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Putative domal microbial structures in fluvial siliciclastic facies of the Mesoproterozoic (1.09 Ga) Copper Harbor Conglomerate, Upper Peninsula of Michigan, USA

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ABSTRACT

The Copper Harbor Conglomerate is a Mesoproterozoic (1.09 Ga) freshwater sedimentary sequence that outcrops in the Upper Peninsula of Michigan. The formation was deposited during infilling of the failed Midcontinent Rift and contains fluvial, lacustrine, and alluvial fan facies. This study describes and analyzes the formation of small domal structures preserved in fluvial sandstone facies within the lower portion of the formation. These domal structures range from millimeters to several centimeters in diameter and height, and are preserved in convex epirelief on fine-grained sandstone beds. The structures have a pustulose texture and a patchy distribution on bedding planes. Slabs containing the structures were collected in the field and analyzed in the laboratory through inspection of cut slabs, petrographic thin sections, X-radiographs, and RAMAN spectroscopy. Results of these analyses reveal that the domal structures often contain weak, wavy horizontal bedding and laminae, and lack any vertical structures. These results support a biogenic origin of the domal structures instead of through abiogenic processes such as loading, sand volcanoes, or adhesion warts. These structures are akin to what were traditionally labeled as 'sand stromatolites', but are now known as 'domal sand structures'. Along with previous descriptions of carbonate stromatolites, organic-rich paleosols, and microbial sand structures, our findings provide further evidence that mat-forming microbial communities thrived in the late Mesoproterozoic freshwater systems of the Midcontinent Rift.

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INTRODUCTION

The Copper Harbor Conglomerate is a freshwater sedimentary sequence deposited in the Midcontinent Rift Valley during the Mesoproterozoic Era (1.09 Ga). Depositional environments vary from alluvial fans to braided fluvial channels to lacustrine settings, forming siliciclastic facies that range from cobble conglomerates fining to siltstones and mudstones (Elmore, 1983). The structures investigated in this study are found scattered on beds of fine-grained fluvial sandstone at two locations in the formation. The features are consistently found preserved in convex epirelief on discrete beds, forming clusters of domes that range from several millimeters to several centimeters in diameter and up to 1 cm high. Visual examination of bed structures beneath the domes reveals no distinctive structures. One of the locations for the domal structures was previously described in a sedimentary study of the Copper Harbor Conglomerate, which noted these features as 'knobbly structures' (Taylor & Middleton, 1990). Taylor & Middleton suggested that these domes may have been abiogenic eolian sedimentary structures called adhesion warts, but no analysis was performed beyond visual inspection in the field.

This study tests the hypothesis that the domal structures preserved in fluvial sandstone facies of the Copper Harbor Conglomerate are microbially mediated structures. The alternative hypothesis is that these domes were formed abiotically through normal sedimentary processes. Possible scenarios for abiotic formation include sand volcanoes, load structures, or adhesion warts. Subsurface structure of the domes was examined by cutting sample beds through the domes themselves, making petrographic thin sections underneath the domes, and performing X-radiography on the domal structures. Results consistently show weak, wavy horizontal laminae running through the sandstone beds underneath domes. These laminae are more pronounced and well developed in beds bearing larger domes. The consistent placement of domes on the top of beds rules out loading structures, the lack of vertical conduit structures or central craters excludes sand volcanoes and similar dewatering features, and the combined placement and symmetry of the domes makes eolian adhesion warts an extremely unlikely explanation. This evidence therefore supports the hypothesis that these domal structures are microbially mediated and did not form through abiotic processes.

The Copper Harbor Conglomerate is well known for carbonate stromatolites preserved draping over cobble conglomerates higher in the formation, approximately 100 km in distance from the sites examined in this article (Elmore, 1983). The immediately overlying Nonesuch Shale has been the subject of geochemical analyses that indicate abundant organic activity in major lacustrine systems (Elmore *et al.* 1989, Pratt *et al.*, 1991). A variety of paleosols, including some with preserved organic material, have been described from sedimentary interflow deposits of the Portage Lake Volcanics during the final stage of rifting, before major sedimentary formations began to fill the basin (Mitchell & Sheldon, 2009, 2010; Sheldon, 2012). This evidence of biological activity suggests that freshwater microbial life inhabited the Midcontinental Rift Valley during the Mesoproterozoic.

Previous work

Microbially mediated sedimentary structures

The physical and chemical properties of prokaryotic colonies often affect their surrounding environments. The interaction between biofilms and sedimentary processes can produce microbially induced sedimentary structures (MISS), which can be preserved in the rock record (Noffke *et al.*, 2001; Noffke, 2009). Most MISS are formed from the organic trapping and binding of sediment grains by microbial mats. Apart from cellular filaments directly affecting local sedimentation by baffling, biofilms are bound together by extracellular polymeric substances (EPS) made primarily of protein and polysaccharide chains. The chemical nature of EPS allows microbes to form more cohesive colonies by adhering to a substrate and other individuals (Donlan, 2002). This adhesive property also traps incoming particulate matter such as sediment grains, which are subsequently incorporated and overgrown by new biotic layers. As the mat grows over time, it forms sedimentary features distinct from its surroundings that can be visible both to the naked eye and on the microscopic level (Noffke *et al.* 2001).

