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**Internal Fabric of Giant Domes in the Mesoarchean Steep Rock
Carbonate Platform, Superior Province, Canada**

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Draft

Abstract

Drivers for accumulation of Archean seafloor carbonate were mostly very different than those operating today. Alternating crystal fan fabric and cusate fenestral fabric forming meter-scale giant domes is rare in Archean carbonate platforms and limited to this time period. Their genesis is poorly understood. The oldest known examples are in the 2.8Ga Steep Rock Group of northwestern Ontario, Canada, where 200 to 500m of carbonate was deposited on a semi-restricted platform. Here the elongate domes are composed of cm to dm alternations of calcite crystal fans and microbialite, commonly separated by thin, dark ferroan dolomite and quartz replaced areas, which have herein been referred to as alteration surfaces. The cusate fenestral fabric is formed of draping, mat-like laminae, vertically oriented support structures, and cement-filled voids. The concave-up mat-like laminae attach to the support structures, which, similar to the alteration surfaces, are primarily composed of ferroan dolomite and quartz. One bedding plane surface consisted of cm-scale polygonal blocks with upturned edges with support structures forming the cracks, leading to the possibility that desiccation may be involved in at least this layer's development. As opposed to the calcite microbialite the crystal fan layers were probably originally aragonite, containing significantly higher Sr contents with less Fe and Mn. This necessitates changes in water geochemistry during deposition of the alternating layers. Possible drivers could be: 1) relative sealevel changes controlling amount of isolation; 2) calcite precipitation changing the Mg/Ca ratio; 3) changes in organic productivity laterally moving the redox gradient; 4) a change in Fe^{2+} concentration, and 5) storm events causing water body mixing.

Keywords: carbonate platforms, Mesoarchean hydrosphere, giant domes, microbialites, crystal fans

Draft

Introduction

The Archean ocean differed vastly in water chemistry and inhabitants from the present day. Yet, even without rigid frame-builders and the existence of multicellular shelled organisms leading to the high productivity of modern oceans, carbonate platforms were capable of developing in Archean shallow seas. The existence of these platforms has led to the preservation of carbonate structures that are unlike any found in more recent marine settings. One of the more interesting features of ancient ocean carbonate sequences are giant domal structures (Truswell and Eriksson, 1973; Beukes, 1987; Simonson et al., 1993; Sumner and Grotzinger, 2000; Fralick and Riding, 2015), which are fairly ubiquitous in thick Archean carbonate successions. These domal structures can reach up to 10 meters in height (Carawine Dolomite; Simonson et al., 1993; Murphy and Sumner, 2008) and are composed of a number of different lithofacies. One of the most common constituents is crystal fan fabric, which is formed of commonly upright, radiating clumps of elongate calcite needles to fingers that are probably pseudomorphing aragonite (Martin et al., 1980; Sumner and Grotzinger, 1996, 2000). Stromatolitic layering can also be present in the giant domes, such as in the 2.65 Ga Cheshire Formation (Martin et al., 1980; Abell et al., 1985), the 2.63 Ga Carawine Dolomite (Murphy and Sumner, 2008), and the 2.6-2.5 Ga Campbellrand Platform (Sumner, 1997a). The third major constituent of some domes is cusped fenestral fabric, which is a biogenic structure composed of stacked, concave-up, fingernail sized laminae with vertical, thin columns extending where the stacks meet. These have been described from a number of occurrences in both Archean giant domes and in non-dome forming associations (2.8 Mosher Carbonate, Fralick and Riding 2015; 2.73 Ga Joutel limestone, Hoffmann and Masson, 1994; 2.72 Ga Tumbiana Formation, Flannery and Walter, 2012; 2.63 Ga Carawine Dolomite, Murphy and Sumner, 2008; 2.6 Ga Huntsmann Limestone, Sumner and

Grotzinger, 2000; 2.6-2.5 Ga Campbellrand Platform, Sumner, 1997a). Of the many occurrences of giant domes formed on the Archean seafloor only the Mosher Carbonate and Huntsmann Limestone domes are composed of regularly alternating layers of crystal fan fabric and cusped fenestral fabric (Figure 1). This alternation records a periodic change in some aspect of the environment that is causing switching between abiotic aragonite precipitation and biologic mat development. Here we examine the morphological and geochemical differences that exist between the layered facies within giant domes in an effort to better understand the processes involved in their formation, as well as to further propagate knowledge of the Archean ocean and biota. The lack of any modern analogues necessitated investigation of the factors driving these changes in sedimentation on the Archean seafloor solely by examination of the rocks themselves from the Mosher Carbonate giant domes.

The ~2.8 Ga (Fralick et al., 2008 and references therein) Mosher Carbonate and its giant domes has been studied for over a century and is widely considered one of the most substantial Archean carbonate sequences, thus making it an important source of information in understanding the nature of the ancient ocean (Grotzinger, 1989; Riding et al., 2014; Fralick and Riding, 2015). The Mosher Carbonate of the Steep Rock Group is located in northwestern Ontario, 5km north of the town of Atikokan, in southern Wabigoon Subprovince of the greater Superior Province (Wilks and Nisbet, 1988; Kusky and Hudleston, 1999; Fralick and Riding, 2015) (Figure 2A, B). It is underlain by tonalite basement of the 3.0 Ga Marmion Complex and is overlain by iron formation, ultramafic pyroclastics, mafic flows, and finally rhyodacite (McIntosh, 1972; Wilks and Nisbet, 1985; Stone et al., 1992; Sumner and Grotzinger, 2000). The Steep Rock Group is separated from the underlying Marmion Complex by a well preserved nonconformity (Smyth,

1891; Jolliffe, 1955; Wilks and Nisbet, 1985; Kusky and Huddleston, 1999) with metasandstones and metaconglomerates of the Wagita Formation conformably underlying the Mosher Carbonate in basement incised channels (Jolliffe, 1955; Wilks and Nisbet, 1985) (Figure 2C). The 200 to 500 m thick Mosher Carbonate is conformably overlain (Shklanka, 1972; Fralick and Riding, 2015) by 100 to 300 m of manganiferous iron formation, followed by 50 to 100 meters of iron formation with a much lower manganese content. Regional studies of igneous geochemistry and the architecture and geochemistry of the sedimentary units infers that deposition occurred in an ocean plateau setting (Wyman and Hollings 1998; Hollings and Wyman, 1999; Hollings et al., 1999; Fralick et al., 2008). As mafic and ultramafic volcanism ended and the oceanic plateau underwent load driven subsidence, submergence of the platform caused a shift to carbonate deposition at Steep Rock. Carbonate deposition was then replaced by deposition of iron formation and chert as water level continued to rise (Fralick et al., 2008).

