



The paleoenvironmental distribution of Phanerozoic wrinkle structures

Scott A. Mata*, David J. Bottjer

Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, United States

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ABSTRACT

Wrinkle structures are microbially induced sedimentary structures that are known to have formed in ancient marine siliciclastic environments. This study reviews the sedimentary context and paleoenvironmental distribution of these sedimentary structures throughout three distinct intervals of the Phanerozoic: the Cambrian, the post-Cambrian Paleozoic, and the Lower Triassic. During these times, wrinkle structures are found primarily within two sedimentary environments, storm-dominated subtidal environments and the intertidal zone. Subtidal occurrences of wrinkle structures during the post-Ordovician Phanerozoic only appear to occur during intervals of environmental stress, while earlier examples from the Cambrian and lowermost Ordovician likely formed prior to significant increases in extent and depth of bioturbation that hallmark most of the Phanerozoic. Intertidal examples occur regardless of severe environmental stress, and may have formed under low levels of bioturbation due to inherent vagaries of a marginal marine setting. These environmental preferences appear to be conservative throughout the Phanerozoic, and may very well extend throughout Earth's history.

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* Corresponding author. Tel.: +1 213 821 6290.

E-mail address: scottmat@usc.edu (S.A. Mata).

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1. Introduction

Much of what has been learned about the ancient distribution of microbial mats throughout Earth's history is derived from stromatolites that grew in carbonate-dominated settings, and it has been realized only recently the extensive influence that microbial mats may have had upon the substrate in siliciclastic-dominated environments of the geologic past (e.g., Hagadorn and Bottjer, 1997; Gehling, 1999; Hagadorn and Bottjer, 1999; Pflüger, 1999; Seilacher, 1999; Bottjer et al., 2000; Noffke et al., 2002). Indeed, microbial mats appear to play a significant role in the way that we perceive the fossil record, as well as the evolutionary paleoecology of early metazoan life, during which microbial mats were far more extensive than today (e.g., Gehling, 1999; Seilacher, 1999; Bottjer et al., 2000). The presence of microbial mats appears to be the sole reason that the earliest macroscopic life—the soft-bodied Ediacara biota—is preserved in the fossil record at all, with the mats serving as a medium of preservation atop a sandy seafloor (Gehling, 1999). The presence of seafloor microbial mats also explains the unusual morphologies of Cambrian ‘matstickers’, such as the enigmatic helicoplacoids and the small shelly fossil *Cloudina*, which are believed to have lived partially embedded in a firm seafloor stabilized by microbial mats (i.e., matgrounds) (Seilacher, 1999; Bottjer et al., 2000; Dornbos and Bottjer, 2000). The distribution of these organisms is observed to decline precipitously with the disappearance of subtidal microbial mats during the Cambrian, suggesting a strong interrelationship (Bottjer et al., 2000).

With so much evolutionary history hanging upon the presence or absence of microbial mats during crucial times such as the Precambrian–Cambrian transition (e.g., Hagadorn and Bottjer, 1997, 1999; Bottjer et al., 2000), preceded by the prevalence of microbial mat-dominated environments during the Archean and Proterozoic (e.g., Hagadorn and Bottjer, 1997; Gehling, 1999; Seilacher, 1999; Hagadorn and Bottjer, 1999; Noffke et al., 2003b), it is important to understand what environmental conditions are necessary for the formation and preservation of microbial mats, taking into account what conditions may restrict their development or prevent their ultimate preservation. These controlling factors may then provide some idea as to the fidelity of the record of ancient microbial mats, and as to what depositional environments are most conducive to preserving these microbial signatures in the sedimentary record.

Microbialites can be subdivided into two main types—those that are found in carbonate-dominated environments, and those that are found in siliciclastic environments. In carbonate-dominated marine environments microbial mats can develop stromatolites, which are attached layered accretionary growth structures that can obtain significant synoptic relief above the seafloor (e.g., Semikhatov et al., 1979; Reid et al., 2000). In modern environments biogenic stromatolites are restricted primarily to stressed marginal marine settings (Garrett, 1970; Awramik, 1971), and can be found in some alkaline and hypersaline lakes (e.g., Kempe et al., 1991; Cohen et al., 1997); however, during the Archean and Proterozoic, stromatolites appear to dominate a wide range of subtidal carbonate environments (Garrett, 1970; Awramik, 1971).

