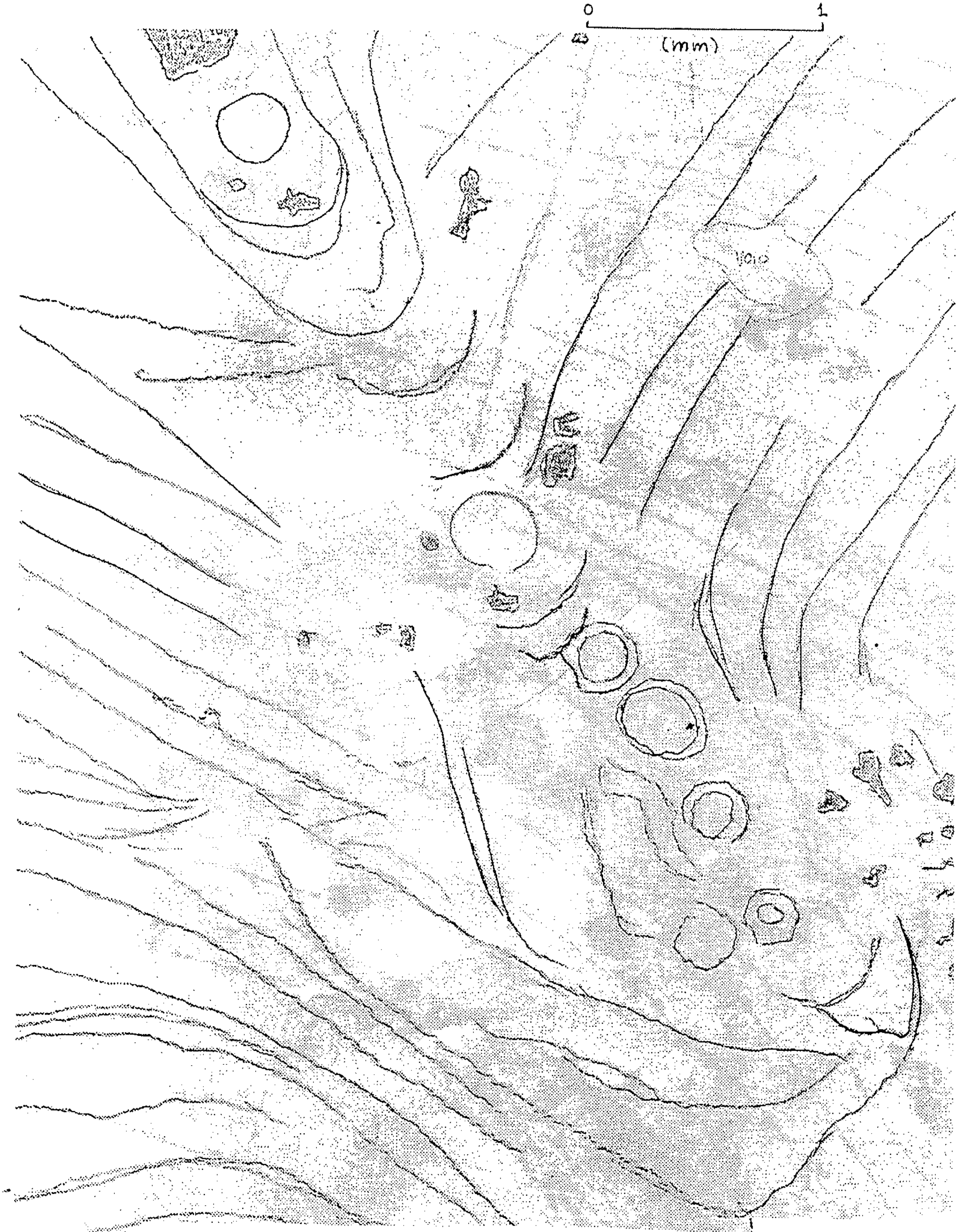


Figure 12: Stromatolite tracing (vertical cut - 13'6" site 1), example of minor sedimentation character of the layer 4 stromatolites.

