

Why is stromatactis so rare in Mesozoic carbonate mud mounds?

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ABSTRACT

The sedimentary–diagenetic structure stromatactis is widespread in Palaeozoic spiculitic carbonate mud mounds, but occurs only sporadically in Mesozoic sponge carbonate mud mounds. Comparative analysis of Palaeozoic and Mesozoic stromatactis limestones suggests that this variation results from the degree of siliceous sponge skeletal rigidity and the amount of internal sediment accumulation in the original cavity network. Partial to entire filling by internal sediment resulted in a continuum, from a small amount of internal sediment and

large amount of cement (stromatactis, common in the Palaeozoic), to only internal sediments (aborted stromatactis, common in the Mesozoic). These observations match independent lines of evidence concerning the siliceous sponge evolution and sediment recycling (e.g. bioerosion) across the Palaeozoic to Mesozoic biotic revolution.

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Introduction

Stromatactis (Fig. 1) is a spar body common in Palaeozoic carbonate mud mounds. Although it has been regarded either as a fossil (Dupont, 1881), as a permineralized unfossilizable organism (Leconte, 1937; Tsien, 1983), or as recrystallized patches of the host lime mud (Black, 1952; Orme and Brown, 1963; Ross *et al.*, 1975), most carbonate workers now agree that it is the result of centripetal cementation in a cavity system. Additionally, although it has been proposed that the cavity system was created on the sea-floor (Schwarzacher, 1961; Bathurst, 1980), most studies have concluded that the cavity system developed within the subsea-floor sediment, in the shallow subsurface environment (Lees, 1964, 1988; Shinn, 1968; Heckel, 1972; Bechstädt, 1974; Bathurst, 1982; Bourque and Gignac, 1983; Lees and Miller, 1985, 1993; Wallace, 1987; Boulvain, 1993; Bourque and Boulvain, 1993).

Bourque and Boulvain (1993), following Bathurst (1982), drew attention to the 3D nature of stromatactis and defined it as 'a spar network, whose elements have flat to undulose smooth lower surfaces and digitate upper surfaces, made up principally of isopachous crusts of centripetal

cement and embedded in finely crystalline limestone'. This definition is used in the present contribution; the original cavity network was created by collapse of material within an organic tissue, mainly sponges (see Lees, 1964 for first discussion). The stromatactid cavity network is defined as the original cavity network that has been subsequently obturated by various proportion of internal sediment and cement. Thus, stromatactis spar bodies represent one end-member of the spectrum of original cavity network infilling, the other being only internal sediment – herein called aborted stromatactis (Fig. 1).

Apart from controversial views about definition, semantics, and generic interpretation, no work has thus far been carried out on the topic of changes through time of stromatactis facies. Bathurst (1982) raised the question 'why is it that both stromatactis and its parent carbonate buildup are apparently missing from post-Palaeozoic limestones?', which was echoed by James and Bourque (1992) who stated that 'such spar bodies are mainly, but not exclusively, a Palaeozoic phenomenon, suggesting some sort of organic control'. Mesozoic stromatactis limestones are apparently present in spicular sediments of the Lower Liassic (Böhm *et al.*, 1999), but these were significantly overprinted by subsequent subaerial exposure (Mazullo *et al.*, 1990). Pascal (1985), Matyszkiewicz (1993), Pratt (1995), and Neuweiler *et al.* (1999) illustrated Triassic to Cretaceous stromatactis and stromatac-

toid (see Fig. 1) structures that are related mostly to incomplete calcification of siliceous sponges. These examples match to some extent the Palaeozoic stromatactis-sponge consortium as stressed by Bourque and Gignac (1983, 1986), Monty (1984), and Bourque and Boulvain (1993).

The present paper examines the link between the Palaeozoic and the Mesozoic stromatactis spiculitic mound facies (Figs 2, 3), and tries to answer the Bathurst's (1982) question expressed in a slightly different manner: why is stromatactis so rare in post-Palaeozoic limestones, despite the spiculitic mound facies is still present?

Palaeozoic vs. Mesozoic stromatactis

In terms of fundamental characteristics, stromatactid cavities share the following: the shape, the network nature, the presence of internal sediment and early marine cement, and the embedding into a microcrystalline carbonate commonly associated with sponge remains. They therefore should share a common origin (Bathurst, 1982; Bourque and Boulvain, 1993), although there could be local variation in features such as lateral extension along bedding plane, the amount of internal sediment vs. cement, and zonation of cement (Bathurst, 1982).

