

Mesozoic Reefal Thrombolites and Other Microbolites

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Abstract. Calcareous microbolites are widespread in the Mesozoic. They play a paramount role in reef-building and often contribute to the reef framework. In the Early Triassic, stromatolites took over the vacant reef habitats. During the Middle Triassic and Late Jurassic, microbolites reached their peak development in the Mesozoic, often forming reefs together with different groups of metazoans. No major break in microbolite development appeared from the Late Jurassic to the Early Cretaceous. In the course of the Cretaceous, microbolites in shallow water reefs were for the most part replaced by encrusting corallinaceans.

1 Introduction and General Trends

Microbolites ("microbialites" sensu Burne and Moore 1987; see Riding 1991) are widespread throughout the Mesozoic, occurring in a great variety of environments ranging from freshwater settings (Leinfelder 1985; Bigot 1981) to the deep shelf (e.g. Pratt 1995). Reefal microbolites were especially frequent during the Triassic and Jurassic (Fig. 1). In particular, they were powerful reef-builders, often contributing greatly to the reef

framework, although they were also of importance for baffling with digitate crusts in microbolite reefs and for binding in many mud-mounds. Reefal microbolites are clearly dominated by thrombolites, although stromatolites and leiolites (sensu Braga et al. 1995) developed as well. Non-reefal stromatolites and oncoids occur throughout the Mesozoic.

Jurassic pseudobioherms, which formed at cold seeps, are generally marked by extremely low ^{13}C values of -10 to -30‰ PDB (Gaillard et al. 1992). However, in some pseudobioherms, Gaillard et al. found exceptional ^{13}C values of up to $+15\text{‰}$ PDB, probably due to CO_2 produced during bacterial methanogenic fermentation. The microbolites described here exhibit normal isotope values and are in no way related to those of cold seeps or hydrothermal vents.

2 Triassic Microbolites

2.1 Early Triassic

Early Triassic stromatolites are reported from several localities in North America, Europe and Asia (Baud et al. 1997). They appear to be more frequent than during the Permian and during the later epochs of the Triassic, so that Schubert and Bottjer (1992) interpreted them as "disaster forms," taking over vacant reef habitats after the major extinction event at the Permian-Triassic boundary. The first metazoan reefs known from the Triassic are middle Anisian, calcisponge-rich reefs apparently avoid of microbolite crusts (Flügel and Senowbari-Daryan 1996).

2.2 Mid-Triassic

The widespread mid-Triassic sphinctozoan reefs are characterized by a large amount of what is known as "cement crusts," consisting of radial-fibrous calcite. These crusts (including the so-called Grossoolithe from the Ladinian Wetterstein Kalk of the Northern Calcareous Alps, see Brandner and Resch 1981) are especially abundant in Middle Triassic reefs (Figs. 1, 4),

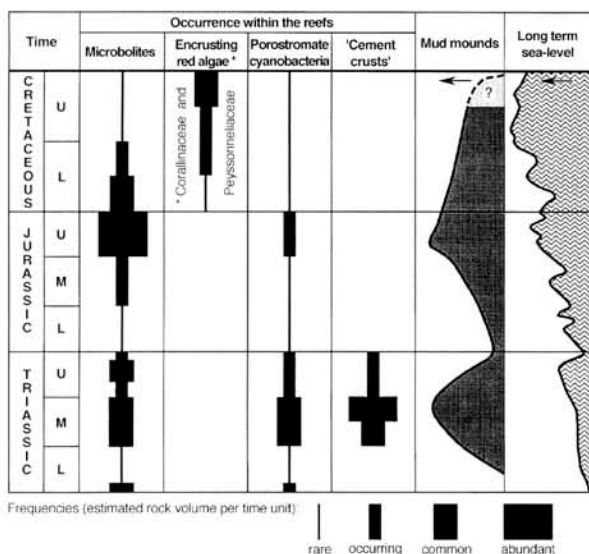


Fig. 1. General trends in Mesozoic microbolites. (Based mainly on data from Baud et al. 1997; Flügel 1981; Haq et al. 1987; Harris 1993; Moussavian 1992; Neuweiler 1995; Senowbari-Daryan et al. 1993; Wendt 1982)

but also still occur in younger Triassic deposits. The cement crusts formed syndepositionally (see Harris 1993). Their precipitation was possibly triggered by microbes (Flügel 1989), as indicated by a brownish color, inclusion of minute microbial peloids, and the occasional repetitive intercalation of micritic crusts. Harris (1993) provided a detailed description of microbial crusts from the Dolomites of Southern Italy, where the crusts together with syndepositional cements create the boundstone fabric. Brachert and Dullo (1994) identified micritic crusts in allochthonous reef blocks ("Cipit" boulders) from the Ladinian of the Dolomites and compared them with Recent crusts from the Red Sea which formed below the euphotic zone.