Unlike stromatolites, MISS form with little to no mineral precipitation, which results in lower relief than similar microbial carbonate structures, and restrict their appearance in the rock record to mainly siliciclastic environments (Noffke, 2009; Noffke & Awramik, 2013). Due to relatively high permeability in sandstones, MISS generally leave behind relatively lower amounts of carbon in their respective environments compared with carbonate features such as stromatolites, or even finer-grained clastic deposits (Schieber, 2007). This trend especially holds true with ancient Precambrian sediments. Therefore, an absence of organic carbon compounds would not necessarily indicate an abiogenic formation for the domes examined in this study.

The morphologies and textures of MISS vary between depositional environments. Of particular relevance to this study are domal sand structures, traditionally known as ‘sand stromatolites’ (Bottjer & Hagadorn, 2007). These structures are clusters of low-relief convex mounds varying in size and mutual proximity on the top surfaces of sandstone beds. They are formed from irregularities on a mat surface that are compounded by the binding of incoming sediment. When sedimentation rates are low, the mat is able to overgrow trapped particles and form successive layers (Bottjer & Hagadorn, 2007). When the mat decomposes, this layered structure underneath domal buildups often loses its integrity, typically revealing only faint laminae in cross section (Bottjer & Hagadorn, 2007). Several types of MISS have been recently described from paleosols and alluvial facies within other areas of the Midcontinent Rift, including domal sand structures (Sheldon, 2012).

Geologic setting

The Copper Harbor Conglomerate occurs at the bottom of the Mesoproterozoic Oronto Group of northern Wisconsin and Michigan (Fig. 1). The formation represents the first continuous sedimentary deposition after the failure of the Midcontinent Rift. The Copper Harbor immediately overlies and interfingers with the Portage Lake Volcanics (1109–1086 Ma) and is conformably overlain by the Nonesuch Shale (Dickas, 1986). Formation thickness increases basinward into Lake Superior, ranging from 200 to 2000 m.

The two primary facies in the Copper Harbor are conglomerates and medium- to fine-grained sandstones. The formation generally fines upward, although intermittent conglomerate beds appear throughout (Elmore, 1984). Conglomerates are generally well rounded and poorly sorted, with cobble to boulder-size grains resting in a sandstone matrix. These beds resemble longitudinal macroforms or bars deposited in high-energy braided streams,

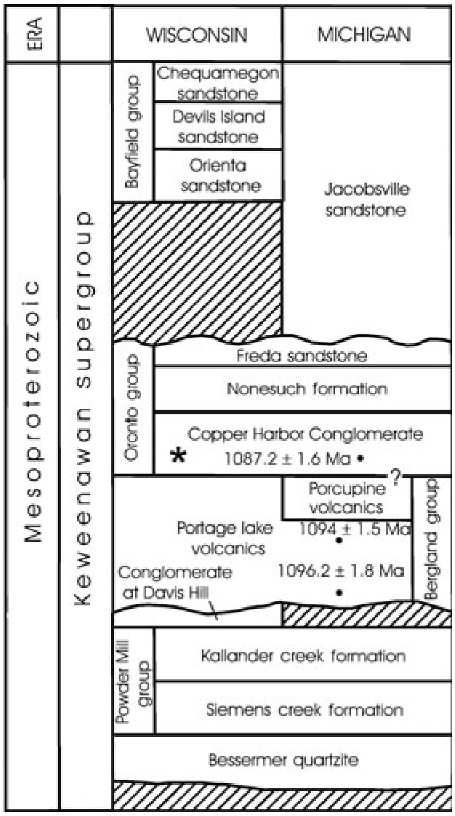

Fig. 1 General stratigraphy of Midcontinental Rift System in Michigan and Wisconsin. Approximate location of domal structures is marked with asterisk. (Modified from Schmidt & Williams, 2003).

which would have transported sedimentary material toward the center of the rift valley (Elmore, 1984). Stromatolites and oncoids have been described draping over cobbles in isolated conglomerate beds near the top of the formation (Elmore, 1983). Their presence suggests a rising water table over time, most likely due to an increasing proximity to the rift lakes that would eventually deposit the Nonesuch Shale (Elmore, 1983).

Copper Harbor sandstones are classified as lithic arenites composed of angular to subangular volcanic grains (Elmore, 1984), which suggests first-cycle sediment deposition. Above the conglomerate beds, sandstones are divided into trough cross-stratified and rippled facies, indicating differing energy levels at the time of deposition. Pebbly sandstones bearing trough cross-beds are interpreted as being deposited by migrating dunes, with occasional mud drapes forming during periods of slack water flow (Elmore, 1984). While most of these are thought to have been formed in water, a subaerial eolian origin has been proposed for some dune-scale features (Taylor & Middleton, 1990). The rippled facies appears as a fine- to medium-grained sandstone bearing horizontal laminations, directional ripples, mud drapes, and mud cracks (Elmore, 1984). This unit was deposited by sheet floods moving across sand flats, with laminations forming in upper plane flow. Ripples and mud drapes represent diminishing energy levels, and mud cracks indicate periodic subaerial exposure (Elmore, 1984).

The Copper Harbor Conglomerate is interpreted as an alluvial-fluvial sequence emptying into the basin left by the failed rift system (Elmore, 1984). As the rift valley gradually filled, deposition shifted from high-energy braided stream channels to shallow sheet floods across fan surfaces. This fining-upward succession culminated in the lacustrine shales of the Nonesuch Formation. The climate at the time of deposition is still poorly understood. Subarid to arid conditions were inferred through potential caliches and desiccation cracks (Kalliokoski, 1986). This interpretation has alternately been disputed (Lewan, 1977) and accepted (Elmore, 1984) by subsequent studies. High, semi-arid montane lakes, and alluvial systems have been proposed as the best potential modern analogues for the Copper Harbor Conglomerate (Elmore, 1984), but no subsequent in-depth paleoclimatic studies have been performed to verify this statement.

