Rice University

Detailed Characterization of Upper Cambrian Microbial Buildups
(Mason County, Texas, USA)

by

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TABLE OF CONTENTS

ABSTRACT

1. INTRODUCTION

2. BACKGROUND

3. METHODS
   3.1 Field Studies
   3.2 Systematic Coring
   3.3 High Resolution Visual and Hyperspectral Scanning
   3.4 Thin Sections
   3.5 Isotopic/Geochemical Studies

4. RESULTS
   4.1 Lower Point Peak and Flat Pebble Deposits
   4.2 Phase 1 Growth
   4.3 Phase 2 Growth
   4.4 Phase 3 Growth
   4.5 $\delta^{13}$C / $\delta^{18}$O Isotope Analyses

5. DISCUSSION
   5.1 Growth Textures
   5.2 Transgressive Lag
   5.3 Phase 1
   5.4 Phase 2
   5.5 Phase 3
   5.6 Modern Bahamian Analog
   5.7 Depositional Model

6. CONCLUSIONS

7. REFERENCES

8. FIGURES
LIST OF FIGURES

Figure 1 – Paleo World Map
Figure 2 - Laurentia Map
Figure 3 – Calcimicrobes of Upper Cambrian
Figure 4 – Llano Uplift Geologic Map
Figure 5 – Llano Uplift Geologic Cross Section
Figure 6 – Google Image of Local Mason County Ranches
Figure 7 – Local Geologic Map and Cross Section
Figure 8 – Shepard Cliff
Figure 9 – Zesch Cliff
Figure 12 – Mill Creek Outcrop
Figure 11 – James River Aerial View
Figure 12 – Mitch Herm Outcrop
Figure 13 – James River Core Transects
Figure 14 – Fallen Block Core Transect
Figure 15 – H1 Core Transect
Figure 16 – H2 Core Transect
Figure 17 – H3 Core Transect
Figure 18 – Twin Herm Core Transect
Figure 19 – Rosie Core Transect
Figure 20 – Andrea Core Transect
Figure 21 – Don Core Transect
Figure 22 – Microbial Fabrics in Core
Figure 23 – Droxrock
Figure 24 – Lower Point Peak Flat Pebble Deposits
Figure 25 – Lower Point Peak 3D Channel Outcrop
Figure 26 – Fallen Block Composite
Figure 27 – Embryonic Core Composite
Figure 28 – Core 86A Thin Sections
Figure 29 – DroxRock Irregular Phase Boundary
Figure 30 – H1 Aerial View
Figure 31 – H1 Transect with Core Scans
Figure 32 – H2 Transect with Core Scans
Figure 33 – H3 Transect with Core Scans
Figure 34 – Phase 1 Cores Siliciclastic Content
Figure 35 – DroxRock Margin
Figure 36 – Phase 2 Twin Herm Core Composite
Figure 37 – Phase 2 Twin Herm Grainstone
Figure 38 – Andrea Transect
Figure 39 – Andrea Interbuildup Core Transect
Figure 40 – Granddaughters and Jack
Figure 41 – Phase 3 Core Scans
Figure 42 – Phase 3 Core Siliciclastic Content
Figure 43 – H1 Isotopic Data
Figure 44 – Don Transect Isotopic Data
Figure 45 – Modern Bahamian Microbialite Analog
Figure 46 – Upper Cambrian Depositional Model
Detailed Characterization of
Upper Cambrian Microbial Buildups
(Mason County, Texas, USA)

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ABSTRACT

Field studies, extensive shallow coring, thin section petrography, and hyperspectral scanning are used to characterize a series of Upper Cambrian (Wilberns Formation) subtidal microbial reefs outcropping in Mason County, central Texas. Results document details of microbial textures that were responsible for growth of the buildups, thereby providing an understanding of the environmental conditions that influenced varied stages in their evolution. Thrombolitic fabrics of dominantly microbial micrite with fossil fragments evidence carbonate precipitation induced by microbial colonies that produced a tight framework hindering diagenesis. Stromatolitic fabrics show alternating laminations of microbially precipitated calcite and amalgamated trapped grainstones exhibiting ferroan dolomite replacement and subsequent oxidation of these grains.
Initial characterization of the microbial reefs identified successive growth stages, repeatedly identifiable across several separate outcrops, from which a three-phase growth model was formulated. Within the context of the three phases, the core-based geologic characterization of the buildups and coeval sediments refines the growth model into a more robust depositional model. Nucleating on lenses of flat pebbles, an initial “colonizing” Phase 1 growth results in 3-4 m high buildups defined by their distinct and early-cemented outer margins of a thick thrombolitic rind. Buildup interiors exhibit amalgamated microbial heads with poorly preserved internal structure enveloped by cm-thin thrombolitic rinds. The buildups grew in high-energy conditions, but without interacting with coeval interbuildup oolitic-bioclastic grainstones. Phase 1 terminated with onlapped terrigenous and calcareous silts (~35% CaCO₃). The overlying Phase 2 growth produced buildups up to 8 m thick, characterized by a mutual interaction with interbuildup high-energy oolitic-bioclastic grainstones and packstones and generally lacking an external rind. Internally, Phase 2 growth consists of vertically aggrading and laterally expanding stromatolitic columns, each exhibiting cm-thick thrombolitic rinds directly interacting with intercolumn bioclastic grainstones. Phase 3 of growth produces a well-defined thrombolitic 2-3 m thick rind atop Phase 2, and in some instances on top of the interbuildup grainstones.

1. INTRODUCTION

Through the past 3.5 billion years microbial reef systems grew through a variable combination of both trapping and binding of grains, transported as suspended load during high-energy events, in addition to microbe-induced precipitation of carbonate material directly from seawater (Burne and Moore, 1987; Riding, 2011; Reid et al., 1999; Reid et
This research directly addresses the role of direct precipitation and/or trapping and binding, as well as the importance of interactions with contemporaneous sediments, to microbial growth in the effort to construct a depositional model for Upper Cambrian microbial reefs.

As reefs grow in an equilibrium state with respect to their environment, characterizing the nature of the microbialites will also provide unique information to help our understanding of their depositional environment conditions, in the context of their three successive well-established growth phases. As sunlight and nutrient availability positively affect reef growth, water turbidity negatively influences their growth and if excessive may trigger demise, while accommodation (water depth) controls the growth structure of a reef. Therefore, variations in growth morphology can be related to variable accommodation throughout the growth of the buildups. Fluctuations in the dominant microbial community, resulting from small-scale changes in the depositional environment, produce variations between the two main styles of accretion, and subsequently, variations within the dominant growth fabric. Therefore, a relationship between the dominant growth fabric and small-scale changes in the depositional environment can also be established.

The study area within Mason County, central Texas, exhibits world-class microbialite outcrops consisting of a combination of recently accessible bedding plane exposures, here termed pavements, and cliff exposures along the Llano and James Rivers, and Mill Creek. Although these outcrops were previously recognized (Bridge et al., 1947; Sliger 1957; Ahr, 1967, 1971; Ruppel and Kerans, 1987; Burne and Moore, 1987; Spincer, 1997; Johns et al., 2007), their inaccessibility on private ranches over the past
several decades has inhibited detailed studies with a more modern view and using newer approaches. In particular along the James River, the extensive outcrop is composed of a pavement of microbial buildups adjacent to a cliff face displaying buildup interactions with coeval interbuildup strata, where some of the buildups are fully cropping out. This juxtaposition of vertical and horizontal cross-sections offers a unique “3D perspective” into an Upper Cambrian microbial reef complex.

Carbonate grain and fossil assemblage analysis, isotopic analysis, and sedimentary structures indicate open marine tidal conditions for growth of the Cambrian microbial complex (Swartz et al., 2015; Kelleher et al., 2016). The presence of modern marine stromatolites within a similar setting on Great Bahama Bank (Lee Stocking tidal channels of the Exuma Cays; Eleuthera Bank) (Logan and Ginsburg, 1962; Dill et al., 1986; Reid et al., 1999; Reid et al., 2000; Dravis, 2006) offers a viable analog that can be used for direct comparison to the Cambrian microbialites, with one exception being the occurrence of siliciclastics in the latter.

2. BACKGROUND

Four main landmasses - Laurentia (present day North America), Baltica, Siberia, and Gondwana - occurred in the Upper Cambrian (Fig. 1). The study area in central Texas would have been located on the southwestern margin of Laurentia, contained within a shallow epeiric sea and forming what is commonly referred to as the Great American Carbonate Bank (Sloss et al., 1949; Morgan, 2012). Laurentia was rotated 90 degrees clockwise from its modern position and the study area would have been situated just south of the equator (Fig. 2) where shallow warm seas within sub-equatorial latitudes fostered prolific growth of carbonate microbial reefs, represented in our study area by the
Point Peak Group of the Wilbersns Formation (Bridge et al., 1947; Ahr, 1967, 1971; Barnes and Bell, 1977; Barnes et al., 1959; Khanna et al., in prep). Following the decline of Archaeocyaths calcimicrobes became the dominant reef-building organisms in the Upper Cambrian (Fig. 3) (Miller et al., 2012; Lee et al., 2014; Chen et al., 2014b). Burne and Moore (1987) define such calcimicrobe-constructed reefs as “organo-sedimentary deposits, which accrete as a result of benthic microbial communities trapping and binding detrital sediment and/or forming the locus of precipitation.” Benthic communities in the Upper Cambrian include microbes, bacteria, and blue-green algae (Pratt et al. 2001) commonly identified as *Girvanella, Epiphyton, Renalcis,* or *Tarthinia* (Ahr, 1971; Riding et al, 1991; Elicki, 1999; Riding, 2000; Pratt, 2001; Rowland and Shapiro, 2002; Woo et al., 2008; Miller et al., 2012).

