



Early non-marine life: Evaluating the biogenicity of Mesoproterozoic fluvial-lacustrine stromatolites



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ABSTRACT

The record of life on land or in non-marine environments during the Precambrian is sparse, limiting our ability to understand life outside of marine settings before the advent of animals. Stromatolites from such environments are known, but demonstrating stromatolite biogenicity remains difficult, as stromatolite growth can be controlled by a spectrum of biologic, chemical, and biologically-mediated processes. Stromatolites from the Mesoproterozoic (1.09 Ga) Copper Harbor Conglomerate, an alluvial fan, fluvial, and lacustrine deposit, offer an interesting test for the presence and nature of microbial life in shallow, Mesoproterozoic non-marine settings.

Stromatolites from a siltstone facies are interpreted as biogenic, as they contain detrital-rich laminae, likely indicative of trapping and binding by microbes and fenestral fabrics suggestive of desiccation or lift-off structures in mats via the presence of gas (perhaps O₂ from photosynthesis or other gases from mat decay). The stromatolites formed as microbial mats grew over a mudflat or sandflat with carbonate filled desiccation cracks on an erosive topography, and thus provide evidence for life in a very shallow, predominantly desiccated environment. Stromatolites from a conglomerate facies are microdigitate and record both isopachous laminae with radial-fibrous calcite fans and botryoids, typically considered abiogenic in origin, as well as wavy, conical laminations likely indicative of the former presence of microbial mats. The conglomerate-facies stromatolites are interpreted to have formed in a flooded braidplain setting with restricted circulation. This study supports the suggestion that microbial communities were abundant in non-marine environments in the Midcontinent Rift during the Mesoproterozoic. It also highlights how variable environmental factors can influence stromatolite growth, even in similar depositional settings and with a consistent microbial presence.

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1. Introduction

Precambrian fossil evidence for non-marine microbial life is rare compared to that for marine microbial life. As a result, microbial colonization of terrestrial environments is poorly understood and the timing is not well constrained. Microbes have been recognized in subaerial environments for at least ~2.7 billion years based on organic matter in paleosols from South Africa (Watanabe et al., 2000). The oldest microfossil evidence of life on land is from a 1.2 Ga paleokarst in Arizona (Horodyski and Knauth, 1994). However, much of the Precambrian evidence for non-marine life is found in

geochemical proxies (e.g. Ohmoto, 1996; Stüeken et al., 2012) or from aquatic terrestrial settings (e.g. Battison and Braiser, 2012; Schopf and Walter, 1983).

There are few examples of the paleoenvironments in which Precambrian non-marine microbes lived and how they were adapted to various environmental conditions. For example, little is known about how such microbes evolved to handle UV radiation, desiccating environments, changes in alkalinity, and variable discharge. Furthermore, the presence of Precambrian non-marine life is largely inferred from stromatolites, whose growth is controlled by an assortment of biologic, chemical, and biologically-mediated processes (e.g. Buck, 1980; Buick, 1992; Elmore, 1983). It is therefore important to investigate the biogenicity and depositional context of Precambrian non-marine stromatolites before making interpretations about the possible microbes that formed them.

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Microbially induced sedimentary structures (MISS) and carbonate stromatolites found within the Mesoproterozoic (1.09 Ga) Copper Harbor Conglomerate of northern Michigan have been interpreted as evidence for fluvial-lacustrine microbial communities that colonized the failed Midcontinent Rift System (Elmore, 1983; Wilmett et al., 2014). There are other signs of microbial activity in the Midcontinent Rift System during the Mesoproterozoic as well. The Nonesuch Shale, which directly overlies and interfingers with the Copper Harbor Conglomerate, contains abundant organic carbon and microfossils (Elmore et al., 1989; Pratt et al., 1991; Wellman and Strother, 2015). Additionally, paleosols containing organic matter have been described within interflow deposits of the Portage Lake Lava Series, which interfingers with the Copper Harbor Conglomerate (Mitchell and Sheldon, 2009, 2010; Sheldon, 2012).

While the Copper Harbor stromatolites were initially interpreted as purely biogenic constructions, some of the stromatolites from the Copper Harbor Conglomerate exhibit characteristics of abiogenic formation (Elmore, 1983). These characteristics include radial-fibrous calcite fans that are commonly thought to form through the direct inorganic precipitation of calcite as opposed to microbially induced formation (e.g. Corsetti and Storie-Lombardi, 2003; Grotzinger, 1989; Grotzinger and Knoll, 1999; Pope et al., 2000). As is common with Precambrian stromatolites, there is a lack of conclusive microfossil evidence in the Copper Harbor stromatolites (Elmore, 1983). These stromatolites developed in a depositional setting that includes evidence for alluvial fan, fluvial, and lacustrine sedimentation. If shown to be biogenic in origin, these stromatolites offer an opportunity to understand the microbial communities responsible for their formation and to characterize the environment in which they formed. In the absence of microfossil evidence, there is no single method that can be used to determine stromatolite biogenicity. Therefore, this study utilizes a suite of evidence to test the hypothesis that the Copper Harbor Conglomerate stromatolites formed primarily through biogenic processes.