METHODS

To test the biogenicity of the Copper Harbor domal structures, observations were made using both field and laboratory techniques. Field studies focused on the sedimentary context of the structures within the formation itself. Exposures of the Copper Harbor at Union Bay and Buckshot Cabin were utilized in this study (Fig. 2). Both lie on the shore of Lake Superior west of Silver City in Michigan's Upper Peninsula, 7 km apart from each other. The outcrops stretch in a thin coastal band dipping ~20° into the lake. The texture and placement of domes relative to bedding surfaces and sedimentary structures were observed in a 25-meter stratigraphic section at Union Bay. The domal structures were also observed on beds at Buckshot Cabin. Both locations are separated from the Freda Sandstone, which has a similar fine-to-medium red-brown lithology, by the Nonesuch Shale 6 km to the east of Union Bay.

Laboratory studies focused on examining the internal structure of the domes. Fourteen slab samples of domal structures from different bedding planes were collected for the examination. Three of these collected samples were selected for their outstanding preservation of different-sized domes (0.5, 1.5, and 3 cm in diameter) and were slabbed 2 cm thick and examined through visual inspection of cut surfaces. Cross sections were made by slicing directly through the largest domes to obtain the best examples of subsurface structure. These slabs were used to make six petrographic thin sections that included the bisected domes and the beds beneath them. Three X-radiographs of these cut samples were also produced to observe millimeter-scale internal structures.

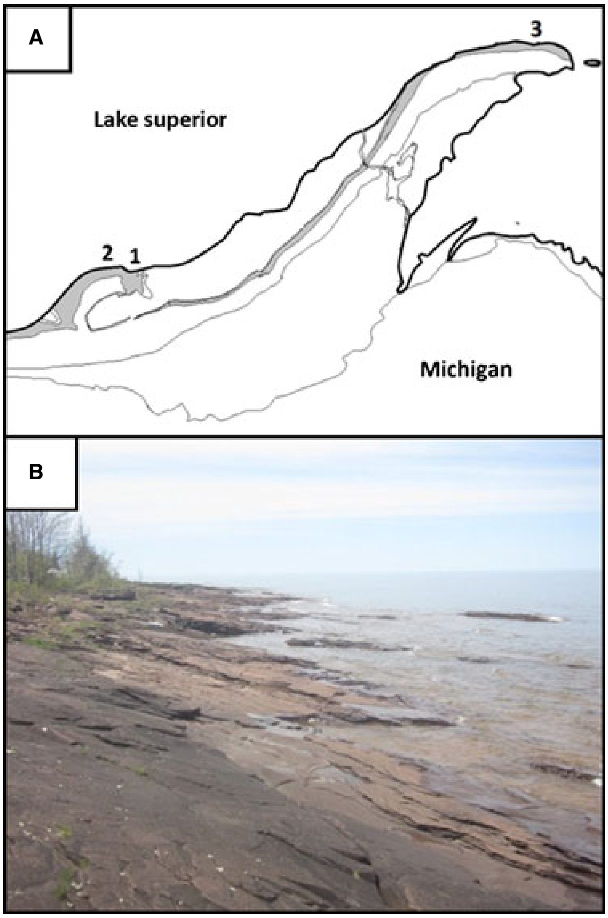

Fig. 2 (A) Locality map of the Keweenaw Peninsula. Copper Harbor Conglomerate in gray. Localities examined in this study: 1. Union Bay, 2. Buckshot Cabin. Locality of previously described carbonate stromatolites: 3. Horseshoe Harbor. (B) Outcrop of Copper Harbor Conglomerate at Union Bay.

Raman spectroscopy was performed to document the presence or absence of organic material in multiple laminae of several domal structures within the three polished slabs. Raman spectra and images were acquired with a Renishaw inVia Raman microscope in the Department of Chemistry at the University of Cincinnati. Spectra were acquired using the 488 nm laser line of an Ar^+ laser.

Site description

The predominant facies throughout the Union Bay and Buckshot Cabin sections is a reddish-brown sandstone. Grain size fluctuates between medium and fine sand, with no consistent fining-upward tendencies seen in section. Bedding is parallel and laterally continuous in section. Individual beds range up to a meter in thickness, although most are less than 10 cm. Flow indicators range from cm-scale cross-laminations (ripples) to dm- and m-scale trough cross-beds (dunes). Thicker beds contain downstream accretion surfaces (macroforms/bars) that bound cross-bed sets. Horizontal laminations with parting lineation and primary current lineations are common and often occur with current ripples (small-scale cross-laminations) in the same bed. All of these unidirectional current structures show fairly consistent current direction toward the center of the basin to the northeast, although some beds vary by more than 90° from this orientation.

A few beds bear bifurcated symmetrical ripples and some flat top ripples also occur where ripple crests are planed off. Occasional syneresis cracks filled in with calcite spar appear in mud drapes on the top of bedding planes, with polygons in between showing a distinctive light gray coloration. Rip-up mud fragments of the same color are also scatted throughout the section, generally appearing on finer-grained plane beds. In one location, these 'mud chips' are found in direct association with syneresis cracks, having been transported only a few centimeters away from their point of origin.