Within central Texas, the targeted Point Peak strata are exposed from a combination of faulting and erosion associated with exhumation of the Llano Uplift (Fig. 4 & 5) (Polk, 1952). More specifically, the study area spans the Zesch and Eagle Ridge Ranches of southern Mason County where the Morgan Creek, Point Peak, and San Saba Members of the Wilberns Formation outcrop along the Llano and James Rivers as well as Mill Creek (Fig. 6). A geologic map and accompanied cross-section (Fig. 7) illustrate how local faulting and channel incision led to these outcrop exposures (5et al., 1957; Khanna et al., in prep). Although these outcrops were previously recognized (Bridge et al., 1947; Sliger 1957; Ahr, 1967, 1971; Ruppel and Kerans, 1987; Burne and Moore, 1987; Spincer, 1997; Johns et al., 2007), their inaccessibility on private ranches over the past several decades has inhibited detailed studies with a more modern view and using newer approaches. Cliff exposures along the Llano River (Fig. 8 & 9) are exquisite
opportunities to study morphological characteristics of the microbial buildups present in 2D at an almost seismic scale, while accessible outcrops along Mill Creek (Fig. 10) and the James River (Fig. 11) allow complementary direct observation and sampling accessibility. In particular, extensive pavement exposures along the James River adjacent to cliff faces offer a 3-D detailed view of a microbial reef complex, outcropping across 0.25 km² and reaching 15 m at its thickest central part (Khanna et al., in prep).

A key example of a well-developed upper Point Peak buildup, a single buildup along the Zesch Cliff referred to as Mitch Herm (Figure 12), illustrates many important aspects of buildup growth and the surrounding strata. The lower Point Peak strata underlying the microbial reef interval consist of dominantly thinly bedded siltstones and sandstones with an admixture of carbonates (Sliger 1957; Kelleher et al., 2016; Khanna et al., in prep). Symmetrical megaripples with bidirectional cross bedding (indicative of tidal currents), fining upward beds of irregular thicknesses (interpreted as tidal channels that have been filled by storm deposits), and abundant ooids (indicating a high energy environment with proximity to a subtidal environment) characterize these strata (Swartz et al., 2015; Kelleher et al., 2016). These beds are highlighted by a greenish tint, evidencing glauconite, and are interpreted to represent a coastal marine setting containing shallow subtidal/intertidal depositional environments. Halfway up the cliff containing the Mitch Herm buildup, a massive 1-2 meter thick orange carbonate skeletal and ooid grainstone bed strikingly contrasts with the underlying lower Point Peak strata. This bed is interpreted to represent a relatively deeper subtidal environment; its base, referred to as “the switch,” marks the initiation of the microbial reef interval (Fig. 12). The transition
from mixed carbonates-siliciclastic to pure carbonate deposition, interpreted to be transgressive in nature, distinguishes the lower and upper Point Peak.

The initial “colonizing” Phase 1 of microbial development is defined by 2-3 meter thick buildups with distinct rinds developed around their outer margins. While Phase 1 initially grows contemporaneously to laterally adjacent oolitic bioclastic grainstones, fine-grained mixed sediments with an aluminosilicate component (hereafter simply referred to as siliciclastics) replace these grainstones and onlap the rind, marking the end of Phase 1 growth. The second growth phase of the buildups occurs on top of Phase 1 and is defined by “vertically aggrading” and “laterally expanding” microbial columns, distinctly interacting with coarser-grained skeletal-oolid and mixed siliciclastic carbonate interbuildup sediments. Growth Phase 3 acts as a distinct “capping phase” on top of the Phase 2 buildup reefs, although in some instance growing on top of the interbuildup grainstone. Phase 3 microbial growth is onlapped by fine-grained mixed sediments, similar to those present at the end of Phase 1, that indicate the ultimate demise of the microbial growth.

3. METHODS

This study is based on the use of field observations, core analyses of an extensive suite of shallow cores drilled from key outcrops, coupled with detailed thin section petrography, hyperspectral core scanning, and isotopic/geochemical data sets. Direct outcrop studies characterize numerous individual microbial buildups and their relationship with interbuildup strata. This approach includes collecting and interpreting individual measured and log sections to correlate the microbial reef unit across several outcrops and placing them within a larger, regional context.
3.1 FIELD STUDIES

Previous observations of the large microbial buildups focused on cliff faces along the cutbanks of the Llano River (Ahr, 1967, 1971; Ruppel and Kerans, 1987). River access via kayaking broadened the current study to the three main cliffs between Whites and James crossings in the southern part of Mason County. Along each cliff, buildup morphologies, interactions between adjacent buildups, and relationships with the coeval strata were studied in detail. High-resolution virtual outcrops were created of whole cliff faces by utilizing mosaics of images acquired using a drone. Through characterizing the buildups contained within the cliff faces, a 3 Phase Growth Model was developed (Khanna et al. in preparation). Expansion of the project to a series of outcrops on the Eagle Ridge Ranch along the James River and Mill Creek proved to be critical for direct observations and sampling of the microbial reefs and their intervening contemporaneous sediments.

3.2 SYSTEMATIC CORING

Approximately 230 oriented cores, either 7.5 or 15 cm in diameter and up to 50 cm long, were collected along a series of transects (Fig. 13) through the different microbial buildup growth phases, as well as the coeval inter-buildup strata on pavements and along cliff outcrops. A series of lateral transects consisting of vertical cores provide insight into spatial variations across the buildups while vertical transects are used for temporal characterization and variations of the microbial growth. These drill core transects include:

1) Cores collected through the initial grainstone bed and base of the contemporaneous Phase 1 growth collected from a fallen block along Mill Creek.
This block, representing an individual microbial buildup lying on its side adjacent to the cliff from which it was dislodged, displays a complete 3D substratum on top of which Phase 1 initially grew (Fig. 14). This transect is used to understand the relationship between the initial growth of a buildup and the Phase 1 interbuildup sediments.

2) A lateral transect of vertical cores, named H1, was drilled across a single microbial reef representing Phase 1 microbial growth (Fig. 15). The buildup across which this transect was taken has been laterally bisected to reveal the internal structure of a Phase 1 buildup.

3) A transect of vertical cores, named H2, was drilled both laterally and vertically through a small buildup representing a full Phase 1 growth (Fig. 16). Using a stair-step pattern, these cores cut through the side, interior, and upper surface of a Phase 1 buildup.

4) A transect of vertical cores, named H3, was drilled both laterally and vertically across a Phase 1 buildup beginning in the interior, continuing through the upper surface and ending in the overlying strata, referred to as “the Cover” (Fig. 17).

5) A vertical core transect, named the Twin Herm Transect, beginning at the upper surface of Phase 1, continuing through Phase 2 and ending in the upper Phase 3 (Fig. 18), is complemented by a series of cores sampling the top of Phase 2, a fully developed Phase 3, and a mixed silty carbonate section in between Rosie and Andrea buildups.
6) A series of cores taken between two large buildups (Rosie and Andrea), named the Andrea Transect, focusing on the upper portion of Phase 2 and associated flank deposits (Fig. 19).

7) A series of cores taken between two large buildups (Rosie and Andrea), named the Rosie Transect, focusing on the upper portion of Phase 2 and associated flank deposits (Fig. 20).

8) A vertical transect of 40 short cores named the Don Transect beginning at the upper part of Phase 1 and continuing through Phase 2 and into the upper Phase 3 of buildup growth (Fig. 21).

3.3 HALF CORE HIGH RESOLUTION VISUAL AND HYPERSPECTRAL SCANS

Cores were cut in half vertically, with one half reserved for polishing and then high-resolution scanning to enhance macroscopic details while the other half was used for subsampling. Important macro-scale textures representing different microbial growth fabrics (stromatolitic versus thrombolitic) were noted for further examinations in reference to styles of microbial growth (trapping and binding versus microbial induced carbonate precipitation). High-resolution scans, taken of the polished halves, were utilized for detailed visual and binocular observations and subsample/thin section targeting.

Hyperspectral scanning of the cores provided detailed data of the bulk compositional mineral characteristics of the cores by a combination of high resolution reflectance spectroscopy (0.5mm), visual imagery (0.05mm) and 3D laser profiling to map mineralogy and geochemistry. Different minerals exhibit spectral characteristics that absorb light at unique wavelengths of the light spectrum. Hyperspectral scanning
identifies relative abundances of multiple minerals within a specific area by detecting multiple wavelengths at which light is reflected.

Core scans illustrating the main growth fabrics and interactions with coeval inter-buildup strata, and complimented with hyperspectral scans, are shown in Figure 22. The high resolution and hyperspectral scans shown the microbial fabrics and indicate the associated dominant mineral composition (including different types of calcite and dolomite, in addition to aluminosilicates). Secondary minerals are not indicated but most likely exist in lower percentages within the same area. Then the overall observations and analyses were placed in the context of the 3 Growth Phase model to understand the compositional nature and evolution of the buildups.

3.4 THIN SECTIONS

Core subsampling by 30-45 mm diameter plugs were used for thin section preparation and analysis for the identification of micro-characteristics that can then be considered in the context of microbial facies identification in the larger microbial reef unit. Carbonate grains were also identified. Thin sections were stained with Alizarin red S and potassium ferricyanide to differentiate dolomite from calcite; calcite would stain red with Alizarin red while potassium ferricyanide would indicate iron-rich dolomite. A blue epoxy additionally indicates porosity within the sample.

3.5 ISOTOPIC/GEOCHEMICAL STUDIES

Geochemical studies (δ¹³C and δ¹⁸O) provide additional insight into paleoenvironmental conditions during microbial growth, as well as alteration effects during diagenesis. Results of isotopic and geochemical analyses also strengthen the 3 Phase Growth Model. An isotopic study was conducted along a vertical core transect
(aforementioned Don Transect) through a large three phase buildup, as well as along a horizontal core transect across a single Phase 1 buildup (H1 transect). Two subsamples from each core were collected with a microdrill for $\delta^{13}$C and $\delta^{18}$O measurements. These two core transects offer a perfect opportunity to systematically study spatial and temporal variations in isotopic signatures across the three phases of buildup growth. Areas that appeared to be less altered were targeted for the isotopic studies due to their propensity to contain original depositional compositions and characteristics, while some altered areas were targeted to understand the diagenetic influence on isotopic values, which can be explored further in future works.

In order to better understand the siliciclastic influences on the buildups and surrounding strata, carbonate content measurements through the carbonate bomb technique were taken. This technique, in conjunction with hyperspectral imaging, provides information regarding the connection between variable influx of siliciclastics into the buildups and coeval sediments, as well as its influences on the microbial growth fabrics (Singh et al., 2016 GSA abstract).

