Microbially induced sedimentary structures in the Carboniferous Horton Bluff Formation near Hantsport, Nova Scotia

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Abstract

The Hurd Creek Member of the Horton Bluff Formation comprises cyclic tidal deposits of early Mississippian age. Near Hantsport, microbially induced sedimentary structures, formed by the growth of cyanobacterial mats, are unusually well preserved on the bedding surfaces of quartz-rich siltstones. The structures match those documented from modern sediments at Mellum Island, North Sea and Archean strata at Barberton, South Africa. The sediments display wrinkle structures and leveled depositional surfaces, in association with wave ripples, planed-off ripples, and desiccation cracks that imply shallow-water and periodically exposed conditions. A single, well exposed surface was mapped in one-metre segments with estimates of the areal percentage of microbial features, descriptions of the main types present, and photographs. The outcrop is ~70 m long and 1 m wide, selected for its high quality and quantity of microbial features. Microbial structures cover 12.6% of the exposed surface. Wrinkles are sub-parallel or lack preferred orientation, and have 1 mm height and 1-2 mm spacing – much smaller than associated ripple marks. The wrinkled patches often occur on ripple crests, especially on flattened, planed-off areas, and are commonly associated with coarse, probably windblown, sand. Some wrinkled patches cover sediment that fills ripple troughs, where mat growth has contributed to levelling of the sediment surface. Desiccation cracks are present, implying that these quartz-rich strata were unusually cohesive, perhaps due to microbial binding. Similar microbial features are present on many other bedding surfaces, and microbial effects were pervasive during deposition.

Microbial effects indicated by wrinkle structures, leveled depositional surfaces and desiccation cracks are complemented by observations from hand specimens and thin sections that suggest an unusual degree of cohesion shortly after deposition. Dark, 1 mm thick wavy-crinkly laminae drape over mounds of sand in ways that are not characteristic of physical deposition. Large, 0.5 mm quartz grains are embedded in these dark laminae and may reflect the microbial process of sediment-grain separation. Individual quartz grains rest in unusual positions, probably bound by dark laminae. Broken fragments of dark laminae are folded and display frayed edges.

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Acknowledgements

As all students of science are aware, the undertaking of an Honors Thesis can be a daunting task. First there is the commitment to uncounted hours of research, data collection and reading, and imposed upon this is the pressure of advancing the name of science. During the course of project, various psychological tests are imposed on the mind of the impressionable honors student. The resulting emotional journey ranges from quivering fear and grinding frustration to the upper limits of elation and the feeling of accomplishment. Fortunately I was blessed from the beginning with an extraordinary supervisor and mentor. I am in sincere appreciation of Dr. Martin Gibling, not just for his vast knowledge of sedimentary geology but also for his sage advice on all matters of subjects. I especially enjoyed the long drives from the field, with far ranging discussions including our favourite literary icons, Tolkien and Dickens among them. I'd like to sincerely thank Mr. Gordon Brown for his dedication and skill in the preparation of our samples. I am very appreciative to Dr. Andrew MacRae, who assisted my photography efforts in miraculous ways in his lab at St. Mary's University. Also may I extend a special thank you to Peter Reagan for his efficiency and assistance in the field. Finally, I would like to express my warm appreciation to the Earth Sciences Department of Dalhousie University where I have had the privilege to expand my knowledge in the company of many stimulating professors and supportive fellow students.

Chapter 1: Introduction

1.1 Microbially Induced Sedimentary Structures

The importance of microbial life to the history of our planet is undisputed. Stromatolites and microbial mats date back 3.5 billion years, making them the oldest ecosystems on Earth. In the Proterozoic, the growth of cyanobacteria changed the global biogeochemical balance by introducing oxygen into the atmosphere and fostering the evolution of life (Olson 2006). Today, cyanobacteria drive global productivity by forming the base of the marine food chain and contributing more than half of the planet's photosynthesis (Nadis 2003). Thus, microbial influence in the rock record is an important resource in understanding Earth's history. Microbially induced sedimentary structures provide a remarkable window into the past, with applications in paleoenvironment and biogeochemistry.

Microbially induced sedimentary structures (MISS: Noffke, 2001) lie at the heart of this thesis. They are syndepositional disturbances in sediment caused by rubbery layers of cyanobacteria or other microbes. There are a variety of ways that these biofilms can influence sediment deposition, depending on the ecological tolerance of the microbes as well as the physical conditions of sediment deposition. They often appear as wrinkled patches in fine-grained, quartzose sediment (Fig 1.1).

Microbial structures have largely been overlooked in the sedimentary record, being ignored due to their small size or confused with physical structures. Their documentation is poor and their physical appearance is subtle. MISS can be irregularly scattered in isolated patches or spread out evenly across bedding surfaces. The individual structures can be as small as 1 mm in diameter. Often these structures are unclear, resembling common sedimentary structures like rill marks or adhesion structures.

Figure 1.1: Microbial wrinkle structure found in the Horton Bluff Formation near Hantsport, Nova Scotia. This specimen is 15 x 7 cm^2 and was described by Gallacher (2010). While not specifically part of this study, this specimen illustrates the excellent preservation of MISS found at Horton Bluff. Coin is 2.4 cm in diameter.

MISS have recently been identified for the first time in the Horton Bluff Formation, which was studied for this thesis. Stromatolites of microbial origin have been discovered in this area, recorded in a B.Sc. thesis by Fiona Gallacher (2010) who noted that these stromatolites exist on the same bedding plane as a large microbial wrinkle patch of 15 x 7 cm^2 (Fig. 1.1).

1.2 Horton Bluff Formation

The Horton Bluff Formation, the lower unit of the Horton Group in the type area, is a succession of fluvial and lacustrine sediments of latest Devonian to early Mississippian age (Martel et al. 1993; Tibert and Scott 1999) that unconformably overlies Paleozoic basement rock, and crops out on the Bay of Fundy coast near Hantsport, Nova Scotia (Figure 1.2). These sediments were deposited in a local half graben called the Minas Basin, created by subsidence along the Cobequid Fault following the Acadian

Orogeny and during the final accretion of Pangea (Martel and Gibling 1996). The Horton Bluff Formation contains four members in ascending order: Harding Brook Member, Curry Brook Member, Blue Beach Member, and Hurd Creek Member (Fig. 1.3). The Hurd Creek Member will be exclusively studied in this thesis; however, paleontological studies from the Blue Beach Member, which is located near the study area, have important environmental implications.

Figure 1.2: Horton Bluff field area (Google Earth). Blue Beach, where field work for this study was done, is located on the western shore of the Avon River, which drains into the Minas Basin, Bay of Fundy.

1.2.1 Blue Beach and Hurd Creek Members

The Blue Beach Member was interpreted by Martel and Gibling (1996) as laid down in a large wave-dominated lake, and is composed of green shales, black shales, and fine-grained siltstones. The siltstones contain abundant symmetrical ripples. The green shales are terrestrial-influenced and contain vertical tree casts, woody material, and plant debris (Rygel et al 2006). The black shales are very fine-grained and contain ostracodes and agglutinated foraminifera that suggest marine incursions and temporary brackish conditions (Tibert and Scott 1999).

The Hurd Creek Member is composed largely of planar and lenticular-bedded siltstone, interbedded rippled sandstone, and clay shale (Martel and Gibling 1996). The coarsening upward cycles in this member are similar to those of the Blue Beach Member, and were probably deposited in a large wave-influenced standing body of water (Martel and Gibling 1996). Throughout geologic time, MISS have regularly been found in brackish, low-energy tidally influenced systems (Noffke et al. 2006) which is consistent with the depositional environment inferred for the Hurd Creek and Blue Beach members. A tidal setting for the bedset studied in this thesis is considered probable, especially in view of frequent mud drapes observed in the bedset; however, a tidal setting is not confirmed by independent evidence at this level.

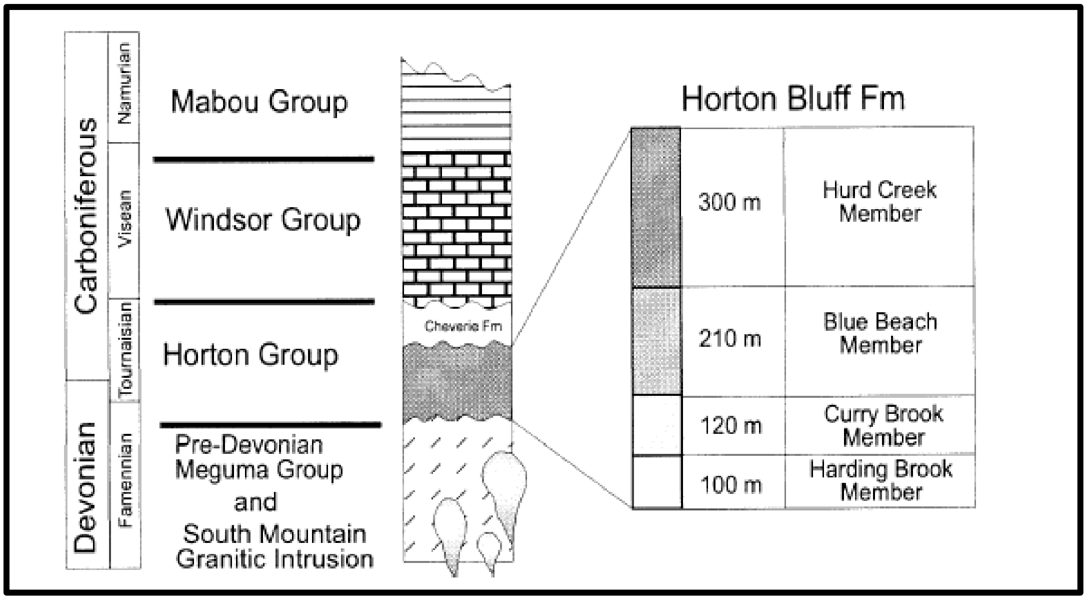

Figure 1.3: General stratigraphy of the Windsor Subbasin and Horton Bluff Formation. The Meguma Group is Cambrian to Ordovician and the South Mountain Batholith is Devonian. After Tibert and Scott (1999).

The microbial structures in question occur within siltstone bedsets of the Hurd Creek Member, near the boundary with the Blue Beach Member. These are fine-grained, quartz-rich sediments that contain wrinkle structures that are excellently preserved. This lithology is consistent with MISS findings all over the world such as in the Chorhat Sandstone of India (Sarkar et al. 2006) and rock units in the Barberton Greenstone Belt, South Africa (Noffke et al. 2006).

1.3 Objectives and Scope

This study aims to find a context for these structures within the current classification scheme for MISS by the careful description of structures, high-resolution photography and detailed comparison with literature as well as with structures formed by modern microbial mats. In addition to research papers in the literature, the comprehensive illustrated atlas of Schieber et al. (2007) was an important resource for this study, and is frequently cited below. The structures that exist at Horton Bluff, Nova Scotia are an important addition to the currently known preserved record of MISS, which is less complete from the Cambrian onwards. As such, a goal of this study is to raise awareness of the importance of microbial-mat structures and their application to the sedimentary record.

The siltstones that crop out at Horton Bluff are very thin (1m) and stretch approximately seventy meters in length across the modern tidal platform. With excellent preservation of the MISS on the bedding surfaces, it was possible to map their distribution along the beds. This detailed mapping of microbial structures has not been attempted in any known previous study.

Although the Horton Bluff section is approximately 1 km long and represents several hundred metres of strata, only one bedding surface was mapped in detail due to time constraints, although some four adjacent surfaces also had MISS occurrences. The beds to the south of the study site are poor in the quality and coverage of microbial structures, whereas beds in the northern part of the outcrop belt (Blue Beach North section of Martel and Gibling 1996) have excellent preservation of MISS. In addition, the presence of carbonate-rich stromatolites in the southern section, described in a B.Sc. thesis by Gallacher (2010), adds further weight to the inference that microbial life thrived in this environment (Fig. 1.4).

Figure 1.4: Stromatolite bed along the southern portion of the transect, located about 1km from the bedset studied in this thesis. These stromatolites beds were described by Gallacher (2010). A large microbial wrinkle patch exists on the same bedding surface as the stromatolites where it connects to the cliff face. Lens cap in central-left portion of the photo has a diameter of 5 cm.

1.4 Challenges

This project is challenging for several reasons. Foremost is the basic challenge of identifying these structures. This sub-discipline of sedimentology is relatively new and structures attributed to microbial mats remain poorly documented. Although some structures are reliably interpreted to show microbial influence, other specimens are ambiguous. Another basic challenge arises in the mapping of these bedding surfaces. Thin, long outcrops are difficult to map because the length scale is large (100 m) while the scale of the wrinkle patches which exist on bed surfaces is small (< 10 cm^2 in area). Considerable experimentation was needed to identify the most suitable means of analysis.

Chapter 2: Microbial Mats

2.1 Introduction

The formation of a microbial mat (Fig. 2.1A) begins with a single filament of bacteria that grows into a colony. Colonies of bacteria that are clustered together form biofilms, which attach to a certain substrate by secreting extracellular polymeric substances (EPS) (Schieber et al. 2007). As the biofilm grows, the microbes create tangled, fibrous networks of organic filaments (Fig. 2.1B), referred to as a microbial mat (Neu 1994). Modern microbial mats often grow in a reticulate pattern (Fig. 2.1C, D) made of intersecting bulges and pinnacles (Schieber et al. 2007). This pattern is the result of changes in the lateral dominance of coccoids and filaments, two types of bacterial cells involved in mat formation.

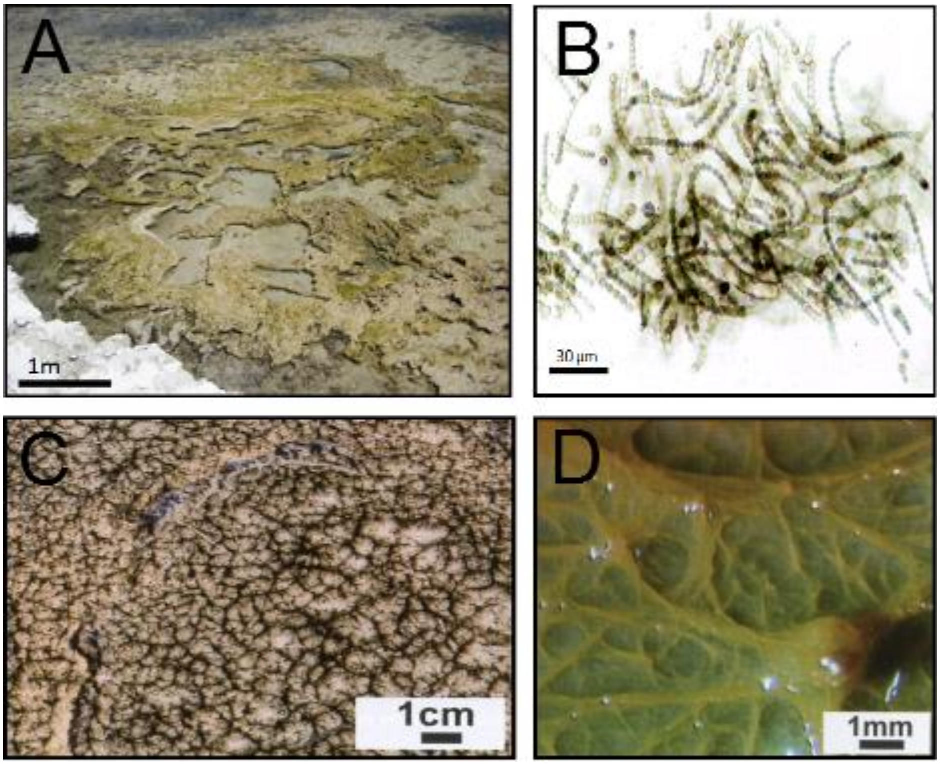

Figure 2.1: (A) Modern cyanobacterial mat colonizing a grey, sandy substrate of a freshwater lake in Los Flamencos Natural Reserve, Chile (http://cabrol.seti.org/HLP2008/HLP2008.html). (B) Cyanobacterial filaments starting to tangle and mesh together. Photo from University of California Museum of Paleontology (http://www.ucmp.berkeley.edu/bacteria/cyanolh.html). (C) Modern microbial mat showing reticulate growth pattern on tidal flats, southern Tunisia (Gerdes et al., 2000). (D) Close up view of reticulated mat cultivated in a laboratory (Schieber et al., 2007).

Most microbial mats are observed colonizing a moist, sandy surface (Fig. 2.1A), but biofilms are versatile in their diversity of environments (Fig. 2.2), occurring from inside Antarctic ice to the walls of deep-sea hydrothermal vents (Vincent et al. 1993; Costeron and Stoodley 2003). Although mostly composed of cyanobacteria, other organisms such as purple sulphur bacteria, diatoms and sulphate-reducing bacteria have been known to occur within the mats (Proctor 1997; Gerdes et al. 2000; Schieber et al. 2007).

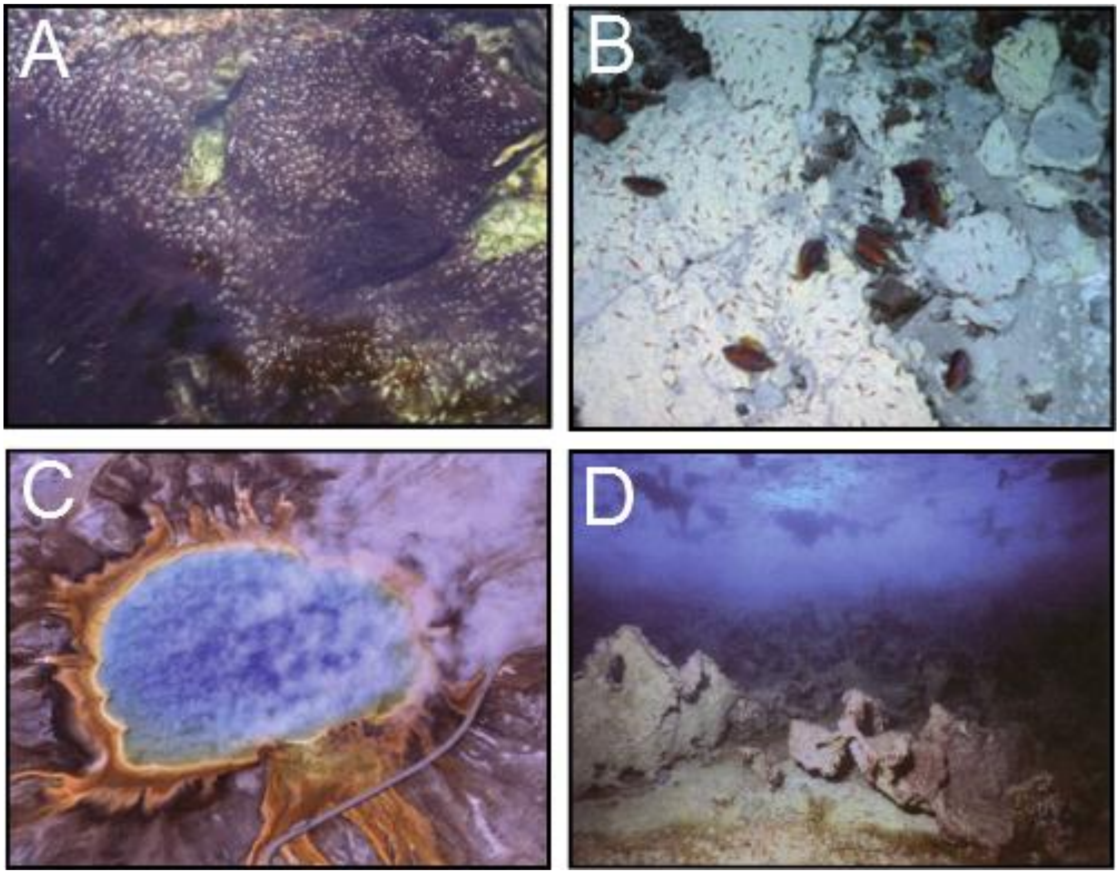

Figure 2.2: (A) Microbial mat made of cyanobacteria and diatoms coating the bottom of a shallow creek near Sulphur, Oklahoma. Trapped oxygen bubbles are 2-5 mm in size. Photo by J. Schieber (Shieber et al. 2007). (B) White sulphide-oxidizing bacteria near an ocean-floor vent. The mat provides the base of the food chain and is eaten by molluscs, crustaceans and fish. Photo from NOAA Explorer web site, http://www.oceanexplorer.noaa.gov/explorations/04fire/logs/april12/. (C) Aerial view of the Grand Prismatic hot spring in Yellowstone National Park, USA. The deep blue water in the center is hot and sterile, while the orange marginal area is composed of microbial assemblages with varying temperature preferences. Image from US National Park Service. (D) Microbial mats at the bottom of Lake Bonney, Antarctica. These mats are photosynthetic in spite of low light intensities caused by permanent ice cover. Photo courtesy of Dale T. Andersen (© All Rights Reserved) Schieber et al. 2007.