A minimum age of 2780.4 ± 1.4 Ma was acquired through dating of lapilli tuff overlying the sedimentary units (Tomlinson et al., 2003). Correlative sedimentary units to the northeast overlie 2828 ± 1 Ma volcanic rocks (Tomlinson et al., 2003). The youngest detrital zircon in a sample from the Wagita Formation gave an age of 2779 ± 22 Ma (pers. comm. Denver Stone, Ont. Geol. Sur.), placing the depositional age of the Mosher Carbonate probably between 2801 and 2780 Ma.

Methods

Samples examined for this investigation were selected from a collection obtained at locality 6 of Fralick and Riding (2015). Hand sample and polished slab observations, as well as binocular and

petrographic microscope observations, were utilized to qualitatively describe samples. Fenestrate microbialite terminology is that of Sumner (1997a,b).

A Hitachi SU-70 Schottky field emission scanning electron microscope (SEM) with energy dispersive spectrometer capabilities was used to observe carbon-coated polished thin sections. Spot analysis was conducted with the SEM on crystal fans, calcite cement, microbialite, and dark ferroan dolomite and quartz-rich contacts between layers. This was accomplished by pre-marking areas of interest prior to analyses with the SEM-EDS, which allowed these areas to be distinguished. Spot analysis was completed at a working distance of 15mm and an accelerating voltage of 20kV with an Oxford Aztec 80mm/124ev electron dispersive X-ray spectrometer. Back scatter electron images and elemental mapping images were also completed. During data collection and analysis, dolomite containing greater than atomic 2% Fe was described as ferroan dolomite.

Lithofacies

Giant Domes

Giant elongate mounds are common in Precambrian carbonate platforms, and above-wave-base, open marine subtidal depositional environments have been well established (eg. Truswell and Eriksson, 1973; Eriksson and Truswell, 1974; Grotzinger, 1986; Pelechaty and Grotzinger, 1989). The giant domes of the Mosher Carbonate are elongated in shape, range in size from 2 to 3.5m wide and 2 to 6m long, have convex surfaces, and are closely stacked upon one another (Figure 1A) (Fralick and Riding, 2015). Current activity acting upon the giant domes led to their elongation perpendicular to the inferred shoreline, and is also the likely culprit for a lack of

intervening sediment between the domes (Fralick and Riding, 2015; and similar to: Hoffman, 1967; Hoffman, 1974; Ricketts, 1983). The giant domes are composed of interlayered crystal fans, and net-like or cusped fenestrate microbialite with the thickness of each layer ranging from 1 to 15 cm. Boundaries between successive layers are formed as a result of irregular surfaces that show oxidation of ferroan dolomite, or by a gradual or abrupt shift in lithology. The giant dome facies has been interpreted as a platform margin deposit in which a laterally fluctuating redox boundary led to precipitation of alternating layers of aragonite crystal fans and calcite cusped fenestrate microbialite (Fralick and Riding, 2015).

Crystal Fan Fabric

The crystal fan fabric present within the giant dome facies at Steep Rock ranges in thickness from centimeters to two decimeters. Fans are most commonly 2 to 5 cm in height and width, with individual crystals not exceeding 1 cm in width. In general, these aragonite pseudomorphs (Sumner and Grotzinger, 2000) are primary seafloor precipitates and have been identified as forming in a wide range of Archean environments, from peritidal to below wave base subtidal (Hofmann et al., 1985; Simonson et al., 1993; Sumner and Grotzinger, 2000; Sumner, 2002). While crystal fans are ubiquitous within the Archean and Paleoproterozoic, their occurrence at Steep Rock is unusual in that they form relatively uniform and continuous layers in the giant domes (Fralick and Riding, 2015). They also exist within net-like microbialite fabrics and rarely in cusped fenestrate microbialite layers. The most common occurrence of crystal fans in the giant domes was forming layers within the net-like microbialite. These fans tended to be a lighter

shade of black than their discretely layered counterparts. Where fans form discrete layers they often lack radial growth due to their close packing.

The fans are distinguishable by their concentration of dark organic matter (Nisbet et al., 2007) surrounded by white to light grey cement. The cement appears massive in nature, but in many instances is cross-cut by thin black laminae that are very similar in appearance to those that constitute the net-like microbialite facies. Where fans are not completely darkened by inclusions, the thin black laminae can also be observed within the fans themselves. The cement consists primarily of calcite, with minor amounts of dolomite and very fine-grained quartz. The fans are variable in shape, with blades ranging from short and stout, to wavy, to almost feathery in appearance. While preservation of fan tips is rare, a few display apparently feather-tipped and blunt ends. Contacts between discrete crystal fan layers and microbialite layers was commonly abrupt, and where discrete crystal fan layers come into contact with microbialite layers alteration surfaces separated the two layers or crystal fans appeared to grow from the tips of cusped fenestrate support structures (Figure 3A, B).

In thin section, rare replacement textures were observed in association with crystal fans, but more commonly there was no identifiable relict fabric. However, the textures that were observed were consistent with calcite replacement after aragonite. A preferred alignment of carbon-rich detritus and inclusions that ran parallel to the elongation of the fans resulting in preservation of the original mineral shape was rarely present (Figure 4A). This texture is akin to the inclusion-rich, equant mosaic of calcite that has been described as replacement of precursor aragonite

(Sumner and Grotzinger, 2000). Also rarely present was a possible relict fan fabric in the form of an elongation of calcite crystals parallel to the fans in a texture that has been described as an elongate mosaic petrographic facies (Sumner and Grotzinger, 2000) (Figure 4B). Aside from these isolated occurrences of replacement textures, petrographic analysis provided no indication of relict fan fabric.

Cement-filled voids between individual crystals were analyzed using an SEM-EDX in an effort to discern whether they contained any internal zonation that may provide information on whether or not they are isopachous in nature. Spot analysis was conducted across the short axis and down the long axis of cement-filled voids, which would allow for any change in geochemistry to be observed. The results from this data collection indicate that there is no change geochemically from the centers of the cements to their contacts with crystal fans. A lack of any pattern in geochemistry leads to the assumption that the cement-filled voids, while somewhat heterogeneous in Mg content, do not display any zonation. However, in terms of the Mg content there does appear to be a pattern in that the cement-filled voids contain, on average, higher concentrations than the adjacent fans. This conclusion is drawn from SEM-EDS mapping that was done on boundaries between the fans and adjacent cements (Figure 5A, B).