4. RESULTS & INITIAL INTERPRETATION

The study area encompasses over 25 square kilometers, and although all of the outcrops fully display the upper Point Peak large microbial buildup-bearing interval and at least some of the underlying lower Point Peak, certain locations were used to answer questions regarding specific aspects of the 3 Phase Growth Model of the upper Point Peak large microbial buildups. Using a variety of outcrops helped to refine the 3 Phase Growth Model by providing the highest possible geologic details to the individual phases of the buildups, as well as the underlying and coeval sedimentation.
For example, the cliff faces along Mill Creek display the best example of the upper part of the lower Point Peak, dominantly containing thinly bedded, recessive, fine-grained, mixed carbonate siliciclastic strata that are periodically interrupted by relatively thick and erosive-resistant layers of mostly flat pebble deposits. Within the same cliff face, these easily erodible layers suddenly pass into a massive carbonate oolitic bioclastic grainstone bed, forming a distinct overhang at the same level of which large microbial buildups are established referred to previously as the “switch.”

A single perfectly preserved microbial buildup, displaying the three growth phases, has been dislodged from the cliff face itself and offers full access to its underside for studying its initial reef growth (aforementioned Fallen Block). Further down Mill Creek an isolated buildup, named DroxRock (Fig. 23), helps directly observing and understanding the construction of Phase 2 on top of the upper rind of Phase 1, and Phase 2 interaction with its surrounding sediments, and the Phase 3 capping of the microbial reef.

This study mostly focused along the James River where the full upper Point Peak crops out. Embryonic buildups within the James River offer an additional opportunity to study reef growth initiation. The H1, H2, and H3 transects within the James River Pavement, where numerous buildups have been horizontally bisected by the river, are used to understand the structure of Phase 1, revealing its thick rind and internal organization. Twin Herms, Andrea, Don, and Rosie buildups were studied to understand the construction of Phase 2, in addition to Phase 2 buildup flanks, and its interactions within coeval sediments. The Twin Herms, Rosie, Andrea, and Don transects are additionally used to study Phase 3.
4.1 LOWER POINT PEAK & FLAT PEBBLE DEPOSITS

Several occurrences of flat pebble deposits are scattered within the lower Point Peak strata, in particular accumulating at the base of beds interpreted as channels. Accessing and describing the sediment and flat pebbles accumulations just under the upper Point Peak large microbial buildups, is particularly easily done along the Mill Creek outcrop with the Fallen Block area. The origin of the flat pebbles is of great importance as it serves as the substratum for the microbial buildups. In outcrop, the upper part of the lower Point Peak mixed carbonate siliciclastic deposits appears as relatively thick resistant layers protruding from the cliff sides that are otherwise dominantly composed of erosive thinly bedded layers of fine-grained material (Fig. 24). These resistant beds pinch out laterally, reaching up to several decameters in lateral extent and ranging from a few centimeters at the margins to a half meter in thickness near the center of the deposits. Their lower surface appears to be erosional in nature, leading to the discovery that many of the thicker resistant beds were actually constructed of multiple, stacked flat pebble deposits, in particular at their bases. With their erosive bases and lens-like morphologies, these resistant beds with irregular thickness are interpreted as high-energy channels forming in an otherwise low-energy setting (Droxler et al., 2016).

One of those channels offers a 3D perspective where a portion protruding from the cliff-side is broken to reveal the interior makeup of the channel deposit (Fig. 25). This single channel is 4 meters wide and is around 40 centimeters thick near the center. The lower surface is erosional and near the margins, the process of flat pebble creation is evident as an intraclast is observed being “plucked” from the underlying strata and incorporated into the channel deposit (Fig. 25). Several ripples are found on the upper
surface of a grainstone that forms the upper part of the flat pebble deposit. A single core, Core 107, located on the crest of a well-preserved ripple, was taken through the entirety of the channel deposit (Fig. 25). The base of the core contains the underlying fine-grained strata being eroded by the channel flow, above which large pebbles appear as channel fill within an oolitic shell hash (Hopson et al., 2015). The pebbles slightly decrease in size upward in the core, and are then overlain by a rippled grainstone consisting of a shell hash with no pebbles. Overall, a clear fining upwards sequence is observed in the core. The compositional equivalence between the flat pebbles and the underlying strata indicate their local origin as rip-up clasts, further supported by the process of pebble creation being “frozen” in the deposit. For fine-grained material to be ripped up in the form of pebbles without dissociation indicates they must have already been relatively well lithified during their deposition (Droxler et al., 2016). Although sub-rounded, these pebbles most likely were not transported significant distances.

Based on cliff observations and fallen buildup blocks along the Llano River, the characteristic flat central base of the microbial reefs is explained by the occurrence of lenses made of flat pebbles deposits similar to those observed in the underlying tidal channel fill (Droxler et al., 2016). A large fallen buildup block, rotated on its side when it was naturally dislodged from the adjacent cliff face at the Mill Creek outcrop, offers unique access to its base for studies of the onset of microbial growth (Fig. 26). Although removed from its growth position, the cliff side behind the buildup evidences the original growth location by a large depression within Phase 1 grainstone where the buildup originally has nucleated on the surface referred to as the “switch.”
The base of the Fallen Block exhibits a circular lens of flat pebbles reaching at least 25 cm thick towards the middle and thinning towards the edges of the buildup. Within this deposit, fine-grained flat pebbles sit within a matrix of dominantly carbonate grains of trilobites, brachiopod fragments, gastropods and minor ooids. A core drilled in the very base of the Fallen Block microbial reef, above the flat pebble lens, exhibits inclusions of smaller pebbles and large bioclasts, on top of which a stromatolitic column grew (Fig. 26). Similar flat pebble deposits serving as substrates for microbial growth have been observed in other Upper Cambrian microbial reef studies (Chen, 2014a; James and Cowan, 1993; Lee et al., 2015).

Additionally, located along the James River, three small “embryonic” buildups that established on small piles of flat pebbles have been drilled (Fig. 27). These small buildups have cropped out due to erosion of the relatively less resistant Phase 1 grainstone that once encapsulated them. Drilling two cores (Cores 86A and 86B) through the buildups revealed the upper surface of the lower Point Peak fine-grained material, on which a small pile of the flat-pebbles acts as a substrate for their growth. The largest of the three small buildups has the thickest accumulation of pebbles (15 cm) while the second largest has a slightly thinner accumulation (13 cm). Core 86C, drilled adjacent to the small buildups, was absent of any pebbles and contained 3 cm of bioclastic hash with a cm-thick lens of microbial deposit.

Hyperspectral imaging of these three cores shows their mineralogical nature (Fig. 27). The buildups themselves are composed of calcite with small areas of iron oxide-coated calcite (Hopson et al., 2015). The substrate contains mixed siliciclastic carbonate pebbles contained within a calcitic shell hash that has largely been cemented together by
calcite. The underlying lower Point Peak is composed of mixed siliciclastic carbonate silts similar to the flat pebble intraclasts.

Thin sections (Fig. 28) confirm the flat pebbles to be the compositional equivalent of the underlying lower Point Peak material, thinly laminated fine-grained mixed carbonate/siliciclastic grains. The fine-grained pebbles are found within a bioclastic shell hash including mainly fragments of trilobites as well as minor brachiopods and gastropods. The first occurrence of microbial nucleating on top of the substrate is dominantly a thrombolitic micrite with incorporated bioclastic grains.

These deposits rest on top of the surface representing the transition from the lower to the upper Point Peak. This “switch” from fine-grained mixed shallow subtidal carbonate siliciclastic sediments to the deeper subtidal microbialite reef–bearing carbonate grainstone bed(s) has previously been interpreted as a deepening event (Droxler et al., 2015), thus leading to an interpretation of the flat pebble rip-up clast accumulations, as distinct lenses or piles of transgressive lag (Hopson et al., 2015). While the transgressive lag can be found on this same surface in areas where no buildups had formed, every buildup base that is accessible for observation exhibits thin lenses or piles of flat pebbles as substratum. The extent of the flat pebble substratum apparently determines the size of the overlying microbial buildup. Small piles of transgressive lag only contain small buildups that ceased to grow during Phase 1. This contrasts with the large buildups where more extensive, relatively thicker transgressive lag flat pebble lenses clearly serve as substratum for initial growth. The potential size of the buildups, therefore, may be controlled by the size of the underlying growth substrate.
Subtidal microbialites in the Exuma Cays have been documented to grow on a wide variety of substrates including beach ridges, marine cemented peloidal packstones, flat pebble deposits, and large shells that all offer some relief and stability for continued microbial growth (Logan and Ginsburg, 1962; Dill et al., 1986; Feldman et al., 1998; Reid et al., 1999; Reid et al., 2000; Andres and Reid, 2006; Ginsburg and Planavsky, 2008). However, the larger buildups reaching comparable sizes and growing within similar deeper subtidal environments as our ancient examples most commonly use flat pebble deposits as a growth substrate.

4.2 PHASE 1 GROWTH

The “colonizing” Phase 1 of microbial growth can be observed along the Llano and James River in addition in Mill Creek within Eagle Ridge Ranch. Mill Creek offers a fully formed 3 Phase buildup, while the extensive James River Pavement displays numerous individual microbial buildups that have been laterally bisected at varying levels, in conjunction with smaller complete buildups that represent the complete Phase 1 of growth. The H1 Core Transect horizontally bisects the Phase 1 reefs, well defined by a prominent and solid external rind observable in the vertical cliff faces above the Llano River. Additionally, the H2 lateral/vertical core transect documents temporal variations in Phase 1 growth through a fully formed Phase 1 small buildup. The H3 compound lateral/vertical transect complements the H1 and H2 transects and documents the transition from the Phase 1 interior to the upper Phase 1 rind and finally into the overlying cover strata.