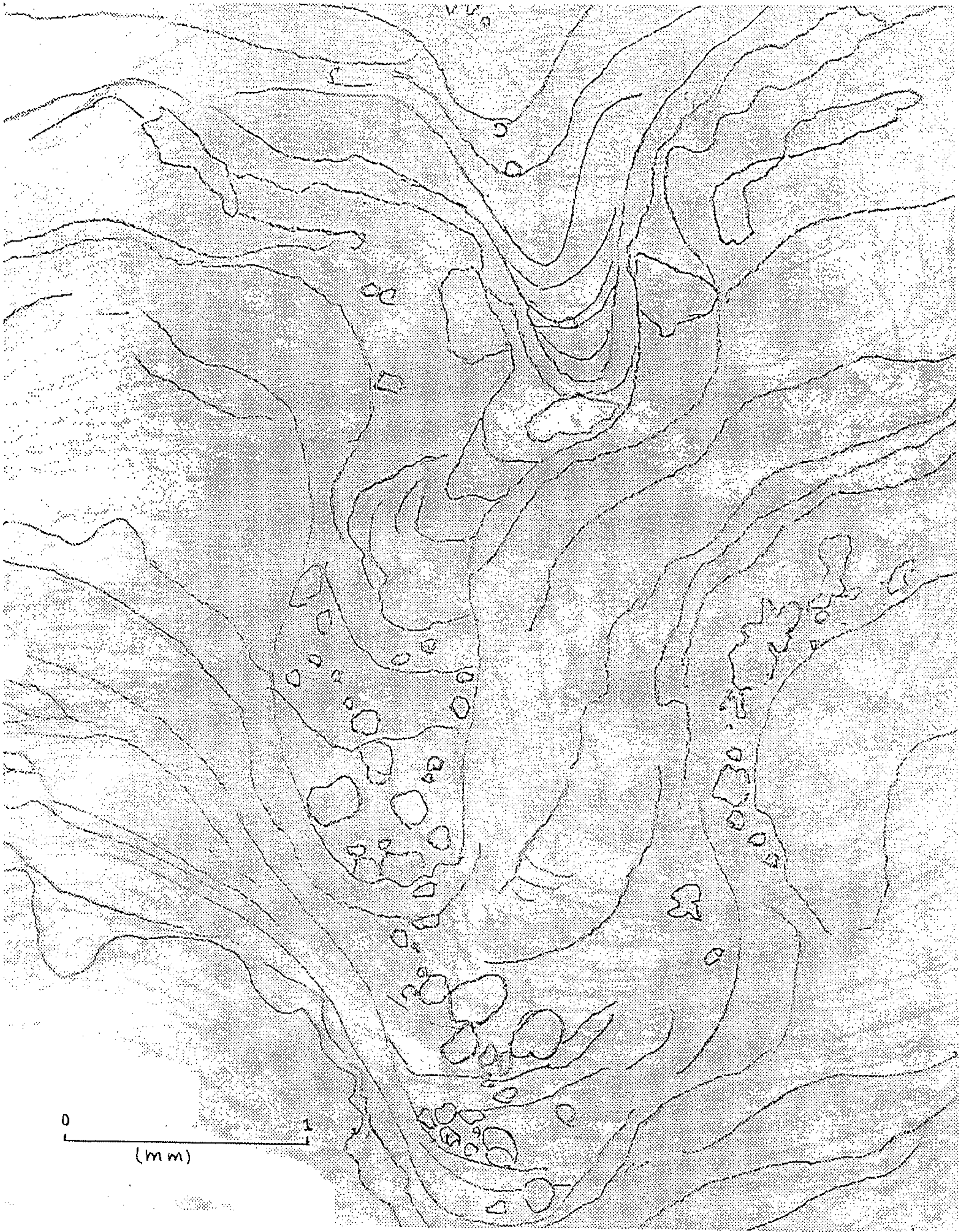


Figure 13: Stromatolite tracing (vertical cut - 13'6" site 1), example of minor sedimentation character of the layer 4 stromatolites.

extent of Hamelin Pool stromatolites appears to be a function of high-water-spring tide level. Likewise, lack of sediment reflects the increased influence of waves and currents (Lowe, 1983; Logan et al., 1974; Playford and Cockbain, 1976) associated with a lower intertidal environment.

Summary

The observations of the Willow River Member stromatolites appear consistent with modern analogues of stromatolite assemblages. Stromatolite morphology is related to physical factors, such as wave action, sediment influx and desiccation rather than to biological make-up of the algal mats (Ginsburg, 1955).

Davis (1966) compared the environment of the Willow River Member with modern algal reefs of Shark Bay, Western Australia as described by Logan and others (1964). He considered the Willow River environment to be one of a warm epeiric sea, with both shallow marine and intertidal regimes extensively represented. He recognized three environmental regimes: (1) a shallow, open marine area with oolitic beds and abundant fossils; (2) an intertidal or near intertidal, high-energy zone where stromatolitic algae flourished; and (3) a locally intertidal and hypersaline, low-energy zone.