Fenestrate Microbialites

Two fenestrate microbialite fabrics, cusate and net-like, occur in centimetric layers within the giant domes. These microbial fenestrate fabrics are composed of three separate parts; thin filmy laminae, vertical supports, and cement-filled voids (Sumner, 1997b). Both the thin filmy laminae

and the vertical supports are discernable due to carbon-rich inclusions, and are argued to be microbial in origin (e.g., Sumner, 1997b). While cusate fenestrate microbialites similar to those found within the giant domes are commonly present in Neoproterozoic carbonate platforms, there are no reported occurrences of cusate fenestrate microbialites in sequences younger than the 2.5-2.6 Ga Campbellrand platform (Murphy and Sumner, 2008; Schroder et al., 2009; Fralick and Riding, 2015). There is still open debate about the processes involved in the formation of the net-like and cusate fenestrate microbialite fabrics and what information they may reveal about environmental conditions and microbial communities in the Archean (Murphy and Sumner, 2008; Fralick and Riding, 2015).

The cusate fenestrate microbialite facies is composed of support structures, draping laminae, and cement-filled voids (Figure 6A). The supports show compaction and appear to be directly attached to the filmy laminae with no visible presence of calcite (herringbone or otherwise) coating them (Figure 6A, B). They are darker due to a higher volume of organic material (Nisbet et al., 2007), now carbon, in comparison to the laminated mat, and in rare instances, have a decrease in crystal size as well. Supports can branch outwards near their lower termination, and form radiating bases. Upwards branching supports are present as well, and growth of supports is typically upright but many have also formed at angles up to 45° (Figure 6B). The supports are between 200-500µm in thickness, and the width of supports does not appear to be directly associated with the volume of filmy laminae present, as was observed by Sumner (1997b).

In general void cements in cusped fenestrae have been estimated to be present as 10-90% of the total fabric (Sumner, 1997b). The Steep Rock cusped microbialites have been described as having rare voids, and where present, the voids are flattened between draping filmy laminae (Sumner, 2000). This is consistent with the samples observed in this study where most cusped samples contained <1-10% void space, with the majority of the voids being dish-shaped and conforming to the cusped fabric. However, some voids displace draping laminae and cause them to swell upwards. Cement-filled voids are in higher concentrations near the supports, although the draping laminae still remain in contact with the supports.

Commonly either a gradational contact or uneven hematite-stained surface separates cusped fenestral fabric from crystal fans, but one bedding plane on a dome displayed a well-preserved polygonal surface texture (Figure 7A). Lamination parallel to the surface was present in the upturned edges of the polygons and represents exposed draping laminae. In cross-section the cracks on the surface are occupied by support structures in the cusped fenestrate fabric (Figure 7B). The supports were slightly indented in places on the surface and thus appeared to be weathered out.

SEM and petrographic analysis on three samples of the cusped fenestrate fabric show that the supports consist of zoned crystals of ferroan dolomite that follow the structure of the support (Figure 8A, B, C, D). The thickest and most dolomite-rich supports are those that formed the polygonal surface expression described above. Along with the presence of ferroan dolomite, the supports also contain high concentrations of carbon. Areas that are higher in carbon tend to have

lower concentrations of Mn, Mg, and Fe. Also, the supports themselves display an internal zonation, with more Fe-rich dolomite at their centers, which becomes more Mg-rich towards the edges. In some samples quartz-rich zones were attached to the dolomite-rich forms, and rarely small Fe- and Mn-oxide grains are scattered within the support structure. While rare concentrations of these oxides are highest within the supports, minor amounts are also present within some adjacent draping laminae.

Net-like Fenestrate Microbialite

Net-like microbialite, which has also been referred to as void-rich microbialites in other studies, contains thin black laminae defined by organic inclusions, within white and light grey cement fills (Sumner and Grotzinger, 2000). These laminae are thin and highly branching, and in some cases, discontinuous and terminate in cement fills. The size of the cement fills, and ratio of cement fills to laminae is variable but usually net-like microbialites consist of roughly equal amounts of draping laminae and supports. The spacing between the supports ranges from 0.5-2cm and also shows some degree of compactional folding. Voids appear to constitute on average 40-70% of the net-like fabric.

The net-like microbialite facies occurs in layers that are usually 1-5cm thick. The fabric terminates where it comes into contact with another facies or at the oxidized and dimpled to irregular surfaces that separate distinct layers within the giant domes. Contacts between the net-like microbialite and cusped fenestrate microbialite, with which it is interbedded, range from gradational to sharp. In samples displaying a gradational change, the change is marked by

supports which form from the thin laminae and converge upwards. This leads to a diffuse base to the support structures in the overlying cusate fenestrate microbialite (Figure 9A). Also, crystal fans are commonly present projecting through net-like fabric, although they rarely displace the delicate laminae (Figure 9B). This may be an indication that the laminae and fans were forming contemporaneously. Small organic-rich inclusions, less than 5mm in size are commonly present scattered throughout the fabric but may be entirely absent.

Alteration/Bounding Surfaces and Transitions

There are two distinct types of contacts between adjacent crystal fan fabric and microbialite fabric. The first type exists where net-like microbialites meet crystal fans and is identified as dark surfaces with sharp, irregular tops that have tentatively been termed alteration surfaces (Figure 3A). These approximately 0.3 to 2cm thick surfaces appear dark grey in hand sample, causing them to stand out against their overlying and underlying facies. Petrographic and SEM-EDS analysis of the surfaces shows that they are composed of quartz and zoned ferroan dolomite (Figure 10A, B). The quartz is microcrystalline and is present intergrown with the dolomite. Zonation within the dolomite crystals is the result of Fe-rich cores and Mg-rich edges. The presence of iron oxides in the alteration surfaces can impart a red-brown colour.

The alteration surfaces range from very sharp contacts to gradational changes that result in the microcrystalline quartz and dolomite forming not a discrete layer, but rather a dispersive area and a less distinct boundary between the microbialite fabric and the crystal fan fabric. Although the timing of the silicification in these surfaces cannot be discerned, it is probable that the

surfaces are primary features and that the changes in facies that accompanies the presence of a bounding surface indicates an environmental change.

The second type of bounding surface exists where discretely layered crystal fan fabric overlies cusate fenestrate microbialite. These surfaces commonly occur where the crystal fans nucleate upon the support structures of the cusate microbialite facies where the upturned draping laminae converge (Figure 3B). This type of facies change was not as prevalent as discrete crystal fan layers and cusate fenestrate microbialite were less commonly adjacent to one another within the giant domes. One interesting feature to note from the crystal fan layers that have nucleated upon the supports is that they are less closely packed than those that have nucleated upon the alteration surfaces, and thus display more significant radial growth.

SEM-EDS analysis of major elements suggests that there is no significant difference in Fe, Mn, or Mg concentrations between consecutive net-like and cusate fenestrate microbialite facies. These values do show variations from sample to sample, but are not markedly different in consecutive microbialite layers. The crystal fan facies, where in contact with net-like fabric, contains lower concentrations of Mn and Fe, but does not show differences in Mg concentrations (Figure 11). Also, the concentrations of Mn were higher than the Fe values consistently across all samples analyzed, and may indicate that Fe had already been largely removed from the system in which the giant domes were forming (Riding et al., 2014; Fralick and Riding, 2015).