When observed from the side, the Fallen Block (Fig. 26) exhibits a well-defined 3 phase growth morphology. Its Phase 1 occurs in the shape of a flattened prolate spheroid
(flattened football) with length, width, and thickness dimensions of around 7, 5, and 3 meters, respectively. In other outcrops, the buildups display either a more elongated shape, with some appearing highly ellipsoidal, whereas others a more rounded in plan view (Khanna et al., in prep.). The full thickness of Phase 1 buildups reaches between 3-4 meters. Generally they are ovular in shape with lengths ranging from a few meters to up to 25 meters. Similar to the individual columns coalescing to form a single buildup, single buildups can grow together to form buildup complexes that can reach hundreds of meters in length and width (Khanna et al., in prep.). The Phase 1 body of the Fallen Block microbial buildup appears to be massive without any noticeable structure or fabrics developed on the surface. While the side margin of Phase 1 is smooth, in some occurrences such as DroxRock and along areas of the James River Pavement such as H1, H2, and H3, the upper surface of Phase 1 appears undulatory with variable highs and lows forming without any apparent pattern (Fig. 29).

Phase 1 buildup interiors accessible along the James River distinctly show their external light grey rims and more orange hued interiors. Compared to the Fallen Block, this reveals the more complex interior structure of Phase 1 growth. Initiating on top of a transgressive lag, the interior of Phase 1 is composed of decimeter-scale diameter, convex upward stromatolite columns, with intercolumn space filled with relatively coarse skeletal and fine-grained non-skeletal carbonate sediments (Fig. 30). The stromatolitic texture of these columns is highlighted by an orangish color. Although initially starting as individual columns, these columns coalesced over time to form the Phase 1 large buildup that can be three to four meters in height. Often a thin centimeter-scale gray rind developed around each individual orangey column. The side and upper margins of the
buildup, formed by the coalesced columns, is eventually fully encapsulated by a large thrombolitic rind. In outcrop, these rinds appear gray and massive, similar to what is observed at the Fallen Block. The Phase 1 buildups in the James River pavement also tend to have a transition zone between the differing textures of the gray rind and the orange interior of the buildup. In the cliffs faces along the Llano River, the side rinds of Phase 1 tend to be thicker (up to 1 m) while the upper Phase 1 rind tends to be thinner (less than .5 m).

The H1 Core Transect details the internal fabrics of Phase 1 observed within the buildup rind as well as in the interior columns (Fig. 31) (Hopson et al., 2015). Core 1, taken within the side rind, exhibits the characteristic thrombolitic fabric that makes up the Phase 1 rind and is dominated by microbial clots with small occurrences of incorporated sediment. Core 8, taken within the transition zone between the thrombolitic rind and stromatolitic interior of Phase 1, shows a stromatolitic column with some intercolumn sediment. The small-scale rind developed around individual columns is also apparent within this core by the darkest tan color. The interior of Phase 1, represented by Cores 4 through 7, is absent of any microbial fabric and appears chaotic with Core 4 exhibiting macroscale vugs. Similar trends are shown within the H2 and H3 transects (Fig. 32 & Fig. 33), taken from the body of a fully formed Phase 1 buildup and another buildup with a fully formed Phase 1 upper rind, respectively. As in the H1 transect, cores taken from the side and upper gray rind exhibit thrombolitic fabrics with small sediment inclusions while the orange interior of the buildup contains either a pseudo-stromatolitic fabric or is chaotic.
The mineralogical differences between the cores become more apparent from the hyperspectral scans (Fig. 34). In the H1 transect, Core 1 is completely calcite, with much of the calcite being coated with iron oxide. Core 8 has both calcite and iron oxide coated calcite but also contains large amounts of dolomite and iron-rich dolomite as well as minor calcite cements. It’s important to note that the column-scale rind of Core 8 is calcitic. Core 6 is completely dolomite, with some occurrences of iron-rich dolomite. The H2 and H3 transects reaffirm these characteristics within the side rind and interior of Phase 1 buildups found within H1, and also confirm the upper rind of Phase 1 to be similar to the side rind (Fig. 32 & Fig. 33). These transects illustrate the typical fabrics and compositions of the side and upper rind, the transition zone between the rind and interior, and the interior of Phase 1. Overall, these cores show an important diagenetic trend observed in the buildups; the thrombolitic rinds remain calcite while the amount of dolomite increases towards the center of the Phase 1 stromatolitic interior. This is also confirmed by CT scanning that indicates the rinds are predominantly calcite whereas the stromatolitic interiors are mostly dolomite (Proctor et al., in press).

Thin sections confirm this mineralogical trend as well, where the rind is composed of microbial micritic calcite with minor sediment inclusions and the interior contains a large amount of dolomite. Both the side and upper rind of Phase 1 contain microbial clots with minimal levels of sediment incorporation in the form of infilled vugs. Siliciclastic silt particles can also be observed within the rind in thin section, in particular towards its exterior. Linked to the low levels of alteration within the thrombolitic fabrics, the rind contains the best examples of incorporated fossil fragments such as trilobites, brachiopods, and the occasional *Nuía*, a member of the problematica
family. Although difficult to find, *Girvanella* was identified in thin section based on the calcified sheaths the microbial communities create. The Phase 1 interior contains dominantly dolomite crystals, and any precursor microbial fabric has been completely overprinted by dolomitization.

Cores, hyperspectral scans, and thin sections all indicate the buildup interior stromatolitic fabric has been much more diagenetically altered compared to the thrombolitic rind. While some of the stromatolitic fabric is still observable within the transition zone between the rind and the Phase 1 interior, pervasive dolomitization has completely destroyed fabrics within the interior center part of the microbial buildups. This selective dolomitization is apparent in outcrop as well, where the iron-rich dolomite of stromatolitic fabrics have become highly oxidized and are much more susceptible to weathering compared to the relatively unaltered thrombolitic fabrics found within the rind.

Interbuildup strata deposited coevally to Phase 1 are oolitic bioclastic grainstones (Kubik et al., 2015). These authors show that one of the cores along the Brian Transect taken through the very base of the Phase 1 interbuildup grainstones exhibits a few transgressive flat pebbles, identifying the “switch” from the lower to the upper Point Peak as clearly observed at the Fallen Block outcrop along Mill Creek. These grainstones are orange in color, contain sparse fragments of trilobites as well as brachiopods and gastropods, and are devoid of siliciclastics. Along the Shepard cliff adjacent to Mitch Herm, the grainstone beds thin and pinch out towards the transgressive lag at the central base of the buildup (refer to previous Fig. 12).
The final interbuildup strata of Phase 1 transition to mixed carbonate siliciclastic siltstones that onlap the rind, exhibited by Mitch Herm above the Llano River (Fig. 12). A small tint of green results from the presence of glauconite. Carbonate content studies indicate a variable siliciclastic content to the fine-grained sediments (ranging around 35% total carbonate content) (Singh et al., 2016).

Additional hyperspectral scans focusing on the presence of Al-rich clays show another important aspect of the microbial fabrics. Whereas the Phase 1 interior is almost completely absent of siliciclastics, sediment pockets containing siliciclastics are visible within the rind (Fig. 34). The fact that the rind contains small amounts of siliciclastics and no grains from the interbuildup carbonate grainstones indicates that it was dominantly formed after deposition of the grainstones. The absence of siliciclastics within the inner rind indicates the siliciclastic influx began after the rind had already started forming before silt grains started to become incorporated in sediment pockets within the outer Phase 1 rind.

5.3 PHASE 2 GROWTH

The best examples of Phases 2 and 3 of buildup growth are shown in fully outcropping microbial buildups in the cliff faces along James River. The Twin Herms, Rosie, and the Andrea Transects were utilized for a systematic interrogation of the successive growth phases, mostly targeting Phase 2. The Granddaughters along the Llano River, DroxRock along Mill Creek and the Don Transect along the James River also provide useful information into different styles of Phase 2 growth. The combination of these outcrops provides information about the buildups and interbuildup sediments of Phase 2.
With the return of carbonate grainstone deposition on top of the siltstone
onlapping Phase 1, Phase 2 growth initiated as well developed stromatolitic columns
using the irregular surface of the Phase 1 upper rind as a substratum for growth. In
DroxRock, the individual columns of Phase 2 clearly initiate on the highs of the
undulated upper surface of Phase 1 (Fig. 29). While similar to the columns of Phase 1
during their initiation, Phase 2 columns tend to become larger, up to 1 meter in diameter.
Outcrops clearly show that the buildups grow upward and outward during Phase 2, with
the thicker columns forming at their margins (Fig. 35). Similar to growth during Phase 1,
individual columns usually form small-scale rinds. Phase 2 also exhibits lateral horizons
that are traceable across juxtaposed stromatolitic columns (Droxler et al., 2015). This
pseudo-stratigraphy can sometimes continue into the interbuildup sediments, and
ultimately results in profiles that resemble a honeycomb or grid-like framework on the
buildup due to differential erosion (Droxler et al., 2015). The main morphologic contrasts
between the two phases of buildup development are the systematic interaction of Phase 2
microbial growth with coarse-grained skeletal oolitic interbuildup sediments and the
absence of a large-scale outer rind. Outcrop studies reveal a more dynamic interaction
between the interbuildup sediments of Phase 2 than previously thought; sediments can be
seen interfingering with the Phase 2 microbial growth (Fig. 35) while well-defined sharp
boundaries are also observed between the two in other instances.

The Twin Herms Core Transect, taken through two large buildups existing in
coeval oolitic bioclastic grainstone, displays stromatolitic columns typical of Phase 2
(Fig. 36). The two buildups at this locality exist within coeval Phase 2 interbuildup
oolitic-bioclastic grainstones. Cores 71-74 exhibit stromatolitic microbial columns and
intercolumn sediments, separated by small-scale thrombolitic rinds developed around the individual columns (Hopson et al., 2015). Hyperspectral scans reveal much of the intercolumn sediments to be dolomite, while the columns themselves are dominantly calcite within iron oxide-coated rinds.

As mentioned, the interbuildup sediments of Phase 2 are oolitic-bioclastic grainstones and packstones deposited coevally to stromatolite formation (Kubik et al., 2015). Generally, thick grainstone beds are intercalated with much thinner packstones and occasionally siltstones. The upper surface of the grainstones often exhibits bed forms, such as the arcuit asymmetric megaripples found between two buildups at the Twin Herms outcrop. At this location, grainstones buttress up against the northern buildup, but form a depression against the southern buildup, interpreted as a moat (Fig. 37). In cores, finer-grained greener sediments tend to be deposited closer to the buildups with the moats or the troughs of ripples (Kubik et al., 2015).