Palaeozoic stromatactis facies

Stromatactis is a major attribute of spiculitic facies in Palaeozoic mud

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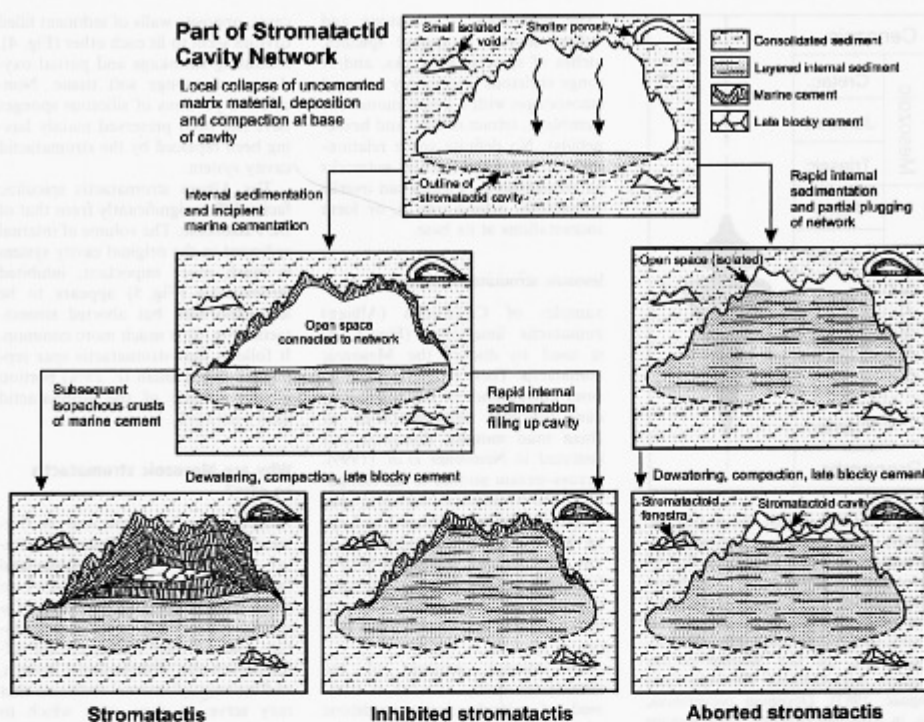


Fig. 1 Infilling processes of the original stromatactid cavity system leading to two end-members, stromatactis and aborted stromatactis, as seen in cross-section of the network. Early internal sedimentation occurred in the open space of the cavity network enhancing the flatness of the floor. Centripetal cementation by early marine cements in residual cavity space following internal sedimentation produced stromatactis. Aborted stromatactis is the term used herein for this more or less laminated fine-grained sediment body that resulted from internal sediment filling of the entire or near-entire original cavity network, plugging the network (or part of it) and preventing efficient seawater circulation. However, inhibited stromatactis refers to incipient marine cementation of the stromatactid cavity followed by entire or near-entire internal sediment filling. A major factor leading to one or the other is the availability of fine-grained sediment to be brought into the cavity system.

mounds and, together with its host microcrystalline facies, it remained the same throughout the Palaeozoic. More often, stromatactis spiculitic facies is one among several facies that make up mud mounds, forming the deepest component of shallowing upward successions (James and Bourque, 1992; Boulvain, 1993; Bourque, 1997). It is commonly, but not always, overlain by mixed heterozoan–photozoan facies, followed by photozoan-dominated facies. However, in the deepest parts of ramps or shelves, these composite mud-mounds pass into fairly homogenous stromatactis mounds.

In cross-section normal to the elongation of the stromatactis network (Fig. 4), the sizes of the spar bodies vary from a centimetre to a metre wide and up to several centimetres high. In comparison, stromatactoid fenestrae are unconnected cavities usually smaller than 5 mm width. Stromatactis networks may constitute up to 40% by volume of the host rock. The flat to undulose base of stromatactis may form an angle of up to 45° with the bedding plane, pointing to steeply dipping depositional palaeoslopes. Stromatactis-rich spicular limestone may alternate with stromatactis-free or -poor spiculitic limestone on metre-

scaled units. First generations of cement in stromatactis are marine isopachous crusts, whereas later cements are usually burial, locally meteoric, blocky spar (e.g. Boulvain, 2001).