Discussion

329

330 *Net-like and Cuspate Fenestrate Microbialites*

331 An initial classification of the cuspate microbialites at Steep Rock as tented microbialites has
332 been previously put forward (Sumner, 2000). The cuspate fenestrate fabric was described as
333 being similar in nature to the tented fabric with supports being more closely spaced and with
334 laminated mat draped between them (Sumner, 1997b). Using this description the microbialites
335 present in the giant domes at Steep Rock would be better classified as cuspate fenestrate fabric, a
336 suggestion that has also been proposed by other authors (Fralick and Riding, 2015). Tented
337 microbialites contain supports that are spaced 10-50cm apart which is an order of magnitude
338 greater than at Steep Rock and are described as being folded or compacted in samples where
339 there are few voids (Sumner, 1997b). In all samples observed in this study, the average spacing
340 between the supports was 0.5-3cm. Compression of supports to some degree was present in
341 almost every sample and did not appear to be largely influenced by the amount of void space.
342 These observations fit well with the latter interpretation of cuspate fenestrate microbialite facies
343 within the giant domes (Sumner and Grotzinger, 2000; Fralick and Riding, 2015).

344

345 Various work has been completed on microbialite morphology in an effort to find modern
346 analogs to the fenestrate fabrics seen in the Steep Rock giant dome lithofacies and other Archean
347 carbonates (Shepard and Sumner, 2010; Tamulonis and Kaandorp, 2014). These studies involve
348 using filamentous bacteria to recreate the reticulate patterns present in Archean carbonates, and
349 have been fairly successful in doing so. The results of the studies completed using the
350 filamentous cyanobacteria, *Pseudanabaena*, have found that the bacteria can organize via gliding

351 motility into a reticulate pattern similar to the net-like microbialite fabric (Shepard and Sumner,
352 2010; Tamulonis and Kaandorp, 2014). Supports within the cusate microbialite layers are
353 similar in appearance to the “pillars” described by Shepard and Sumner (2010) in regards to their
354 crinkled nature which bears resemblance to the serrated compaction of the supports. There have
355 also been comparisons made between Archean fenestrate microbialites and microbial mats from
356 ice-covered Antarctic lakes, hot springs at Yellowstone National Park, and from the closed
357 coastal lagoon of Laguna Mormona in Baja California (Horodyski, 1977; Sumner, 1997b).
358 Conophyton observed in Yellowstone national park have been found to be composed of more
359 than one type of bacterium and thus led to the interpretation that cusate fenestrate fabric may
360 have been formed from two distinct microbes (Walter et al., 1976; Sumner, 1997b).

361
362 Fenestrate microbialite morphology is currently interpreted to be influenced primarily by the
363 timing of carbonate precipitation, and not by the mineralogy and form of the precipitates
364 (Sumner, 2000). The differences in morphology between the cusate fenestrate and net-like
365 microbialite facies may therefore be influenced in part, or in whole, by the amount of void-filling
366 cements deposited contemporaneous with microbialite growth. This would not only influence
367 primary morphology, but also the amount of compaction that the fenestrae would undergo, as
368 void-filling cements would increase the structural rigidity (Sumner, 1997b; Sumner, 2000). Also,
369 fenestrate microbialites are described as having a delicate morphology which leads to the
370 interpretation that they form in generally low energy environments below wave base and are
371 often constrained to deep subtidal assemblages (Sumner, 2000; Sumner and Grotzinger, 2000;
372 Murphy and Sumner, 2003, 2008; Bartley et al., 2015). The presence of net-like and cusate
373 fenestrate microbialites within the giant domes of the Mosher Carbonate agrees with the

interpretation of a subtidal environment. However, wave and current activity was influencing the elongation of the giant domes, indicating that the giant domes were likely forming largely above wave base (Fralick and Riding, 2015). Perhaps, if the void-filling cements formed early or contemporaneous with the fenestrate microbialite of the giant domes, this would have allowed for enough structural integrity for the delicate morphology to withstand the higher energy wave and current activity.

One common interpretation of cusped fenestrate microbialites is that the supports and laminated mats are formed from two separate and different microbial communities. Sumner (1997b) argues that the preferential precipitation of herringbone calcite upon the supports over the draping laminae seen in microbialites from the Gamohaan Formation of the Transvaal Supergroup indicates that the supports were formed from a different microbe than the draping laminae. A similar observation of herringbone calcite mantling supports in fenestrate microbialites was observed in the Carawine Formation of the Hamersley Group (Murphy and Sumner, 2008). The preferential precipitation of herringbone calcite indicates that the microbes forming the supports interacted differently with their environment and influenced calcite precipitation (Sumner, 2000). Cusped fenestrate microbialites in the Mesoproterozoic Sulky Formation of the Dismal Lakes Group have also been argued to be formed by two microbial communities, yet in this formation herringbone calcite mantles both supports and draping laminae indiscriminately, and instead diagenetic pyrite is associated with the draping laminae and is absent in the supports (Bartley et al., 2015). This observation has led to the interpretation of the supports being formed by a photosynthetic or sulfide-metabolizing community and the draping laminae by anaerobic bacteria (Bartley et al., 2015). A more recent study conducted on the fenestrate microbialites of the

Gamohaán Formation suggests that the supports may furthermore be subdivided into two distinct microbial communities on the basis of those which are oriented near vertically and others which are shallowly dipping (Stevens et al., 2011).

Herringbone calcite, which preferentially precipitated on the supports in the Gamohaán and Carawine Formations, is not present in the Mosher Carbonate. It was either destroyed by recrystallization in the giant dome lithofacies at Steep Rock, or it did not form at all in the microbialite facies. The former is unlikely as in both hand sample and in thin section it can be seen that the laminated mats are connected directly to the supports as is accentuated by the presence of carbonaceous inclusions. The lack of a gap between the supports and mat indicates that there was no herringbone calcite present surrounding the supports. Also, in general there is a distinct lack of isopachous and herringbone calcite cements in the giant domes at Steep Rock despite the fact that these are both common cements seen in microbialite lithofacies of other Archean platforms (Sumner and Grotzinger, 2000). Similarly, the diagenetic pyrite which is found within the draping laminae of the Sulky Formation but not in the vertically oriented supports is also a feature that is not observed in the microbialites of the giant domes.

Thus, the evidence for different biologic communities forming the laminated mat and the supports are not present at Steep Rock. These support structures are primarily composed of quartz and ferroan dolomite, with iron-rich cores and iron-poor rinds. This is similar to the mineralogy of what are termed alteration surfaces separating some layers of the two lithofacies in the domes. In both cases the quartz and ferroan dolomite are replacing what was probably

original calcium carbonate. There is also the singular occurrence of cusate fenestral fabric forming what appear to be desiccation cracks on a bedding-plain surface of a dome. The cracks display a polygonal arrangement with triple junctions that meet at angles of 120° , but also with some T-junctions present. Hexagonal crack pattern formation (120° triple junctions) is thought to be an evolution of rectilinear formation (90° T-junctions) as a result of continued opening and closing of crack networks (Goehring, 2003). In this sense, both patterns can be found co-existing on the fragment of the bedding plane, and are the result of the same process (Goehring, 2003).

