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Magnetic susceptibility as a biosignature in stromatolites

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ABSTRACT

Microbialites have long been a focus of study in geobiology because they are macroscopic sedimentary records of the activities of microscopic organisms. However, abiotic processes can result in microbialite-like morphologies. Developing robust tools for substantiating the biogenicity of putative microbialites remains an important challenge.

Here, we report a new potential biosignature based on the detrital magnetic mineral component present in nearly all sedimentary rocks. Detrital grains falling onto a hard, abiogenic, chemically precipitated structure would be expected to roll off surfaces at high incline angles. Thus, the distribution of grains in an abiogenic microbialite should exhibit a dependence on the dip angle along laminae. In contrast, a microbialite formed by the active trapping and binding of detrital grains by microorganisms could exhibit a distribution of detrital grains significantly less dependent on the dip angle of the laminae. However, given that most ancient stromatolites are micritic (composed of carbonate mud), tracking detrital grains vs. precipitated carbonate is not straightforward.

Recent advances in our ability to measure miniscule magnetic fields open up the possibility to map magnetic susceptibility as a tracer of detrital grains in stromatolites. In abiogenic carbonate precipitation experiments, magnetic susceptibility fell to zero when the growth surface was inclined above 30° (the angle at which grains rolled off). In cyanobacterial mat experiments, even vertically inclined mats held magnetic material. The results indicate that cyanobacterial mats trap and bind small grains more readily than abiogenic carbonate precipitates alone. A variety of stromatolites of known and unknown biogenicity were then analyzed. Tested stromatolites span many different ages (Eocene to Holocene) and depositional environments (hot springs, lakes), and compositional forms (micritic, sparry crusts, etc.). The results were consistent with the laboratory results. The results of these experiments suggest that magnetic susceptibility shows promise as a new biosignature in the study of putative microbialites.

1. Introduction

Microbialites are macroscopic sedimentary structures built by or influenced by microorganisms. Stromatolites, laminated structures accretionary away from a point or surface (Semikhatov et al., 1979), are some of the better-studied microbialites. First appearing in the Archean (e.g., Walter, 1976; Awramik, 1992; Grotzinger and Knoll, 1999; Hofmann et al., 1999; Allwood et al., 2006), stromatolites constitute some of the oldest putative evidence for life on Earth. However, abiogenic mineral precipitation is now known to create structures indistinguishable from biogenic stromatolites at some scales (Grotzinger and Rothman, 1996; McLoughlin et al., 2008). Furthermore, some numerical stromatolite growth models imply that microbial involvement may not be required to form many stromatolite morphologies (Grotzinger and Rothman, 1996; Grotzinger and Knoll, 1999). Microscopic investigation can provide some indication of biogenicity, but many, if not most, putative microbialites in the rock record have been subjected to post-depositional alteration that obscures the original microfabric, rendering the biogenicity of most ancient stromatolites ultimately ambiguous.

Terminology used in discussing biogenicity can be vague and even misleading. In this work, we define:

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(1) Abiotic structure: a structure that formed in the absence of life. Given that nearly all surface environments on the Earth today contain life, this is a rare condition for a sedimentary structure. In ancient putative microbialites, this requires a burden of proof that will not often be possible, but would indicate a sterile environment.
(2) Abiogenic structure: a structure whose formation was dominated by inorganic processes. Although life may have been present in the environment or even on or in the structure, it was not actively involved in the structure's building or precipitation. An ancient putative microbialite deemed abiogenic is ambiguous as to whether or not life was present at the time it formed.
(3) Biogenic structure: a structure built by the activity of organisms. This includes trapping and binding of sediment by a microbial mat, or a mineral precipitating because of the activity of an organism. The structure would not exist in the same form if life had not been present. Biogenic structures are a positive indication of the past presence of life.
(4) Biotic structure: a structure that was once part of a living organism (e.g., a shell, bone, or tissue). Biotic structures are also a positive indication of the past presence of life.

Most of the structures discussed herein, and indeed most microbialites in general, would be considered either abiogenic or biogenic.

The majority of microbialites are composed of carbonate minerals, so carbon isotopes are commonly cited as a potential biosignature. However, isotope ratios can also be ambiguous; microbial phototrophic CO_2 fixation drives the surrounding DIC $\delta^{13}C$ positive, while bacterial sulfate reduction drives it negative, making carbon isotopes a problematic biosignature in stromatolites (e.g., Guy et al., 1993). Organic matter is rarely preserved in such structures, and actual microbial fossils are even more rare and usually require special circumstances, such as early silicification, for preservation (e.g., discussion in Grotzinger and Knoll, 1999).