In recent decades it has become accepted that microbial mats can create and syn-depositionally modify sedimentary textures. These microbially-mediated structures are caused by the interference of the microbial mat with the physical deposition and erosion of sediments (Noffke et al. 2001). For example, the preferential growth of microbial mats in ripple troughs can cause the leveling of rippled surfaces, producing planar, wrinkled surfaces in a process known as leveling (Fig. 2.3, Noffke et al. 2001):

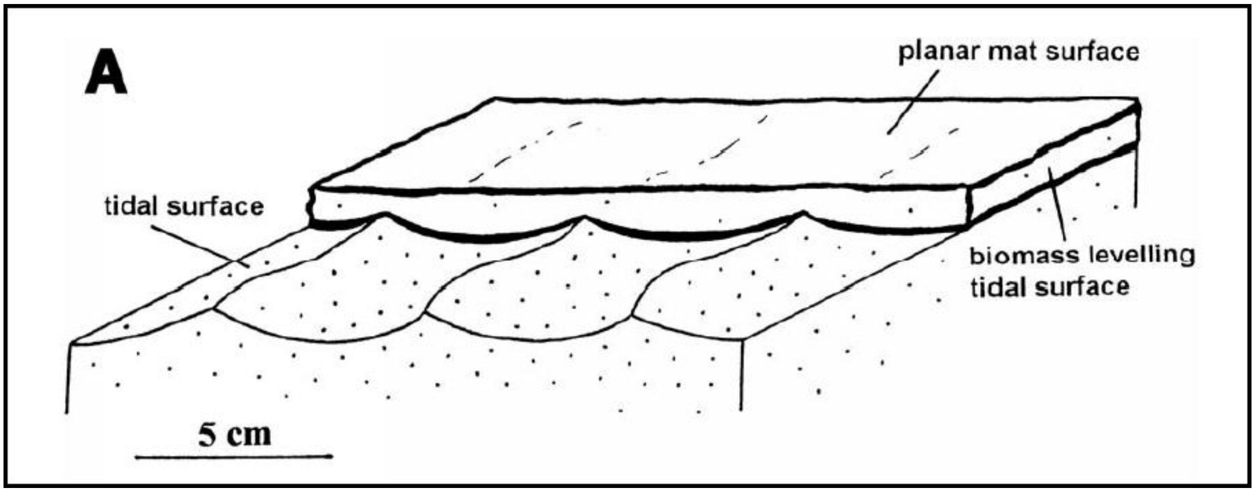

Figure 2.3: Sketch showing the process of leveling by microbial mats. The bacteria grow preferentially in the deepest topographical relief, the troughs. Over time, bacterial growth will create a 'leveled depositional surface'. Photo from Noffke et al. (2001).

Imprinting is another process that can occur, in which physically shaped sedimentary structures are overgrown by biofilms with the original morphology conserved (Noffke et al. 2001). For example, if the rippled surface shown in Figure 2.3 was imprinted rather than leveled, the buried ripple marks would be preserved and could be detected later in vertical section with their surfaces marked by the organic films (Noffke et al. 2001).

Another process of microbial influence on sediment textures is sediment grain separation, when biofilms elevate and separate quartz grains as they grow around them as shown in Figure 2.4 (Noffke et al. 2001).

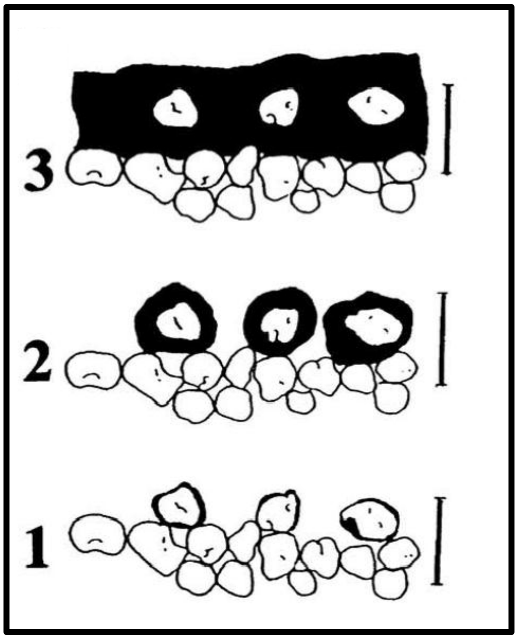

Figure 2.4: Schematic showing progressive development of a microbial mat on a sandy substrate. In Stage 1, thin biofilms begin to adhere to grains. In Stage 2, growth continues equally on all sides of the grain. In Stage 3, continued growth has caused individual biofilms to join as a thick microbial mat, with quartz grains floating in the center. This process is called grain separation. From Noffke et al. (2001).

Primary sedimentary structures can also be formed due to ‘baffling, trapping and binding’, in which projecting cyanobacterial filaments lower the current velocity and induce settling of suspended particles. The resulting structures are termed biolaminates and are visible in thin section as lenses of sediment bound to the bottom of microbial mat layers.

The presence of microbial mats can also have a post-diagenetic effect, such as a change in the cohesiveness of the sediment that results in an atypical response to compaction (Gingras 2002; Schieber 2004; Sarkar et al. 2006). Figure 2.5 shows several photographs of active microbial mats as they influence deposition in modern tidal flats and sabkhas.

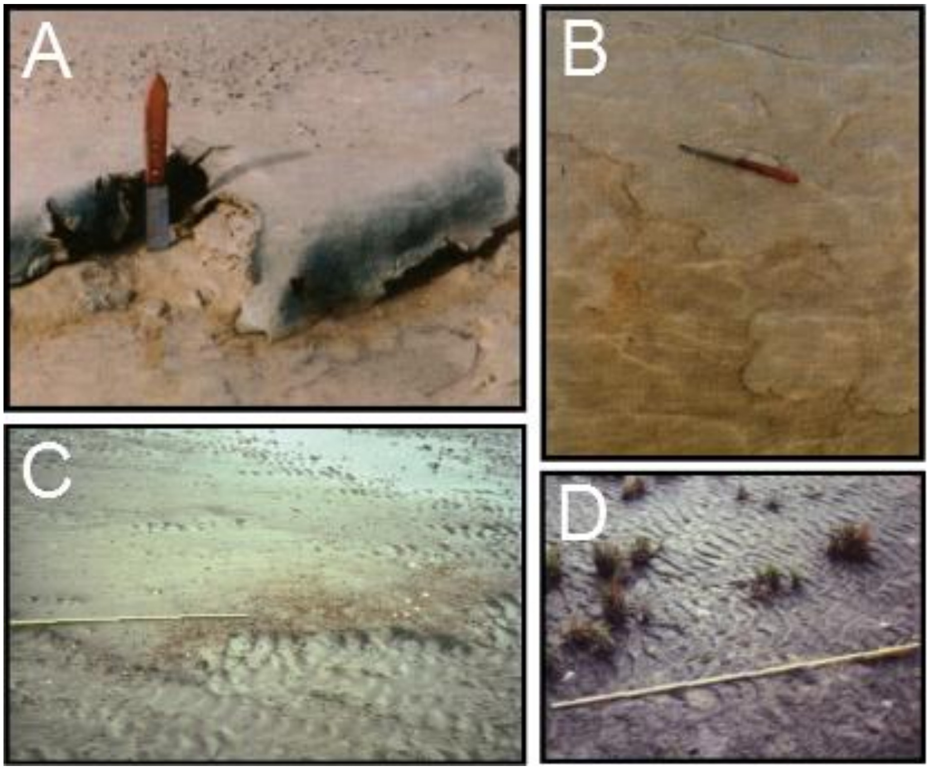

Figure 2.5: (A) Coherent microbial mat hanging over a small terrace undermined by water agitation. Structure marking the shoreline of a hypersaline lagoon in a sabkha environment, southern Tunisia. Photo by Nora Noffke. (B) Loose and thin mats growing on soft muddy sediments producing fragile mat chips. Photo by Nora Noffke, southern Tunisia. (C) Surface with meter stick has been biostabilized, protected from erosion by microbial binding of sediment while the surrounding areas are subject to reworking by tidal currents. Photo by Nora Noffke, Mellum Island, North Sea. (D) Rippled surface of tidal flats completely overprinted and stabilized by a highly productive microbial mat. Microbes preferentially colonize the ripple troughs, which are moist and protected against erosion. Note the difference in appearance below the meter stick, where microbial colonization has nearly leveled the bedding surface. Photos from Schieber et al. (2007).

Microbial mats produce a wide variety of effects on primary sediment texture, such that the use of a classification system for structures caused by microbial activity is necessary.

2.2 Classification

Three main classification schemes for sedimentary structures produced by microbial activity have appeared in the past decades. Gerdes et al. (2000) examined modern microbial activity in the tidal flats of Tunisia and the North Sea and classified microbial structures by the processes which formed them. They recognized six types of biological processes that produce sedimentary fabrics (Table2. 1.):

Biologic Process	**Example sedimentary fabric**
1. Intrinsic biofactors	Cohesive sand layers
2. Biological response to physical disturbances	Ripple leveling
3. Trapping and binding	Wavy-crinkly laminae
4. Mechanical stress acting upon biostabilized surfaces	Erosional remnants and pockets
5. Post-burial processes	Sponge pore fabrics
6. Bioturbation and grazing	Traces of burrowing insects

Table 2.1: Gerdes et al. (2000) classification of biogenic sedimentary structures.

This classification scheme is all-encompassing, including trace fossils, bioturbation and stromatolite fabrics as well as the targeted microbial fabrics (Schieber et al. 2007).

Noffke et al. (2001) produced a classification system exclusive to microbial fabrics, which they called ‘microbially-induced sedimentary structures’ (MISS). They proposed that MISS should become a fifth category of primary sedimentary structures in the well-known Pettijohn and Potter (1964) classification scheme. Noffke et al. (2001) divided MISS into five processes which create two classes of structures: (class A) structures atop bedding planes, and (class B) structures within beds (Table 2.2):

Class A: Structures atop bedding planes	**Class B: structures within bedding planes**
1. Leveled depositional surfaces, wrinkle structures	1. Sponge pore fabrics, gas domes, fenestrae structures
2. Microbial mat chips	2. Sinoidal laminae
3. Erosional remnants and pockets	3. Oriented grains, benthic ooids
4. Multidirectional/ palimpsest ripples	4. Biolaminites, mat-layer-bound grain sizes
5. Mat curls, shrinkage cracks	

Table 2.2: Noffke et al. (2001) classification of microbially-induced sedimentary structures.

The structures listed in Table 2.2 are formed by five different processes of microbial growth: (1) leveling; (2) biostabilization; (3) imprinting; (4) grain separation; and (5) baffling, trapping and binding. This classification scheme has been widely used in the literature of the past decade, and is preferred here because it can be readily applied to the information obtained as part of this thesis.

A third system (Schieber 2004) separates microbial fabrics into host lithologies of sandstone or mudstone, and categorizes the process continuum from active mat growth through to mat decay and diagenesis (Schieber et al. 2007). This system emphasizes that physical processes such as hardness, sediment cohesion and tensile strength are altered by the presence of mats, and evidence concerning these parameters can be used to infer the past existence of mats based on field data. For microbial-mat features preserved in sandstone (relevant to the present study), Schieber's (2004) classification scheme includes (Table 2.3):

Features formed due to:	**Example microbial fabric**
1.Mat growth	Multi-directional ripple marks
2.Metabolic effects	Floating grains
3.Physical mat destruction	Flipped-over edges, shrinkage cracks
4.Mat decay and diagenetic effects	Gas domes, ruptured gas domes

Table 2.3: Schieber (2004) classification of microbial fabrics by biological process.

While Noffke's (2001) classification is preferred, Schieber's (2004) classification will be investigated and referred to where relevant to the intentions of this thesis.

2.3 Age Range

Microbial structures are found throughout the rock record from the Archean to the Recent. The oldest example comes from the Moodies Group (3.2 Ga) of the Barberton Greenstone Belt, South Africa (Fig. 2.7A, Noffke 2006), with some excellent younger specimens from the Eocene Green River Formation in the USA (Fig. 2.10F, Schieber et al. 2007). The majority of samples come from the Proterozoic Era, an ecologically favourable time for microbial organisms. In the Hadean, bacterial life did not yet exist, while in the Phanerozoic, the evolution and diversification of plants and grazing organisms severely hindered the preservation of MISS in the rock record (Garrett 1970; Noffke 2000; Sarkar et al. 2006; Schieber et al. 2007).

2.4 What Organisms make Microbial Mats

Microbial mats are produced by the colonial growth of autotrophic bacteria, either photoautotrophs which metabolize sunlight, or chemoautotrophs which use various elemental constituents and do not require oxygen to survive. The vast majority of modern and fossil microbial mats that have been studied are attributed to cyanobacteria (Noffke and Krumbein 1999). However, a bias exists because many discoveries in the ancient record represent shallow marine settings, where cyanobacteria thrive. In addition cyanobacteria are one of the oldest life forms on the planet and have had more time to colonize the rock record. Research on modern microbial mats has revealed that mat-producing organisms such as green sulphur bacteria and diatoms occur alongside cyanobacteria (Fig. 2.2A). New research is currently investigating the mat-forming abilities of iron bacteria (Schieber et al. 2007).

2.4.1 Cyanobacteria

Cyanobacteria are photosynthetic single-celled bacteria. They are one of the most successful groups of microorganisms on Earth, based on their genetic diversity, occupational range of habitats, and abundance through geologic time. They are the dominant mat-forming organism, due to their rapid growth rates, metabolic efficiency and adaptive capacity to inhabit sunlit sedimentary surfaces (Schieber et al. 2007).

2.4.2 Other Photoautotrophs

Studies of modern microbial mats have shown that numerous other bacterial groups form mats in a variety of different environments. However, while the simple challenge of identifying microbial structures in the rock record is formidable, determining the taxonomic grouping of the original organism is nearly impossible for most outcrops. If the researcher is fortunate enough to find preserved organic material, this question could potentially only be answered by advanced geochemical technology. Sulphur bacteria thrive in hot springs, as found in Yellowstone National Park, USA (Fig. 2.2C). Purple bacteria use elemental sulphur or hydrogen as a metabolic pathway, and they thrive in illuminated anoxic zones of lakes or stagnant water (Proctor 1997) (Fig 2.6).

Most microbial mats are composed of more than one taxonomic group of microbes. A typical microbial mat consists of several layers, each of which is dominated by a certain type of microbe which capitalizes on its ecological advantage. For example, in a typical wet, sunlit environment, the surface layer is dominated by cyanobacteria, which metabolize sunlight and produce oxygen. Sediments below this layer may contain purple or green sulphur bacteria, which are photosynthetic but cannot compete at the surface level (Gerdes et al. 2000; Lucas, 1995; Shieber et al. 2007). The lower layer generally consists of sulphate-reducing bacteria, which respire using sulphate rather than oxygen (Risatti et al. 1994). Some mats have a white layer consisting of chemoautotrophic bacteria that oxidize sulphur (Garcial-Pichel et al. 1994). Figure 2.6 shows Winogradsky columns preserved from lake mud, and illustrates the various stratified components of microbial mats (Schieber et al. 2007).

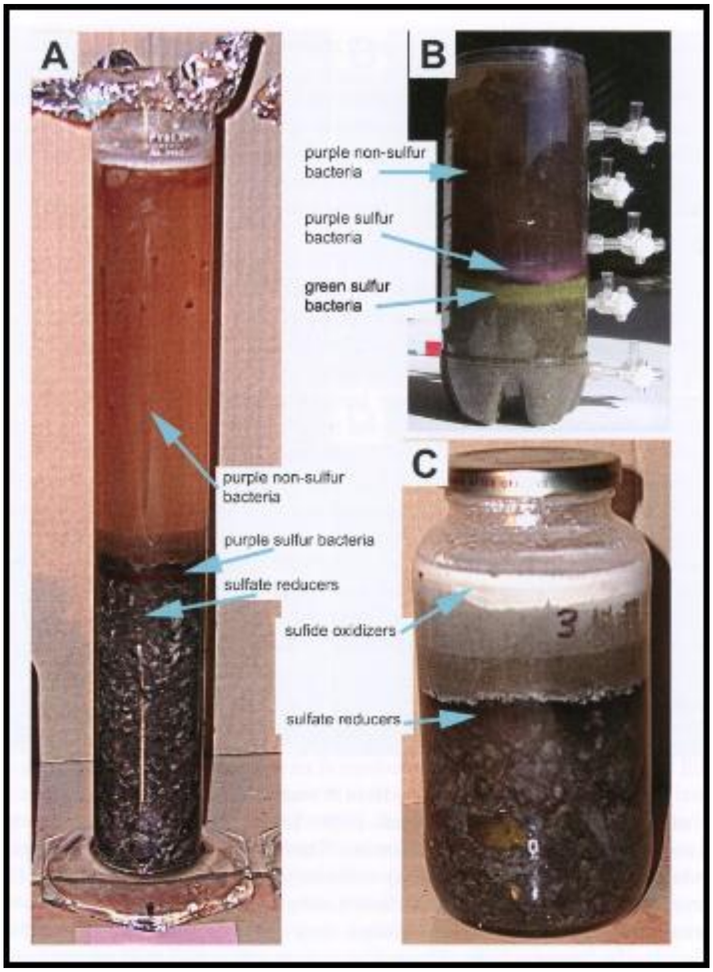

Figure 2.6: Winogradsky columns prepared from lake mud. (A) Dark layers of non-sulphur, purple sulphur, and sulphate reducing bacteria. Photo by J. Schieber (Schieber et al. 2007). (B) This column has well developed zones of purple and green sulphur bacteria, and with a cyanobacterial layer on top, could represent a modern tidal flat. Image courtesy of Dr. Joe Vallino, Marine Biological Laboratory, Woods Hole, MA 02543. Image taken from Schieber et al. (2007). (C) A column with restricted oxygen access. Sulphate-reducing and -oxidizing bacteria would thrive in anoxic conditions, for example a white smoker vent. Photo by J. Schieber (Schieber et al. 2007).

2.4.3 Chemoautotrophs

The current knowledge base on microbial mats constructed by chemoautotrophs is relatively small (Schieber et al. 2007). Methanogens are chemoautotrophs that take carbon and hydrogen from the atmosphere and form methane gas. They form mats in marshes, swamps, hot springs and deep-sea ocean vents. Halophiles are chemoautotrophs that thrive in high-salinity environments such as the Dead Sea, Great Salt Lake or Lake Magadi. While it is known that chemoautotrophs form microbial mats in a wide variety of hostile environments, identification in the rock record is rare.

2.5 Modern Environments

Microbial mats currently thrive in a range of different sedimentary environments. They are generally found in transitional environments such as intertidal flats, lagoonal and adjacent areas, supratidal flats and sabkhas (Hagadorn and Bottjer 1997; Gerdes et al. 2000; Noffke et al. 2001; Schieber et al. 2007). They have also been documented in lacustrine, riverine and other settings (Marriott et al. 2012). A critical issue is sedimentation rate and lapse time. The microbes grow outward from a substrate, requiring certain periods of non-deposition in order to grow. It is known that the transition from fragile biofilm to condensed fibrillar meshworks of mat consistency requires several weeks following cessation of deposition (Schieber et al. 2007). For example, lee-side shallow water environments of unusual salinity are suitable for mat growth.

The temperate humid tidal flats of Mellum Island in the southern North Sea, Germany, represent excellent ecological and sedimentological conditions for the formation of microbial mats. At Mellum Island, extensive cyanobacterial films and mats have colonized the fine sands of the intertidal and supratidal zones. The organisms prefer to colonize sediments of fine-sand grain size due to the moistening of the deposits by ascending capillary water during subaerial exposure of the flats (Noffke et al. 2001). Mats benefit from the low rate of sedimentation, but occasionally become buried in landward settings due to storm deposition (Gerdes et al. 2000; Schieber et al. 2007).

The subtropical and semi-arid coastal bays of southern Tunisia are another ideal site to observe modern microbial mats. This southern Mediterranean region is characterized by lower supratidal shallows, higher-lying sabkhas and extended coastal plains. The sediments are quartz-rich but are composed mostly of clays and silts mixed with gypsum crystals. In this environment, biofilms are observed in lower intertidal and sabkha zones, while fully developed mats occur in lagoons and near the intertidal-supratidal transition and in the lower supratidal zone (Gerdes et al. 2000).