Cracks, which form the depressions that are visible on the surface, are expressed as supports below the surface. These supports are slightly eroded out where exposed and display the common features seen in other cusate fenestrate microbialite layers including the concave nature of the draping laminae and the greater accumulation of cements along the supports. Concave-upwards layers associated with desiccation cracks is a feature reported on in other ancient carbonate rocks (Aitken, 1967; Picard and High, 1973; Schieber, 1998) and their upturned form adjacent to the supports has been described as growth ridges seen in modern day microbial mats (Ginsberg, 1960; Horodyski and Bloeser, 1977; Gerdes et al., 1993; Schieber, 1998). The upturned edges of the desiccation cracks may have been sites of preferential crystal fan nucleation as is evidenced by their growth from these points.

The preservation of the desiccation surface present on the one bedding plain was not observed on any others, which is not surprising considering that preservation of desiccation cracks is a reasonably rare occurrence (Picard and High, 1973). While the surficial expression of the

desiccation cracks is very typical of that described in the literature (Goehring et al., 2015), the cross-sectional morphology of the supports is atypical. Desiccation cracks are often v-shaped upwards and pinch out at depth (Picard and High, 1973) but the supports seen in all cusate fenestrate microbialite samples from the giant domes are relatively narrow and do not show any consistent increase in width upwards. This atypical morphology of the supports may be a result of desiccation being a secondary process that acted upon the preexisting primary pattern generated by the microbialites. In the event of exposure, cracks could have preferentially adopted the network formed by the supports.

The ferroan dolomite and quartz replacing calcite associated with supports in all samples observed is similar to the type of alteration seen on bounding surfaces between layers in the giant domes and forming thin replacement surfaces on limestone layers in the stromatolitic lithofacies. Fralick and Riding (2015) hypothesized that these replacement surfaces were produced during incursions of offshore iron- and silica-rich water during storm or other longer term transgressive events. Precipitation from offshore derived waters would be capable of driving the replacement reactions, and possibly open space filling cements producing the ferroan dolomite and silica present in the upright structures. This does not necessarily negate a biological origin for the supports as possibly they arrange in hexagonal patterns and would probably provide permeability conduits.

Alteration/Bounding Surfaces

The alteration surfaces may represent hardgrounds, which silicified and dolomitized during flooding events, preferential fluid pathways allowing for silicification and dolomitization in support structures underlying these surfaces. Hardgrounds are features that represent early

marine cementation and are thought to be associated with periods of reduced sedimentation (Shinn, 1969; Purser, 1969; Kennedy and Garrison, 1975; Schlager and James, 1978; Bromley and Allouc, 1992; Savrda, 1995; Obrochta et al., 2003; Roberts and Boyd, 2004; McLaughlin et al., 2008; Christ et al., 2015). In particular, regressive-marine hardgrounds can develop as a result of sediment entrainment and non-deposition due to wave activity (Christ et al., 2012). While clastic sedimentation was not a dominant processes involved in the formation of the giant domes (as is evident by a distinct lack of intervening clastic sediment (Fralick and Riding, 2015)) environmental changes occurring as a result of fluctuations in the water level may have led to early diagenetic cementation. Unfortunately, there is no documentation of hardgrounds found in carbonate sequences prior to the Proterozoic, making comparisons of the alteration surfaces in the giant domes to similar features impossible (Christ et al., 2015).

Crystal Fans

Crystal fan fabric is described as being possibly primary aragonitic sparry seafloor crust and can be identified as radiating fans that are discernible by dark, carbon-rich material (Sumner, 1997b; Riding, 2008). Aragonite pseudomorphs are also common in the 2.5 Ga Campbellrand-Malmani platform in South Africa, and are argued to be present only in shallow water facies, above wave base, as these waters would have been supersaturated with aragonite (Sumner and Grotzinger, 2004).

Pseudomorph crystal fans are found in every well-preserved Archean carbonate sequence, and while they have been referred to as primary aragonite in this discussion, there has been ongoing

485 debate as to their primary mineralogy with proposed precursors of barite, gypsum, or aragonite
486 (Bertrand-Sarfati, 1976; Hardie, 2003; Sumner and Grotzinger 1996, 2000; Fralick and Riding,
487 2015). However, most work favours an aragonitic precursor due to suggestive recrystallization
488 fabrics and square to feathery terminations (Grotzinger and Reed, 1983; Kusky and Hudleston,
489 1999). Even within the giant domes, the crystal fans vary in their shape and size. As a result of
490 rare cement fill mantling of fan tips, blunt and feather tipped fan terminations were observed.
491 This is a common feature of aragonite crystals (Grotzinger and Reed, 1983; Peryt et al., 1990;
492 Sumner and Grotzinger, 2000). In thin section, rare preservation of what may be aragonite
493 replacement fabrics was present and has also been noted in other studies (Kusky and Hudleston,
494 1999; Fralick and Riding, 2015). The elongation of the replacement calcite crystals is a typical
495 characteristic of calcite after aragonite (Assereto and Folk, 1980; Mazzulo, 1980; Sandberg,
496 1985; Sumner and Grotzinger, 2000) and was rarely observed along with carbon detritus
497 mantling and an accumulation of inclusions along the long axis of pseudomorphed fans.

498

499 Another piece of evidence that may suggest primary aragonite is the Sr concentrations within the
500 crystal fans, as one of the more common and distinguishing characteristics of aragonite is its
501 tendency towards high concentrations of Sr relative to calcite and gypsum (Assereto and Folk,
502 1976; Davies, 1977; Mazzulo, 1980; Sandberg, 1985; Sumner and Grotzinger, 2000). Aragonite
503 often has higher Sr concentrations than both calcite and gypsum because the strontium partition
504 coefficient for aragonite is 1.13 whereas for gypsum it is <0.1 and for calcite it is 0.2 (Kinsman,
505 1969; Kinsman and Holland, 1969; Katz et al., 1972; Kushnir, 1980; Lorens, 1981; Sumner and
506 Grotzinger, 2000). Fralick and Riding (2015) obtained values of 600-800ppm for Mosher crystal

507 fans, which is similar to values from Campbellrand crystal fans and supports a primary aragonite
508 interpretation (Sumner and Grotzinger 1996, 2000, 2004; Sumner, 2004).