2.3

Late Triassic

Late Triassic, reefal microbolites are generally less frequent than in Middle Triassic reefs (e.g. Flügel 1981), although for the first time well-developed scleractinian coral reefs appeared. Wendt (1982) described thrombotic patch reefs from the Carnian of the Southern Alps. Reid (1987) concluded that peloidal sediments and crusts, probably of microbial origin, form up to 75% of Upper Triassic reefs from Canada. As to non-reefal microbolites, cyclic, peritidal fenestral limestones developed extensively in platform carbonates of the Northern and Southern Calcareous Alps. Wright and Mayall (1981) reported stromatolites and thrombolites from the Upper Triassic of England; these also form cyclic successions which are mainly controlled by sedimentation, early lithification and salinity changes.

3

Jurassic Microbolites

3.1

Lower and Middle Jurassic Carbonate Microbolites

Whereas non-reefal microbolites, such as oncoids and peritidal fenestral carbonates, were common during the Early Jurassic (e.g. Calcare Massiccio-platform, Cocozza and Gandin 1990), reefs were actually rather rare and restricted to certain regions (Leinfelder 1994). Milhi (1992) describes siliceous sponge-microbolite bioherms from the Sinemurian of the High Atlas (Morocco). In the Atlantic realm, deep water microbolites were reported by Jansa et al. (1989).

During the Mid-Jurassic, microbolites developed widely in siliceous sponge reefs (e.g. Rehfeld-Kiefer in Leinfelder et al. 1994), but were still mostly absent in shallow-water coral reef facies. This may be at least deduced from the Bajocian-Bathonian coral reef facies of the Paris Basin (see Geister and Lathuilière 1991). Peritidal fenestral limestones and oncoids are again a com-

mon feature of Mid-Jurassic carbonate platforms, but stromatolitic structures and oncoids were widespread even in the pelagic Rosso Ammonitico facies from the Southern Alps (Massari 1983).

3.2

The Extensive Development of Carbonate Microbolites During the Late Jurassic

The Late Jurassic represents a time of extensive microbolite development (Fig. 1), with many different environments being conquered by calcifying microbes. This section mainly focuses on examples from the northern Tethys margin (see Leinfelder 1994; Leinfelder et al. 1994; Nose 1995).

3.3

Classification

Schmid (1996) suggested a new classification of Jurassic microbolites based on the classification of Kennard and James (1986). This system (Fig. 2) may also be applied to the entire Mesozoic, but it is apparently not applicable to Precambrian and Early Palaeozoic microbolites due to the larger variability of the latter. In this new classification, both macro- and microstructure are taken into account, but we would like to emphasize the importance of clearly distinguishing between both categories. It is also crucial to separate structure from growth form (e.g. "oncoids"). A special growth form frequently found in Upper Jurassic coral-thrombolite reefs is represented by "downward-facing hemispheroids" (Fig. 3; Leinfelder et al. 1993).