Across the study area, variations occur within Phase 2 in both the buildups and the interbuildup sediments. While Phase 2 typically consists of accumulations of grainstone and columnar stromatolites, some areas exhibit an abnormally thick grainstone bed while others have a short interval of siliciclastic input and possibly microbial subphases within Phase 2. A very large grainstone bench adjacent to Andrea buildup represents the lower Phase 2; a core taken at the margin of the buildup here reveals an interesting interaction with the grainstone (Fig. 38). Within the core, the contact between the sediments and the microbial body forms a jagged vertical boundary that resembles a pseudo-interfingering nature. Although there is an excessively large accumulation of grainstone at this locality when compared to the normal amount of grainstone present
during Phase 2, this bench still doesn’t represent the full thickness of Phase 2. Above these lower Phase 2 sediments, there is an uncommon accumulation of mixed carbonate-siliciclastic silts (Fig. 39). Between the Rosie and Andrea buildups, these mixed silts highlight the changes in siliciclastic input in the upper Phase 2 interbuildup sediments (Sing et al., 2016). The carbonate content of upper Phase 2 begins as low as 40% indicating high initial levels of siliciclastics (Figure 39). The carbonate content increases up section to 80% where an ooid-rich bed was deposited at the end of Phase 2, as observed at DroxRock and between the Andrea and Rosie Buildups. The upper Phase 2 interbuildup sediments at Rosie consist of fine-grained siltstones, dominantly absent of any coarser grainstones. Cores 90 and 91, taken from within the upper Phase 2 buildup body, do not exhibit the stromatolite fabrics typical of Phase 2. Core 92, taken within the upper Phase 2 interbuildup sediments, exhibits some thinly bedded strata, absent of any obvious microbial influence. Hyperspectral scans of these cores (90-92) display similar mineralogies to those found between Rosie and Andrea, of dominantly calcite with minor dolomites and calcite cements. Compared to the Twin Herms transect, the Andrea and Rosie upper Phase 2 outcrops contain relatively little dolomite, which is possibly related to the absence of Phase 2 oolitic bioclastic grainstones.

The effects of variations in siliciclastic input on the growth morphology of buildups are most evident within the Granddaughters and Jack localities on the western part of the Shepard Cliff above the Llano River (Fig. 40). This is a single Phase 2 buildup that abnormally does not occur on top of a Phase 1 body, although it can be argued that the underlying Phase 1 may not be shown within the plane of the cliff face. The interbuildup grainstones of Phase 2 are interrupted by an accumulation of mixed
carbonate-siliciclastic silt that is coeval to a change in microbial growth where the buildup growth area decreases by around 50%. This interval of mixed silt separates the lower and upper Phase 2 sediments. Although some other areas do exhibit the Phase 2 silty unit, the Granddaughters and Jack most strongly evidence two subphases within Phase 2 growth.

4.4 PHASE 3 GROWTH

Phase 3 of buildup growth, referred to as the “capping” phase and the final form of microbial growth, initiated on Phase 2 microbial reefs and, in several locations, extended beyond the underlying Phase 2 buildup and above the interbuildup sediments. Phase 3, which is well-displayed on the Shepard and Zesch cliffs along the Llano River, is only accessible at the Twin Herms, Andrea, Rosie, and Don Transects along the James River in addition to DroxRock and the Fallen Block along Mill Creek.

Phase 3 in Twin Herms (Fig. 41) fully encloses the upper surface of the underlying Phase 2. The lower extent of Phase 3, occurring on the upper sides of Phase 2, are generally thicker (0.6 m) and Phase 3 thins towards the top of the buildup (0.3 m). The side surfaces of Phase 3 are generally smooth though with a lumpy, “clouded” texture, which differs from Phase 1 external rind. Much like Phase 1, Phase 3 generally does not have any distinguishable internal fabrics evidenced on the surface and appears to be mostly massive. Core 75, drilled on one of the two microbial buildups side of Phase 3 (Fig. 41), exhibits a thrombolitic texture with very little sediment incorporation (Hopson et al., 2015). Core 63 penetrates the top of Phase 3 and displays a similar thrombolitic texture but evidences more sediment incorporation compared to Core 75. This difference is enhanced by hyperspectral scans, where Core 75 is entirely composed of calcite with
iron-oxide coating most of the calcite, while Core 63 does not contain as much iron-oxide coatings and also exhibits calcite cements. Core 98, drilled on the side of Rosie buildup Phase 3, also exhibits the typical clotted thrombolitic fabric (Fig. 41). Hyperspectral scans reveal that core 98 is almost entirely made of calcite with occurrences of iron-oxide coatings on the calcite and minor calcite cements. A typical thin section of Phase 3 taken from Core 75 shows the side Phase 3 is almost completely microbial micrite with no inclusion of shells or sediments and very minor calcite cement. Thin sections within Core 62 of the upper Phase 3 reveal the composition to be dominantly microbial micrite with small levels of carbonate sediment incorporation including some trilobite fragments and, more importantly, green glauconitic silt.

These features closely resemble the Phase 1 rind that is also dominantly composed of a thrombolitic fabric resulting from direct calcitic micrite precipitation. However, there is evidence for relatively greater siliciclastic influx during the formation of the outermost Phase 3 rind compared to the Phase 1, indicating that most of the Phase 1 rind had already formed before siliciclastic influx began (Fig. 42). Lack of interbuildup coarse and fine-grained sedimentation during Phase 3 growth contrasts with the underlying Phases 1 and 2 and implies that the synoptic Phase 3 microbial reef reliefs above sea floor were as high as during Phase 1. Fine-grained interbuildup mostly siliciclastic sediments systematically onlap the very end of Phase 3 microbial growth and mark the ultimate demise of microbial growth in the Upper Point Peak. The high siliciclastic content (as high as 84%) of the initial onlapping fine silt and the inclusion of aluminosilicates with the outmost Phase 3 rind suggest that the microbial Phase 3
buildups, during their final growth, were bathed in increasing turbid waters and perhaps at the very end of their growth even smothered by fine siliciclastics (Singh et al., 2016).

4.5 δ\(^{13}\)C/δ\(^{18}\)O ISOTOPIC ANALYSES

The H1 Core Transect (Fig. 43) horizontally cuts across a single Phase 1 buildup, containing samples from both the relatively dolomitized interior and the undolomitized exterior rind. Though still targeting the apparently most undolomitized material for micro drill samples, this transect provided information regarding the effect of dolomitization on δ\(^{13}\)C and δ\(^{18}\)O isotopic values. δ\(^{13}\)C values begin around 1 ‰ PDB within the side rind and decrease slightly to 0.7 ‰ PDB in the transition zone between the rind and buildup interior (Fig. 43), but increase to 1.5 ‰ PDB as the dolomitized interior of the buildup is encountered. Mirroring the increase in δ\(^{13}\)C values from the side rind into the interior, isotopic values once again decrease by to 0.7 ‰ PDB within the transition zone between the rind and interior before slightly increasing to around 0.9 ‰ PDB within the side rind. Areas high in dolomite content have heightened δ\(^{13}\)C values, while relatively unaltered areas contain lower values that are most likely closer to depositional values. Similarly, δ\(^{18}\)O values show the effect of dolomitization. Within the side rind, values range from -5.2 to -6.1 ‰ PDB while the dolomitized interior has a range of -4 to -4.6 ‰ PDB. This single transect evidences the effect of diagenesis on isotopic values, and the importance of targeting unaltered material for isotopic sampling to recover as close as feasible the original δ\(^{13}\)C and δ\(^{18}\)O isotopic values during the microbial growth. The rind, more specifically the microbial micrite within the rind, remains the most unaltered material that closely matches the background isotopic values of the Upper Cambrian (Elrick et al., 2011; Auerbach, 2005.). Although preserved best
within the Phase 1 and 3 rinds, microbial micrite is also available for sampling within Phase 2 if unaltered buildups are targeted.

Although not as apparent as the $\delta^{13}$C and $\delta^{18}$O isotopic values shifts from the rinds to the interior in the H1 transect, isotopic values along a vertical transect through Don buildup still exhibits slight isotopic variations between the three growth phases. Based upon what was learned from the H1 transect in terms of the alteration of $\delta^{13}$C and $\delta^{18}$O isotopic values due to dolomitization, the Don Transect (Fig. 44) was chosen within a relatively diagenetically unaltered buildup that contained all three growth phases and was also accessible for high resolution sampling. Hyperspectral scans within the Don Transect confirmed that this buildup remains mostly unaltered by dolomitization. Although dolomite is still present within the buildup, calcite still exists in abundance throughout the transect cores. With the help of thin sections, microsamples were taken from within microbial micrite with minimal dolomite occurrence. The Don Transect truly consists of two separate transects; one small transect taken within upper Phase 1, and the next taken across the three phases. Phase 1 $\delta^{18}$O values range between -6.5 and -5.5 $^\circ/oo$ PDB, but dominantly exhibit values lighter than -6.0 $^\circ/oo$ PDB (apparent in 21 out of 31 measurements). $\delta^{18}$O values in Phase 2 show a slightly heavier shift, where a similar range of values as in Phase 1 still exists -6.5 to -5.2 $^\circ/oo$ PDB, but values heavier than -6.0 $^\circ/oo$ PDB are most common (apparent in 35 out of 40 measurements). Phase 3 shifts back to values similar to those found in Phase 1 with a range of -6.5 to 5.9 $^\circ/oo$ PDB, but mostly exhibits $\delta^{18}$O values lighter than -6.0 $^\circ/oo$ PDB (4 out of 5 measurements). Overall therefore, $\delta^{18}$O values lighter than -6.0 $^\circ/oo$ PDB occur within Phase 1 and 3 while Phase 2 exhibits values heavier than -6.0 $^\circ/oo$ PDB. There is an
opposite trend within $\delta^{13}C$ values across the three phases. Phase 1 exhibits a range of 0.6 to 1.4 $\%_{\text{PDB}}$ but dominantly contains values heavier than 1.0 $\%_{\text{PDB}}$ (24 out of 31 measurements). Phase 2 exhibits a range of 0.5 to 1.2 $\%_{\text{PDB}}$ $\delta^{13}C$ values, but dominantly contains values lighter than 1.0 $\%_{\text{PDB}}$ (32 out of 40 measurements). Phase 3 has a range of 0.9 to 1.1 $\%_{\text{PDB}}$ and is mostly 1.0 $\%_{\text{PDB}}$ or heavier (4 out of 5 measurements). Overall, trends of $\delta^{13}C$ values that are heavier than 1.0 $\%_{\text{PDB}}$ are present within Phase 1 and 3 while Phase 2 contains $\delta^{13}C$ values that are lighter than 1.0 $\%_{\text{PDB}}$.