509
510 Pseudomorph crystal fans are believed to be a synsedimentary seafloor precipitate and formed
511 either directly on the seafloor or below the substrate in the Mosher Carbonate (Fralick and
512 Riding, 2015). This observation is consistent with this study of the giant domes as it seems quite
513 likely that the discrete crystal fan layers formed on the seafloor, while the isolated crystal fans
514 formed within microbialite facies. The growth of the fans was likely synchronous with the
515 microbialites as quite commonly the fans overprint the net-like fabric. Other studies have noted
516 the presence of crystal fans within the microbialite fabrics of the Mosher Carbonate, but with
517 contention about whether they are more commonly found within void-poor (cusped fenestrate)
518 or void-rich (net-like) fabrics (Walter, 1983; Sumner and Grotzinger, 2000). In this study, the
519 net-like microbialite fabrics within the giant domes were more commonly found to host crystal
520 fans.

521
522 The interpretation of the giant domes experiencing periodic subaerial exposure may provide a
523 possible explanation for the presence of crystal fans within the net-like microbialite where it
524 underlies cusped fenestrate microbialite. If the domes became exposed, not only would water
525 flooding over the surface infiltrate into the domes, but evaporative pumping would cause fluids
526 to move upwards and concentrate near the surface. This feature was observed from the Bee
527 Gorge Member of the Wittenoom Dolomite in Western Australia where evaporative pumping
528 occurring at mud-cracked horizons led to Sr-rich aragonite being precipitated in the drying layers

(Kargel et al., 1996). If indeed the crystal fans in the giant domes of the Mosher Carbonate were primary aragonite, and if the aforementioned interpretation of desiccation cracks is correct, then the observations made in both of these Precambrian carbonate sequences have interesting similarities. Furthermore, the evaporative pumping hypothesis may also provide an alternative explanation for the preferential dolomitization of the support structures, as dolomite infilling of mudcracks via capillary movement of Mg-enriched waters has been observed from Devonian and modern carbonates (Shinn and Ginsburg, 1964; Shinn et al., 1965; Laporte, 1967).

SEM analysis of five samples showed that, on average, the discrete crystal fan layers contain lower concentrations of Mn and Fe than adjacent microbialite fabrics. This may indicate that the primary mineralogy of the fans was different than that found within the fenestrate microbialites, and furthermore indicates that the fans precipitated as aragonite. Iron has an inhibiting effect on calcite precipitation meaning that should the concentration of iron in the water become too high, calcite precipitation will no longer occur, and instead aragonite will dominate (Herzog et al., 1989; Sumner and Grotzinger, 1996, 2004; Riding et al., 2014). Thus, changing water chemistry to more iron-rich would lead to aragonite with low Mn and Fe levels precipitating (Fralick and Riding, 2015). SEM analysis of the crystal fan fabric also showed a tendency for the cement fills present between the fans to be higher in Mg than the fans. This trend is opposite to that found between the microbialites and fan fabrics, where Mn and Fe differed, while Mg was unaffected.

Giant Domes

Precambrian giant domes similar to those found at Steep Rock have been well-described from the Campbellrand-Malmani platform, the Carawine Dolomite, and the Huntsman Limestone (Truswell and Eriksson, 1973; Beukes, 1987; Simonson et al., 1993; Sumner and Grotzinger, 2000; Barlow et al., 2016). In the literature, giant domes have quite often been referred to as elongate mound stromatolites (Eg. Truswell and Eriksson, 1972; Sumner and Grotzinger, 2000), while at Steep Rock these giant domal features have been described more recently as hybrid stromatolites (Fralick and Riding, 2015) as they consist of interlayered microbial mat (fenestrate microbialites) and abiogenic precipitates (crystal fan fabric) (Riding, 2008). What makes the giant domes of the Mosher Carbonate particularly interesting is the internal alternations of layers of crystal fan fabric and microbialite fabric. In comparison, the well-studied giant elongate mound stromatolites of the Campbellrand-Malmani platform are composed of columnar stromatolites, smooth to peaked laminae, and fanning pseudomorphs that form as both isolated crystal fans as well as continuous layers (Sumner and Grotzinger, 2000). The Carawine Dolomite contains giant domes which have been compared to those found in the Campbellrand-Malmani platform and consist of smooth to wavy laminae, smaller stromatolites, crystal pseudomorphs, and zebraic dolomite cements, which are now referred to as herringbone cements (Simonson et al., 1993; Sumner and Grotzinger, 1996; Barlow et al., 2016). Internal composition of the giant domes of the Huntsman Limestone is less well understood due to poor preservation but appears to be laminated, and overlying the giant domes are fenestrate microbial structures with pseudomorphed fans that become discrete interstratified beds moving up section (Sumner and Grotzinger, 2000). The occurrence of interbedded microbialite and crystal fan fabric associated with, but possibly not occurring within, the giant domes of the Huntsman Limestone is an interesting contrast with the giant domes of the Mosher Carbonate.

573

574 The regular alternation in the Mosher Carbonate of the fenestrate microbialite layers and crystal
575 fan layers, commonly with intervening alteration surfaces, requires changes in the chemistry of
576 the overlying water. Fralick and Riding (2015) have shown that the changes in lithofacies were
577 accompanied by changes in mineralogy between the calcite microbialites and aragonite crystal
578 fans. This is further complicated by some contacts between the two being altered by the
579 formation of ferroan dolomite and quartz. In the paleogeographic setting the Mosher Carbonate
580 formed in, a central lagoon producing oxygen with giant domes causing restricted circulation
581 with the ocean (Riding et al., 2014; Fralick and Riding, 2015), four main processes could cause
582 changes in water chemistry:

- 583 1) Relative sealevel change causing either restriction from the world ocean or influx of Fe^{+2} -
584 rich ocean water.
- 585 2) Carbonate precipitation on the platform removing Ca from the water causing the Mg/Ca
586 ratio to rise.
- 587 3) Changes in organic productivity, and thus oxygen production, causing the redox gradient
588 from the more oxygenated platform to the relatively anoxic offshore ocean to change
589 position.
- 590 4) Storm events causing a storm surge that would deliver Fe^{+2} enriched water to the platform
591 and the return geostrophic flow that would move more oxygenated water offshore.