2.6 MISS in the Rock Record

There are many different morphological expressions of MISS. Wrinkle structures, or wrinkle marks, for instance, are comparatively easy to identify because of their size, irregular shape and three-dimensional expression (Fig. 2.7). However, some microbial fabrics can be subtle, including multi-directional ripple marks, which are formed when microbes stabilize ripples in localized areas, allowing ripples of different orientations to form in nearby areas. Winkle marks will be emphasized because they constitute the vast majority of structures seen at Horton Bluff. Several other microbial fabrics will be briefly introduced.

2.6.1 Wrinkle Structures

Wrinkle structures are irregularly shaped networks of alternating mm-scale crests and troughs (Schieber et al. 2007). They have a wide variety of morphological expressions, from linear to honeycomb to undefined shapes (Fig. 2.7). They occur in oddly shaped patches, have a wrinkled appearance and occur on bedding surfaces which have been colonized by microbial mats. Wrinkle structures vary in size, appearance, and microbial process. For example, they may be formed during the growth, desiccation, or detachment and decay of a microbial mat.

There has been some confusion in the literature on the connotation of the phrase “wrinkle mark” or “wrinkle structure” (Häntzschel and Reineck 1968; Hagadorn and Bottjer 1997; Pflüger 1999; Schieber et al. 2007). This confusion is largely the result of misidentification and the lack of differentiation between structures created through physical processes, such as compactionally generated crenulations, and biological processes, such as microbial growth. However, for the purpose of this study, the word “wrinkle” will be used to imply a microbial origin. They are differentiated from wave ripples or current ripples, which are physical sedimentary structures formed by currents moving over sandy surfaces. Two types of wrinkle structure are prominent in the rock record: elephant skin, and Kinneyia structures (Schiber et al. 2007).

‘Elephant skin’ (Fig. 2.7B) is characterized by “reticulate patterns of sharp-crested ridges forming millimeter-to centimetre-scale polygons, occurring on argillaceous veneers above fine-grained sandstone and likely reflecting growth structures of microbial mats” (Porada and Bouougri, 2007). This reticulate pattern is a simple product of microbial growth, which includes formation of bulges and tufts which create a polygonal network. This growth pattern has been observed and studied in modern microbial mats, which allowed conclusions to be drawn when compared with ancient examples (Schieber et al. 2007).

“Kinneyia” structures, also termed wrinkles and ripples in the literature, are shown in Figure 2.7 D-F and are characterized by “millimeter-scale, winding, flat-topped crests separated by equally sized round-bottomed troughs and pits” (Porada et al. 2008). Kinneyia wrinkles have two morphological expressions: a crest-dominated linear pattern (Fig. 2.7D) and a trough-dominated honeycomb pattern (Fig. 2.7E). Since Kinneyia wrinkles have not been observed in modern microbial mats, there is still confusion on how they form. This study will consider the interpretation by Porada et al. (2008), who suggest that Kinneyia ripples form not from the microbial mats themselves but by groundwater flowing beneath a microbial mat. In the aftermath of storms or floods in intertidal settings, downslope groundwater flow causes liquefaction in the top portion of the sediment underneath a microbial mat which survived the storm. In the lower part of the tidal flat, tidal hydrodynamics are superimposed on groundwater currents, creating alternating signals of compression and liquefaction on the sediment, which may produce a pattern of alternating ridges and troughs (Porada et al. 2008).

Where it was difficult to distinguish Kinneyia wrinkles from elephant skin, the structure will simply be called a wrinkle mark or wrinkle structure.

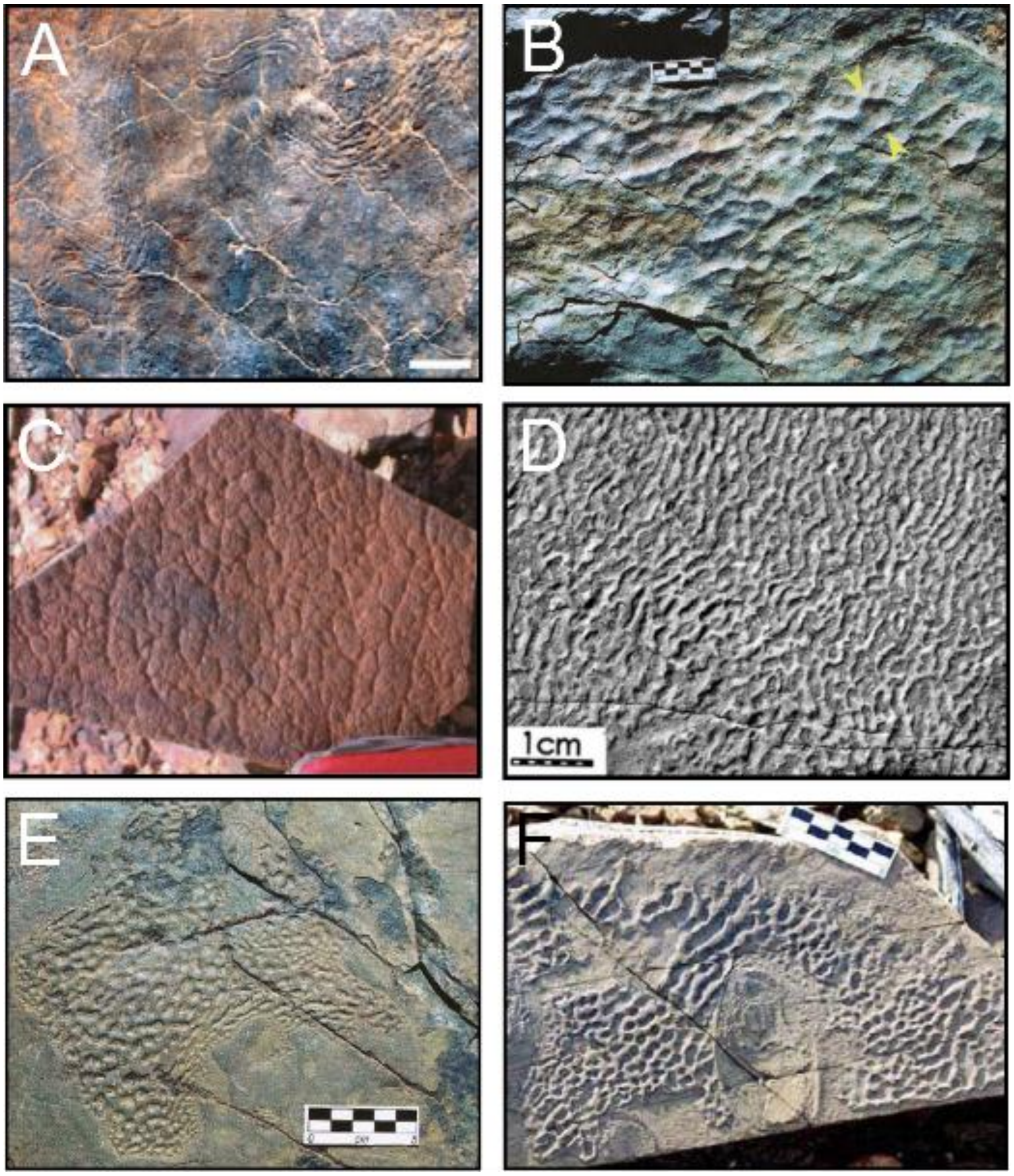

Figure 2.7: Microbial wrinkle structures. (A) Sinuous wrinkle covering an Archean sandstone surface in the Barberton Greenstone Belt, South Africa (Noffke et al. 2006) Scale: 10 cm. (B) Sharp-crested wrinkle structure covering upper bedding surface in Haruchas, Namibia (Bouougri and Porada, 2006). Arrows point out asymmetric ripple crests. (C) "Old elephant skin", characterized by reticulate growth pattern of the microbial mat. Locality: Grand Canyon, USA (Schieber et al. 2007). (D) Kinneyia wrinkles, with linear form characterized by smooth, flat crests in a semi-parallel network. Haruchas, Namibia (Porada et al. 2008). (E) Kinneyia wrinkles, with honeycomb form. Troughs consist of rounded pits and grooves, crests are non-parallel. Haruchas, Nambia (Porada et al. 2008). (F) Sample showing both linear and honeycomb arrangement of Kinneyia wrinkles. Haruchas, Namibia (Porada et al. 2008).

2.6.2 Other Microbial Fabrics

Desiccation cracks are irregular or polygonal networks of fractures in silt or mud, caused by the drying effects of the atmosphere. While desiccation cracks regularly occur only on muddy substrates, the presence of microbes, which 'biostabilize' quartz grains and increase grain cohesion, has been known to result in desiccation cracks in sandstones and siltstones (Schieber 2004).

Gas domes are formed when the growth of a microbial mat is thick and widespread enough to seal the sediment from the surrounding atmosphere, causing gases to build up in the sediments. The rising gases form hollows in the sand and become trapped in domal structures on the bed surface (Fig. 2.8C). Domal structures range from several millimetres to several centimeters in diameter (Schieber et al. 2007).

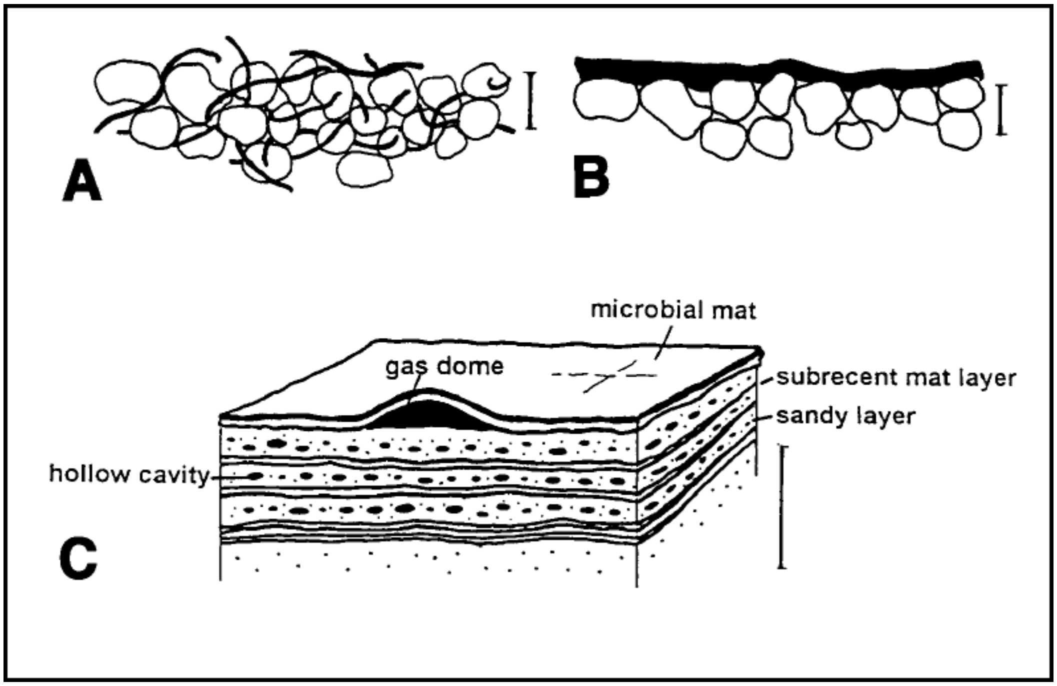

Figure 2.8: Schematic showing the process of biostabilization. (A) Cyanobacterial filaments interweave through sedimentary grains, stabilizing them against erosion. (B) Continued growth results in smooth, mucous-rich microbial mat. Reduction of the surface roughness decreases friction, increasing stability against erosion. (C) Sustained mat growth seals the sediments from the atmosphere, trapping intrasedimentary gases. The gas pressure increases over time and generates hollow cavities within the sands and domal structures in the overlying microbial mat (Noffke et al. 2001).

2.7 Pseudo-mat Textures

Many physical processes can create sedimentary surface structures that are small, subtle and easy to misidentify (Fig. 2.9A-E). Some structures that could be confused with MISS include:

1. Ripple marks (Image A) are sedimentary structures formed by the shaping of sand grains by fluvial or tidal currents. Ripples have a wide variety of shapes, including symmetrical or asymmetrical, sharp or flat-crested, straight or sinuous. They range in wavelength from a few centimetres to a few tens of centimetres (much larger than the wrinkles at Horton Bluff), are a few cm in height and have a characteristic sediment size of 0.03-0.6 mm (Boggs 2006). Ripples often form in conjunction with microbial mats; however, the preferential growth of microbial mats in the troughs of ripples works to eliminate ripples by creating planar, wrinkled surfaces (Noffke et al. 2001).
2. Swash marks (Image B) are isolated low ridges that form on a beach from clumps of fine sediment and organic debris (Boggs 2006). They indicate a beach or lakeshore environment, representing the farthest advance of waves during high tide. While similar to certain expressions of MISS documented in the literature, swash marks bear little resemblance to the wrinkled surfaces described at Horton Bluff.
3. Rill marks (Image C) are dendritic channels or grooves that form on beaches as pore waters are discharged from sands at low tide (Boggs 2006). Rill marks are incised features, and they can be distinguished from MISS by the absence of associated ridges.
4. Adhesion structures (Image D) form by the adhering of dry, wind-blown sand to a wet or damp surface. This phenomenon can form a wide variety of structures, including ripple marks produced by wind stress upon sand-sprinkled tidal ripples. The highly irregular shape of some adhesion structures can bear high resemblance to MISS, and some structures have not been classified in this thesis due to their ambiguity.

5. Load structures (Image E) are unusual shapes formed on bed soles where a denser sediment layer or object overlies a less-dense layer. Small-scale load structures can form bulbous and irregular protuberances, the shape of which can be confused with a microbial structure. Load structures have higher relief than most types of MISS and form on bed soles rather than bed surfaces.

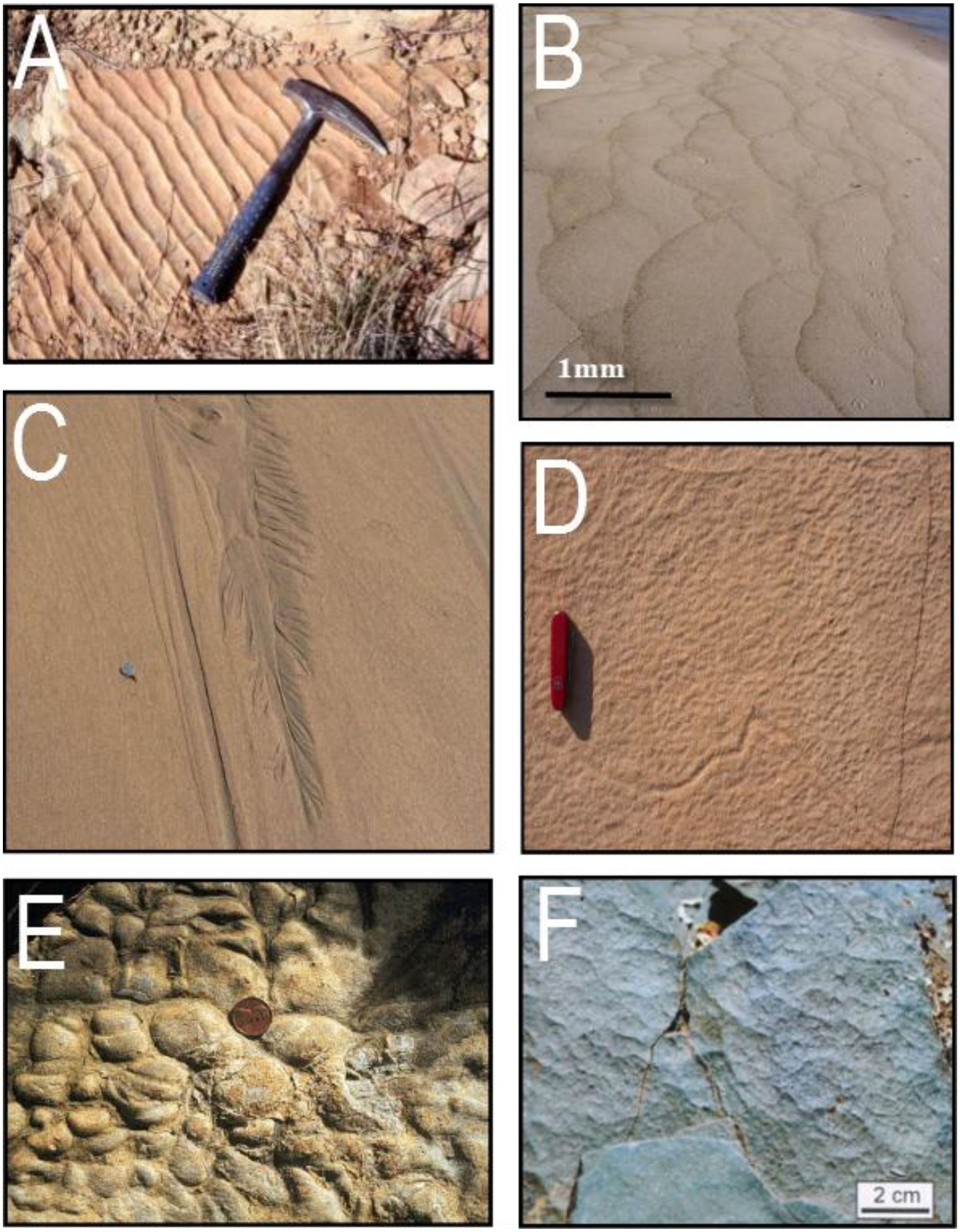

Figure 2.9: (A) Ordovician ripple marks in the Roubidoux Sandstone. Photo from Department of Earth and Planetary Science website, Washington University. (B) Modern day swash marks. http://geology.uprm.edu/Morelock/north/qbswmks.jpg. (C) Modern day rill marks on a sandy beach. http://www.geologyrocks.co.uk/images/rill_marks. (D) Adhesion structures in sandstone. Photo from Department of Geology website, Amherst College. (E) Load casts. Photo from SEPM Strata website. http://www.sepmstrata.org/page.aspx?pageid=359. (F) Elephant skin microbial wrinkle structure consisting of reticulate pattern of sharp crested ridges arranged in polygons. Haruchas, Namibia (Schieber et al. 2007).

2.8 MISS in Thin Section

In thin section, preserved microbial mats cannot accurately be identified using simple petrography. However, they are often preserved as dark, carbonaceous laminae that have a wavy-crinkly appearance (Fig. 2.10 C, E). Being a dark colour brings ambiguity as to whether this material is not simply mud. There are certain properties that can be observed in thin section that suggest a microbial origin. For instance, microbial laminae are often broken into fragments, which were probably pieces of the original mat, torn off by wind or storms. These microbial fragments retain an internal cohesion and rigidity such that they are able to bend, fold over and fray at the ends (Fig. 2.10 B-D, F). Another telling feature is the variation in lamina thickness as the material rises and falls in elevation. While one would expect soft mud that is settling though suspension to be thin in high areas and to collect in troughs, a microbial mat will likely be of an even thickness throughout its length.

Figure 2.10A shows the active process of grain separation (Fig. 2.4) in a modern microbial mat from Mellum Island, southern North Sea coast (Germany). During initial colonization of a sandy substrate, biofilms begin to evenly coat individual quartz grains. Because the biofilms grow equally around each grain, the result of favourable ecological conditions will be single sand grains which “float” without contact with other grains in the organic matrix of the newly formed microbial mat (Noffke et al. 2001).