We interpret the environment at both Union Bay and Buckshot Cabin to be an alluvial fan/alluvial plain setting characterized by episodic discharge matching that of Elmore's (1983) rippled sandstone facies. Deposition was dominated by shallow sheet floods of less than a meter depth with sand lobes or bars migrating over the sand flat. The bars may indicate deeper higher discharge events or locally channelized flows on the alluvial surface. These features occasionally are dissected by small channels that developed during falling discharge. Ripples and upper flow regime plane beds formed in shallow water areas during waning flow. Slight fluctuation in flow depth allowed these structures to form laterally to each other. Wave ripples, flat top ripples, and mud drapes formed during slack water conditions where water ponded in shallow depressions in front of dunes and bars on the alluvial surface. Occasional syneresis cracks were likely formed during isolated seismic events, while subsequent erosion and transport of mud chips formed intraformational conglomerates.

Observations

The putative MISS form a convex domal epirelief on the surfaces of planar sandstone beds at Union Bay and Buckshot Cabin (Fig. 3). The features are never seen on the undersides of beds, with up directions consistently indicated throughout the section by cross-bedding, ripple marks, and syneresis cracks. The two main variables in texture are the size of individual domes and their distance from each other. Individual domes range from 0.5 to 3 cm in diameter, and vertical relief is rarely greater than 1 cm (Fig. 3). 'Cauliflower heads' occur where individual nodules amalgamate and form compound domal structures several centimeters across (Fig. 4). Individual domes on the same bedding plane, whether isolated or agglomerated,

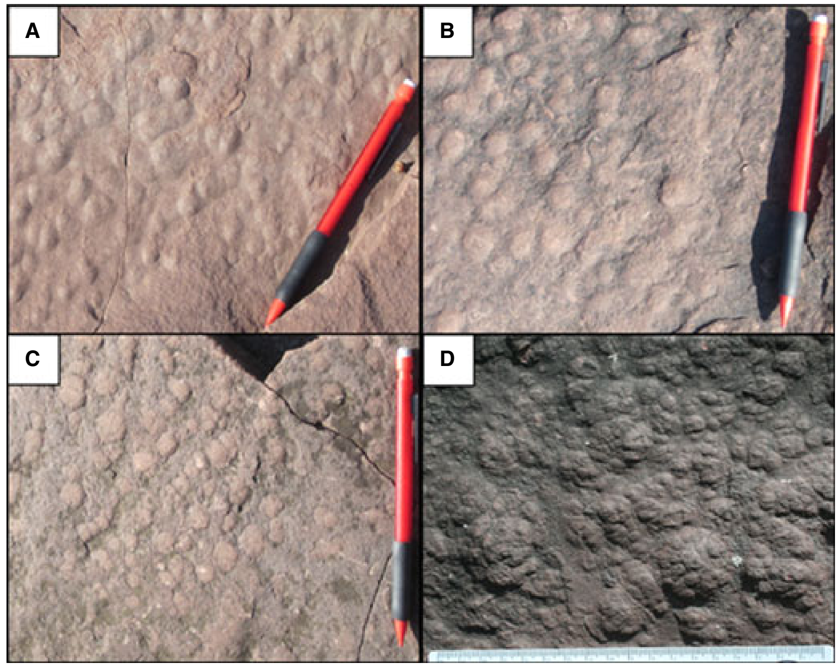

Fig. 3 Copper Harbor Conglomerate domal structures at Union Bay. Pen for scale = 15 cm, units on ruler are in cm. All images show top surfaces of bedding planes. Note circular habit of domes across beds and textures, showing no axes of lineation. (A, B) Pustulose textures of isolated domes. (C) Smaller domes exhibiting a more clustered structure. (D) 'Cauliflower head' texture seen in largest domes. Note individual nodules set within larger domal features.

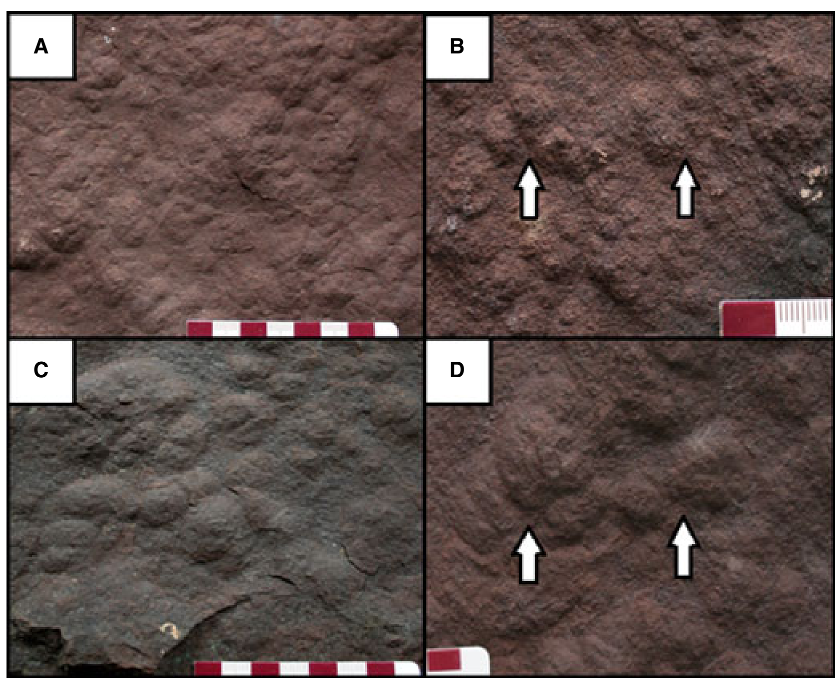

Fig. 4 Laboratory photographs of Copper Harbor Conglomerate domal structures. Red scale bar = 1 cm. Arrows indicate locations of individual domal clusters. (A, B) Smaller, clustered 'cauliflower head' textures. (C, D) Larger pustulose textures.