592

593 During a cycle consisting of the influx of off-shore water and subsequent reestablishment of
594 semi-isolation these processes can combine to drive the changes in lithofacies present in the

595 domes. One possible scenario is: During intervals when the platform was less restricted than at
596 other times, and enhanced exchange with the open ocean was possible, an influx of Fe^{+2} -bearing
597 water would alter the substrate to ferroan dolomite, the stable phase at elevated dissolved iron
598 levels (Herzog et al., 1989; Sumner and Grotzinger, 1996, 2004; Riding et al., 2014). The influx
599 of off-shore water was probably a brief episode as only limited ferroan dolomite and chert
600 alteration is present on these surfaces. Oxygen generated by the microbial communities (Fralick
601 and Riding, 2015) was able to once again move the redox gradient sufficiently offshore to lower
602 Fe^{+2} on the carbonate platform so that calcite was the stable phase. After the influx the platform
603 became progressively more isolated from the world ocean and calcite precipitation without
604 sufficient recharge caused the Mg/Ca ratio to increase. This slow increase in the Mg/Ca ratio
605 during calcite precipitation eventually changed the stable phase to aragonite and promoted the
606 growth of crystal fans rather than calcite fenestral fabric. This is in agreement with the crystal
607 fans having heavier $\delta^{13}\text{C}$ than the other lithofacies, probably caused by loss of light carbon
608 during conditions of restricted circulation (Fralick and Riding, 2015). If during this interval a
609 dome was exposed prior to the Mg/Ca ratio reaching the point aragonite became stable, a
610 hardground alteration surface would have developed on the surface of the microbialite. If the
611 ratio was higher and crystal fans formed then the surface of the top of the fans would have been
612 altered obscuring their tips, which is commonly the case. Any expansion of the submerged area
613 on the carbonate platform could cause an increase in productivity and the redox gradient to move
614 further offshore. These changes in restriction of circulation could have been driven by either
615 relative sea-level change or influxes of off-shore water during storm surges. The thick succession
616 of near-shore carbonate infers subsidence and therefore relative sea-level change was occurring,
617 as deposition rate would not be expected to match subsidence rate at all times. However, the

spatial frequency of the changes of aragonite crystal fans to calcite fenestrate microbialite implies that the alternations in isolation occurred over relatively short time periods. Thus, storm events producing storm surges, possibly coupled with upwelling, are preferred as the driver of such changes. This is just one possible scenario for the development of the layering. What it shows is that small changes in isolation can cause changes in Fe^{+2} content of the platform water, the Mg/Ca ratio, position of the redox gradient and productivity, which will affect the lithofacies capable of forming.

Conclusions

Why the alternating lithofacies at Steep Rock formed an at least 70m thick succession of domes that build upon one another in a somewhat random manner with no visible clastic sediment in depressions is unknown. However, it is clear that the alternation of cusped fenestral fabric and crystal fan fabric, which compose the domes, reflects changes in the geochemistry of the overlying water. Combinations of storm surges, possibly also causing upwelling events, carbonate precipitation changing the Mg/Ca ratio and changing organic productivity laterally moving the redox gradient are capable of producing the alternations observed. Storm surges, or, less likely, highstand sea-level events, would have also caused development of the dark alteration surfaces that separate many of the layers by introducing iron- and silica-rich offshore water, which may have led to a hiatus in carbonate precipitation, and quite possibly intervals during which carbonate was physically eroded, dissolved or subjected to a replacement reaction forming ferroan dolomite. A shift back to a stable environment for the precipitation of calcite or aragonite would then result in the recommencement of depositional processes. The replacement

surfaces tend to separate changes between net-like microbialite fabrics and crystal fan fabrics, which contain differing concentrations of Mn and Fe. This strengthens the argument that the surfaces represent a change in the geochemistry of the environment.

While this research has disclosed some possible conclusions as to the formation of the giant domes at Steep Rock, it has arguably opened just as many avenues of further research. The cusplate fenestrate microbialite fabric is composed of microbial draping laminae and vertically oriented supports with cement-filled voids similar to other Archean examples (e.g., Sumner, 1997b). While abiotic analogs have been previously dismissed for the formation of supports in cusplate fenestral microbialite, the, all-be-it one, well-preserved desiccation surface may re-open discussion as to the genesis of the support structures. Though it is likely that the rare desiccation features are controlled by the preexisting cusplate fenestral fabric, this leads to the question as to what is the 3-dimensional pattern of the supports: is it systematic; does it vary through time or space; and most interestingly, does it have a generally polygonal pattern with t-junctions?

In the Cambellrand-Malmani platform, aragonite pseudomorph crystal fans are only present within the facies that are interpreted to have been deposited above wave base, indicating that these waters were supersaturated with respect to aragonite (Sumner and Grotzinger, 2004). Also, while precipitation rates of aragonite may have been higher, a lower influx of sediment may have contributed to the ability of the crystal fans to reach such a large size (Sumner and Grotzinger, 2004). This observation fits well with the interpretation that the giant domes at Steep Rock were influenced by wave and current activity, as the relatively high energy of the system and a higher topographic level may have resulted in little detritus being deposited on the giant domes and an associated lack of intervening sediment (Fralick and Riding, 2015). It is also interesting to note that at Steep Rock calcite was probably the stable carbonate phase on the platform with aragonite

only able to precipitate when Ca loss from the water through precipitation altered the Mg/Ca ratio or through a change in the concentration of dissolved Fe^{2+} (Riding et al., 2014). If aragonite was the stable phase alteration of the seawater geochemistry to facilitate extensive carbonate precipitation both temporally and spatially is difficult to envisage.

Draft

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Draft

Figure Captions

Figure 1: Giant Domes of the Elbow Point Member. A) Plan view of domes that outcrop at Hogarth Pit, Steep Rock. B) Internal lamination of the domes consists of interbedded fenestrate microbialite and crystal fan fabric.

Figure 2: A) Outcrop map of the Steep Rock Group east of Steep Rock Lake (after Kusky and Hudleston, 1999) with outcrop locations of the Elbow Point Member (Fralick and Riding, 2015). B) Geologic map showing the location of the Steep Rock Formation on the southern border of the Wabigoon Subprovince (after Card and Ciesielski, 1986). C) Generalized stratigraphic column showing the lower three units of the Steep Rock Formation and the occurrence of the giant domes within the Mosher Carbonate.

Figure 3: Layers composing the Steep Rock giant domes. A) The yellow arrow indicates the dark contact between the underlying net-like microbialite and the overlying, carbon-rich, crystal fans. The red arrow indicates the more serrated and less defined boundary between the underlying crystal fans and the overlying microbialite. B) Net-like microbialite overlain first by cusped fenestrate microbialite and then crystal fans. The yellow arrow points to a support structure within the cusped fenestrate microbialite that is the point from which a crystal fan has nucleated.

Figure 4: Fan replacement textures observed in plane polarized light (PPL). A) Inclusion-rich, equant mosaic. B) Elongate Mosaic. In hand sample these areas display crystal fans within microbialite layers.

Figure 5: A) SEM backscatter electron maps of a crystal fan on the right and a cement-filled void on the left. The vertical darker area in the center of the image is the marker line used to

distinguish the two areas. B) The Mg values display the greatest variation, with the cement containing visibly higher concentrations of Mg.