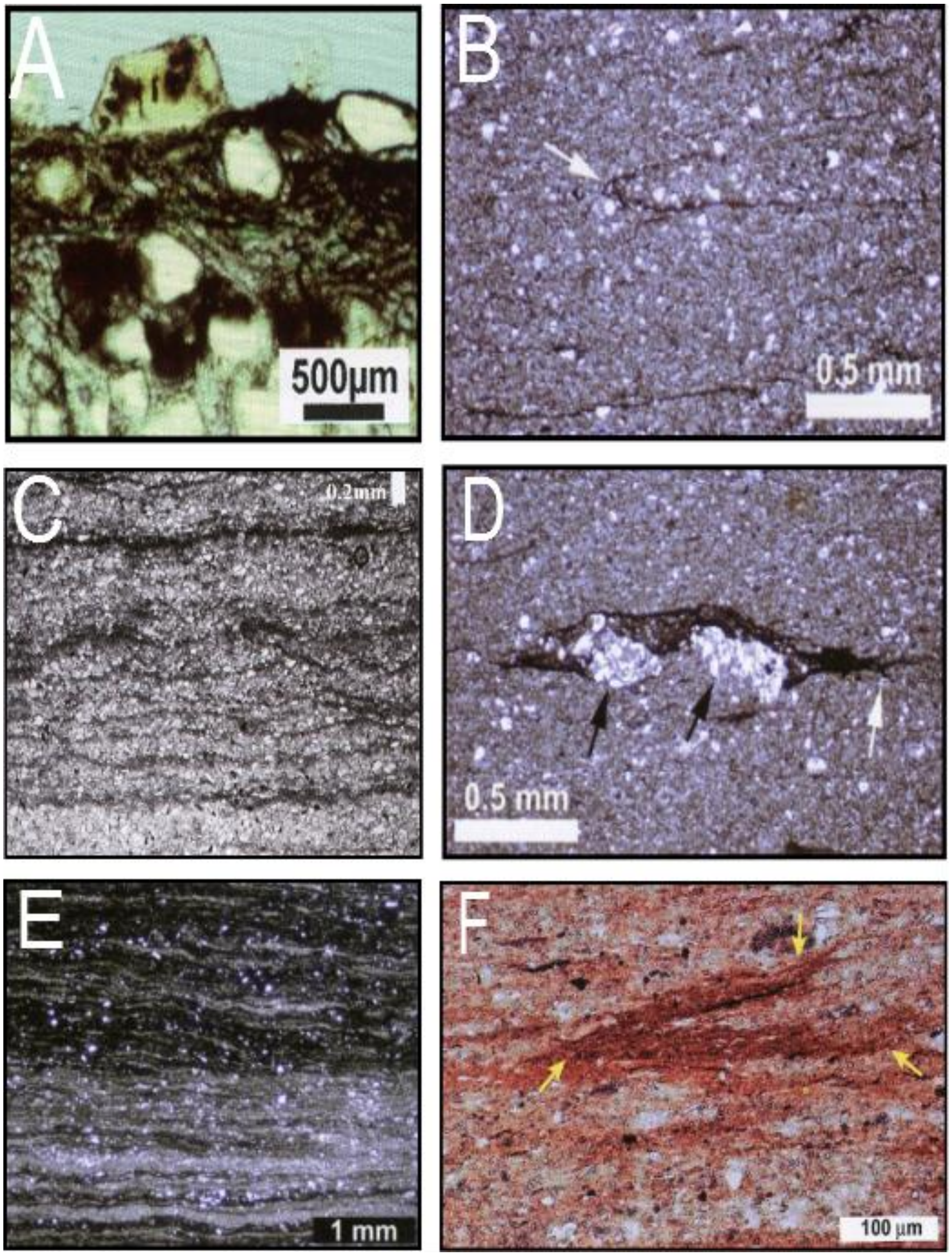

Figure 2.10: (A) Vertical section through living microbial mat composed of cyanobacteria. Note that the quartz grains are "floating" within the microbial material. Photo by Gisela Gerdes (Gerdes et al. 1993). (B) Photomicrograph of grey shale with thin carbonaceous wisps (black material). White arrow denotes a "fold over", suggesting this material was sheet-like and cohesive at the time of deposition. Kopela Shale, India (Schieber et al. 2007). (C) Fine-sand and silty laminae in Mt. Shields shale. Note the wavy-crinkly laminae that contrast with the more planar laminae typical of physical deposition. The style of lamination may indicate surface binding by microbial mats. Montana, USA (Shieber et al. 2007). (D) Dark, carbonaceous shale clast deforming around two silt-pockets (black arrows). Note the frayed character of the carbonaceous laminae to the right of the clast (black arrow), showing internal rigidity probably caused by microbial slime. Kopela Shale, India (Schieber et al. 2007). (E) Wavy-carbonaceous laminae and and intercalated clay drapes. Kajrahat black shale, India (Shieber et al. 2007). (F) Eroded piece of organic material from the Eocene Green River oil shale, Colorado. Yellow arrows denote shape. Deformation and folding implies internal cohesive strength and is suggestive of a microbial mat origin. This is the youngest preserved example of MISS. Schieber et al. (2007).

Chapter 3: Methods

3.1 Field Data Collection

Field work began in September 2012 and was conducted during various day trips that occurred throughout the fall. The actual time span during which field work could be performed depended on outcrop exposure at low tide, which in this area was about 5 hours. Initial visits to the field area in September provided orientation to the geography and the local stratigraphy. In October, microbial structures were examined along the length of Horton Bluff to determine which area contained the most compelling evidence of MISS. Microbial structures are abundant at the northern end of the traverse, where they spread over the tops of five separate bed sets in varying abundance and quality. In the southern part, microbial structures are scarce. However, this area contains two beds of domal stromatolites, one of which has a large, well preserved microbial wrinkle patch on a laterally equivalent bedding surface.

On a final field excursion in November, all relevant detailed data for this project were collected during a 5 hour period. A bedset was selected in the northern end of the traverse for its widespread occurrence and high-quality preservation of MISS. This bedset was 71 m long and protruded from the beach at a low dip angle of 15^{o} (Fig 3.1). The beds project from muds of modern day tidal flats formed by the Avon River and the Bay of Fundy. Because these beds are buried above and below by mud, and are also not exposed on the adjacent cliff face, it was not possible to measure a geological section to correlate to the selected bed.

Figure 3.1: Thin, low-dipping bedset at Horton Bluff, Nova Scotia. This bedset, which also extends offshore from the photo site, was exclusively mapped for this study. Boulder is approximately 1 m wide.

The full length of the bed was divided into segments one meter long. The exposed width of the bed varied slightly (Fig. 3.1), as did its thickness and elevation. Each segment was sketched in a field notebook for a visual record of all structures. In addition to the sketch, the following quantitative measurements were taken for each segment: percent estimation of surface coverage of MISS, size, spacing, wavelength and amplitude of wrinkle patches, ripple orientation, orientation of MISS relative to ripples, and various non-MISS sedimentary structures. Figure 3.2 shows an annotated photograph of a microbial wrinkle patch, illustrating several field observations which were usually recorded.

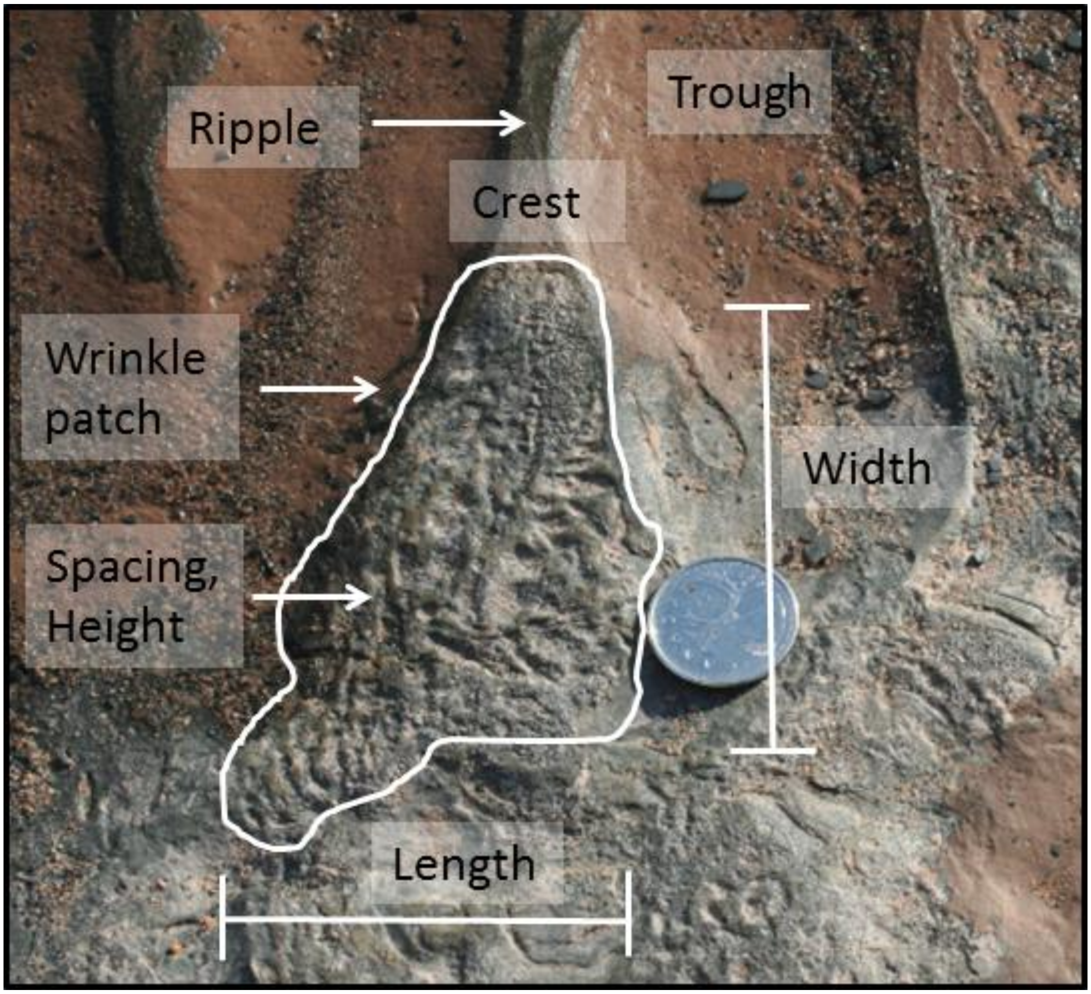

Figure 3.2: Photo annotated with some of the important parameters observed during field data collection. Relationship between the 'wrinkle' and the 'ripples' was carefully noted. For instance, in this sample microbial wrinkles are observed only on ripple crests. Within the wrinkle patch, height and spacing of individual wrinkles was also noted. Coin is 2.4 cm in diameter.

Due to the irregularities of the bed surface, the difficulty of observing these fine-scale structures, and tidal inundation, a grid system was not feasible to estimate microbial coverage. Instead, two workers independently estimated the percentage cover visually, meter by meter. The results were then compared, discussing the cover until an agreement was reached. A meter stick and permanent markers were used to measure and record each one meter segment, and a compass was used to measure orientations. Reliable observations could only be made under conditions of bright sunlight, as the features were difficult to pick out under low light. Some surfaces were covered with mud, seaweed and barnacles, reducing exposure. In these cases, data was collected and a decision was made later to keep or remove these surfaces from the dataset. Exposed surfaces of adjacent unmapped bedsets were examined carefully, and some photographs from these beds are included in Chapter 4.

Detailed photographs were taken of each one meter segment. Where specific structures were unusually well preserved, high-resolution photos were taken and used as a visual confirmation of the notes taken in the field. In addition, photos were used to extrapolate data in certain cases where an observation was missed in the field.

Two large samples of rock were taken from the bedset. The first (HBF-1) was taken at Meter 34 for its continuous vertical stratigraphy. This piece was removed from an area where the bed was at its thickest (13 cm) to study the stratigraphic column from base to top. The second block (HBF-2) was taken at Meter 40 for its excellent surface preservation and coverage of MISS.

3.2 Processing of Samples

3.2.1 Ammonium Chloride Process

Sample HBF-2 was taken to Dr. Andrew MacRae's laboratory at St. Mary's University. Under a fume hood, a glass tube filled with ammonium chloride crystals was heated using a butane burner, while a weak air flow was inserted at one end of the tube (Fig 3.3). The tube was held several inches away from the hand sample, which was also under the fume hood. As the crystals super-heated they sublimated into gaseous phase and flowed out of the non-pressurized end of the tube to coat the surface of the hand sample. This process turns the sample white, removing the distraction of colour, and the gas settles on the surface of the specimen in such a way that the relief stands out clearly. Photography of the specimen produced an effective image to analyse. Figure 3.4 shows the photographed result of the sample after being coated with ammonium chloride.

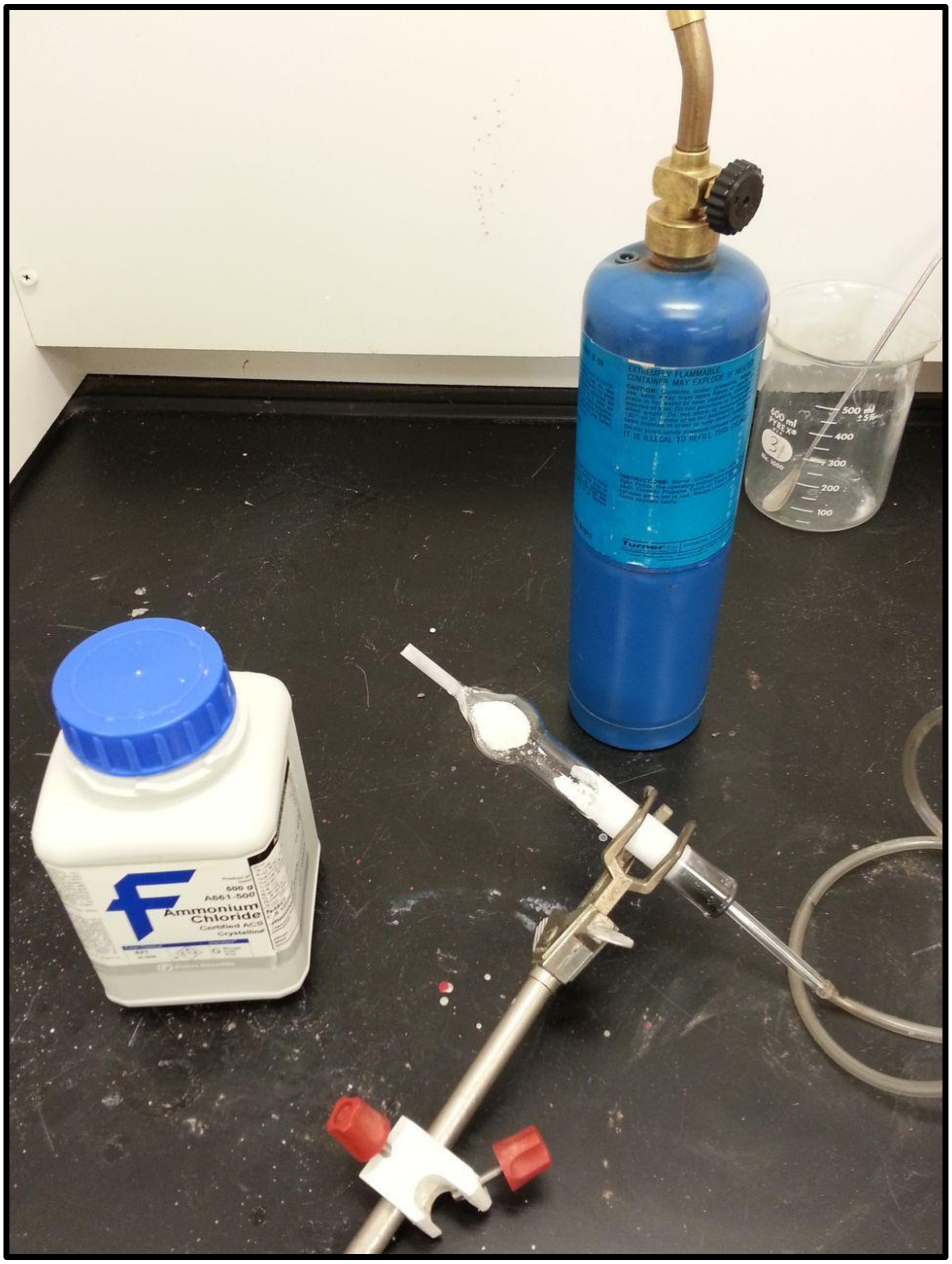

Figure 3.3: Equipment needed for the ammonium chloride process. Under a fume hood at St. Mary's University, Halifax, a butane burner, solid ammonium chloride crystals, glass tube and gripping device for the heated tube. Weak airflow coming through the tube from right to left pushes ammonium chloride gas out of the other end, where the sample would rest several inches away. As the gas exits touching the sample, it sublimates immediately, coating the surface white and making the relief stand out.

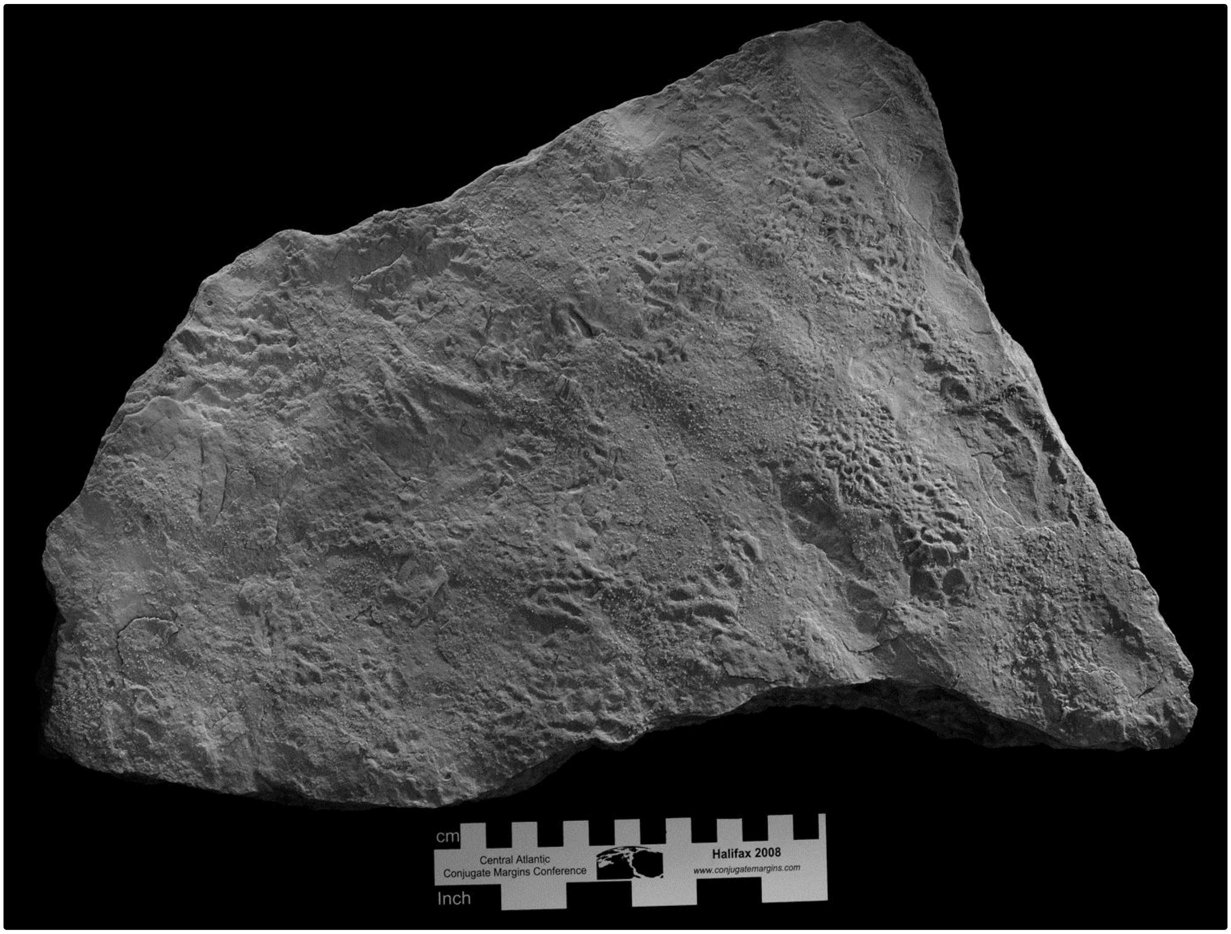

Figure 3.4: Image taken of sample block HBF-2 from Meter 40 after being coated with ammonium chloride. Image has been rendered black and white and the area surrounding the sample has been digitally altered to black for contrast. Photo taken by Andrew MacRae at St. Mary's University, Halifax.

3.2.2 Thin Section and Hand Specimen

Sample HBF-1 was cut normal to bedding in order to view the internal structures. This sample was also used to make thin sections, which were cut and polished in the Dalhousie University thin-section preparation facility by Gordon Brown. These thin sections show the full bed thickness. The thin sections and hand samples were analyzed for composition, internal structures, and evidence of organic matter (Chapter 4: Figures 4.13-4.15).

3.3 Classification of MISS

For each meter-long segment, the field data were entered into an Excel© spreadsheet. The digital data could then be manipulated to show distribution of sedimentary features, including relationships between microbial and non-microbial features. Surface area of microbial coverage, preferred colonization sites of microbes, and relationship between MISS and ripples were studied. Microbial-wrinkle spacing, height, and the geometry of crests and troughs were also examined. Finally, attempts were made to group the structures observed at Horton Bluff under existing classification schemes for MISS (Noffke et al. 2001; Schieber 2004).

Chapter 4: Results

4.1 Description of MISS

The bedset mapped at Horton Bluff had many patches of surficial wrinkles presumed to be of microbial origin. In some places bed segments were evenly covered with abundant wrinkles (Fig. 4.1), while other sections contained isolated, superbly preserved patches on otherwise microbially barren surfaces (Fig. 4.2). There is no indication that organic laminae observed in hand sample and thin section are present on the bed surface in association with the wrinkles, and it is not clear whether they were originally present but have been weathered away.