5. DISCUSSION

The Upper Cambrian microbial buildups had to be studied at various scales in relation to their coeval sedimentation to fully understand their development. This project has further refined the 3 Phase Growth Model with additional outcrop observations, extensive core work, high resolution visual and hyperspectral scans, thin section petrography, and isotopic analysis. Collectively, these analyses have led to an understanding of the importance of large and small-scale environmental fluctuations on the microbial buildups, both within their growth morphology and growth texture.

5.1 GROWTH TEXTURE

The main growth forms observed within this study vary between thrombolitic, i.e., lacking order with clotted structures, and stromatolitic, i.e., displaying convex upward fine laminations. The dominant growth texture, and therefore the dominant microbe community, at any point seem to be linked to coeval sedimentation within the depositional environment. When mobile bioclastic grainstones occur during Phase 1 and 2, stromatolitic textures dominate due to the fact that stromatolites form in part through
the agglutination of these mobile grains into their growth structure. However, once grainstones deposition ceases, the dominant growth texture becomes thrombolitic, and the buildup is formed exclusively through direct precipitation of calcium carbonate by the microbes themselves. This transition in textures indicates the importance of grainstones for the formation of stromatolites within this area; substantial volumes of stromatolitic buildups can only be formed when there are ample grains to incorporate into their growth, otherwise thrombolitic fabrics will dominate. This information leads to a characterization through time of buildup growth in relation to the coeval sedimentation, and therefore, to varying depositional environments that is important for constructing the depositional history across the three growth phases.

As evidenced in thin section, the growth texture exhibits an important influence on the extent of diagenesis, most likely controlled by original porosity and permeability of the differing fabrics (Hopson et al., 2015). In general, thrombolitic fabrics have minimal porosity and permeability and have been mostly unaffected by diagenesis compared to the relatively high porosity and permeability of stromatolitic fabrics, which have been heavily dolomitized. These differing characteristics are the result of how these two fabrics are originally formed, through trapping and binding of carbonate clastic grains or through direct precipitation of calcium carbonate by the microbe communities. Porosity results from the trapping and binding of clastic grains, while little porosity is developed when microbes are precipitating calcium carbonate. Thin sections show the microbe-precipitated micrite has been relatively unaffected while the incorporated carbonate detrital grains have been highly dolomitized. This selective dolomitization
mirrors the fabric destructive dolomitization that occurred within interbuildup grainstones.

5.2 TRANGRESSIVE LAG

Understanding the formation of the flat pebble deposits within the immediately underlying lower Point Peak strata is critical for understanding the development of the transgressive lag, which serves as a growth substrate for the large microbial buildups within the upper Point Peak. As evidenced by the channel studied within the cliff side on Mill Creek, the creation of these flat pebbles involves erosion of deposited material and redeposition. The absence of clear clues indicating exposure or desiccation indicates the erosion occurred within the marine environment and was unrelated to subaerial exposure. The fine material was originally deposited within a shallow marine environment, possibly very shallow subtidal, and began to consolidate into a firmground through early marine cementation possibly related to microbial interaction. The material was not cemented well enough to become a true hardground, thus a high-energy event such as a storm could rip up variously sized pieces of the firmground, to create the flat pebbles. Partial cementation of the pebbles is further evidenced by the rounded edges of the pebbles; partial cementation allowed rounding of the edges rather than complete disassociation of the fine-grained material during transportation.

The pebbles within the lower Point Peak were deposited in a channel-fill, identified by an erosive base and a lensed-shaped morphology, which pinches out laterally. The upper Point Peak only has one interval of flat pebble deposits, which is found on the surface marking the boundary between the upper and lower Point Peak. As this surface was interpreted to represent a deepening event, these flat-pebble deposits are
subsequently interpreted as a transgressive lag. This lag is deposited as lenses or piles that appear to not be extensive, and do not have an erosive base. This lag is most likely used as a substrate because of the stability of the flat pebbles and the small bathymetric high they form. The upper Point Peak then becomes a high-energy tidal zone, deeper than the immediately underlying lower Point Peak, dominated by an oolitic bioclastic grainstone that is continually in motion. Contrary to the overlying mobile grainstone, the coarseness of the lag inhibits movement by the tidal energy, creating stability that is further supported by any submarine cementation of the deposits. This stability, in conjunction with the small relief of the lag, allowed the establishment and continued growth of microbial communities to create the large upper Point Peak buildups.

The potential size of the overlying buildup is controlled by the aerial extent of the growth substrate. Larger transgressive lags areas, commonly in the shape of lenses, allow the formation of the large three phase buildups typical of the upper Point Peak, while small lag deposits such as piles restrict the continued development of the buildups beyond the initial first phase of growth.

5.3 COLONIZING PHASE 1

The transition from the lower Point Peak to the upper Point Peak is interpreted as a deepening event due to the introduction of a high-energy carbonate environment containing open marine fauna and larger bedforms typical of a deeper tidal environment compared to the underlying mixed carbonate siliciclastic deposits. This transgression, resulting in the creation of accommodation and constraining the siliciclastics along a new coastline further towards the hinterland and away from the shelf, allowed the development of the large Upper Cambrian microbialites in the upper Point Peak.
As exhibited by the modern analog in the Bahamas, similar stromatolitic fabrics rely on the availability of these mobile grainstones for incorporation into the microbial growth. This is evident by the transition to the development of thrombolitic fabrics once grainstones no longer became available during the end of Phase 1. A very low rate of sedimentation led to the formation of very tight, micritic rinds that were dominantly developed by direct precipitation of micritic calcium carbonate by the microbe communities.

The final strata developed during Phase 1 are thinly laminated layers of mixed carbonate-siliciclastic silts partially onlapping the Phase 1 external rind. This influx of siliciclastics is very important to the depositional history of the Phase 1 buildups because it indicates an environmental shift to a low energy setting. The transition from a purely carbonate system to a mixed carbonate siliciclastic system indicates a more proximal shoreline resulting from a relative drop in sea level. Small amounts of these siliciclastics are incorporated into the outer margins of the Phase 1 rind within sediment pockets, indicating an increase in turbidity of the water column during the end of Phase 1 development. This increase of turbidity, and therefore decrease in sunlight availability, would have inhibited the sustained growth of Phase 1.

5.4 AGGRADING AND PROGRADING PHASE 2

Nucleating on top of a well cemented and therefore stabilized bathymetric high formed by the upper surface of Phase 1, stromatolitic columns develop again coeval with the reintroduction of oolitic bioclastic grainstones that are used to develop the stromatolitic fabrics. Interbuildup sedimentation within Phase 2 is dominantly carbonate grainstone with occasional short-lived occurrences of mixed carbonate-siliciclastic
siltstones, thus restricting the development of a thrombolitic fabrics and a large-scale rind (similar to those of Phase 1 and 3). Thrombolitic fabrics are limited to small-scale rinds developed around the individual stromatolitic columns of Phase 2.

Significant siliciclastic influx during Phase 2 is regional, such as around the Granddaughters and Jack Buildups. This influx, and pause in grainstone accumulation, resulted in the development of a surface marking the boundary between the upper and lower portions of Phase 2.

Variation within the weathering profile of Phase 2 depends on the amount of diagenetic alteration the buildup has undergone. This is well-shown by comparing DroxRock to the Twin Herms; DroxRock has undergone high levels of preferential dolomitization and subsequent preferential erosion of altered material to create a honeycomb structure on northern face of the buildup, whereas Twin Herms has been relatively less altered and does not exhibit high levels of differential erosion. This level of alteration also likely connects to the level of sediment inclusion between the two areas where DroxRock exhibits an interfingering nature with coeval sediments while the Twin Herms seem to have defined margins during Phase 2. By including the Don Transect, the same buildup can have differing levels of alteration and erosion. The Don Transect cuts through the northeast side of the Don buildup where relatively little diagenetic alteration has occurred and differential erosion is nonexistent. However, another margin of the Don buildup has relatively high levels of diagenetic alteration and subsequent differential erosion. The obvious difference between the two areas is that the south side represents the interior of a Phase 2 buildup while the east side represents the flank of a buildup where grainstones directly interacted with the buildup. The flank would intuitively
undergo more alteration due to its juxtaposition with porous sediments that can transfer diagenetic fluids to the buildup while the same fluids would have less affect on the interior of a buildup where there movement is hindered by relatively low permeability and porosity.

5.5 CAPPING PHASE 3

Phase 3 of buildup growth initiates on top of the synoptic relief developed by the upper surface of Phase 2. A relative deepening event results in a transition from a high-energy to lower energy tidal environment and the absence of grainstone deposition within the region. As a result, thrombolitic fabrics construct the third phase rind through direct precipitation of micritic calcite by the microbe communities, and there is a pause in coeval interbuildup deposition. A drop in relative sea level led to the encroachment of the coastline and the introduction of siliciclastic-rich sediments that onlap the base of the rind. These sediments are also included in the outermost rind growth as sediment pockets. Siliciclastic-rich siltstones (84% SiO$_2$) ended the third phase of growth, with an increase of turbidity being the likely cause for the ultimate demise of the microbial buildups.

5.6 MODERN BAHAMIAN ANALOG

Modern marine microbialites are well described from two different settings: hypersaline environments in the restricted embayment of Shark Bay, Australia, and within high-energy tidal channels and beaches of the Great Bahama Bank. To better understand the ancient Upper Cambrian microbialites, an effort was made to establish one of these two modern areas as a depositional environment analog. Open marine indicators within the Upper Cambrian example imply microbialites of the Bahamas
would possibly be a better fit as an analog, supported by the presence giant modern stromatolites occurring within large accumulations of ooid grainstones.