In modern siliciclastic settings, microbial mats are known to generate distinctive microbially induced sedimentary structures—abbreviated MISS (*sensu* Noffke et al., 2001)—that can be used to infer the presence of a microbial mat in an ancient siliciclastic environment.

The most common forms of MISS include wrinkle structures (Hagadorn and Bottjer, 1997), palimpsest ripples (Seilacher, 1999), and roll-up structures (Simonson and Carney, 1999), although many others can occur (e.g., Noffke et al., 2001; Noffke, 2008).

Wrinkle structures are perhaps the best documented microbially induced sedimentary structure (e.g., Hagadorn and Bottjer, 1997, 1999; Noffke et al., 2002), and many hypotheses have been put forth for their formation, with nearly all proposed methods requiring the presence of a cohesive microbial mat at the sediment's surface (e.g., Hagadorn and Bottjer, 1997; Noffke et al., 2002). Wrinkle structures are bedding plane features comprised of a series of low amplitude crests, pits, and sinuous troughs (Fig. 1) that have been interpreted to form during primary mat growth (Hagadorn and Bottjer, 1997), or during the liquefaction of a microbial mat during burial (Noffke et al., 2002).

Wrinkle structures from the Archean and the Proterozoic have been well documented with respect to the depositional environments that they occur in, as well as the mechanisms by which they formed (e.g., Noffke et al., 2002). A unique aspect about these Precambrian wrinkle structures is that they were allowed to manifest themselves in the sedimentary record uninhibited by factors such as bioturbation, which can be detrimental to microbial mat growth (e.g., Fenchel, 1998). Therefore, it should be expected that Precambrian wrinkle structures should provide the best record of the potential siliciclastic marine environments in which microbial mats might have formed and ultimately been preserved in the rock record, providing insight into the various niches that microbial mats occupied prior to increases in extent and depth of bioturbation during the Cambrian and into the Ordovician (e.g., Droser and Bottjer, 1988, 1989; McIlroy and Logan, 1999).

While Precambrian wrinkle structures have been well documented, wrinkle structures from the Phanerozoic have received less attention with regards to paleoenvironmental distribution, as well as what sedimentary facies wrinkle structures most frequently occur in. This present study will focus on the paleoenvironmental distribution of wrinkle structures during the Phanerozoic, and present a literature-based review of the sedimentary facies and depositional environments in which these features have occurred throughout this time interval to examine whether wrinkle structures occupy a wide range of paleoenvironments, or only a select few; also, whether the environmental distribution of Phanerozoic wrinkle structures has changed significantly from that of the Archean and Proterozoic. This review will be divided into three select intervals throughout the Phanerozoic: 1) the Cambrian, 2) the post-Cambrian Paleozoic, and 3) the Lower Triassic. These intervals were chosen because they highlight discrete intervals of relatively consistent seafloor character (e.g., firmness, water content) and infaunal activity. The Cambrian period is marked by low levels of infaunal activity and shallow penetration of the seafloor, prior to increases in extent and depth of bioturbation in the Ordovician (Droser and Bottjer, 1989; Sepkoski et al., 1991). The post-Cambrian Paleozoic is hallmarked by these increases in bioturbation relative to the Cambrian period and exhibits deeper penetrating and more extensive bioturbation than preceding intervals, with the subsequent development of well-mixed seafloors (Bottjer and Ausich, 1986; Sepkoski et al., 1991; Hagadorn and Bottjer, 1999; Bottjer et al., 2000; Ausich and Bottjer, 2001). Lower Triassic strata record the aftermath of the end-Permian mass extinction, in which much of the world's seafloors reverted back in character to the

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