Early internal sedimentation in the stromatactid cavity network formed geopetal structures prior to any early cement lined the cavity walls. The base and sides of this generation of internal sediment form a diffuse contact with the host microcrystalline carbonate, whereas the contact becomes clearer upward with subsequent internal sedimentation that occurred before and/or during the marine cementation into the residual cavity system. In places,

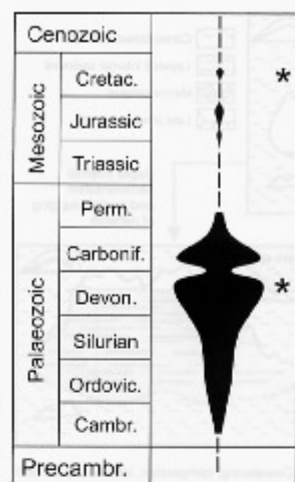


Fig. 2 Tentative sketch illustrating the relative importance of stromatactis through time. Typical examples for the Palaeozoic are: the early Cambrian, Flinders Ranges, Australia (James and Gravestock, 1990); the Ordovician of central Sweden (Bathurst, 1982; Middleton, 1988); the late Silurian of the Québec Appalachians (Bourque and Gignac, 1983); Devonian occurrences, e.g. in Australia (Kerans, 1985; Kerans *et al.*, 1986; Wallace, 1987), Belgian Ardennes (Dupont, 1881; Boulvain, 2001), and southern France (Bourroailh and Bourque, 1995); and several Carboniferous (Wantsortian) occurrences, e.g. in Ireland (Laes and Miller, 1985, 1995; Labiaux, 1997), Algeria (Bourque *et al.*, 1995; Madi *et al.*, 1996), and USA (Ahr and Stanton, 1996; Jefferey and Stanton, 1996). See text for sporadic Mesozoic examples. Asterisks mark the examples illustrated herein.

both sediment and cement may inter-layer. Internal sediment consists of faintly laminated microspar passing upward into pseudospar. Like the host rock, it contains sponge spicules, ostracodes, crinoid fragments, microfossils, and small intraclasts. In places, it may consist of microspar with vermicular texture (Kapp, 1975), or be composed of laminar peloidal sediment, locally haematitic, with small intraclasts, microfossils and ostracodes.

The host rock is mudstone and wackestone rich in sponge spicules, patches of spicular networks, and/or sponge skeletons (commonly nonrigid demosponges with a simple monaxone assemblage, tetractinellids, and hexactinellids). No definite space relationship exists between spicular networks and stromatactis. Spicules can overlie stromatactis, extend into it, or form concentrations at its base.

Mesozoic stromatactis facies

Examples of Cretaceous (Albian) stromatactis limestones (Figs 3, 4) are used to discuss the Mesozoic stromatactis. These stromatactis limestones correspond to the microcrystalline siliceous sponge facies of Albian mud mounds discussed and illustrated in Neuweiler *et al.* (1999). In cross-section normal to the elongation of the stromatactis network, spar bodies range in width from 3 to 5 cm and have a maximum thickness of 1 cm. The network represents 5–10% of the rock volume (Fig. 4) and comprises early marine isopachous cement crusts followed by burial cement mosaic.

The internal sediment of the stromatactid cavity network is composed of microbioclastic mudstone and wackestone, and is more voluminous than stromatactis, constituting about 40% of the rock volume. The internal sediment may contain unsupported voids resulting from collapse. It often grades into peloidal or clotted micrite of hydromechanical (laminated) or organomineralical origin. Collapse pores are mm-sized and in turn their volume has been reduced by geopetal internal mud. There are patches of mottled fabrics of deposit feeders. Most of the stromatactis flat bases are subparallel each other, but locally internal rotation indicates collapse during differential sediment compaction prior to spar cementation (Fig. 4).

The stromatactid cavity network is often bordered by a consortium of siliceous sponges (Fig. 4). The sponge fauna (up to 40% of rock volume) mainly consists of calcified hexactinellids, lithistid and nonlithistid demosponges. Together with patches of early consolidated sediment, the calcified sponge remains support the stromatactid cavity network. In some

cases, opposite walls of sediment filled cavities seem to fit each other (Fig. 4), indicating shrinkage and partial oxydation of sponge soft tissue. Non-calcified portions of siliceous sponges have not been preserved mainly having been replaced by the stromatactid cavity system.