The Willow River stromatolites observed at the Root River roadcut distinctly represent the second and third environmental regimes, as described by Davis. Layers 1-3 are dominated by a low-energy, consistently stratiform to (1st order) psuedocolumnar morphology. Layer 4 stromatolites are distinctly larger and consistently discontinuous. Laminations lack significant sediment load associated with high-energy environments.

Figure 14 illustrates three examples of stromatolite propagation: Andros island, Bahamas; Adu Dhabi, Trucial coast; and Hamelin Pool, Shark Bay, Western

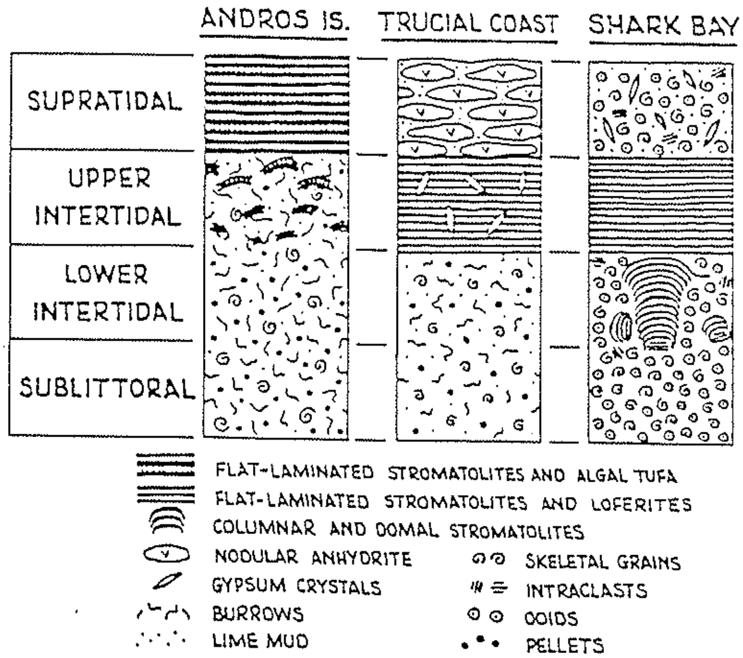


Figure 14: Shoaling upward sequences of carbonate sediment produced by progradation of recent tidal flats in Andros islands, Bahamas; Abu Dhabi, Trucial coast; and Hamelin Pool, Shark Bay. Reproduced from Ginsburg (1973).

Australia. Each example illustrates the stromatolite morphologies associated with specific tidal zones. The Willow River stromatolites reveal similar morphological characteristics in association with their proposed depositional regime. Thus, it appears that changes in the physical environment generated changes in the stromatolite morphology. The stromatolite assemblages of the Willow River Member, therefore, represent two distinct environments of stromatolite growth and propagation.

The importance of these findings is the contribution they make to our overall knowledge of stromatolite morphology and development. Likewise, these conclusions extend our overall understanding of the natural history and evolution of Minnesota.

APPENDIX
Thinsection Descriptions

Site 1

1V13.5A: vertical section 13'6"

Overall Morphology - Laminations appear smoother in psuedocolumns and more undulating in the lower stratiforms. Psuedocolumns exhibit a more even/symmetrical trapping of micritic sediment. Basal growth is initially stratiform (0-3.5 cm). Growth pattern then becomes irregular and increasingly turbimnate, exhibiting the psuedocolumnar structure (4 cm long axis).

Lamination Thickness - a) Stratiforms: avg. 0.5 mm (1.5-0.25 mm)

b) Psuedocolumns: avg. 0.15 mm (0.75-0.15 mm)

Particle Size - 0.5 mm (-1ϕ) remarkably homogeneous

Mineralogy - Recrystallization has made determining original mineralogy not possible. Present crystallographic orientation and character would indicate calcite/dolomite replacement of existing sediment grains and matrix.

1V13.5B: vertical section 13'6"

Overall Morphology - Very finely laminated and regular with very few disruptions in continuity. Lower laminations exhibit *pene*-flat morphology. Growth sutures are faint, but visible.

Upper laminations, the growth sutures are very defined as successive laminations acquire inheritance from the preceding morphology. Single, sand grain size particle can be seen - enhancing the trace of the growth intersection.

