Journal of Palaeogeography
2013, 2(3): 275−296
DOI: 10.3724/SP.J.1261.2013.00031

Biopalaeogeography and palaeoecology

Environment controls on Mesoproterozoic thrombolite morphogenesis: A case study from the North China Platform

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Abstract Thrombolites are widespread in the Mesoproterozoic Wumishan Formation in the North China Platform. This study shows that they mainly concentrated in subtidal carbonate facies with relatively low hydrodynamic conditions, rather than in intertidal zone as suggested previously. From the deep lower to the shallow upper subtidal facies, the thrombolites show evident changes in morphology from dominantly domal to tabular forms, likely suggestive of environmental controls on their morphogenesis and distribution. As the most important component in thrombolites, mesoclots typically consist of organic-rich micritic nuclei and organic-poor fibrous aragonite rims. Mesoclots may vary considerably in their morphology, but a type of specifically shaped mesoclots tends to concentrate predominantly in a particular group of thrombolites. The proportion of the fibrous aragonite rims in mesoclots decrease as the depositional environments become shallower, likely suggesting that the environmental changes also have controls on the internal fabrics of thrombolites. Putative filamentous bacterial colonies are well preserved in some aragonite fans in the matrix between mesoclots, invoking rapid precipitation and aragonite-supersaturated conditions in the ambient waters. It seems that a suboxic to anoxic environment, highly alkaline seawater and relatively low hydrodynamic conditions were among the important factors that facilitated the development and preservation of thrombolites in the Mesoproterozoic epeiric sea on the North China Platform.

Key words mesoclots, fibrous aragonite, bacterial sulfate reduction, organo-mineralization, carbonate supersaturation

1 Introduction

Thrombolites are a kind of bio-sedimentary structure formed through interactions of microbes and sedimentation, and constitute a major group of microbialites (Kennard and James, 1986; Aitken and Narbonne, 1989; Riding, 1999, 2000, 2006), in addition to stromatolites, oncolites and leiolites (Riding *et al*., 1991; Riding, 1999, 2002; Altermann, 2008). They are often associated with stromatolites in the geological record, but differ from the latter markedly in their clotted rather than stratified internal fabrics (*e.g.*, Aitken, 1967; Kennard and James, 1986; Burne and Moore, 1987; Kennard *et al*., 1989; Riding *et al*., 1991; Riding, 2002, 2006, 2008).

Chronologically, thrombolites abound in carbonate successions of the Late Neoproterozoic to Early Ordovician times, and often occur as a major component in build-ups

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Received: 2013−03−04 Accepted: 2013−04−15

(*e.g.*, Aitken and Narbonne, 1989; Kennard, 1989, 1994; Feldman and Mckenzie, 1998; McCormick and Grotzinger, 2001; Grotzinger and James, 2000; Adams *et al*., 2005; Hicks and Rowland, 2009; Raviolo *et al*., 2010). Since the Early Ordovician, thrombolites declined sharply due to the diversification of metazoans (Walter and Heys, 1985; Sheehan and Harris, 2004; Riding, 2006) and became restricted largely to highly stressed environments or the aftermaths of mass extinctions. For instance, thrombolites have been well documented in strata of the latest Ordovician to earliest Silurian age (*e.g.*, Sheehan, 2001; Sheehan and Harris, 2004), latest Devonian (*e.g.*, Whalen *et al*., 2002), Early Triassic (Grotzinger and Knoll, 1995; Ezaki *et al*., 2003, 2008, 2012; Kershaw *et al*., 2007, 2011; Yang *et al*., 2011) and in the Miocene interval of the Messinian Salinity Event (Feldmann and McKenzie, 1997). During the Mesozoic, thrombolites seem to have had a resurgence, especially in the Late Jurassic, when they often constituted a prominent portion of reefs (Olivier *et al*., 2003; Mancini *et al*., 2004; Helm and Schulke, 2006; Matyszkiewicz *et al*., 2006), and were able to form noticeable oil reservoirs in marine settings (*e.g.*, Leinfelder and Schmid, 2000; Mancini *et al*., 2006). It is worth noting that thrombolites are rare in strata prior to the Late Neoproterozoic, with only a few examples known from the Paleoproterozoic of Canada, which may represent the earliest records of thrombolites, although they were commonly regarded as inorganic in origin (Kah and Grotzinger, 1992). To date, thrombolites are virtually unknown from the Mesoproterozoic successions (Grotzinger and James, 2000; Riding, 2000, 2008; Harwood and Sumner, 2011), except for those from the North China Platform (Tang *et al*., 2013a).