The Albian stromatactis spicular facies differs significantly from that of the Palaeozoic. The volume of internal sediment in the original cavity system is much more important, inhibited stromatactis (Fig. 5) appears to be less important, but aborted stromatactis (Fig. 5) is much more common. It follows that stromatactis spar represents only a small (c. 25%) portion of the volume of the stromatactid cavity network.

Why are Mesozoic stromatactis so rare?

Although the Palaeozoic and the Cretaceous stromatactis (described herein) limestones share fundamental features such as the nature of the host rock, their shape, the presence of a sponge consortium, and the cementation pattern, there are significant differences in size, distributional pattern, and amount of internal sediment that may serve as clues with which to elucidate the evolutionary biosedimentology causing the decrease of stromatactis during the Palaeozoic to Mesozoic biotic revolution (cf. Vermeij, 1977). Three lines of evidence are useful in interpreting this change: sponge skeleton rigidity, cavity formation, and cavity reduction in terms of the abundance of internal sediment accumulation.

Cavity formation and sediment stabilization

The fabric of the stromatactis spicular limestone suggests that cavities formed during degradation of the sponge biomass and biopolymer–geopolymer transfer acting within the interstitial space of the surrounding sediment. Early phases of bioenergy transfer encompass oxidation and nitrate reduction accompanied by chemical stabilization or humification via an intermediate stage of dissolved organic carbon (cf. Ziehmman, 1994). Humification is one of the most effective mass transfer mechanisms on

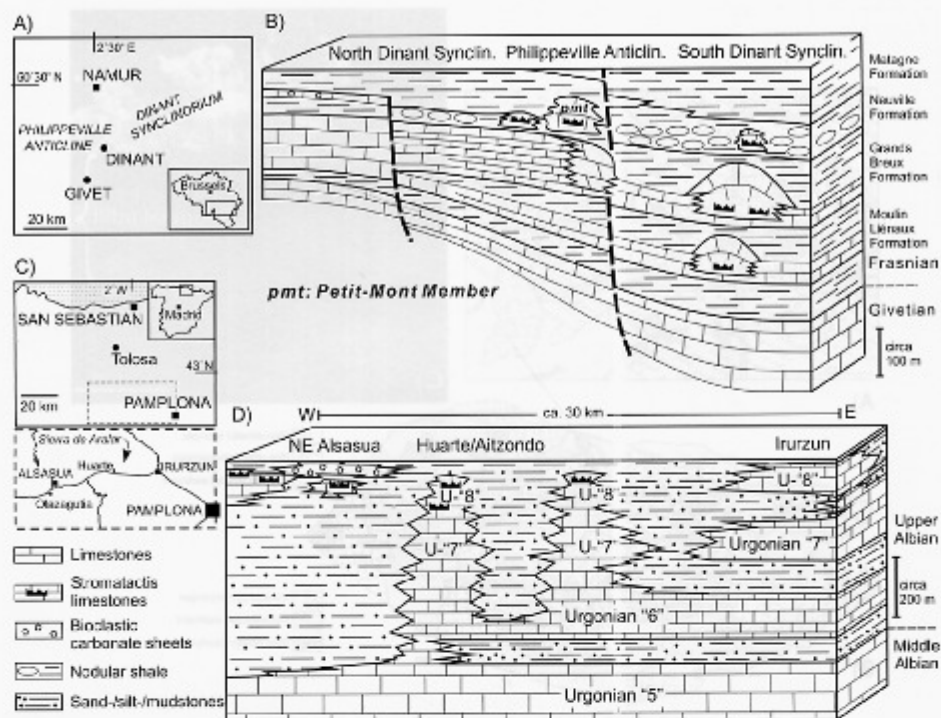


Fig. 3 Localities and geological background of stromatactis limestones treated in this paper. (A, B) Upper Devonian (Frasnian) stromatactis limestones of the Petit Mont Member. They have a stratigraphic range from the top of the Early *theuana* conodont zone up to the base of the Late *rheuma* conodont zone (Bultynck *et al.*, 1998, based on Boulvain (2001)). (C, D) Lower Cretaceous stromatactis limestones range from the upper parts of the Upper Albian (*Mesorbitholina texana-aperta*), locally extending into the uppermost Albian (Vraconian) with *Rotalipora appenninica* and *Planomalina buxtorfi*; cf. Pasca (1985). Based on Floquet *et al.* (1977).