maintain nearly equal radii in all instances. In the few cases where several subsequent beds bear domal textures, this pattern is maintained even when the edges of domes begin to infringe upon each other. While nearly all domes are circular in nature, several select beds show more elongate oval and teardrop-shaped morphologies.

Domal textures occur in finer-grained beds 1–5 cm thick, forming patches that range from a few cm^2 to several m^2 in area (Fig. 3). These beds are found in close association with those bearing ripples, truncated ripples, syneresis cracks, and mud chips, although these structures are seldom found on the same layers as domes themselves. The domes are usually restricted to single bedding planes, with strata immediately over- and underlying generally showing no visible sign of domal features. However, the few areas that exhibit continued domal presence over several

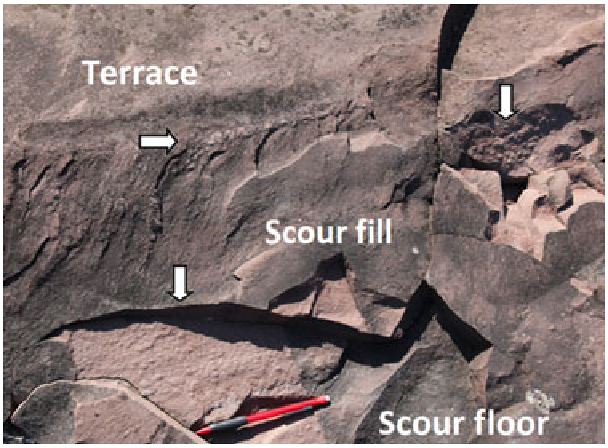

Fig. 5 Scour mark bearing domal structures. Pen for scale = 15 cm. Arrows indicate locations of domal structures. Note the presence of domes from the floor of the scour up the walls to the lip of the terrace, but not above the terrace itself. The domes were formed as water ponded during a period of low stream flow after erosion of the scour. Their absence outside of water makes subaerial adhesion warts an unlikely possibility.

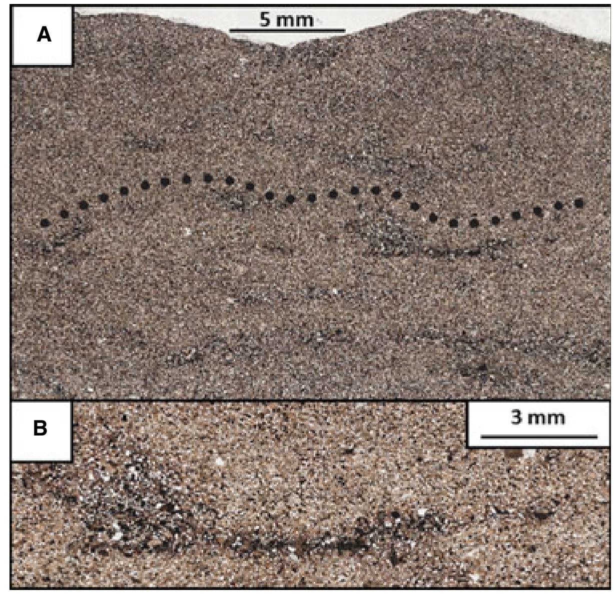

Fig. 6 Photomicrographs of domal structure thin sections. (A) Sample showing repetitive layers of convex features underneath 3-cm diameter surface domes. Black lines trace some convex features. (B) Inset of A, focusing on difference in grain size between laminae and background sediment.

successive deposits show an increase in radius and relative proximity of nodules to each other over time. The structures are most commonly preserved in planar beds, but were also occasionally seen at the toesets of macroform sand bars. One bed in particular showed domal structures lining the walls and floor of a small, steep-sided scour ~10 cm in height (Fig. 5). One side exhibited a small terrace several centimeters below the top of the scour. A layer of sandstone fill above the scour depression covered portions of the walls and floor, but never extended above the terrace line. Nearly every exposed surface below this fill layer showed small domal textures. The structures were seen immediately below the upper terrace, continuing down the walls onto the scour floor, but were not seen above the terrace.

When dome-bearing beds are slabbed and initially observed, fresh surfaces show faint indications of wavy lamination with bands of coarser, darker grains appearing within the regular fine-grained lithology. Petrographic thin sections of cut surfaces that include the domes show irregular mm-thick laminations comprised of medium to coarse sand grains (Fig. 6). These laminae only extend for 2–5 cm before returning to fine-grained material, but often form convex domal structures in similar position with the domes in epirelief (Fig. 6). Laminations are more pronounced laterally and vertically under larger domal textures. While mica grains are noticeably more prevalent on the surfaces of domal beds than rippled or planar beds, these abundances are not high enough to form distinctive micaceous layers in thin section. Hematite cement is prevalent between grains in both dome-bearing and non-domal samples. This cement is seen in Copper Harbor sediments throughout the formation and has been interpreted as an authigenic pigment due to the martitization of hematite (Elmore & Van der Voo 1982).