Modern subtidal microbialites in the Bahamas grew in the last few thousand years following the Holocene transgression on top of transgressive lags composed of lithoclasts, large shells, or firmgrounds (Dill et al., 1986; Feldman et al., 1998; Reid et al., 1999; Reid et al., 2000; Ginsburg and Planavsky, 2008). These characteristics compare well with the Upper Cambrian where large microbial buildups developed following a transgression on accumulations of flat pebbles transgressive lags.

The modern Bahamian microbialites thrive within fields of mobile ooid grainstones. Similarly, although punctual siliciclastic influxes occur within the Upper Cambrian, most of the volumetric buildup growth occurs when the system was purely carbonate and dominated by oolitic-bioclastic grainstone accumulation. Similar flow patterns are interpreted to exist within the Upper Cambrian due to the presence of megaripples, dunes, and moats partially around the periphery of the large microbial buildups while sediments otherwise buttress against the margin. Figure 45 shows similar bedforms developed around large modern microbial bodies within the subtidal Adderly Channel in the Exuma Cays, where the interaction of the flow of mobile ooid grainstone and the microbialites results in the development of bedforms. This is mirrored within the Upper Cambrian grainstones developed between the Twin Herms outcrop (Fig. 45) and between the well-developed Phase 1 rinds on the James River pavement (Kubik et al., 2015). In both microbial systems, large dunes are developed by tidal flow between two microbial bodies with smaller-scale flow patterns developing arcuit ripples (and megaripples).
5.7 DEPOSITIONAL MODEL

The descriptions and interpretations presented in this study from outcrop studies, core analysis, and thin section petrography refine the initial 3 Phase Growth Model introduced by Droxl er et al. (2015). The refined 3 Phase Growth Model (outlined in Figure 4) is further developed to include the role of accommodation, buildup and inter-buildup sediment accumulation, microbial growth forms, turbidity, and siliciclastic fluxes in the establishment, growth, and ultimate demise of the microbial buildups.

An initial transgressive lag formed a series of lens-like accumulations of flat pebble intraclasts with a mixed grainy bioclastic matrix. The intraclasts are interpreted to have formed during a transgression by the reworking and winnowing of partially cemented fined grained, mixed carbonate-siliciclastics. Following the deepening event that transitioned the locality from a mixed carbonate-siliciclastic, shallow subtidal/intertidal depositional environment into a high-energy, pure carbonate subtidal environment, these lenses of flat pebble intraclasts acted as a stable substrate with relatively high bathymetric relief on which microbial growth initiated.

Microbial buildup Phase 1 growth occurred contemporaneous to the deposition of inter-reef 1-2 m thick oolitic-bioclastic grainstone deposits. Phase 1 microbial buildups grew on the transgressive lag in the form of numerous juxtaposed, decimeter-width, convex upward, stromatolitic columns. Over time, the different columns coalesced to form larger meter-scale buildups. These columns exhibit a small-scale thrombolitic rind, usually grey in color, no more than a centimeter in thickness. With sufficient accommodation, microbial growth outpaced the inter-reef grainstone deposition and developed an appreciable 2-3 meter high synoptic relief. The size of Phase 1 growth is
initially controlled by the extent of the underlying growth substrate; small dimension of the transgressive flat pebble lag, such as small piles, inhibited the formation of large fully developed buildups, but more extensive lenses allowed for buildups to grow very large and eventually form all 3 of the growth phases. Deposition of the inter-reef grainstone sediment within the area slowed resulting in a transition in the microbial textures developed from stromatolitic to thrombolitic, as the microbe communities could no longer include grains in their growth. Continued cementation and lithification within an open marine environment developed the buildup margin into a well-defined, thrombolitic microbial rind (Swartz et al., 2015). At this transition in growth fabrics, the buildups are no longer growing as coalesced microbial columns, as this thick microbial rind now completely encompasses the full Phase 1 buildup. This thrombolitic rind thickens towards the buildups sides, reaching thicknesses up to one meter while the top rind of Phase 1 is more typically around 20 to 40 centimeters in thickness. A shallowing event, reducing accommodation and increasing the siliciclastic sediment input, is marked by siltstones onlapping the sides of Phase 1 rind and ends Phase 1 microbial growth. The shallowing event increased the siliciclastic influx as the shoreline advanced shelfward, subsequently leading to a decrease in carbonate content due to the negative effects of turbidity on the carbonate factory. Evidence of increased levels of siliciclastic influx, occurring while the end of the Phase 1 was forming, is shown by the inclusion of small amounts of siliciclastics within the outside of the large-scale Phase 1 rind. Typically, these silts onlap the sides of Phase 1 buildups, without any interfingering nature, and never cover the full Phase 1 microbial reefs.
As bioclastic grainstone deposition replaced siliciclastic accumulation, Phase 2 growth initiates using the top of the Phase 1 rind as a substrate. The growth structures are characterized by numerous juxtaposed columnar stromatolites similar to the ones observed in the Phase 1 reef interior. Incremental pauses in relative sea level rise periodically constrained vertical growth of the columns and induced lateral expansion beyond the margins of the underlying Phase 1 growth. These lateral expansions, coupled with low synoptic relief of the buildup, allowed interaction of the reef margin with interbuildup sediment creating an interfingering nature between boundstone and surrounding bioclastic grainstones and inhibiting the formation of a well-defined buildup rind. More localized variations in the influx of fine mixed carbonate siliciclastic sediment during Phase 2 might explain the two observed upper and lower subphases of Phase 2. Termination of Phase 2 microbial growth resulted from a deepening and is marked by the end of bioclastic grainstone deposition. The end of Phase 2 is characterized by a sudden influx of ooid-rich grainstones before grainstone deposition in the locality once again ceases. Unlike Phase 1, a large-scale thrombolitic rind around the buildup body is not developed within Phase 2.

Phase 3 of microbial growth acts as a “capping phase” for the full Phase 2 buildup, but also forms individual mounds overlying the some of the Phase 2 buildup flanks and the interbuildup sediment. With the end of grainstone deposition between the Phase 3 buildups and mounds, Phase 3 growth became thrombolitic in nature. Increased accommodation allowed the buildups and mounds to develop significant synoptic relief of 2 to 3 meters in height. Phase 3 grows beyond the boundaries of the underlying Phase 2 and downlaps onto the Phase 2 interbuildup grainstones. The ultimate demise of the
upper Point Peak microbial reef complex is marked by a large flux of fine siliciclastics. The first siltstones initially onlapping the sides of the Phase 3 rinds contain as much as 84% siliciclastics, explained by closer proximity to shoreline and a reduction in accommodation. This increase in turbidity in the water column would have limited light penetration and ended microbial growth.

6. CONCLUSIONS

Results presented here on the detailed analysis of the Upper Cambrian microbial reef complex outcropping in Mason County allowed the development of a depositional model detailing variations in the evolution of the microbial buildups, as well as the environment of growth. Phase 1 of growth results in 3-4 m high buildups defined by their distinct and early-cemented outer margin, a thick thrombolitic rind composed of micrite. Buildup interiors exhibit amalgamated microbial heads, dominantly composed of dolomite, displaying poorly preserved internal stromatolitic structures enveloped by cm-thin thrombolitic rinds. The buildups grew in high-energy conditions, but without interacting with coeval deposition of dolomitized interbuildup oolitic bioclastic grainstones with minor packstones. The overlying Phase 2 growth produced buildups up to 8 m thick, though with limited synoptic relief compared to Phase 1, characterized by a mutual interaction with interbuildup grainstones and, with few exceptions, lacks a large-scale external thrombolitic rind. Internally, Phase 2 growth consists of vertically aggrading and laterally expanding stromatolitic columns, each exhibiting cm-thin thrombolitic rinds directly interacting with dolomitized intercolumn bioclastic grainstones. Phase 3 of growth develops a well-defined 2-3 m thick micrite rind composed of micrite and crowning the top of Phase 2.
Thrombolitic fabrics evidence carbonate precipitation directly induced by microbial colonies. This fabric dominantly consists of original microbial micrite with minor fossil fragments in an extremely tight framework that hindered diagenesis. Stromatolitic fabrics show alternating laminations of microbially precipitated calcite and amalgamated trapped grainstones that were relatively susceptible to dolomitization due to relatively higher levels of porosity and permeability.

These results further our understanding of key fabrics and textures that can be expected in microbial buildups and related deposits, and present a well-calibrated example showing their spatial and temporal variation. Establishing a clearer relationship between microbial fabrics and coeval sedimentation for ancient and modern examples builds a robust foundation for continued studies into nonphysical interactions.
7. REFERENCES


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Figure 1 – Upper Cambrian paleoreconstruction showing the equatorial and rotated position of Laurentia (6-topographic high; 7-topographic low; 8-slope; 9-shallow epeiric seas; 10-deep ocean) (modified from Golonka, 2002)

Figure 2 – Upper Cambrian Laurentia illustrating submergence of central Texas within tidal environments (adapted from Lochman-Balk, 1970)
Figure 3 – Major reef building organisms through time, showing the dominance of calcimicrobes after the decline of Archaeocyaths during the end of the Lower Cambrian (modified from Rowland and Shapiro, 2012)
Figure 4 – Geologic map of Llano Uplift region of central Texas with red box indicating study area and red line indicating position of following cross-section (http://geology.uprm.edu/Morelock/images/llanopaleozoic.jpg)