earth, and includes transient stages of highly reactive geopolymers close to chemical chaos (Ziechmann, 1994). Oxidation vs. shrinkage/humification of sponge biomass is suggested from the rock fabric, and Ca-carbonate precipitation during humification has been shown by Neuweiler *et al.* (2000; 2001), who detected low-molecular weight, marine humic substances intimately connected to the authigenic mineral network. Effective calcification is obvious from spicular patches calcified during skeletal collapse of nonrigid sponges. The few modern examples of postmortem/syn-vivo sponge calcification stem from Froget (1975) and Reitner *et al.* (1995). This scarcity probably reflects a twofold

control: extrinsic-chemical control related to the ambient environment (restricted oxygen supply, i.e. today's less accessible oxygen minimum zones, reef caves and shallow subsurfaces) and intrinsic-microbiological control owing to the variable type of bacterial biomass in sponges (Wilkinson, 1978; Schumann-Kindel *et al.*, 1996; Haygood *et al.*, 1999). All of this suggests that humification is also important for the patchy consolidation of the host via fluid migration (dissolved stage of organic carbon) and early condensation reactions to form polymer gels (Neuweiler *et al.* 2000), organic micro-aggregates which could well account for the cohesive nature of mud mound sediments in general (see Monty, 1995,

for a discussion of rheological attributes). Thus, sponges do not appear to be a strict prerequisite for formation of the original stromatactid cavity network, but they do represent an effective source of biopolymers and help to identify the chronology of the involved fabrics owing to their skeletal nature and partial calcification.

Cavity reduction

Because of the 'carbonate island' character of carbonate mud mounds (Monty, 1984), an *in situ* production is required to account for the loose carbonate sediment in the stromatactid cavity network. Disarticulation (crinoids, bivalves, ostracodes),

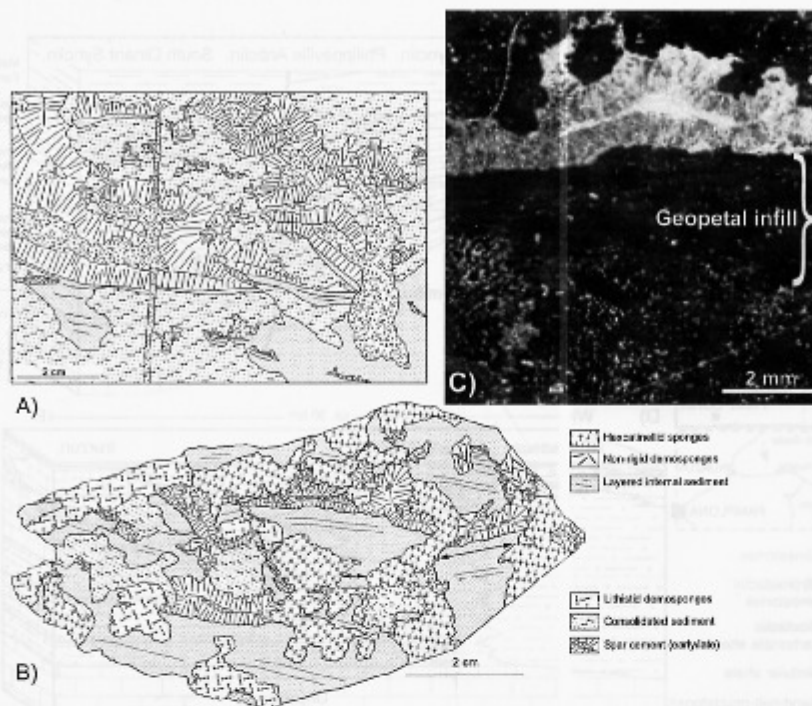


Fig. 4 Devonian and Cretaceous stromatactis. (A) From Upper Devonian Petit Mont Member of Belgian Ardennes, see Bourque and Boulvain (1993) for an entire set of illustrations. (B) From Lower Cretaceous (Upper Albian) siliceous sponge limestones of the Sierra de Aralar, northern Spain. Arrows indicate opposite boundaries of cavities which nearly match each other. (C) Thin-section micrograph of details of stromatactis of (B) showing the stromatactid cavity bordered by lithistid and hexactinellid sponges, and reduced by geopetal internal sediment and marine cement.