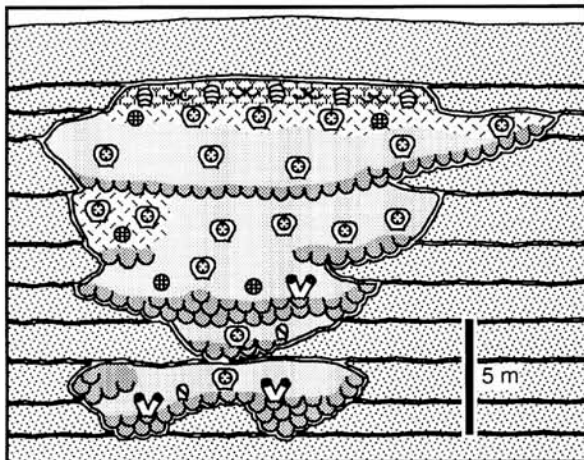
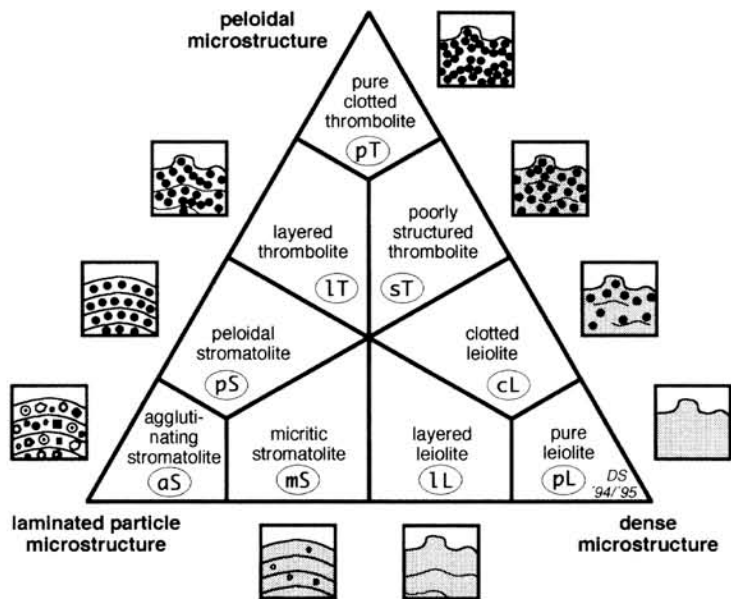
3.4

Environmental Interpretation

Upper Jurassic microbolites are often associated with reef-building fauna such as corals, stromatoporoids and siliceous sponges, but pure microbolite reefs, up to 30 m in height, can also be found. Non-reefal microbolites, such as oncoids or peritidal, fenestral laminated limestones (loferites), existed as well (e.g. Leinfelder 1992).

Combining microbolite fabrics, growth forms and abundance allows the interpretation of several environmental parameters. However, thrombolites in particular were widespread, occurring in very different settings. Therefore, some additional characteristics are needed for the precise reconstruction of the environmental setting, especially when reef metazoans are lacking or their bathymetric distribution is discussed controversially (e.g. siliceous sponges). These characteristics are represented by micro-encruster associations which allow deduction of a much more detailed, palaeoecological interpretation (Schmid 1996; Leinfelder et al. 1993). New results on the enigmatic micro-encrusters "*Tubiphytes*"

Fig. 2. Classification of Upper Jurassic microbolites according to their fabric, which may also be applied to Mesozoic microbolites in general. Partly based on the classification of Kennard and James 1986. (Schmid 1996)



- | | |
|--|----------------------------------|
| Microbolite | Coral (massive) |
| Microbolite, forming downward-facing hemispheroids | Coral (phaceloid) |
| Coral thrombolite | Stromatoporeid/Chaetetid |
| Coral boundstone | Demosponge with isolated spicula |
| Solenoporecean-oyster biostrome | Solenopora |
| Bedded limestones (Bioclast packstones) | Oysters |

Fig. 3. Schematic diagram of a Late Jurassic coral-thrombolite reef, including downward-facing hemispheroids. Several reef growth stages are indicated, each with a relief of 2 m. (Schmid 1996)

morroneensis Crescenti and *Lithocodium aggregatum* Elliott show that both should be interpreted as foraminifers (Schmid 1995, 1996; Schmid and Leinfelder 1996).

Pure microbolite reefs which contain hardly any macroorganisms occur in deep-ramp settings and tolerate dysaerobic conditions. Only clusters of the dysaerobic, epibenthic pectinid bivalve *Aulacomysella* probably living in symbiosis with sulfur bacteria and *Chondrites* burrows can be found in distinct horizons between the reef bodies. Additionally, framboidal pyrite and authigenic glauconite may be abundant in such dysaerobic levels (Leinfelder et al. 1993).

A cryptic micro-encruster association dominated by thecideid brachiopods has been found in the aphotic part of reef caves which developed within and between the coral thrombolite reefs of La Rochelle, France (Leinfelder et al. 1996). This demonstrates that the thrombolite-forming microbes were at least partly light-independent. This is also demonstrated by microbolite reefs that grew in aphotic settings in water depths of approximately 400 m (Dromart et al. 1994).

Another interesting feature of Upper Jurassic microbolites is that they are normally restricted to poorly agitated environments. High energy reefs of the Late Jurassic are normally represented by debris-rich coral reefs with microbolites largely lacking. This indicates that high accumulation of bioclastic particles and, possibly, high abrasion could not be tolerated. If steep, tectonically induced reef margins allowed the export of most of the debris produced by the high wave energy, microbolites suddenly appeared and were able to stabilize the remaining reef debris (Leinfelder 1992, 1994).