Figure 6: A) Image of a fenestrate microbialite layer. The yellow arrow indicates a support, the red arrow indicates a cement-filled void, and the blue arrow indicates draping laminae. B) Upward branching support. Calcite has preferentially formed cement separating upturned microbial laminae on the right-hand side of the support. The yellow arrow indicates a branch of the support that is dipping at an angle of approximately 45° . Compaction gives the support a slightly serrated appearance. Also, the support appears to terminate prior to the top of the bed (red alteration).

Figure 7: Cuspate fenestrate microbialite sample displaying a desiccation surface. A) Bedding plane view that shows a well-preserved polygonal desiccation surface. B) Cross-sectional view in which the support structures are seen to correspond to the upturned edges of the polygonal structures. The yellow arrow indicates a support structure.

Figure 8: A) Petrographic image of a support structure (PPL). B) SEM backscatter electron image of a dolomite-rich support. The yellow arrow indicates the support structure (top is north in A, right in B, C, D). A quartz-rich area on the top half of the image is associated with this feature. a. Quartz, b. Calcite, c. Dolomite. C) Mg-values are higher in the dolomite-rich support. D) Fe-values similarly show a higher concentration within the support.

Figure 9: A) Sample showing cuspate fenestrate microbialite overlying net-like microbialite. Arrows indicate the transition zone where the laminae appear to change from one form to the next. Also note the crystal fan in the bottom right hand corner that is growing within the net-like microbialite. B) Pseudomorph crystal fans projecting through net-like microbialite.

Figure 10: A) Cross-polarized light image of an alteration surface composed of very fine-grained quartz. Below the layer is crystal fan fabric while above is a carbonate layer with no discernable fabric. Note that there is a change from finer-grained calcite below the layer, to coarser-grained above. B) SEM analysis shows that the alteration below layer contacts is composed mainly of quartz (top is north in A, right in B). The lighter mineral intergrown with the quartz is ferroan dolomite.

Figure 11: Plots displaying the atomic percent of Mn, Mg, and Fe vs. Ca in the calcite of sample shown in Figure 3A. The net-like fabric contains a higher concentration of Mn and Fe relative to the adjacent crystal fan fabric (B.D. is below detection). Mg values are quite similar between the two lithologies. Also, note that the net-like microbialite has a higher concentration of Mn compared to Fe in the calcite. The image on the bottom right has a blue arrow indicating the net-like microbialite and a red arrow indicating the crystal fan fabric.

Figure 1: Giant Domes of the Elbow Point Member. A) Plan view of domes that outcrop at Hogarth Pit, Steep Rock. B) Internal lamination of the domes consists of interbedded fenestrate microbialite and crystal fan fabric.

237x111mm (96 x 96 DPI)

Figure 2: A) Outcrop map of the Steep Rock Group east of Steep Rock Lake (after Kusky and Hudleston, 1999) with outcrop locations of the Elbow Point Member (Fralick and Riding, 2015). B) Geologic map showing the location of the Steep Rock Formation on the southern border of the Wabigoon Subprovince (after Card and Ciesielski, 1986). C) Generalized stratigraphic column showing the lower three units of the Steep Rock Formation and the occurrence of the giant domes within the Moshier Carbonate.

322x197mm (96 x 96 DPI)

Figure 3: Layers composing the Steep Rock giant domes. A) The yellow arrow indicates the dark contact between the underlying net-like microbialite and the overlying, carbon-rich, crystal fans. The red arrow indicates the more serrated and less defined boundary between the underlying crystal fans and the overlying microbialite. B) Net-like microbialite overlain first by cusate fenestrate microbialite and then crystal fans. The yellow arrow points to a support structure within the cusate fenestrate microbialite that is the point from which a crystal fan has nucleated.

286x93mm (96 x 96 DPI)

Draft

Figure 4: Fan replacement textures observed in plane polarized light (PPL). A) Inclusion-rich, equant mosaic. B) Elongate Mosaic. In hand sample these areas display crystal fans within microbialite layers.

344x137mm (96 x 96 DPI)

Draft

Figure 5: A) SEM backscatter electron maps of a crystal fan on the right and a cement-filled void on the left. The vertical darker area in the center of the image is the marker line used to distinguish the two areas. B) The Mg values display the greatest variation, with the cement containing visibly higher concentrations of Mg.

273x118mm (96 x 96 DPI)

Figure 6: A) Image of a fenestrate microbialite layer. The yellow arrow indicates a support, the red arrow indicates a cement-filled void, and the blue arrow indicates draping laminae. B) Upward branching support. Calcite has preferentially formed cement separating upturned microbial laminae on the right-hand side of the support. The yellow arrow indicates a branch of the support that is dipping at an angle of approximately 45° . Compaction gives the support a slightly serrated appearance. Also, the support appears to terminate prior to the top of the bed (red alteration).

190x75mm (150 x 150 DPI)

Figure 7: Cuspate fenestrate microbialite sample displaying a desiccation surface. A) Bedding plane view that shows a well-preserved polygonal desiccation surface. B) Cross-sectional view in which the support structures are seen to correspond to the upturned edges of the polygonal structures. The yellow arrow indicates a support structure.

275x103mm (96 x 96 DPI)

Figure 8: A) Petrographic image of a support structure (PPL). B) SEM backscatter electron image of a dolomite-rich support. The yellow arrow indicates the support structure (top is north in A, right in B, C, D). A quartz-rich area on the top half of the image is associated with this feature. a. Quartz, b. Calcite, c. Dolomite. C) Mg-values are higher in the dolomite-rich support. D) Fe-values similarly show a higher concentration within the support.

156x127mm (96 x 96 DPI)

Figure 9: A) Sample showing cusped fenestrate microbialite overlying net-like microbialite. Arrows indicate the transition zone where the laminae appear to change from one form to the next. Also note the crystal fan in the bottom right hand corner that is growing within the net-like microbialite. B) Pseudomorph crystal fans projecting through net-like microbialite.

286x87mm (96 x 96 DPI)

Draft

Figure 10: A) Cross-polarized light image of an alteration surface composed of very fine-grained quartz. Below the layer is crystal fan fabric while above is a carbonate layer with no discernable fabric. Note that there is a change from finer-grained calcite below the layer, to coarser-grained above. B) SEM analysis shows that the alteration below layer contacts is composed mainly of quartz (top is north in A, right in B). The lighter mineral intergrown with the quartz is ferroan dolomite.

316x121mm (96 x 96 DPI)

Figure 11: Plots displaying the atomic percent of Mn, Mg, and Fe vs. Ca in the calcite of sample shown in Figure 3A. The net-like fabric contains a higher concentration of Mn and Fe relative to the adjacent crystal fan fabric (B.D. is below detection). Mg values are quite similar between the two lithologies. Also, note that the net-like microbialite has a higher concentration of Mn compared to Fe in the calcite. The image on the bottom right has a blue arrow indicating the net-like microbialite and a red arrow indicating the crystal fan fabric.

184x164mm (96 x 96 DPI)