Lamination Thickness - 0.167 mm (between laminations)

Particle Size - consistent with 1V13.5A - 0.5 mm mean grain size

Mineralogy - mineralogy consistent with 1V13.5A

1V10.0: vertical section 10'0"

Overall Morphology - Initial growth is relatively undisturbted, stratiformal laminations (0-9mm). Above 9 mm, growth lines begin to intersect at arbitrary angles trapping large pockets (4 mm thick) of micritic sediment. This overall character may be attributes to natural sediment laminations rather then stromatolite trapping. Many of these pockets are both convex up and down.

Disturbed areas, where stromatolite integrity has been destroyed, suggests some form of abrasion (i.e. turbulent water) or dessication.

Lamination Thickness - Laminations: 0.1 mm; however, between individual laminations, as much as 4mm.

Particle Size - clay size particles, larger grains absent.

Mineralogy - mineralogy consistent with 1V13.5A

Site 3

3V4.00A: vertical section 4'0"

Overall Morphology - Laminations appear continuous with no areas of disruption. However, lamination morphology is not highly congruent and exhibit large pockets of trapped micritic sediment - as much as 5 mm thick.

Lamination morphology appears to be a function of sedimentation rates; however, thicknesses may be dependent upon dips and humps of the stromatolite surface.

Lamination Thickness - 0.167 mm

Particle Size - clay size particles, larger grains absent.

Mineralogy - mineralogy consistent with 1V13.5A

3V4.00B: vertical section 4'0"

Overall Morphology - Laminations remain continuous with no areas of disruption. Sediment deposition however, appears to retard growth forming a "synformal" structure (eventually producing a pseudocolumn). Retardation become inherent in the character of the stromatolite layers until additional sediment compensates elsewhere along the stromatolite community.

Lamination Thickness - 0.167 mm

Particle Size - clay size particles, larger grains absent.

Mineralogy - mineralogy consistent with 1V13.5A

3V11.6: vertical section 11'6"

Overall Morphology - Laminations are continuous with normal interruptions in continuity (i.e. sediment deposition).

Slide shows an area of two periods of stromatolite growth. Contact between the two is marked by a dark line transversing the sample. Below the line "old growth" shows signs of deterioration and collapse of organic structure.

Above this contact, pockets of sediment fill in preexisting surface morphology creating a somewhat level surface upon which new growth occurred. Areas where sediment infill did not occur, stromatolites inherit existing morphology.

Upper extreme of the slide shows a thick episode of burial - as much as 10 mm - blanketing completely all organic material (i.e. stromatolites). Another sequence of growth occurs atop this micritic layer; , however not enough observable sample present to draw a hypothesis.

Lamination Thickness - 0.143 mm (between laminations)

Particle Size - clay size particles, larger grains absent.

Mineralogy - mineralogy consistent with 1V13.5A

3V12.0: vertical section 12'0" (Non-Stromatolite sample)

Sediment Character - sediment is very fine grained composed entirely of dolomite. Thinsection reveals circular structures exhibiting a subtle concentric lamination; however, the degree of replacement makes it difficult to say with certainty what these grains may be. Nonetheless, structure and sphericity would suggest an oolithic sediment.

Sediment exhibits some crude large-scale laminations, bisected by a finely laminated micrite layer, exhibiting more of a wavy morphology. A mysterious structure also appears between these two sediments which may possibly be a burrow or mudcrack infilling. Structure is simply a wedge shaped intrusion into the underlying sediment.

Particle Size - 0.5 mm very homogeneous (within a clay size matrix)

Mineralogy - as mentioned above, is predominantly dolomitic and is also consistent with 1V13.5A

3V12.7LC: vertical section 12'7" (Sample taken from the interior of a layer 4 Bulbous stromatolite)

Overall Morphology - Laminations are highly deteriorated. Lower laminations are flat lying descending into pockets of spherical debris (i.e. sand size grains) interdisbursed between undulating chaotic remains of stromatolite growth. Much of the lamination structure is lost to a porous, massive, dark matter. Suggestion is that observed morphology is a result of organic decomposition...degassing of the organic rich material creating the observed vuggy porosity

3H13.00: horizontal section 13'0"

Overall Morphology - Individual laminations appear as rings, much like that of a topographic map showing highs and lows. The interface between individual psuedocolumns is outline by trapped sediment. This sediment ranges from a fine micritic clay to more substantial sand size particles. Lines forming boundaries between different sediment particles would suggest repetitive deposition between these structures.

Particles Size - 0.25-0.5 mm (only observed between psuedocolumns, not within individual laminations)

Mineralogy - mineralogy consistent with 1V13.5A

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