Interestingly, very well-developed coral-thrombolite reefs are largely restricted to settings close to siliciclastic coastlines. Although during the time of growth of these reefs direct siliciclastic influx was minimal, it may be concluded that nutrient values were mesotrophic rather than oligotrophic, supporting the flourish-

ing of microbes. Such an interpretation is corroborated by the ecological analysis of coral faunas, which indicates that many Upper Jurassic reef corals, though having already developed symbiosis with zooxanthellae, benefited from slightly elevated nutrient levels (Nose and Leinfelder 1997). This may partially explain the less frequent occurrence of reefal microbolite crusts and the apparently lower diversities of coral faunas in large carbonate platform settings such as the Paris Basin.

3.5

Microbially Induced Calcification

Microbolites both from Upper Jurassic reefs and from oncoids normally exhibit distinct microbial fabrics. However, in peritidal limestones as well as in mud-mounds, microbial activity is obvious but did not necessarily lead to distinct calcification products: Laminated fenestral fabrics developed frequently in intertidal and supratidal environments from the Late Jurassic (e.g. Leinfelder 1992). Although the fabric of the carbonates is often very dense, microbial trapping, binding and, probably, calcification are obvious by the laminoid character of the fenestrae, owing to repetitive desiccation and decay of organic matter in combination with the existence of horizontal microbial mats and rapid cementation. The lack of diagnostic microbolite calcification fabrics is thought to be due to a higher sedimentation rate than in the reef examples described above.

Siliceous sponge-bearing mud-mounds from the Late Jurassic may show great variations in the content of distinct microbolite participation (also known as automicrites). The steepness of mud-mound walls and the relatively large amount of firm-bottom dependent fauna suggest that microbial activity helped to stabilize, and possibly to cement, such mounds. Leinfelder and Keupp (1995) developed a generalized model for the formation of Upper Jurassic mud-mounds, implying that mounds with a high participation of distinct microbolites may indicate episodes of very reduced background sedimentation, whereas mounds with less well-developed microbolite crusts may represent episodes of higher background sedimentation. In the latter case, distinct microbial calcification fabrics could not develop owing to "dilution" with allochthonous material.

Some Upper Jurassic mud-mounds from southern Germany show large amounts of peloids and coated grains being stabilized by thin layers of leiolithic microbolites. Poor sorting, partial clotting and domed structures suggest that all these grains are products of microbial activity, representing incompletely calcified or partially reworked remnants of microbial mats. Koch et al. (1994) interpreted these peloids and coated grains as allochthonous particles of shallow-water origin. Whereas we agree that parts of these grains are of allochthonous, partly even shallow-water, origin, we re-

late the origin of the majority of the grains to in-place microbial activity.

4

Cretaceous Microbolites

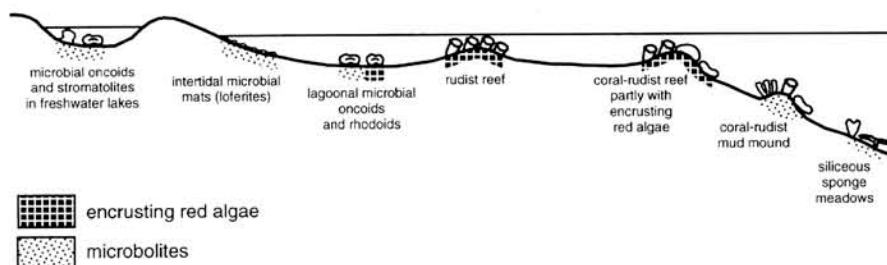
From the Late Jurassic up to the end of the Early Cretaceous, no major break existed in microbolite development. Peritidal fenestral microbolites were widespread (Strasser 1988). Masse (1979) reported pure Lower Cretaceous microbolite reefs from Urgonian limestones of France and Algeria. Neuweiler (1995) described microbial reefs and mounds from the Albien of Spain, with a siliceous, sponge-dominated aphotic community and a coral-calcisponge dominated photic community. Scott (1990) found a reef core rich in stromatolites in one Albian coral reef from the Gulf of Mexico.