X-radiographic imaging of cut slabs provides the most detailed evidence of their internal structure. The most pronounced features are irregular wavy mm-thick laminations running nearly continuously through the slabs (Fig. 7). These form repeated intervals up to five laminae deep, which lie directly underneath and parallel the convex nature of the domes. This type of layering is not seen further than 2 cm from bedding surfaces. In contrast, the bottoms of the examined beds often bear strict horizontal laminae distinct and separate from that seen directly underneath the domes. In some locations, the upper laminae contort in features similar to roll-up structures, folding over themselves before straightening out horizontally (Fig. 7). The wavy layering and roll-up structures are most pronounced in samples with larger domes, similar to the subsurface trend seen in thin section analysis. No other sedimentary structures were seen underneath any cross-sectioned domes, even smaller features that lacked subsurface laminae.

DISCUSSION

Based on observations of the internal structure within dome-bearing beds, compounded with stratigraphic information from the field, we propose that the domal textures seen at Union Bay and Buckshot Cabin were formed by

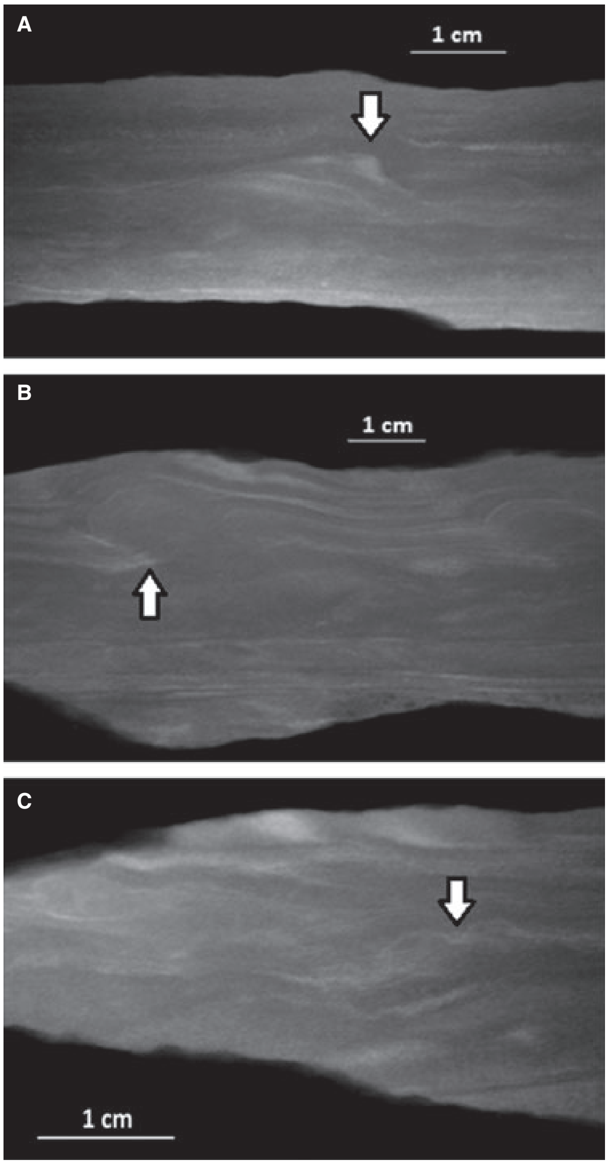

Fig. 7 X-radiographs of domal structures. (A) Sample containing 1.5-cm diameter domes. Arrow points to individual 'relict dome'. (B) Sample containing 3-cm diameter domes showing multiple laminae directly underneath surface domes. Arrow points to potential roll-up structure. (C) Samples containing 3-cm diameter domes. Arrow points to wavy-crinkly laminae.

microbial mediation of sediment. Three alternate hypotheses for the structures' origin were additionally proposed before the examination: adhesion warts, dewatering features such as sand volcanoes, and load casts due to soft-sediment deformation. These abiogenic sedimentary processes can lead to convex domal structures that are superficially similar to those left behind by sandy microbial biofilms but bear different internal morphologies. Using the methods described above, the subsurface structures of the domes were analyzed and compared with known studies of abiotic domes.

The Union Bay domes were briefly described as 'knobbly structures' during a previous study of the Copper Harbor Conglomerate (Taylor & Middleton, 1990). Their study found no internal structure below any domes in the field and noted preferential placement of domes on planar beds, suggesting adhesion warts as a possible explanation (Taylor & Middleton, 1990). Adhesion warts are subaerial features preserved when dry sand grains adhere to a wet sandy surface after eolian transport, preserving surface irregularities even after lithification. Adhesion warts form irregular domelike structures, usually showing asymmetrical orientation based on the wind direction, but occasionally displaying symmetrical, equally rounded morphologies (Olsen *et al.*, 1989).

Sedimentary evidence from Union Bay suggests that the domal structures were formed in subaqueous conditions. A particularly well-preserved scour exhibited a small terrace most likely formed by ponded water at its highest point in the depression. Domes were seen on the scour floor, side walls, and head walls, but never above the terrace mark or in subsequent sandstone fill. This particular demarcation of dome formation suggests that at least some of the features were formed beneath the water surface and not subaerially.