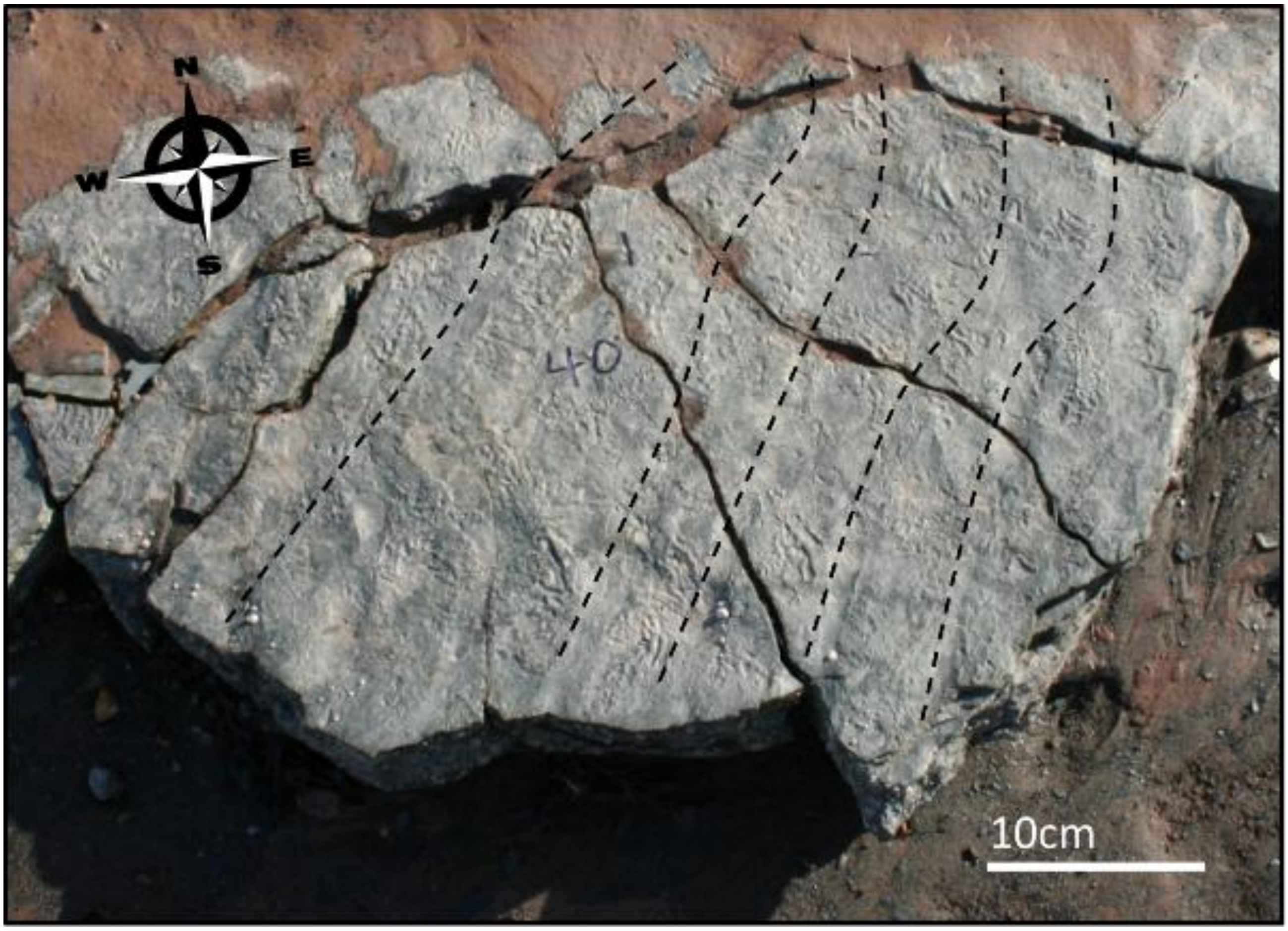

Figure 4.1: Microbially wrinkled bed surface at Meter 40. This section was once rippled, but has since been leveled by the growth of microbial mats. The trace of the ripples is still present, with former trough positions annotated with dashed lines.

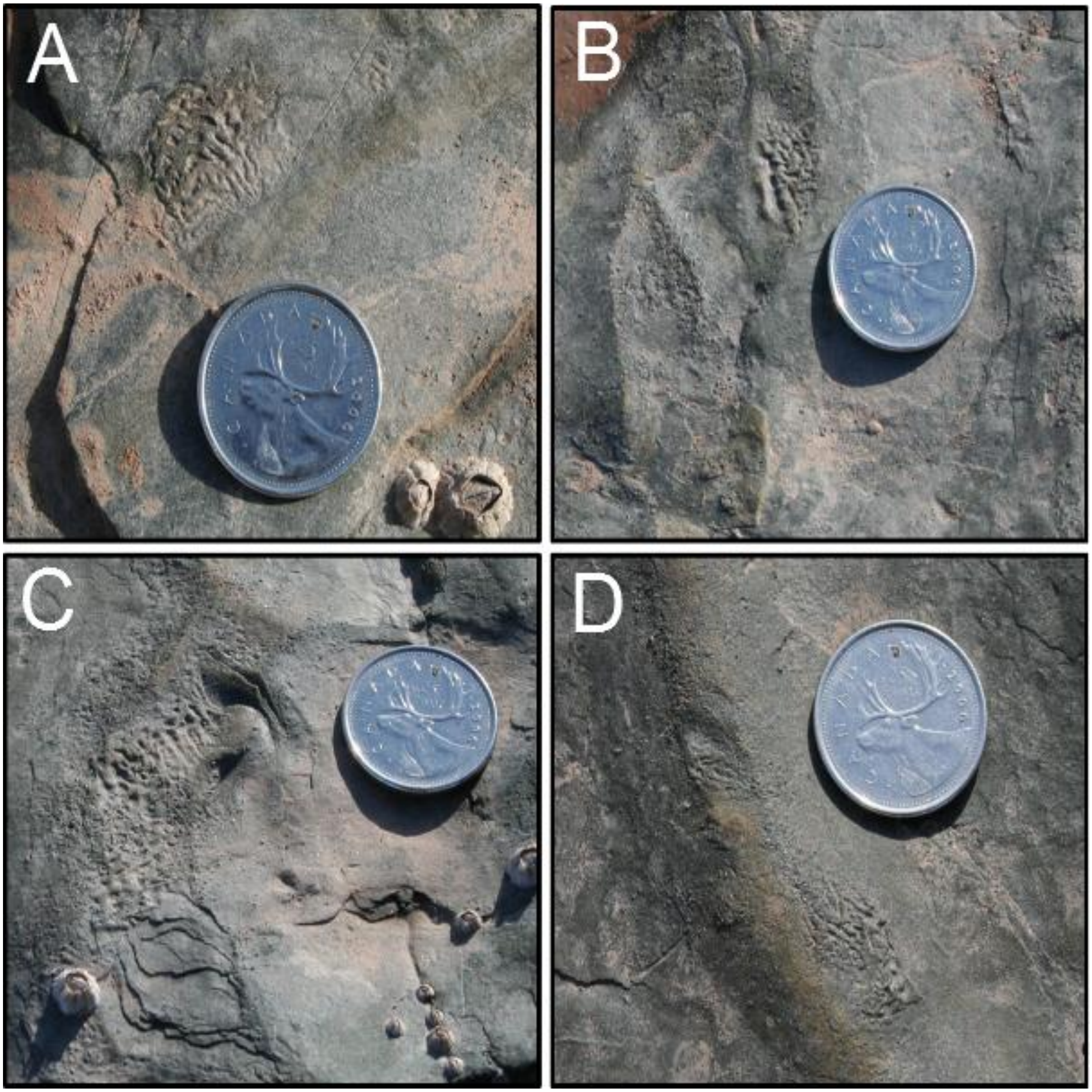

Figure 4.2: Isolated wrinkle patches. (A) Circular wrinkle structure with curving, flat topped crests and rounded pits forming a honeycomb structure. (B) Wrinkle structure occurring on flattened segment of ripple crest. (C) Low-relief, wrinkle structure occurring on flattened ripple crest and displaying non-linear honeycomb structure of crests. (D) Elongated wrinkle structure occurring along the crest of a ripple and with the same orientation. Scattered coarse grains are present along ridge crest at top left. Coin is 2.4 cm diameter for scale. Pale structures in A and C are barnacles.

The individual wrinkle patches range in size, the smallest identified being 1 x 1 cm^2 and the largest being 3.5 x 2.5 cm^2. The large microbial wrinkle patch located within the stromatolite beds south of the studied section and described by Gallacher (2010) is about 15 x 7 cm^2 in size.

The patches are rounded and range in shape from circular to ovoid to s-shaped. Wrinkle spacing is 1-2 mm, as is wrinkle height. The tops of the wrinkles are smooth and flat in nearly every case. Wrinkle crests are locally linear, but generally are semi- or non-linear, tending to join and divide and are separated by pits and grooves that form a honeycomb pattern. This honeycomb pattern is nicely displayed on a patch occurring on sample block HBF-2 that was coated with ammonium chloride (Fig. 4.3).

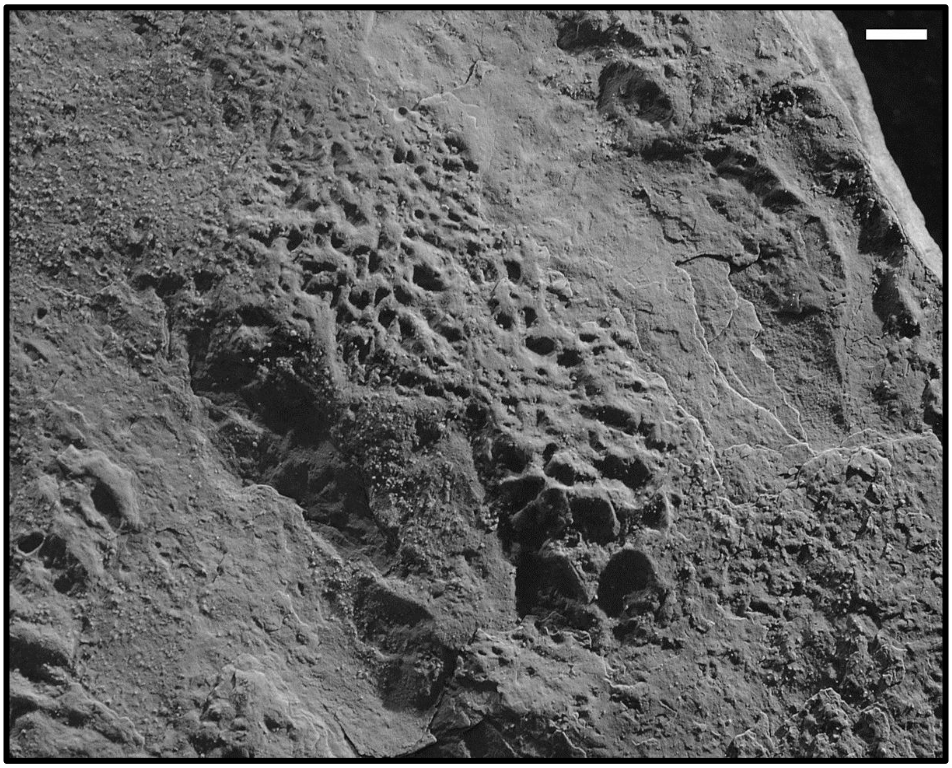

Figure 4.3: Magnified image taken from photograph of sample at Meter 40 which was coated with ammonium chloride sublimate in order to make relief stand out. Honeycomb pattern of rounded pits, low relief and localised crest pinch-outs is displayed. Scale bar at upper right is 1 cm long. Photo taken by Andrew MacRae, St. Mary's University, Halifax.

4.2 Other Relevant Features

Although several other non-biogenic sedimentary structures were observed, the relationship between the microbial surface wrinkles and ripples was deemed particularly important in this study. Ripples are prominent throughout the length of the siltstone bedset (Fig. 4.4), and are slightly sinuous, symmetrical to slightly asymmetrical ripples with a wavelength of 5-8 cm and a trough-to-crest amplitude of 2 cm. A crest orientation of 020-200° is consistent throughout the length of the bedset and is also consistent with ripple-crest measurements taken by Martel and Gibling (1996) for the Hurd Creek Member.

Figure 4.4: Slightly sinuous, symmetrical ripples in Meter 18-19, as commonly seen along the Horton Bluff section. Orientation is 200°. Length of photo is 1 m.

Figure 4.5: Planed-off ripples at Meter 19. Ripple crests have been truncated by exposure, with the natural erosion lines visible. Near the quarter (2.4 cm diameter), a small wrinkle patch is present in a flattened area (see Fig. 4.2B for close-up).

Ripple crests commonly have curved tops or sharp peaks, but in many cases had been planed off, indicating sub-aerial exposure (Fig. 4.5) as documented in modern tidal flats. The result was a flattened, tabular area which commonly had a low rim around it. Although microbial evidence was not universally present on flattened ripple crests, MISS were commonly located within these areas, so they may have been sites of preferential microbial colonisation. In other instances, large microbial wrinkle patches were seen in transitional areas between planar, wrinkled areas and rippled, non-wrinkled areas, suggesting that the growth of microbial mats had been leveling the depositional surface (Fig. 4.6, 4.7).

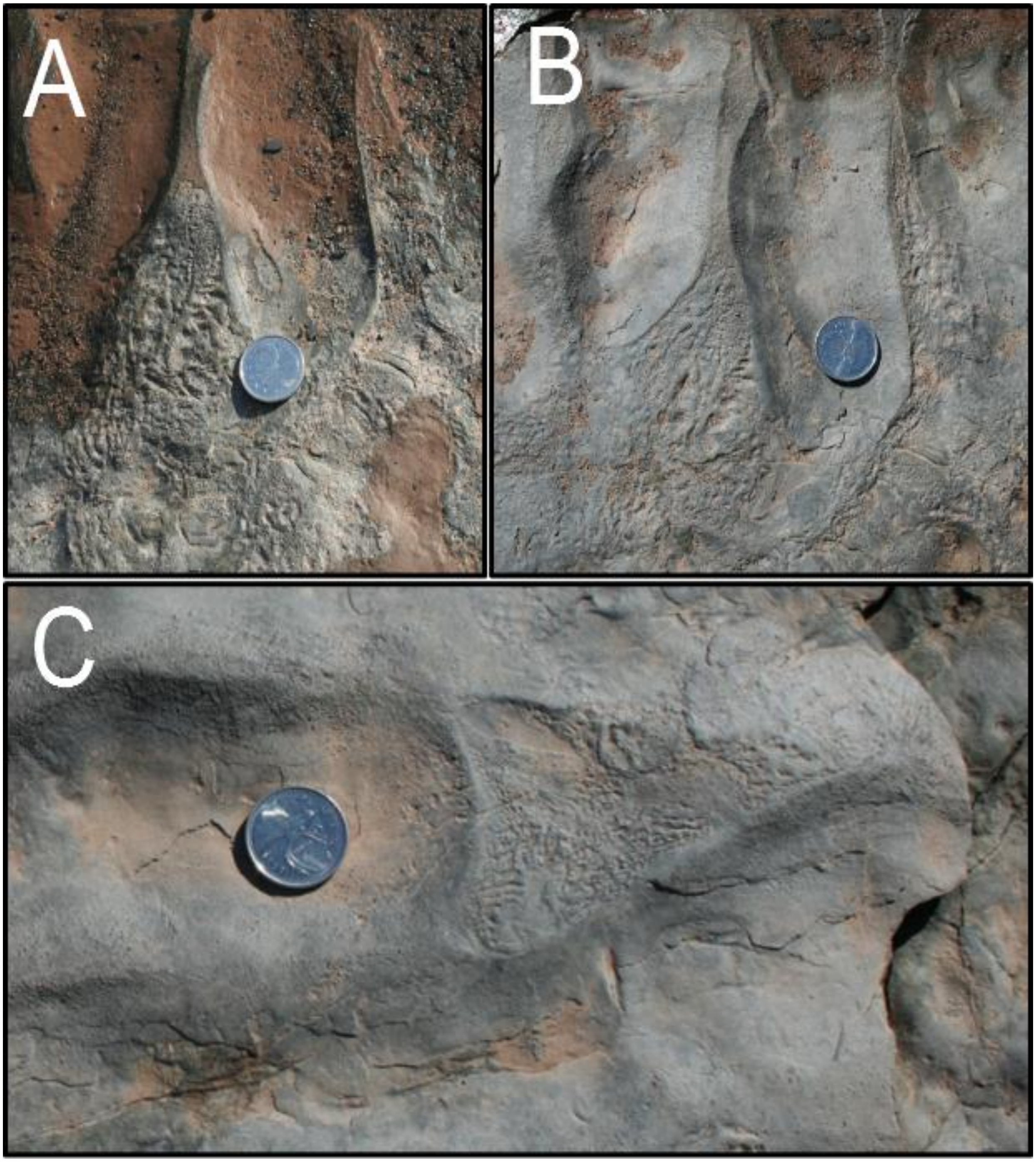

Figure 4.6: Rounded, triangular wrinkle patches preserved alongside ripples. (A, B) Wrinkle patches colonizing ripple crests, which are now flat due to sediment buildup and previous growth of microbial mats. Since the microbes favour moist, protected areas, the crest would presumably not be colonized until growth in the troughs had created a level surface. (C) Wrinkle patch which spans the distance between two crests. Note that the area underneath the wrinkle patch is flat with a bounding rim, while the coin sits in an area which still has relief. Coin 2.4 cm in diameter.

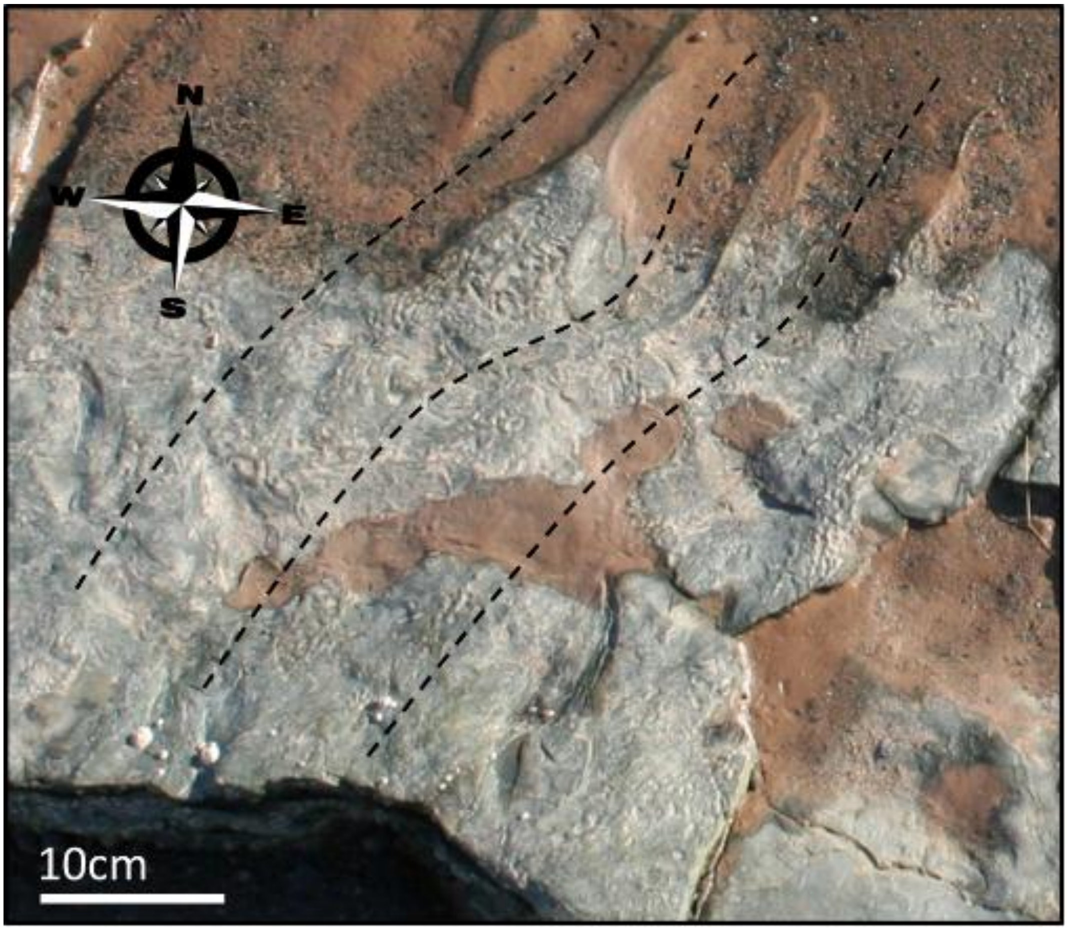

Figure 4.7: Wrinkled surface at Meter 23-24. These wrinkles are overprinting ripples and leveling the depositional surface. Ripple troughs are shown with dashed lines. Close up of large wrinkled patch near top of photo is shown in Fig. 4.6A.