Although solenoporaceans and *Marinella lugeoni* Pfender, a precursor of the corallines (Leinfelder and Werner 1993), existed already prior to the Cretaceous, it was only in the late Early Cretaceous that red algae, both corallines and the newly arisen peyssonneliacean algae, started playing a major role in shallow-water reef formation, initially competing with the microbial crusts. Especially during the Late Cretaceous, microbolites were gradually substituted by encrusting red algae (Corallinales and Peyssonneliaceae) in shallow-water coral reefs (see Leinfelder 1992; Moussavian 1992). Interestingly, neither microbolites nor coralline algae play a major role in most rudist reefs, which might be related to higher background sedimentation rates (Fig. 4).

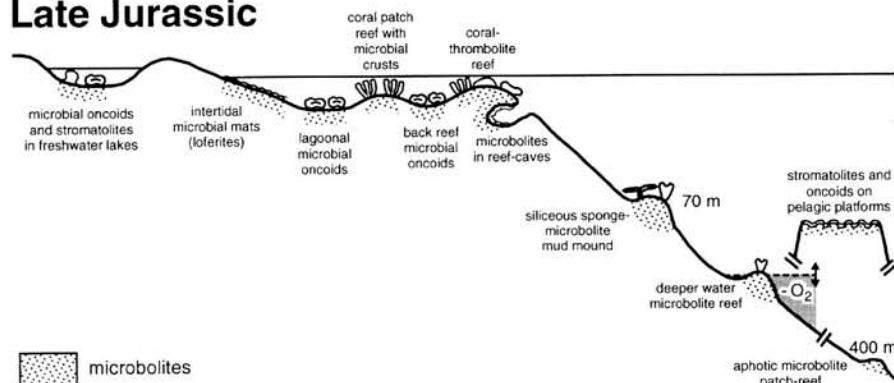
In deeper settings, microbes appear to be of continued importance, to some extent. Camoin (1995) describes deeper water mud-mounds from the Turonian and Coniacian of North Africa with abundant microbial fabrics in the core matrix. Cretaceous, siliceous sponge facies from northern Spain also includes microbolite development (Rehfeld and Otto 1995), although the importance seems to be less than for many Jurassic examples. Also, deeper shelf biogenic mound structures became rare during the Late Cretaceous. This could possibly be an effect of elevated sedimentation rates of calcareous nannoplankton remains, so that habitats for calcifying microbial activity were less common. Alternatively, the longevity of the high sea-level might have caused a global reduction of microbially induced and inorganic carbonate precipitation as a consequence of high rates of skeletal precipitation (Riding 1993).

Coralline algae probably grew faster, could stabilize better, were better adapted to abrasive settings and could conquer oligotrophic environments. Therefore, extant microbolites are only found in restricted settings unsuitable for corallines such as reef cavities, hypersaline or brackish ponds, or freshwater deposits (see Reitner 1993; Burne and Moore 1987). However, microbolites have one great advantage over coralline

Late Cretaceous



Late Jurassic



Middle Triassic

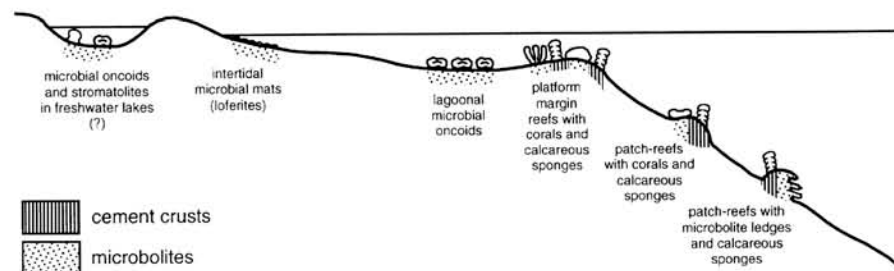


Fig. 4. The occurrence of microbolites, encrusting red algae and cement crusts within mesozoic shelf-slope carbonate systems. Large reef caves have to date only been reported from the Late Jurassic and middle Cretaceous. Based mainly on data from: Triassic: Brachert and Dullo (1994); Brandner and Resch (1981); Flügel (1989); Harris (1993); Jurassic: Leinfelder (1985); Leinfelder et al. (1993); Dromart et al. (1994); Massari (1983); Cretaceous: Bignot (1981); Camoin (1995); Moussavian (1992); Rehfeld and Otto (1995); Reitner et al. (1995); Scott (1990)

algae: they are facultatively independent of light. This is why, even today, calcifying microbes greatly contribute to reef formation by fixing and binding reef material from voids, cavities and reef caves.

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