Adhesion warts nearly always form preferred surface orientations based on the direction of wind flow, with the most elongate axis corresponding to primary air currents. Symmetrical warts were once interpreted as forming under multiple wind directions (Reineck, 1955), based on laboratory experiments on fresh sand. However, subsequent experiments could not easily replicate these findings (Kocurek & Fielder, 1982), and epoxy sections of the closest results showed various cross-laminations inherited from different wind directions, which have not been seen in field samples. In the same laboratory study, Kocurek & Fielder (1982) hypothesized that well-rounded warts could potentially be formed by near-vertical deposition on biological mats.

While these findings do not exclude the possibility of wind transport for asymmetrical adhesion warts, they call into question the nature of symmetrical structures previously interpreted as adhesions. Several scattered beds at Union Bay and Buckshot Cabin show slight domal elongation, but the vast majority of samples in several dozen discrete beds showed little if any axes of preferred orientation in the field. Taylor and Middleton's (1990) analysis also found no major directional indication in their 'knobbly structures'. On a smaller scale, no directional cross-laminations can be seen under any domes in cross sections, thin sections, or X-radiographs, even under the largest domes which would theoretically have the best chance of preserving such structures.

Sand and mud volcanoes are centimeter-to-meter scale sedimentary structures that propagate at the top surfaces of planar beds, usually by extrusion of fluid or gas from underlying sediments (Dionne, 1973). Well-preserved examples of sand volcanoes in the field and the laboratory are known to bear steeply dipping laminae and remnants of vertical pipes below the bedding surface, as well as craterlike 'vents' on top of mounds (Neumann-Mahlkau, 1976). Experimental studies have shown that if pipes migrate as water escapes, these vertical structures can be obliterated, leaving a featureless subsurface excepting for pockets of finer sediment (Ross *et al.*, 2011). However, this migration also affects the epirelief of the volcanoes, forming structures with more poorly defined boundaries (Ross *et al.*, 2011). Observing the top surfaces of the Union Bay beds, no dome bears any evidence of cratering, and most domes still retain well-defined circular boundaries. If the structures had been created by dewatering conduits, one would expect either intact circular domes with craters or deformed domes without craters, but not intact domes without craters. Further analysis of cross sections, thin sections, and X-radiographs shows no indication of linear, laminae steeply dipping away from domal apexes, nor do the laminae appear to have been modified from such a position.

Loading casts and similar soft-sediment deformation can easily be distinguished from MISS using basic stratigraphic principles. Loading structures occur when dense water-laden sediment is disturbed shortly after deposition, causing the heavier beds to slump down into less resistant layers below (Allen, 1982). While nearly all biofilms form at or near the sediment–water interface, loading casts generally form on the bottom of depositional beds. No sedimentary structures, domal or otherwise, were seen on the bottom of bedding planes in the field or in the laboratory examination. Consistent position of fluvial ripples and syneresis cracks throughout the Union Bay section provided a constant up-indicator for direction. Domal structures were always found in the same position as these directional features, albeit on different beds.

In terms of external morphology, the Copper Harbor domal structures most closely resemble MISS known as 'domal sand structures'. These are characterized by low-relief mounds forming isolated nodules and clustered 'cauliflowerlike patterns' with little internal structure apart from convex laminae (York *et al.*, 2005; Bottjer & Hagadorn, 2007). The wavy-crinkly laminae seen in sample thin sections, and X-radiographs most closely resemble layering textures previously used as defining indicators of microbially influenced sediments (Schieber, 1998). The preferential placement of larger grains along these layers as seen in thin section reflects the ability of biofilms to trap coarser sediments than non-microbial sedimentary surfaces.