bioerosion and burrowing, rather than fragmentation related to water energy, more likely acted to produce the microbioclastic fraction of the sediment, e.g. because of the general lack of sediment export on deep-water mounds and mound flanks. Accumulation of (soft) faecal pellets and ingestive lime mud was suggested by Neuweiler *et al.* (2000) to account for the microcrystalline fraction of the sediment. From pore formation resulting from partial collapse and related geopetal filling, it is evident that sediment consolidation persisted during the accumulation of internal sediment. Precipitation of marine cement is needed to produce stromatactis. However, residual space in the stromatactid cavity network available

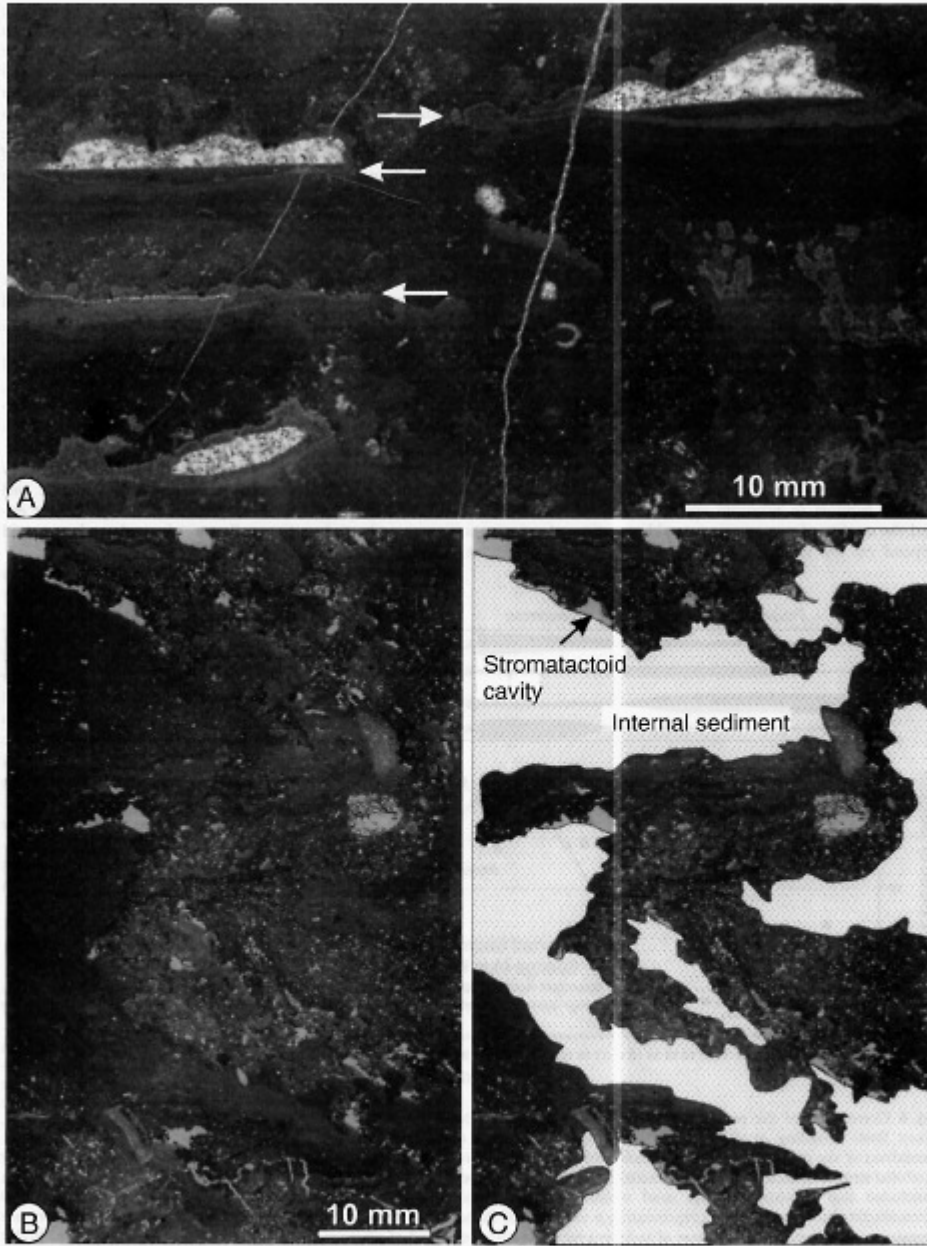
for isopachous marine cementation was scarce during the Mesozoic, owing to greater availability of loose sediment that more commonly resulted in total filling of the cavity network and therefore abortion of stromatactis formation (Fig. 5).