2. Stromatolite biogenicity

A non-genetic stromatolite definition that is suitable to this study is “an attached, laminated, lithified sedimentary growth structure, accretionary away from a point or limited surface of initiation” (Semikhatov et al., 1979). Precambrian stromatolites have been used extensively as evidence for some of the earliest life on Earth, as well as indicators of geochemical and other paleoenvironmental conditions (Bosak et al., 2013; Grotzinger and Knoll, 1999). Microbial trapping and binding of sediment dominates classic models of stromatolite formation and is common in modern marine examples (e.g. Gebelein, 1969; Reid et al., 2000). However, there is also evidence that encrusting cements are capable of forming stromatolites and associated morphologies without a clear biogenic component (e.g. Grotzinger and Knoll, 1999; Grotzinger and Rothman, 1996; Knoll and Semikhatov, 1998). Grotzinger and Rothman (1996) used the Kadar-Parisi-Zhang (KPZ) equation to demonstrate that some stromatolite forms (such as domal morphologies) can be created abiogenically. Additionally, a diffusion limited aggregation (DLA) model in which particles (sediment, ions, and nutrients) arrive at an aggregate through a path similar to Brownian motion (diffusion) can be coupled with episodic sedimentation to create columnar branching stromatolite morphologies (Grotzinger and Knoll, 1999; Verrecchia, 1996). The morphology and microstructure of stromatolites has also changed through geologic time (e.g. Grotzinger and Knoll, 1999; Riding, 2011), and thus it is likely that the various processes that interact to form stromatolites have likewise changed through time

(Bosak et al., 2013). For these reasons, macroscopic stromatolite morphologies, with the possible exception of some conical morphologies (e.g. Batchelor et al., 2004), alone are not very useful in determining biogenicity. However, there are a number of features, as well as combinations of these features, that are unlikely to have been formed by purely abiotic processes (Awramik and Grey, 2005). Therefore, each structure must be evaluated individually using multiple lines of evidence at multiple scales to test where it falls within a spectrum of biogenicity, with the understanding that some stromatolites may lack sufficient evidence to make a clear determination.

A number of attempts have been made to establish comprehensive criteria for determining stromatolite biogenicity (e.g. Buick et al., 1981; Hofmann et al., 1999; Walter, 1983), although none of them have become definitive (Awramik and Grey, 2005). In the absence of organic matter or microfossils, evidence of biogenic structures commonly includes wavy or crinkled detritus-rich laminations with grains trapped beyond the angle of repose (e.g. Buick et al., 1981). This suggests that the blockage of grain movement (baffling) or adhesion to the extracellular polymeric substance (EPS) produced by microbial communities, as well as microbial binding, played a role in forming the stromatolites (e.g. Riding, 2000). Microbial mat baffling, trapping, and binding may also result in biostabilization of the substrate, in which sediment may experience flexible deformation (e.g. Noffke et al., 2003). Evidence of phototropism, in which stromatolites are inclined towards the direction of maximum insolation, may also be used as evidence for stromatolite biogenicity (e.g. Awramik and Vanyo, 1986; Petryshyn and Corsetti, 2011). Additionally, the photosynthetic production of O₂ and other gases originating from mat decay can build-up under a microbial mat and contribute to the creation of conical stromatolite morphologies that contain fenestrae or lift-off structures between laminations (Bosak et al., 2009, 2010).

Indirect evidence of abiogenic precipitation may include oscillating Ca/Mg ratios between laminae and compositional differences between stromatolites and the surrounding sediment (Frantz et al., 2014; Grotzinger and Knoll, 1999). For example, when entirely calcareous stromatolites are surrounded by siliciclastic sediment it suggests that trapping and binding were not involved in stromatolite formation (Grotzinger and Knoll, 1999). In addition, isopachous laminae and a number of cement textures within stromatolites have been recognized by most authors as indicators of direct precipitation. These include textures such as radial-fibrous, herringbone calcite, radiaxial-fibrous, and fascicular-optic calcite or dolomite (e.g. Grotzinger and Knoll, 1999; Pope et al., 2000; Sumner and Grotzinger, 1996). Isopachous laminae with radial-fibrous fans or botryoids are highly uniform and exhibit a high degree of inheritance. This is inconsistent with accretion in which crystal nucleation and growth is controlled by microbial mats that exhibit spatial heterogeneity (e.g. Bartley et al., 2000; Grotzinger and Knoll, 1999; Knoll and Semikhatov, 1998; Pope et al., 2000).

3. Geologic setting

3.1. Depositional setting and location

The Copper Harbor Conglomerate is a Mesoproterozoic (1.09 Ga) succession located within the upper peninsula of Michigan, northern Wisconsin, and on Isle Royale in Lake Superior. It is comprised of fluvial, lacustrine, and alluvial fan derived volcanoclastic sandstone, mudstone, and conglomerate that was infilling the Keweenaw Trough (Elmore, 1984). This basin is part of the Midcontinent Rift System, which extends from Canada to Kansas and, before failing, threatened to split the North American Craton (Van Schmus

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