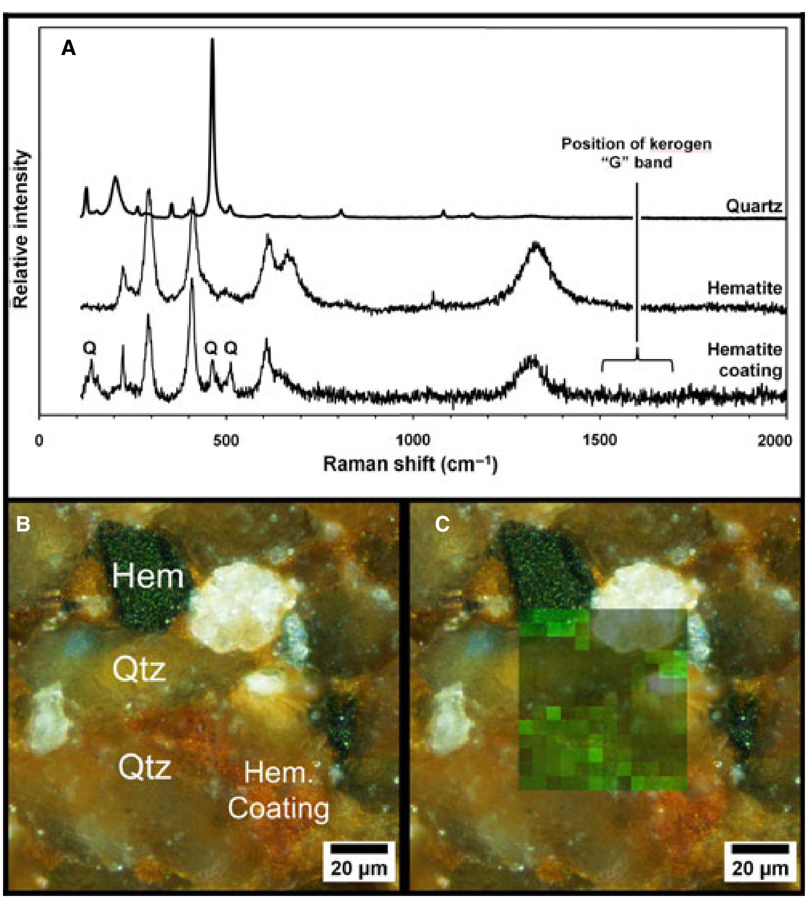

Fig. 8 Representative Raman spectra and images of selected regions within a domal structure. (A) Raman spectra of quartz grain (upper spectrum, cf. Kingma & Hemley, 1994), hematite grain (middle spectrum, Wang *et al.*, 2004), and orange hematite stain between grains (lower spectrum). Note the small quartz bands ('Q') apparent in the spectrum of the thin hematite stain due to its proximity to the surrounding grains. Raman spectroscopy of numerous laminae within three different polished slabs (see Fig. 6) showed no evidence of preserved kerogen, which has its most prominent Raman band at ~1600 cm^{-1}. (B) Reflected light image under crossed polarizers of one of the areas studied. (C) Same image as in part B with an overlaid Raman image produced using the intensity of the band at ~1300 cm^{-1}, which indicates that the orange stain is in fact hematite. Hem, hematite; Qtz, quartz.

This cohesion is also apparent in X-radiographs, which show evidence of roll-up structures underneath the largest domes (Fig. 7B). Roll-up structures form when microbially mediated sands contort and fold over themselves due to stresses that would disintegrate unbound sedimentary structures (Schieber, 1998; Hagadorn & Mcdowell, 2012). This cohesion comes from the binding processes of microbial mats, namely EPS adherence and filamentous baffling of grains (Westall *et al*., 2000). While the Copper Harbor structures show consistently equal radii of individual nodules, most domal sand structures bear larger central nodules when aggregated into 'cauliflower head' clusters. As the Union Bay structures that showed the highest degree of aggregation also showed the most convincing microbial subsurface textures, this difference is most likely due to distinct mat growth patterns rather than abiogenic processes.

Organic geochemical analysis using Raman spectroscopy revealed no indication of any detectable organic material in the laminae of the domal structures (Fig. 8). This absence of organic molecules been noted in other well-studied Precambrian continental microbial deposits (Eriksson *et al*., 2000) and has been attributed to the relatively high permeability of sandstones (Schieber, 2007), which allows for higher metabolization of carbon during the initial stages of burial and efficient removal of remnant organics afterward. The presence of oxidized iron (hematite) grains and staining between quartz grains (Fig. 8B,C) in the Copper Harbor sample is consistent with the syn- or post-depositional migration of an oxidizing fluid through the sandstone, which could be responsible for the oxidation and removal of any remnant organic carbon. Thus, while the Union Bay domal structures left no detectable organic geochemical traces, this is not an immediate indicator of an abiogenic origin.

IMPLICATIONS

Previous physical and chemical evidence from around the world indicates that prokaryotes have been present in non-marine environments for at least 2.8 billion years. These include chemical signatures in ancient paleosols and paleokarsts (Horodyski & Knauth, 1994; Ohmoto, 1996; Watanabe *et al*., 2000), stromatolites in lacustrine environments (Buck, 1980; Buick, 1992; Rasmussen *et al*., 2009), microbial mat features in eolian interdune and fluvial deposits (Eriksson *et al*., 2000; Prave, 2002; Simpson *et al*., 2013), and widespread geochemical proxies (Stüeken *et al*., 2012). While many of these known locations are isolated occurrences, the sandstone domes within the Copper Harbor Conglomerate fit within a continuum of biological activity within the Midcontinent Rift. Paleosols as well as domal textures similar to those seen at Union Bay have been described in interflow sediments from the North Shore Volcanic Group (1108–1094 Ma) in Good Harbor Bay, Michigan (Sheldon, 2012). Carbonate stromatolites and oncoids have been described from conglomerate beds stratigraphically higher in the Copper Harbor (Elmore, 1983). Above the Copper Harbor Conglomerate, the Nonesuch Shale holds original biomarkers such as n-alkanes and steranes which indicate the presence of photosynthetic activity (Hieshima & Pratt, 1991). Facies differences in Midcontinent Rift sediments where MISS and geochemical evidence are found indicate that life inhabited a variety of environments including soil horizons, flood-dominated alluvial fans, lake-proximal conglomerates, and open lacustrine waters. These distinct habitats would have presented different environmental stresses, including varying degrees of aridity and nutrients available for microbiota. The Mesoproterozoic in general appears to be a time of high microbial biodiversity, including the highest levels of stromatolite morphology seen in Earth's history (Awramik & Sprinkle, 1999). The exact cause of this peak is unknown, but potentially represents a complex interaction between the ancient biosphere, climate, and geologic cycles (Noffke & Awramik, 2013; Sheldon, 2013). While the evidence for life in the Midcontinent Rift is by no means the earliest, the relative diversity seen over a short timeframe is unique and supports previous evidence that life inhabited non-marine environments by the Neoarchean, reaching high diversities in both the marine and terrestrial realms by the Mesoproterozoic.

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