Scattered grains of coarse, probably windblown sand were commonly seen covering the crests of ripples in a ‘sprinkled’ pattern (Figs. 4.2D, 4.8C). These grains were cemented and are of the same age as the host lithology. Although microbial wrinkles were often seen nearby and in the same bed segment, many instances of coarse-grained sand were observed on microbially-barren surfaces, so no correlation was evident.

Rill marks and other scoured surfaces caused by water erosion are present locally, sometimes cross-cutting wrinkle structures. Figure 4.8A shows elongate, sub-rounded scooped depressions which sharply cut a surface heavily wrinkled by microbial activity.

Desiccation cracks are common on the bed surface, locally with polygonal patterns. Although most desiccation cracks were observed on surfaces with abundant microbial coverage, Figure 4.8B shows a desiccated surface without any evident microbial activity.

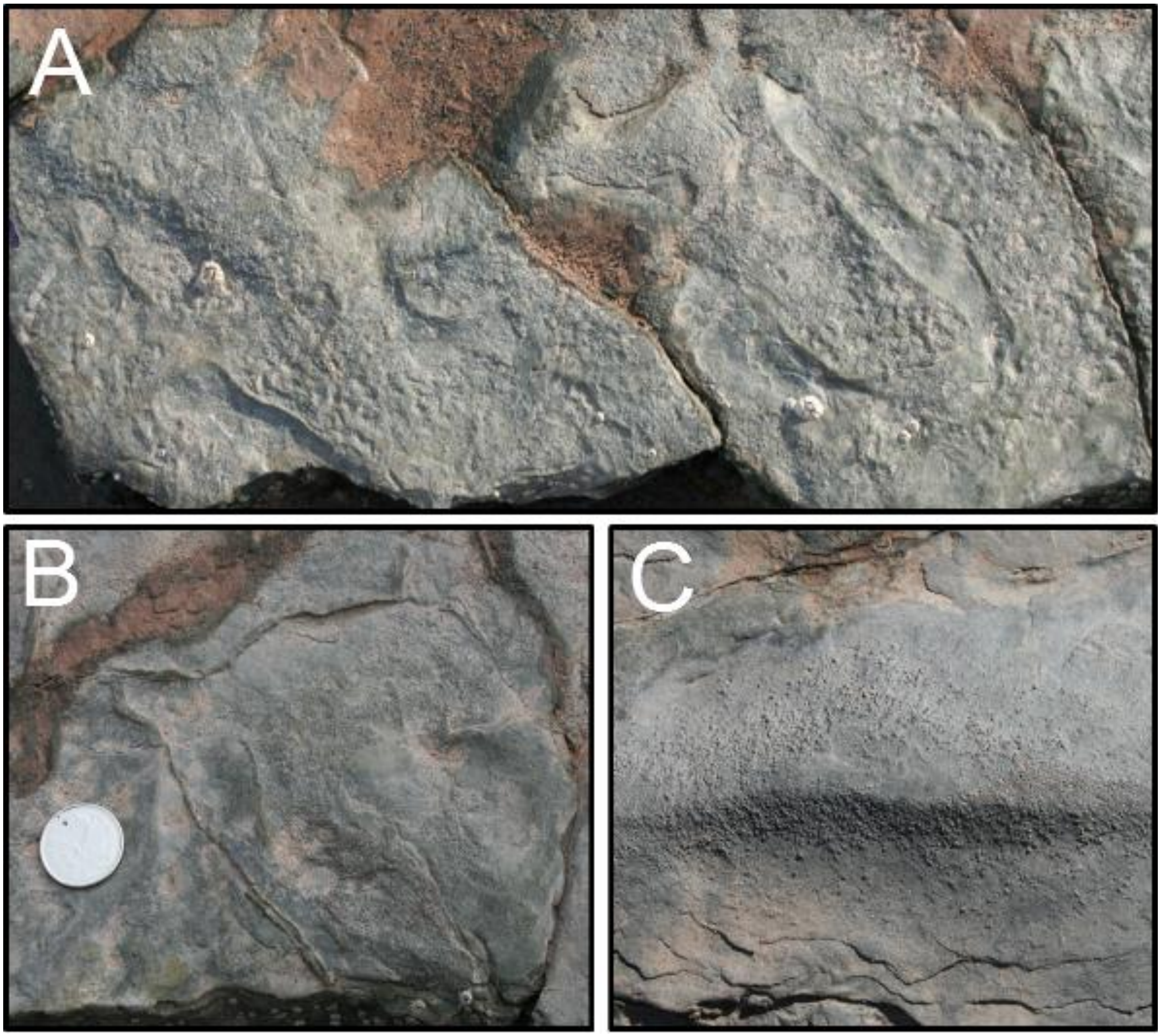

Figure 4.8: Physical sedimentary structures found along the studied bedset in the Horton Bluff section. (A) Rounded scoop depressions, causing erosional scouring into a heavily wrinkled area at Meter 31-32. Length of photo is 50 cm. (B) Desiccation cracks with polygonal patterns, also present in several other bedset segments. (C) Coarse-grained sand scattered over the stoss surface and crests of ripples, locally associated with microbial coverage. Length of photo is 10 cm.

Figure 4.9: Domal structures found on a bed surface in the near vicinity of the Horton Bluff bedset mapped for this study. They resemble gas domes formed in association with microbial structures (Noffke et al. 2001). Coin 2.4 cm in diameter.

Figure 4.9 shows domal structures which were found on a bed surface adjacent to the mapped bedset. They are circular in planform, 1 cm in diameter on average, and have a relief of 3 mm. No microbial structures were observed near the domes. Although these structures are ambiguous, they resemble the gas domes illustrated in Figure 2.8 and linked to microbial stabilization by Noffke et al. (2001).

One short (6 cm) invertebrate trackway was noted on a surface within the mapped bedset. The trackway was close to wrinkled areas but not directly on a wrinkled surface.

4.3 Areal Coverage of MISS

The total area mapped was approximately 45m^2. Of this area, 5.67 m^2, or 12.6% was covered by microbially-induced sedimentary structures. These consisted of Kinneyia-type surface wrinkles as described in Chapter 2 and shown in Figures 4.1-3, 4.6-7, 4.10.

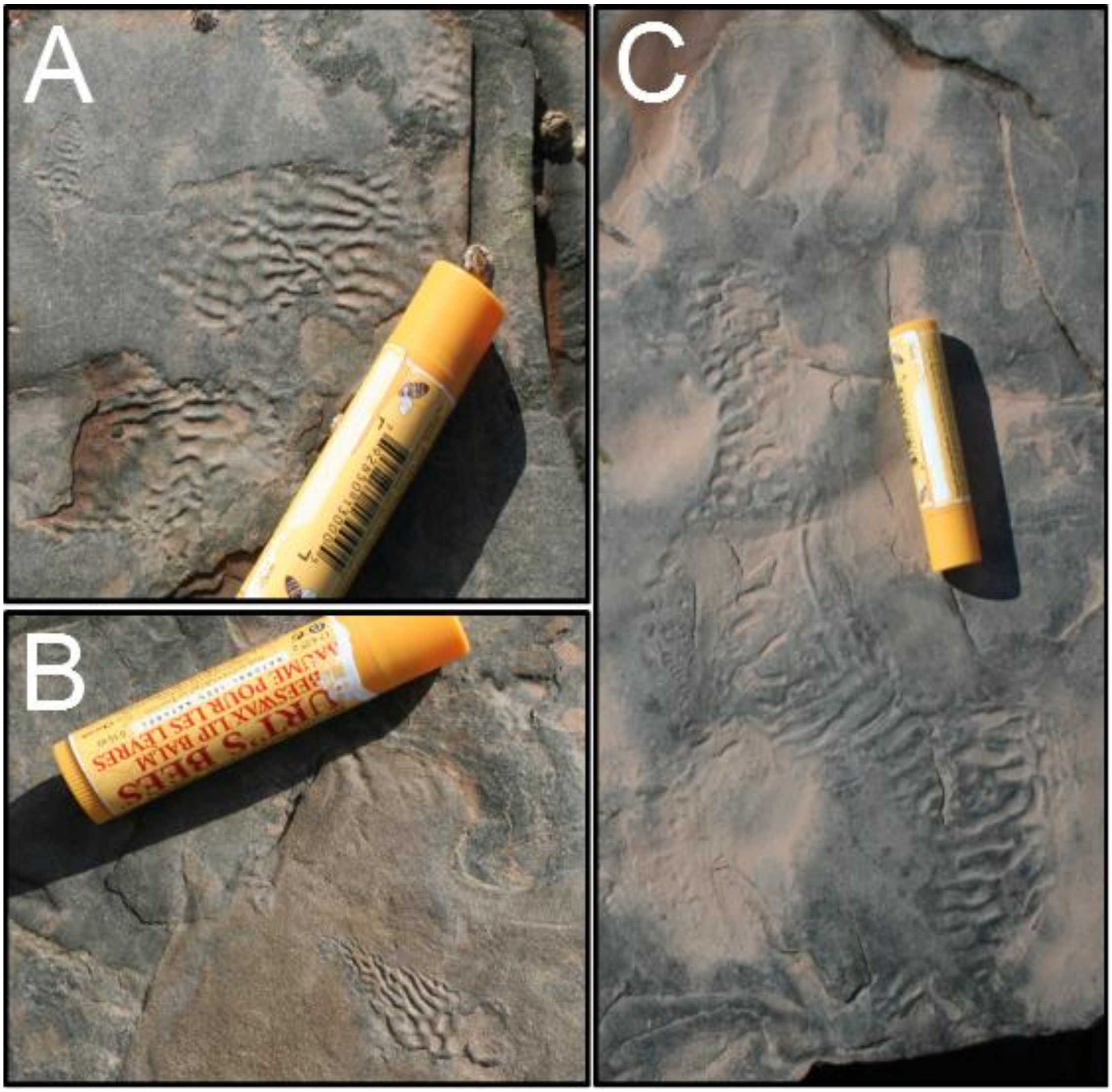

Figure 4.10: Kinneyia-type wrinkles found in the Horton Bluff area along a beset adjacent to the mapped bedset. Note that the wrinkles all have smooth, flat tops. (A) Rectangular wrinkle structure displaying linear and semi-parallel crest arrangement. (B) Irregular wrinkles displaying both honeycomb (bottom of patch) and linear (top) Kinneyia wrinkles. (C) Linear-style Kinneyia wrinkle patch which has been carved by erosion into a curving, S-shaped structure. Scale = 6.5 cm long.

Microbial structures were noted on 50 out of 65 metre-long segments accepted as useable data (Fig. 4.11). They are especially common on the crests of ripples. Of 17 bed segments where wrinkle structures are localized on certain areas of ripples, 60% of these have occurrences on ripple crests, 24% occur on the flanks of ripples, and 18% occur in the troughs of ripples (Fig. 4.12). An additional 20 bed segments contained un-localized wrinkles, which were spread evenly over a previously rippled surface and did not show preferential colonization of a specific ripple feature (Fig. 4.1). Small, isolated wrinkles often had similar orientations to ripples in the same segment.

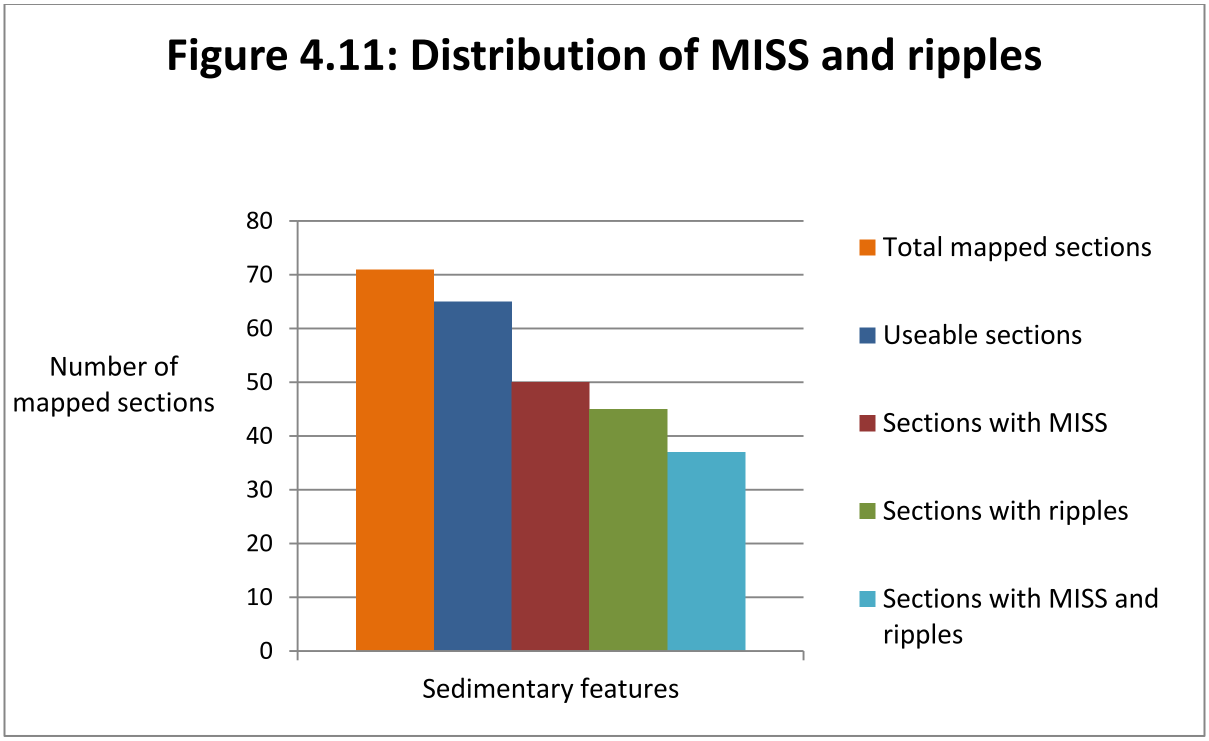

Table 4.11: Histogram showing proportion of microbial coverage in relation to total mapped sections, and ripple coverage in relation to MISS. Useable data reflects poor exposure of some metre-long segments, which were not used for estimates of microbial cover.

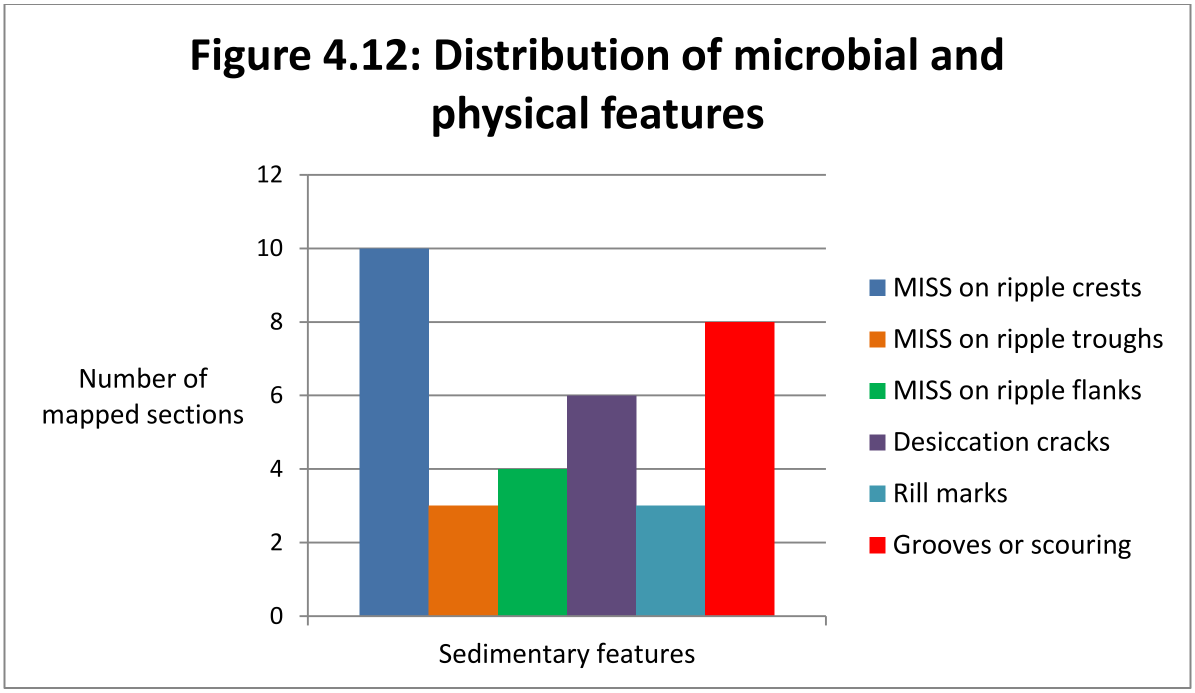

Figure 4.12: Histogram showing localization of MISS to certain areas of ripples, and other, physical sedimentary structures that existed along the mapped bedset.

4.4 Stratigraphic Column

Sample HBF-1 is composed of two blocks, which together are about 13 cm in height and represent the full bed thickness (Fig. 4.13). This sample was cut through the center in order to observe the internal structures. The lower section is largely composed of massive siltstone without much lamination. Higher up in the column, thick dark brown, wavy laminae are seen. These laminae are of an irregular shape and vary in thickness throughout their length. Note the difference in colour between the dark brown laminae indicated with a white arrow and the mud laminae below, signifying that this layer is of a unique composition. Although no geochemical analysis (Section 6.4: Recommendations) is available, the unusually dark colour of the laminae compared with other layers suggests that organic matter is an important constituent.

Figure 4.13: Vertical section through the Horton Bluff bedset of sample HBF-1. White arrow denotes dark brown, wavy-crinkly laminae that are less regular than the paler, continuous laminae at other levels, interpreted as mud lenses. Sample is 13 cm tall and 10 cm wide in this photograph. Curved marks are from the saw used to cut the sample.

Figure 4.14 shows a section from the upper block of Figure 4.13, again drawing attention to the thick, dark brown tabular laminae, which appear to occupy hollows and are discontinuous and noticeably darker than other, more continuous layers. Figure 4.15 shows the cut thin section juxtaposed with the block that it came from. Image B shows a corner of the block, whereas Image A corresponds to the face on the right side of Image B. In thin section and hand sample, a dark brown lamina is draped over an irregular mound of large quartz grains, maintaining a near-uniform thickness across the mound.