Here we present how recent advances in the ability to measure minute concentrations of magnetic minerals have made it possible to detect the prior presence of microbial communities, introducing a new potential biosignature.

2. Grain trapping and magnetic susceptibility as a potential biosignature

2.1. Gravity-defying detrital grains as a biosignature

Microbial mats (especially those with a filamentous microbiota or perhaps copious quantities of extracellular polymeric substances, EPS) would be expected to trap and bind grains more effectively than mineral surfaces alone (e.g., Frantz, 2013; Frantz et al., 2015). The following is hypothesized:

1) Grains that come into contact with a mineral structure in the absence of a microbial community should exhibit a distinct angle of slide relationship (defined below), in which detrital grains should not be present where slopes are at high angles ($>\sim 45°$, discussed below) (Fig. 1A).

2) Grains adhered to or embedded within a biological surface community will appear to defy the angle of slide relationship and be present in positions inconsistent with simple physical sorting, such as steeply angled sides of stromatolites (Fig. 1D).

The angle of sliding friction is "the angle of slope (with respect to the horizontal) of an inclined plane at which a body resting on the plane will first begin to slide" (Van Burkaxow, 1945). Maximum angles of slide friction are somewhat variable, depending primarily on surface roughness and the weight of the material, but generally less than 45° (e.g. Van Burkaxow, 1945). The angle of sliding friction is a similar concept to angle of repose, the "angle with the horizontal at which loose granular material will stand when piled or dumped" (Carrigy, 1970, p. 148), and the two values are often within $\sim 10°$ of one another (e.g. Nedderman and Laohakul, 1980). These terms define the approximate angles at which grains would be expected to roll off versus remain settled on a non-horizontal surface. The angle of repose differs for different sediment types and grain sizes, but is typically 45° or less in both subaerial and subaqueous abiotic systems (Carrigy, 1970). Although not exactly the same as angle of repose, the angle of slide, which for the purposes of this paper we define as the slope at which a grain would roll off the edge of a domal stromatolite, is analogous to the angle of repose concept.

The communities that build microbialites have an enhanced potential for stabilizing loose sediment, even at high angles (e.g. Bailey et al., 2009; Tice, 2009; Flood et al., 2014). Filamentous forms, for example, can trap detrital sediment within the mesh of filaments or bind them via gliding behaviors (e.g., Frantz, 2013). In addition, microbes may produce significant amounts of EPS that could aid in the trapping and binding of grains, and may provide a template for the nucleation of calcium carbonate (e.g. Reid and Browne, 1991; Visscher et al., 1998; Laval et al., 2000; Reid et al., 2000; Konishi et al., 2001; Dupraz et al., 2009; Decho, 2010). Modern marine stromatolites, such as those forming in the Bahamas, are known to form by the trapping and binding activity of microbes in close association with diatoms and algae (Reid and Browne, 1991; Reid et al., 2000). Additionally, trapping and binding ability is not limited to photosynthetic organisms. Bailey et al. (2009) showed that mats in various environments have the ability to trap and bind sediment. Thus, in standard environments at the surface of the earth (e.g., marine shelves or lacustrine environments), detrital mineral grains (a fraction of which will be magnetic) can adhere to the microbial mats that build microbialites.

2.2. Magnetic susceptibility as a tracer of detrital material

Typically, the grain-size in Proterozoic stromatolites is micritic (e.g., Awramik and Riding, 1988; Riding, 2011), and via petrographic investigation alone it is not possible to determine whether the micrite precipitated in place abiogenically or was influenced by a biological community via trapping and binding or precipitation. All sedimentary environments, including carbonate-dominated environments, contain a certain fraction of extremely fine micron-scale detrital magnetic minerals (e.g., Lund et al., 2010). This detritus is commonly windblown in the dust fraction that can be near the same scale as the micrite found in stromatolites.

Magnetic susceptibility (χ) is the response of a material to an applied magnetic field. A sample with a large amount of magnetic material will produce a large response when an external magnetic field is applied. Because magnetic mineral grains are present as a fraction of nearly all depositional environments, most stromatolites, as sedimentary structures, will contain a fraction of magnetic grains. We hypothesize that the distribution (location and concentration) of magnetic grains within a putative microbialite will depend on the presence or absence of adhesive microbial mats or biofilms (versus a non-adhesive abiotic structure) (Fig. 1B and E). The use of magnetic susceptibility as a test for biogenicity is not impacted by the grain/crystal size limitation that can plague microscopic investigation.

2.3. Magnetic susceptibility biosignature proof of concept – Tahitian microbialites

The concept for magnetic susceptibility as a biosignature grew out of observations made on geologically young microbialites from Tahiti (Lund et al., 2010), which we briefly review here. Integrated