Cross Section along Llano Uplift

Exposed study area

Reference: http://hlmn.281.com/march/fig/LUxSec.jpg

Figure 5 – Schematic cross-section taken from previous map showing how faulting and erosion associated with exhumation of the Llano Uplift resulted in exposure of lower Paleozoic strata (http://hlmn.281.com/march/fig/LUxSec.jpg)
Figure 6 – Google Earth view of cliff and pavement microbialite on the Eagle Ridge and Zesch Ranches, focusing on Fallen Block/DroxRock, James River Section, and the Zesch Cliff for this project.
Figure 7 – Geologic map of the study area showing microbial outcrops within Point Peak member and accompanied cross-section showing how faulting and channel incision exposed two of the main outcrops (Mill Creek and James River) used in this study (both adapted from Sliger, 1957)
Figure 8 – The Shepard Cliff above the Llano River exhibits multiple outcropping buildups. Many of these buildups have been named and studied in detail. The lower and upper surfaces of the upper Point Peak are highlighted in yellow and blue, respectively.
Figure 9 – The Zesch Cliff above the Llano River exhibits a collection of particularly large buildups, including the very well-studied Mitch Herm.
Figure 10 – The Mill Creek outcrop exhibits a large section of the lower Point Peak containing flat-pebble deposits as well as the whole upper Point Peak containing large microbial buildups. Large fallen buildups allow access to their bases for the study of the onset of microbial growth.
Figure 11 – The James River outcrop exposes a lateral pavement of Phase 1 buildups adjacent to a cliff face with 3D fully outcropping buildups.
Figure 12 – a) Image of “Mitch Herm” microbial buildup initiating on flat-pebble sheet contained within Zesch Cliff above the Llano River, b) 3 growth phase interpretation of Mitch Herm and coeval sediments showing lower Point Peak below “the switch,” the upper Point Peak microbial interval, and the overlying San Saba Limestone.
Figure 13 – The core transects along the James River used to study the buildups in detail.
Figure 14 – Fallen Block Transect taken along Mill Creek where a large 3 phase buildup has been dislodged from the Cliffside and now lies on its side (A), allowing access its base for studies of microbial buildup growth initiation. A large lens-shaped flat pebble deposit (B) acts as a growth substrate in the center of the block’s base.
Figure 15 – H1 lateral core transect across the full bisected ~5 meter wide body of a Phase 1 buildup along the James River

Figure 16 – H2 vertical transect through an exposed 3 meter tall Phase 1 buildup exhibiting 3D architecture
Figure 17 – *H3 compound vertical and horizontal core transect through the transition from the interior of a Phase 1 buildup to the Phase 1 rind that continues into the overlying cover strata, representing the end of microbial growth*.

Figure 18 - *Twin Herms vertical transect from the top of Phase 1, through Phase 2, and into the Phase 3 rind*.
Figure 19 – Rose Transect used for studies of the upper Phase 2 and flank deposits, along with well-defined Phase 3 rind

Figures 20 – Andrea Transect along the James River is used for studies of the upper Phase 2 and flank deposits, as well as carbonate content studies of the upper Phase 2 and post Phase 3 siltstones.
Figure 21 – The Don Core Transect along the James River cuts through a fully formed three phase buildup that is relatively unaltered, and therefore can potentially provide original isotopic values for isotope analyses.
Figure 23 – DroxRock along Mill Creek provides information as to the internal structure of Phase 2 and its interaction with coeval sediments. Horizontal layering can be observed across the Phase 2 buildup body as well. (Photo taken by Brandon Harper)
Figure 22 – (lower) Core 73 showing typical stromatolitic fabric present during Phase 2, (middle) Core 1 showing typical thrombolitic, clotted fabric of Phase 1, (upper) Core 133 showing example of interfingering Phase 2 buildup and interbuildup sediments.
Figure 24 – (A) The lower Point Peak strata along Mill Creek contains flat pebble deposits in the form of channel fill (indicated by the red arrows), observable as nonrecessive beds below the “switch” into the upper Point Peak. (B) The deposits appear are discontinuous channels (highlighted in red). (C) Flat pebbles are visible within these deposits that erode down into the underlying fine-grained thinly bedded lower Point Peak strata.
Figure 25 – (A) A 3-dimensional outcrop of channel fill within the lower Point Peak strata studied to understand the construction of flat pebbles deposits. (B & C) The margins of the channel evidence erosion and reworking of the underlying partially cemented fine-grained sediments. (D) A single core taken through the crest of a ripple on the upper surface of the deposit reveals the internal structure of the channel fill.
Figure 26 – The Fallen Block core transect taken within the Phase 1 base, used to study the onset of microbial growth within the upper Point Peak. (A) The Fallen Block exhibits the typical 3 phase morphology. (B) The original resting place of the block within the cliff is located by a depression in the Phase 1 grainstone. (C & D) The base of the Fallen Block exhibits a lens of flat pebbles used as a growth substrate. (E, H, & I) A single core taken behind this lens exhibits small flat pebbles above which a stromatolite column occurs. (F & G) Two cores taken within the rind have the typical thrombolitic texture.
Figure 27 – (A) The embryonic Buildups in the James River outcrop on top of the surface representing the transition between the lower and upper Point Peak. These buildups nucleated on a small pile of rip up clasts and never grew beyond Phase 1. (B) Three cores taken within the buildups and adjacent to the buildups show the typical underlying Point Peak on which a small pile of flat pebbles is used as a growth substrate for Phase 1 microbial growth.
Figure 28 – Core 86A and associated thin sections located with adjacent blue circles. Thin section 86AA was taken within the Phase 1 microbialite and exhibits a thrombolitic micrite. 86AB was taken within the transgressive lag containing fine-grained flat pebbles within an oolitic bioclastic shell hash. 86AC was taken across the surface representing the “switch” from the lower to the upper Point Peak (represented by white line).
Figure 29 – (A, B, & C) The lower half of DroxRock containing the irregular upper surface of the Phase 1 rind on which Phase 2 nucleates. (D) The columns constructing Phase 2 are observed to nucleated on top of highs within the surface.

Figure 30 – Aerial view of H1 Buildup exhibiting the typical gray outer rind and orange interior. The rind and transition zone between the rind and interior are well shown.
Figure 31 – H1 Transect taken across a buildup along the James River exhibiting the rind, transition zone, and interior of Phase 1. The rinds exhibit a thrombolitic fabric composed of calcite and the interior is absent of any systematic texture and composed of dominantly dolomite while the transition zone is a mix of the two.
Figure 32 – The H2 Transect taken within a single Phase 1 buildup on the James River well illustrates the textures and compositions, visible in hyperspectral scans, typical of Phase 1 builds. The rinds remain thrombolic calcite while the interior are dominantly dolomite and lack fabrics, while the transition zone is a mix of the two.
Figure 33 – The H3 Core Transect taken across two Phase 1 buildups is used to study the transition into the Phase 1 upper rind. Textures and compositions match that of the H1 and H2 transects. This transect also contains the transition into the cover with core 47.
Figure 34 – Phase 1 Rind Siliciclastic Content showing the inclusion of aluminosilicates in red within the outermost Phase 1 rind. Almost no aluminosilicates are present within the interior of Phase 1. (Hotter colors indicate a higher abundance of aluminosilicates)
Figure 35 – (A) The margin of DroxRock along Mill Creek showing the interaction between the buildup and interbuildup sediments. (B) The columns within Phase 2 becomes larger at the margin of the buildup, linked with horizontal accommodation.
Figure 36 – The Phase 2 Twin Herm Transect exhibits typical fabrics of Phase 2. The remnant of stromatolitic textures can be observed within the cores. Small-scale rinds are iron oxide coated calcite, while much of the intercolumn sediments have been dolomitized.
Figure 37 – Phase 2 Grainstone between Twin Herms exhibiting moat and buttress zones against the margin of the Phase 2 buildups. The left side of the image shows grainstones pinching out and dipping down towards the buildup, where a moat (blue) is created where finer particles may be trapped. The right side shows a grainstone beds “buttressing” up against the Phase 2 buildup without pinching out or dipping.
Figure 38 – (A) Andrea Transect along the James River where a very large grainstone bench interacts with the Phase 2 buildup. (B) A single core taken adjacent to the buildup within the lower Phase 2 interbuildup grainstone. (C) Core 133 exhibits an interfingering nature with the grainstone bench and is absent of any rind.
Figure 39 – (A) Andrea-Rosie interbuildup Sediment Transect taken along the James River illustrates the variable siliciclastic influence of the upper Phase 2 interbuildup sediment. (B) Carbonate content studies illustrate two main influxes of siliciclastics during this time. (C & D) During the middle of the upper Phase 2, the highest siliciclastic content corresponds with the most dolomitized cores of the 4 (highlighted in blue on the carbonate content graph).
Figure 40 – Rosie Core Transect taken along the James River illustrating the Upper Phase 2 microbial fabrics developed in an Upper Phase 2 flank. These deposits contain some horizontal stratigraphy not evident in many other Phase 2 microbialites such as Twin Herms.
Figure 41 – Granddaughters (left) and Jack (right) buildups above the Llano River evidencing subphases within Phase 2. A short-lived influx of siliciclastics within this area influenced the growth of the buildups to pause, creating a traceable surface across the buildups. Additionally, the buildups seemed to “backstep,” where the upper Phase 2 buildup is smaller than the underlying lower Phase 2.
Figure 42 – Phase 3 rind found along Rosie and Twin Herms outcrops. Multiple cores were taken within the side and upper rind of Phase 3, all exhibiting the typical thrombolitic texture composed of calcite and iron oxide-coated calcite.
Figure 43 – Phase 3 aluminosilicate content scans illustrating the inclusion of silicates into the outer Phase 3 rind in sediments pockets.
Figure 44 – H1 Transect Isotope values indicating a shift in both the carbon and oxygen isotope systems across a Phase 1 buildup. The observed shifts are attributed to dolomitization of the Phase 1 interior, as evidenced within the hyperspectral scans.
Figure 45 – Don Transect Isotope Analyses, consisting of a small and larger core transect, indicating the shifts within the carbon and oxygen isotope systems across the three phases. Phase 1 and 3 have generally heavier $\delta^{13}C$ values (heavier than 1.0 ppt) and lighter $\delta^{18}O$ values (lighter than 6.0 ppt) than Phase 2.
Figure 46 – The modern carbonate system of the Bahamas (upper image) containing large modern microbial buildups exist in a similar setting as Phase 2 of the Upper Cambrian (lower image). Mobile inter-reef grainstones, influenced by tidal flows, create large dunes with smaller-scale ripples and megaripples. The flow interacting with the large buildups creates a scouring zone that may create a moat around the lower margin of the buildup. Otherwise, the grainstones buttress directly against the microbial buildup.
Figure 47 – Depositional model for the large Upper Cambrian large microbial buildups recording factors influencing the growth of the buildups from initiation to demise. See detailed description in text.