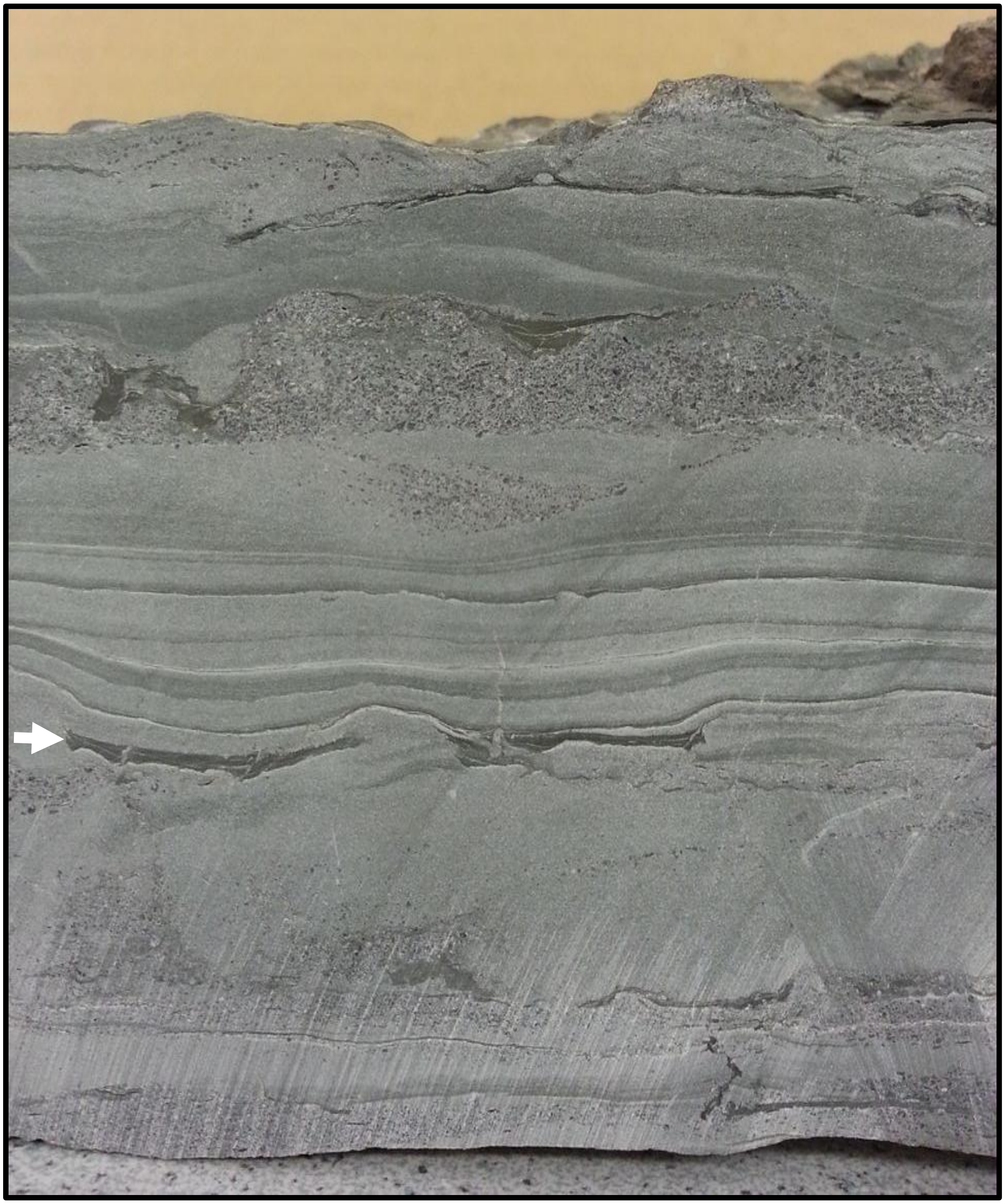

Figure 4.14: Vertical section through the top block (stratigraphically younger) of sample HBF-1 of the Horton Bluff bedset. This section is from the same block but is moved laterally to the right of Figure 4.13 and is from the opposing face. The central area shows two thick (2 mm) dark brown tabular fragments in the center of the section, denoted by the white arrow. Section is 7 cm tall and 8 cm wide.

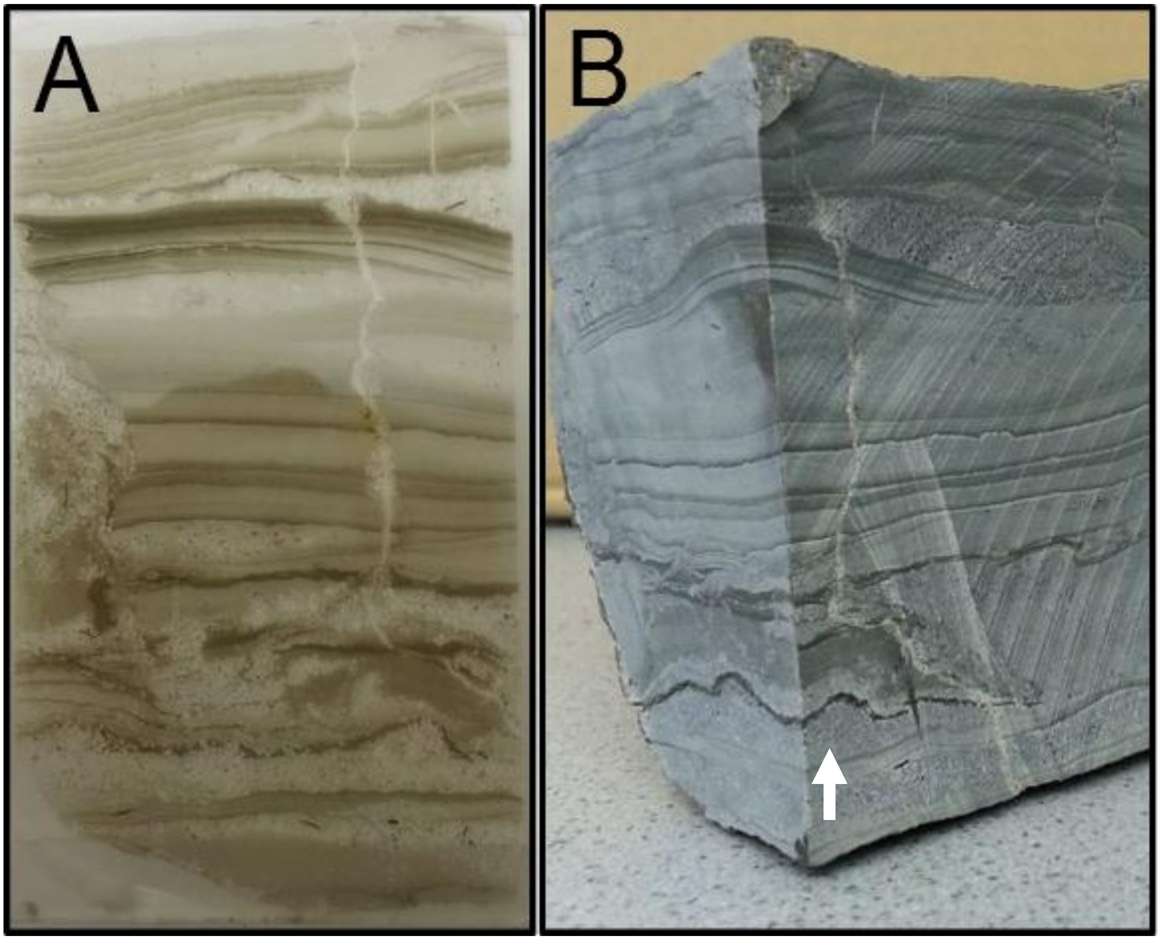

Figure 4.15: Thin section (A) and corresponding rock sample (B) taken from Meter 34. Note the thick dark brown laminae draped over the mound of large quartz grains (white arrow). Dimensions of thin section and hand sample are 7 cm tall x 5 cm wide.

4.5 Petrographic Analysis

The sediment was identified in thin section as a predominantly fine-grained, laminated quartz-rich siltstone (Fig. 4.16B). The lithology is primarily quartz, with muscovite and clays visible in the clay-rich layers. A large fracture filled with calcite runs through the upper section, vertically cross-cutting beds (Fig. 4.16A). Silt-sized layers are interspersed with coarser-grained sandy layers, in which large quartz grains range from 0.1 to 1 mm in size. The lower portion of the section contains a poorly-sorted chaotic mixture of large sand grains, mud laminae, and thick dark fragments and wavy laminasets (Fig. 4.17B, C). Some irregular, inclined layers are poorly sorted and contain abundant fish bone material, suggesting episodic high-energy depositional events. Black organic grains about 0.01 mm in length are dispersed throughout the rock and are circular to elongate in cross section. In some places they lie at irregular angles within an unsorted matrix, while in other places they lie parallel to the bedding. These black grains are probably fragments of leaves, spores, and bark. They were not observed in the thin dark laminae, which do not owe their dark colour to discrete higher plant components. A single clinopyroxene grain is present as detrital material, but no laminae rich in heavy minerals were observed.

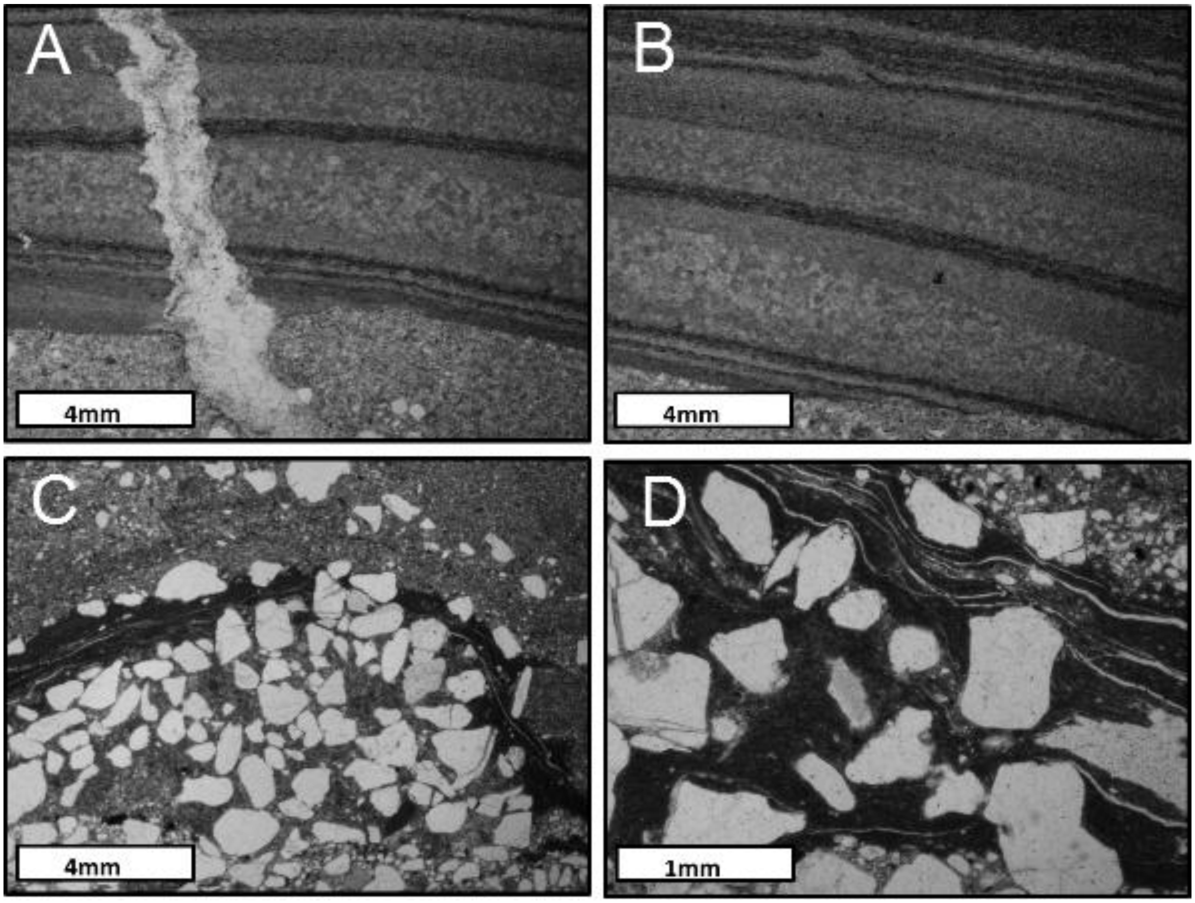

Figure 4.16: Photomicrographs of the Horton Bluff mapped section at Meter 34. (A) Calcite-filled fracture cross-cuts beds and runs through about half the thickness of the bedset. (B) Horizontal and weakly inclined beds of interlaminated silt and clay, the general lithology of the bedset. (C) Mound of large quartz grains draped by a thick (1 mm) dark layer. Note that the layer thickness does not change over the crest and sides of the mound. Quartz grains also lie within the topmost part of the layer and are present on the steep right-hand side of the mound, suggesting binding by the dark material. (D) Dark layer with large quartz grains embedded within it and separated by the dark material. The thin pale bands are fractures, apparently generated during thin-section manufacture.

Of particular interest to this thesis are thick, chestnut brown laminasets that have a wavy-crinkly appearance. These layers are shown in Figure 4.16 (C, D) and Figure 4.17 (A-D) and are darker in colour than the clay-rich laminae shown in Images A and B of Figure 4.16. Image C shows a dark layer about 1 mm thick that drapes over a mound of large quartz grains. The layer drapes over the mound without thinning over the crest or thickening into the troughs, but maintains an even thickness throughout. With reference to this layer, Image D follows the layer to the left, to an area where large quartz grains are isolated in the dark matrix without contact with one another. The white laminae within the layer represent fine fractures filled with the epoxy used to make the thin section. Figure 4.17A follows the layer to the right of the mound, where it terminates by breaking into two robust pieces. Also note in Figure 4.17A the large quartz grains in the top-left portion of the image. There are three grains here that rest within the top part of the dark layer along its steepest segment. One is these grains is elongate and is projecting upward. These are unusual positions for such large grains to maintain, unless they were bound in some manner. Figure 4.17B, C and D show other dark laminae, which range in thickness from 0.1 mm (B) to 1 mm (D) and are locally broken into discrete fragments. Many of these fragments exhibit frayed ends and no signs of smearing, implying that they were originally cohesive. Others are bent and folded, further suggesting internal cohesion.

During sampling, care was taken to collect from the full thickness of the bedset, including the topmost laminae. In both cut block and thin section, the dark wavy-crinkly material described above is not present in the topmost laminae, although the top of the sampled block does not have wrinkles.

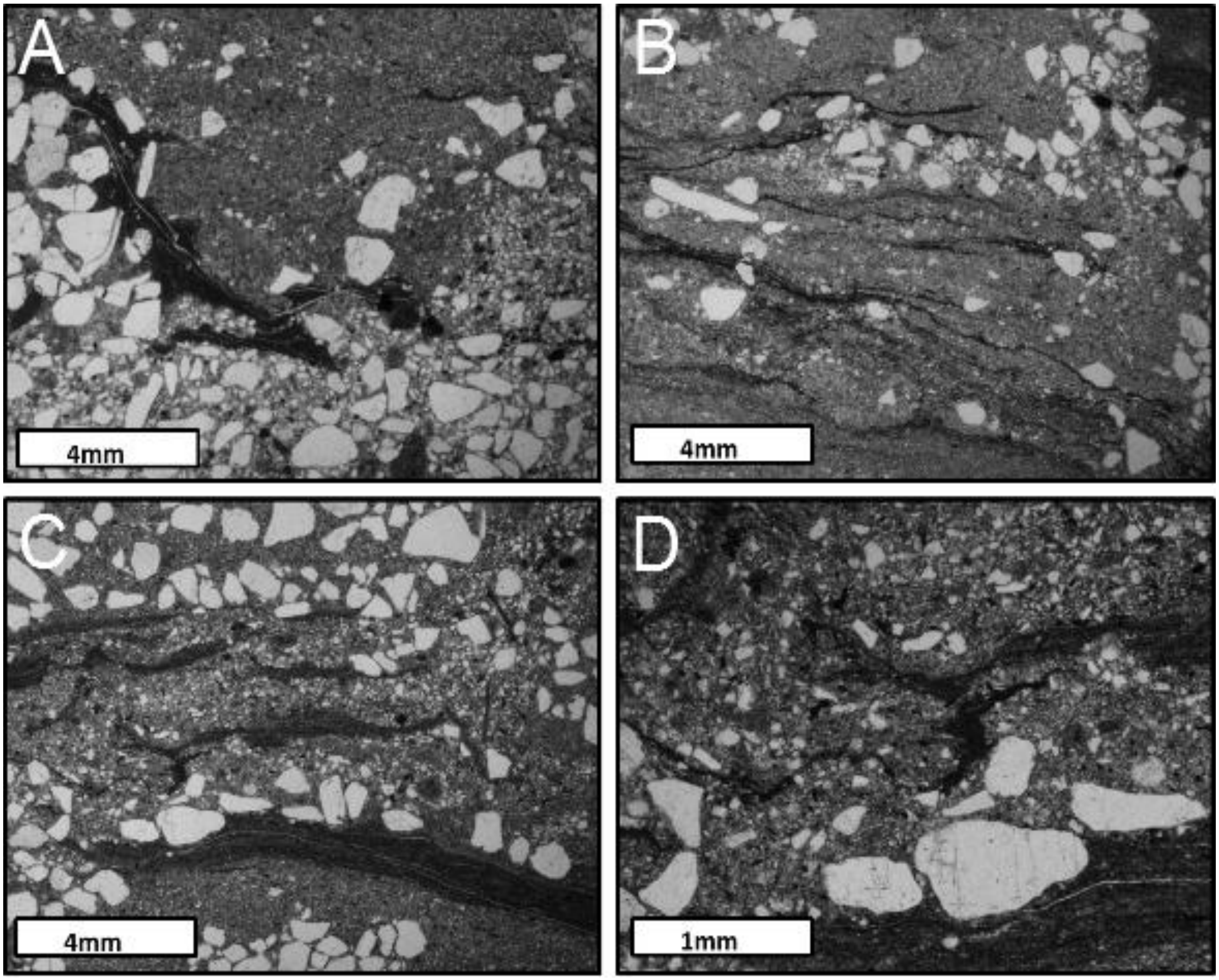

Figure 4.17: Photomicrographs of the Horton Bluff mapped section at Meter 34, continued from previous figure. (A) Dark layer breaking into two robust fragments and showing no smearing. Note elongated, vertical quartz grain that seems to be bound in this irregular position. (B) Thin, wispy dark laminae with a wavy-crinkly appearance. (C) Discrete dark laminae displaying bending and frayed edges. (D) Close up of S-structure in left-central area of Image C. Ability to fold suggests internal rigidity.

Chapter 5: Discussion

5.1 Evidence of Microbial Life in the Horton Bluff Section

5.1.1 Surface wrinkles

The sinuous smooth-crested patches of wrinkled sediment preserved at Horton Bluff closely resemble microbial wrinkle structures described and photographed in various ancient settings and documented in the literature by Hagadorn and Bottjer (1997), Pflüger (1999), Noffke et al. (2001) and Porada et al. (2008), among others.

Throughout the geologic record, MISS are commonly hosted in siliciclastic tidal flats with a quartz-rich (often > 90%) lithology. The Horton Bluff specimens have a depositional environment and lithology that agrees with this trend. The bedset in question is a siltstone that is primarily quartz in composition, and is complete with sinuous, symmetrical ripple marks, which are interpreted as tidal ripples. Desiccation cracks and coarse, windblown sand grains indicate that these beds were subaerially exposed periodically – further evidence for a tidal-flat setting. This interpretation agrees with Martel and Gibling (1994, 1996), who inferred a wave-or combined-flow origin for these ripples based on association with hummocky cross-stratification and recurved groove casts. In addition, a tidal inference is supported by the fine interlamination of varied grain sizes, as well as associated brackish fauna in the Blue Beach Member (Tibert and Scott 1999).

The wrinkle structures are not likely to have been produced by post-diagenetic structural deformation. While this area has experienced some tectonic deformation, the bedset in particular shows no signs of foliation, cleavage, or metamorphic minerals.

5.1.2 Desiccation cracks

Desiccation cracks are observed on 9% of all sections mapped as useable data. Shrinkage cracks are not generally common in quartz-rich sand and silt, which is prominent in the bedset. A possible explanation is that the presence of microbial biomass can cause normally cohesionless grains to maintain cohesion, allowing shrinkage cracks to occur in sandstones and siltstones (Schieber et al. 2007).

5.1.3 Structures observed in thin section

The siltstone bedset in question was confirmed by thin section to consist primarily of quartz with lesser fine clay particles and muscovite. In addition, the thick, unusually dark layers and fragments of laminae (Fig. 4.16C-D; Fig. 4.17) are likely to contain organic matter that may have been derived from microbial mats. The laminasets drape over large mounds of quartz grains in a way that is uncharacteristic of clay (Fig. 4.16C), which would be expected to accumulate in hollows and thin out over mounds. These laminasets instead evenly cover the surface, similar to how a microbial mat might colonize a sandy substrate, as described in Schieber et al. (2007). The structure in Figure 4.16C suggests the process of imprinting, in which biofilms overgrow sedimentary structures while preserving the shape of the original structure (Noffke et al. 2001).

In areas of thicker dark laminasets, quartz grains seem to float in the dark matrix (Fig. 4.16D), resembling textures produced by sediment-grain separation described by Noffke et al. (2001). Sediment-grain separation (Fig. 2.4; Fig. 2.10A) is the process by which thin biofilms progressively grow around quartz grains until individual grains float without contact with one another in the organic matrix of the mat (Noffke et al. 2001). Discrete fragments of dark laminasets are frayed, twisted and folded suggesting a high degree of cohesion (Fig. 4.17C, D). Because these fragments are not associated with any fractures or structural breaks, they are evidence that the host lithology was not deformed, but that the material had enough rigidity to bend and break shortly after deposition.

5.2 Classification of MISS

Noffke et al. (2001) introduced five structure-producing processes in their classification scheme: (1) leveling, (2) biostabilization, (3) imprinting, (4) grain separation and (5) baffling, trapping and binding. In this study we observed structures caused by four of the above processes: (1) Wrinkle structures and leveled surfaces are present in abundance (Fig. 4.1, 4.2, 4.7). (2) Desiccation cracks and perhaps gas dome features suggest biostabilization (Fig. 4.8, 4.9). (3) The process of imprinting was observed by dark, wavy-crinkly laminae draping over physical sedimentary features while still preserving their structure (Fig. 4.16C). (4) The process of grain separation was observed where 'floating grains' are embedded in dark, organic material (Fig. 4.16D). The process of baffling, trapping and binding (5) was not observed in the samples taken for this thesis. Table 5.1 highlights the structures seen at Horton Bluff matched to the microbial process that created them, based on Noffke et al. (2001).