Ecologically, modern thrombolites are known from a variety of environments, such as the restricted hypersaline embayment at Shark Bay, Australia (*e.g.*, Riding, 2000; Jahnert and Collins, 2011, 2012), an open subtidal setting in the Bahamas (*e.g.*, Feldmann and McKenzie, 1998; Planavsky and Ginsburg, 2009; Myshrall *et al*., 2010; Mobberley *et al*., 2012), freshwaters (*e.g.*, Ferris *et al*., 1997; Laval *et al*., 2000; Gischler *et al*., 2008, 2011), as well as hypersaline (*e.g.*, Puckett *et al*., 2011) and alkaline lakes (*e.g.*, Kempe and Kazmierczak, 1993; Arp *et al*., 2003), with a few examples also reported from hot spring settings (*e.g.*, Campbell *et al*., 2008). In comparison with stromatolites, however, far less attention has been paid to thrombolites, partly due to the presence of many transitional forms between the two that have obscured a conclusive separation, and partly due to the relative restriction of thrombolites in both temporal-spatial distribution and abundance. In many cases, therefore, thrombolites have been studied under the umbrella term of microbialites (Riding, 2000, 2006; Sheehan and Harris, 2004; Kershaw *et al*., 2011).

As to the genesis of thrombolites, opinions are controversial. A common idea is that thrombolites developed since the Late Neoproterozoic are biogenic, with their mesoclots (Shapiro, 2000) probably derived from the calcification of microbial colonies in sediments (Kennard and James, 1986; Kennard, 1989; Myshrall *et al*., 2010). However, earlier thrombolites from the Paleoproterozoic, such as those from the Rocknest Formation, Canada, were thought to have resulted mainly from abiotic processes (Kah and Grotzinger, 1992; Grotzinger and James, 2000), due to the high proportion of fibrous aragonite cement in their interior, which was commonly interpreted as a kind of sea-floor precipitation (Kah and Grotzinger, 1992). In regard to the morphogenesis of thrombolites, opinions are also divergent. For instance, some researchers suggest that they may have resulted from the destruction of stromatolites either through diagenetic alteration or metazoan bioturbation (*e.g.*, Hofmann, 1973; Walter and Heys, 1985), or from a high proportion of microbial eukaryotes involved (*e.g.*, Feldmann and McKenzie, 1998) and therefore reflect different microbial metabolisms (Myshrall *et al*., 2010; Harwood and Sumner, 2011). Whereas some others propose that they may have resulted from taphonomic factors (Turner *et al*., 2000; Planavsky and Ginsburg, 2009). Nevertheless, most researchers agree that thrombolites represent a distinct type of microbialites and are generated by microbial communities and their interactions with the environments where they have lived (*e.g.*, Kennard, 1989; Shapiro, 2000; Riding, 2002, 2006; Tang *et al*., 2013a).

Thrombolites from the Mesoproterozoic Wumishan Formation (ca 1.5−1.45 Ga) of the North China Platform (NCP) (Figs. 1A, 1B) have been recently studied by Tang *et al*. (2013a), with a focus on their biogenicity and organomineralization, mainly from the angle of ultra-fabrics and constituent organominerals. In this paper, based on their macro- to microscopic texture variations and distribution in relationship to depositional environments, we primarily focus on mesoclot genesis, possible environmental controls on their morphogenesis, as well as their palaeoecologic constraints.

2 Geological setting

The NCP witnessed a tectonic evolution from the breaking-up of the Columbia supercontinent to the assembly of the Rodinia supercontinent. During Proterozoic times, it