Structures induced by…	**Structures seen at Horton Bluff**	**Figures in text**
Leveling	Leveled depositional surfaces, where microbial structures are associated with the filling of ripple troughs to form an even surface; wrinkle structures	3.2, 4.1-4.3, 4.6, 4.7, 4.10
Biostabilization	Desiccation cracks within sand and silt, which do not usually have sufficient cohesion to fracture	4.8B
Imprinting	Thick mat layers draped with near-uniform thickness over sediment mounds	4.16C, 4.17A
Grain separation	"Floating grains" within dark laminae, locally held in unusual orientations	4.16D
Baffling, Trapping and Binding	Not observed	NA

Table 5.1: Placement of Horton Bluff structures into the Noffke et al. (2001) classification for MISS.

In reference to the Schieber (2004) classification (Table 2.3), desiccation cracks would be classified as a feature formed by the physical destruction of a microbial mat, while all other observed structures would be classified as features formed by mat growth.

5.2.1 Microbial wrinkles

The origin and formation of “Kinneyia” type wrinkle structures remains controversial (Walcott 1914; Hantzschel and Reineck 1969; Hagadorn and Bottjer 1999). However, this study will follow the definition and understanding of Kinneyia wrinkles as provided both by Porada et al. (2008) as well as the comprehensive atlas of microbial features edited by Schieber et al. (2007). As noted in the atlas, Kinneyia is characterized by “sinuously curved, frequently bifurcating, flat-topped crests, usually 1 mm high and 1-2 mm wide, which are separated by parallel, round-bottomed depressions. The usually steep-sided crests may run parallel or form honeycomb-like patterns, sometimes with lateral transitions between the two shapes on the same surface” (Schieber et al. 2007).

Many of the wrinkles observed on bed surfaces at Horton Bluff match this description accurately. All wrinkles observed in the field had amplitudes of ~1-2 mm and wavelengths of 1-2 mm. Nearly all wrinkles were characterized by smooth, flat-topped crests. In addition, both linear and honeycomb forms are present. Smooth tops, low relief, and honeycomb structure are apparent in Figures 4.2C and 4.3, which have striking similarities with Images E and F in Figure 2.7. Figure 4.10 displays the linear Kinneyia form at Horton Bluff, dominated by winding, steep-sided, and flat-topped crests that are parallel to sub-parallel.

Not all wrinkles observed in the field are necessarily Kinneyia ripples, formed by hydrodynamic movement through sediments underneath a mat (Porada et al. 2008).

5.2.2 Non-microbial structures

When identifying MISS, difficulties may arise from ambiguity between the appearance of biological and physical sedimentary structures. Examples of similar-looking structures include rill marks, swash marks, adhesion structures and small-scale load structures (Fig. 2.9 B-E). Firstly, the wrinkle structures are not rill marks; rill marks display a regular drainage fan pattern which does not match the irregular appearance of these wrinkles. They are not swash marks, having a much higher relief and smaller wavelength, as well as forming small patches rather than elongate single ridges.

Adhesion structures are present as coarse-grained sand which is scattered over the crests of ripples; these are probably wind-blown and are not liable to be confused with wrinkle marks. In addition, irregular, millimetre-scale protuberances were present on some bed surfaces, and may be microbial in origin. However, these were not included in this study, because of their resemblance to some adhesion 'warts' described from modern settings. The distinctively wrinkled crests and troughs observed at Horton Bluff are not closely similar to the interfering growths of small adhesion structures described from modern settings.

Small-scale load structures have in the past been a source of confusion with MISS, especially in broken blocks. However, most of the microbial structures exist as patches on an otherwise smooth surface. In addition, while load structures are found on the soles of coarser beds, the MISS described here all exist on the top surfaces of beds.

5.3 Paleoenvironmental Implications

5.3.1 Leveled depositional surfaces

The superb three-dimensional preservation of wrinkle structures at Blue Beach indicates advanced stages of microbial mat growth. Their presence on relatively flat upper surfaces of sandstone beds implies that the bed has been leveled (Noffke 2001). Leveling refers to the process shown in Figure 2.3, in which microbial growth first occurs in ripple troughs because of the ecological advantage of moisture and protection against erosion. Growth continues upward until the previously rippled surface is now leveled, covered with a rubbery microbial mat which will wrinkle when exposed to wind shear or water friction. Planar, wrinkled surfaces with traces of ripples still present are observed in 20 segments of the Horton Bluff bedset.

An additional 17 segments contain wrinkles that are localized on certain areas of ripples. Of these, 10 occur on ripple crests (60%), 4 occur on ripple flanks and 3 occur in ripple troughs (Fig. 4.12). The apparent preference of microbial mats for the crests of ripples seems to contradict the conventional understanding of MISS, especially with respect to the 20 bed segments representing 'leveled depositional surfaces'. Some speculation will be offered.

In every MISS occurrence on ripple crests, the ripple crests have been planed off by sub-aerial exposure caused by a drop in water level. Often the planed off areas had low rims around them. It could be that the rims enabled enough water to be retained in the flattened area to provide a moist, favourable colonization site for microbial growth. In addition, the material eroded from the crests of the ripples during exposure was likely shed into the troughs, contributing to the leveling process. This sediment deposition into the troughs of ripples worked in conjunction with upward microbial growth to create a leveled surface across which the original ripples are barely visible. This process would require a low enough sediment influx that the mats were not rapidly buried.

It is known that a variety of different microbial growth processes can occur in the same region as a result of the sensitivity of microbial mats to highly localized environmental conditions. For example, it is plausible that microbial mats could be 'leveling' ripples in one area, while 'imprinting' them in another (Noffke et al. 2001).

During storm events, which inevitably bury and preserve the mats, perhaps the flattened crests of ripples form neat impressions that are easily preserved, while the troughs are buried in excess sediment, eliminating the trace of microbial mats.

The seemingly anomalous data may in fact be a coincidence due in part to the small size of the dataset. The understanding of the relationship between localized MISS and their corresponding ripple marks could be greatly improved the mapping of four adjacent bed surfaces which show similar quality and abundance of microbial wrinkle coverage as the bedset mapped in this study.

5.3.2 Kinneyia wrinkles

Porada et al. (2008) suggested that Kinneyia ripples are formed not by the mats themselves but by groundwater flowing through the sediment beneath a microbial mat. In the aftermath of floods or storms, downslope groundwater currents are superimposed on tidal hydrodynamics in the lower part of the tidal flat. Alternating signals of compression and liquefaction in the “mat-confined” layer of sediment produces the pattern of flattened alternating ridges and troughs called Kinneyia (Porada et al. 2008).

In addition to the striking similarity in appearance of the structures at Horton Bluff to Kinneyia wrinkles in the literature, the paleoenvironment of Horton Bluff matches the intertidal setting described by Porada et al. (2008)(Section 5.1). However, acceptance of the process inferred by Porada et al. (2008) implies that the wrinkle structures must in fact be the sediment underneath a former mat. No original organic mat is evident on the exposed surface of the Horton Bluff bedset, nor in the topmost laminae of the cut block and thin sections. The mudstone directly above the mapped section that is eroding away to expose the wrinkles may include the mat-containing layer, but this is difficult to determine.

It should be noted that the motion of hydrodynamic energy through the sediments underneath a mat, as proposed by Porada et al. (2008), is one of several theories on the formation of Kinneyia ripples. While the structures observed at Horton Bluff are most easily classified as Kinneyia, other processes may have formed some wrinkle marks. Wind shear acting on a tidal platform can fold or tear apart a microbial mat, deforming the attached substrate underneath. This process occurs regularly on modern microbial mats (Singh and Wunderlich 1978; Schieber et al. 2007). The friction of a detached mat traveling slowly down a tidal slope may also cause wrinkles in the sediment. In addition, the desiccation of a mat would have a compressional effect on its attached substrate as it shrinks in size (Gerdes et al. 2000).

5.3.3 Increased cohesion

Desiccation cracks are common throughout the mapped section. However, grain-supported layers like the quartz-rich siltstone surface in question should not shrink upon desiccation (Schieber 2004). Thus an additional substance must have been present between the sand grains. Microbial filaments and the mucilage of extracellular polymeric substances that coat individual quartz grains change the cohesion of the bed such that it can shrink upon desiccation (Bouougri and Porada 2002; Sarkar et al. 2006). Therefore, the shrinkage cracks seen throughout the section are likely a reflection of microbial influence.

5.3.4 Addition of carbon

The result of field mapping produced an estimate that 12.6% of the surface area was covered by wrinkled patches linked to microbial mats. This number is striking in its implication of the amount of microbial biomass that originally existed in this environment, which was previously unknown. Furthermore, a much larger area may originally have been covered but is now partially eroded. Several other bedsets nearby have not been mapped but also contain excellently preserved surface wrinkles, and therefore could have similar proportions of areal coverage.

The thin section results present convincing evidence that the preserved remnants of microbial mats exist in the strata at Horton Bluff. The presence of microbial organic material, in addition to the plant fragments observed in thin section, has implications of a potential source of hydrocarbon deposits in the Horton Bluff area. While an estimation of preserved organic matter has not been attempted, standard volumes of total organic carbon (TOC) as low as 0.5% have generated economic volumes of petroleum deposits for unconventional resources like shale gas (Rokosh et al. 2009).

5.4 Impact on Geological Record

The preserved microbial wrinkles at Horton Bluff are arguably a world-class example of microbially-induced sedimentary structures. As such, this site is an important addition to the geologic record of sites that display MISS. While the geologic record is long, spanning from the Archean to the present, it is by no means complete.

The world's oldest example comes from the Archean located in Barberton, South Africa, and corresponds to the geologic time period when cyanobacteria first evolved. There are several examples of preserved MISS from rocks of this age (Hagadorn and Bottjer 1997; Noffke et al. 2006; Noffke et al. 2008). The vast majority of specimens come from the Proterozoic (Bouougri and Porada 2002; Sarkar et al. 2006), which corresponds to a time when cyanobacteria had witnessed enough evolution to become a successful taxonomic group, but before the evolution of plants and, until late in the Proterozoic, grazing predators. After the Cambrian, few occurrences of MISS have been identified.

Thus, the discovery of MISS within these Carboniferous rocks is a striking addition to the geologic record. Simultaneously, the very existence of MISS raises the question of preservation. The Mississippian-aged Horton Bluff paleoenvironment is characterized by vertebrate and invertebrate trackways, preserved trace fossils, agglutinated foraminifera, ostracodes, fish, tetrapods, and terrestrial plant matter. In short, this paleoenvironment supports many organisms that would presumably graze on or compete with microbial life, raising an obstacle to preservation. A probable answer lies in the stressed conditions of the environment.

Brackish conditions caused by marine fluctuations, erosive tidal energy, highly variable exposure periods and temperature fluctuations all contribute to create an environment that is inhospitable to many plants and animals, allowing microbial life to flourish. With plentiful invertebrate fauna and plant material in the strata above and below this bedset, a rapid, localized change in environment must have occurred. The only other fossil evidence found along the bedset was one invertebrate trackway, which was not enough to make an inference.

Finally, rapid burial must have occurred to preserve the wrinkle structures through diagenesis. This is supported by the thin section results, which show thin laminae and varied grain size, suggesting episodic deposition.

5.5 Novelty of the Results

This study is among the first of its kind. While the study of microbial mats and the structures they form is relatively recent in sedimentology, this specific study is novel in its attempt to quantify microbial colonization of a bed surface. Noffke and Krumbein (1999) created a Modification index (MOD-I) based on the proportion of mat coverage, steepness of slope of erosional remnant, and degree of microbial levelling at a site of modern microbial mat growth on Mellum Island, southern North Sea (Germany). However, no study known to us has attempted to quantify the degree of microbial colonization of an ancient surface. These results are therefore novel and useful as an initial benchmark for other studies to come.

Chapter 6: Conclusion

6.1 Microbial Mats at Horton Bluff

1) MISS are preserved in fine-grained siliciclastic sediments of Mississippian age in the Horton Bluff Formation near Hantsport, Nova Scotia. Abundant wrinkle structures exist on bed surfaces and fragments of microbial mats exist in thin section and hand samples. The widespread presence of microbial life in this paleoenvironment was previously unknown.
2) A total of 12.6 % of the mapped bedset surface is covered with sinuous, flat-topped wrinkle structures. These structures resemble Kinneyia ripples, some of which formed by small channels of water forming grooves in the substrate underneath a microbial mat.
3) The microbial structures observed at Horton Bluff fit with the classification scheme for MISS proposed by Noffke et al. (2001) and reflect four of five defined processes of mat-sediment interaction. The structures reflect (i) leveling of the sediment surface as mats and sediment infill topography, (ii) biostabilization of surfaces, (iii) imprinting of physical structures by the mat, and (iv) sediment-grain separation within growing mats. Structures reflecting an additional process, (v) baffling, trapping and binding, were not observed.
4) Due to grazing by animals and competition for food and nutrients by plants, microbial mats are rarely preserved in the fossil record after the Cambrian. The unique preservation and excellent exposure seen at Horton Bluff implies that the ecological conditions of this particular bedset were stressed by tidal energy, brackish conditions, exposure and temperature variation, reducing the growth and survival of other life forms. The stressed conditions must have been highly localized, as preserved plant and animal fossils exist in the strata above and below the bedset. Rapid sedimentation and burial must have occurred in order to preserve both the surface wrinkles and the organic mat fragments seen in thin section.

6.2 Effect on the Environment

1) Surface Leveling–Cyanobacterial mats have leveled surfaces that were previously covered in ripples and have stabilized these surfaces against erosion.
2) Increased cohesion–The presence of microbial EPS coating around quartz grains may have added cohesion to the sediment layer, allowing it to shrink and crack upon desiccation.
3) Addition of Carbon–The colonization percentage and presence of organic matter in thin section suggest that this depositional system was much more productive than previously believed. This new knowledge of substantial microbial matter present both in the past and present increases the source rock potential of the area, which in the past has been considered poor.

6.3 Geological Record

This study represents a novel data source in the published material on microbial mats, namely, the degree of microbial colonization of an ancient surface. While already a location of excellent preservation and therefore importance, the Mississippian age of the rocks adds weight to the value of this location because of the scarcity of MISS after the Cambrian. Further study of this site can be used to gain insight on the relationship of microbial mats and sedimentary environments after the Cambrian.

6.4 Recommendations

There are four other bedsets in the near vicinity of the bedset mapped in this study. These should ideally be mapped in similar fashion, with thin sections taken vertically through the bed in the same fashion as this study has done. The addition of these bedsets would greatly increase the sample size of this dataset, adding weight to the interpretations. Comparison between bedsets would also provide further constraint on the stratigraphy and paleoenvironmental conditions of this time in which microbial life was able to flourish. In addition, candidate microbial laminae in polished thin sections and blocks should be examined under ultraviolet light to confirm their organic nature.

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Appendix A: Field data from Horton Bluff bedset

Length	MISS (bin)	% MISS	Ripples (bin)	MISS & ripples	MISS ripple crest (bin)	MISS ripple trough (bin)	MISS ripple flank (bin)	Desiccation cracks (bin)	Rills/water marks (bin)	Grooves or scouring (bin)
0-1m	1	5	1	1	1	0	0	0	0	1
1-2m	1	0.9	1	1	1	0	0	0	0	0
2-3m	0	0	1	0	0	0	0	0	0	0
3-4m	1	0.9	0	0	0	0	0	0	1	1
4-5m	0	0	1	0	0	0	0	0	1	1
5-6m	0	0	0	0	0	0	0	0	0	0
6-7m	0	0	1	0	0	0	0	0	0	0
7-8m	1	1	1	1	0	0	1	0	0	0
8-9m	0	0	0	0	0	0	0	0	0	0
9-10m	1	1	1	1	0	0	0	0	0	0
10-11m	0	0	1	0	0	0	0	0	0	0
11-12m	BD	-	-	-	-	-	-	-	-	-
12-13m	1	0.9	1	1	0	0	0	0	0	0
13-14m	1	0.9	1	1	0	0	1	0	0	1
14-15m	1	0.9	1	1	1	0	0	0	0	0
15-16m	1	0.9	1	1	0	0	0	0	0	0
16-17m	0	0	1	0	0	0	0	0	0	0
17-18m	1	0.9	1	1	0	0	0	0	0	0
18-19m	1	0.9	1	1	1	0	0	0	0	0
19-20m	1	10	1	1	0	0	0	0	0	0

20-21m	1	15	0	0	0	0	0	0	1	0
21-22m	1	20	0	0	0	0	0	0	0	0
22-23m	1	30	0	0	1	0	0	0	0	0
23-24m	1	70	0	0	1	0	0	0	0	0
24-25m	1	60	0	0	0	0	0	0	0	0
25-26m	0	0	0	0	0	0	0	0	0	0
26-27m	0	0	0	0	0	0	0	0	0	0
27-28m	BD	-	-		-	-	-	1	-	-
28-29m	1	50	0	0	0	0	0	0	0	0
29-30m	1	0.9	1	1	0	1	0	0	0	0
30-31m	0	0	0	0	0	0	0	0	0	0
31-32m	1	60	0	0	0	0	0	0	0	1
32-33m	1	20	0	0	0	0	0	0	0	0
33-34m	1	15	1	1	0	0	0	0	0	0
34-35m	1	10	1	1	0	1	1	0	0	0
35-36m	1	4.9	1	1	0	0	0	0	0	1
36-37m	0	0	1	0	0	0	0	1	0	0
37-38m	1	10	1	1	0	0	0	0	0	0
38-39m	1	5	0	0	0	0	0	0	0	0
39-40m	1	40	0	0	0	0	0	0	0	1
40-41m	1	50	0	0	0	0	0	0	0	1
41-42m	1	50	1	1	1	1	0	0	0	0
42-43m	1	10	1	1	1	0	0	0	0	0
43-44m	0	0	0	0	0	0	0	0	0	0

44-45m	1	5	1	1	1	0	0	0	0	0
45-46m	1	5	1	1	0	0	0	1	0	0
46-47m	1	4.9	1	1	0	0	0	1	0	0
47-48m	1	4.9	1	1	0	0	0	0	0	0
48-49m	1	5	1	1	0	0	0	0	0	0
49-50m	1	5	1	1	0	0	0	0	0	0
50-51m	1	3	1	1	0	0	0	1	0	0
51-52m	1	4.9	1	1	0	0	0	0	0	0
52-53m	1	4.9	1	1	0	0	0	0	0	0
53-54m	0	0	0	0	0	0	0	0	0	0
54-55m	1	0.9	0	0	0	0	0	0	0	0
55-56m	1	0.9	1	1	0	0	0	0	0	0
56-57m	1	30	1	1	0	0	0	0	0	0
57-58m	1	10	1	1	0	0	0	0	0	0
58-59m	1	10	1	1	0	0	0	1	0	0
59-60m	1	50	1	1	0	0	0	0	0	0
60-61m	1	70	1	1	0	0	0	0	0	0
61-62m	1	10	1	1	0	0	0	0	0	0
62-63m	BD	-	-	-	-	-	-	-	-	-
63-64m	BD	-	-	-	-	-	-	-	-	-
64-65m	BD	-	-	-	-	-	-	-	-	-
65-66m	0	0	1	0	0	0	0	0	0	0
66-67m	BD	-	-	-	-	-	-	-	-	-
67-68m	0	0	1	0	0	0	0	0	0	0

68-69m	1	30	1	1	1	0	1	0	0	0
69-70m	1	15	1	1	0	0	0	0	0	0
70-71m	1	4.9	1	1	0	0	0	0	0	0
SUM	**50**	**12.605***	**45**	**37**	**10**	**3**	**4**	**6**	**3**	**8**

Field data from the Horton Bluff bedset displayed in spreadsheet fashion. Most sedimentary features are recorded in binary form (bin), with the value 0 indicating the section does not have the feature in question, and the value 1 indicating the feature is present. % MISS refers to the proportion of the total surface area that is covered in microbial features, determined by visual estimate. BD stands for ‘bad data’, indicating the surface was covered in mud, algae or other, preventing reliable estimate of sedimentary features. There are 71 sections in total, 6 of these being marked as BD for a total of 65 sections of reliable, useable data. The bottom row illustrates the sum of features in that particular column out of 65, with the exception of the third column (% MISS), denoted by an asterisk. 12.605% is the average of the visual estimates of microbial surface coverage for the 65 sections. This number represents the colonization rate of the entire bedset. In this column, a value of 4.9 represents the qualitative estimate of “less than 5%”, whereas the value of 0.9 represents the estimate “less than 1%”.