Evolutionary biosedimentology

From the above, it appears that Palaeozoic and Mesozoic stromatactid cavity networks share the same physico-chemical pathway, but differ in sponge typology and rates of internal sediment accumulation. First-order factors controlling reef and mound typology include community and trophic structure, environment, biota's functional parameters, morpho-

logies and growth forms, bioerosion, and cementation. In the present case, community and trophic structure, environment, and cementation are similar enough to exclude them as factors

Fig. 5 Inhibited and aborted stromatactis, Lower Cretaceous (Upper Albian). (A) Inhibited stromatactis (arrows), i.e. stromatactid cavities which show incipient marine cementation followed by internal sediment. (B, C) Aborted stromatactis, thin-section micrograph: (B) part of stromatactid cavity network near to the entire obturated by internal sediment; (C) as (B) schematically illustrating the abundance and distribution of internal sediment, largely mirroring the original stromatactid cavity network.



responsible for the differences, but growth forms with related functional parameters and morphologies, and bioerosion may be responsible for the observed variations.

A first type of modification reflects the fact that siliceous sponges with rigid skeletons became generally dominant in mounds or sponge limestones not before the Mesozoic (Fig. 6; Rigby, 1991; Mehl, 1992). Spread of skeletal rigidity via fused desmata (lithistid demosponges) or dictyid skeletons of Hexactinellida lead to diagenetically more stable, erect growth forms, and therefore acted to some extent as a skeletal support for the primary fabric. In contrast, non-rigid sponges dominate Palaeozoic stromatactis limestones. Early skeletal collapse and *in-situ* accumulation of sponge spicules in layers and nodular patches therefore represent the main feature. Collagen may induce some skeletal support in nonrigid sponges and the quality of preservation would depend on the relative rates of soft

tissue degradation vs. sponge calcification. In the Palaeozoic, skeletal support for the primary fabric is therefore negligible. Thus, in a macroscopic-descriptive mode, it can be concluded that the Mesozoic siliceous sponge mud mounds mirror and expand the Palaeozoic stromatactis mud mounds in terms of innovations and spread in sponge skeletal rigidity, a situation that correlates with the Palaeozoic to Mesozoic biotic revolution (Fig. 6).

A second type of modification is the abundance of internal sediment, i.e. aborted stromatactis, observed in the Cretaceous stromatactis limestones (Figs 5, 6). Geochemical data (Neuweiler *et al.* 2000) indicating biological sediment cycling (bioerosion, deposit feeding) correlate well with a Phanerozoic trend (Kießling *et al.* 1999) concerning the percentage of reefs affected by bioerosion (Fig. 6). Thus, the size of stromatactis, and the ratio of stromatactis vs. aborted stromatactis appears to mirror the

degree of biological sediment recycling at mound surface and its variation in space and time. In Mesozoic sponge mud mounds, excavating sponges and lithophagous bivalves are a common feature, whereas boring is uncommon in Palaeozoic stromatactis spiculitic facies. Again, this increasing degree of skeletal breakdown correlates with the Palaeozoic to Mesozoic biotic revolution as discussed in Vermeij (1977).

Conclusions

1 Stromatactis is common and widespread in Palaeozoic limestones, but occurs only locally and sporadically in Mesozoic material. It resulted from cementation of a cavity system, partly infiltrated with internal sediment, in the shallow subsurface environment under marine conditions.

2 The original stromatactid cavity network formed during sponge soft tissue degradation, i.e. partial or entire collapse of rigid and nonrigid spicular skeletons.

3 Stromatactid cavity networks have been partly to entirely filled by internal sediments, giving rise to a continuum, from a small volume of internal sediment and large amount of cement (stromatactis), to only or near only internal sediment (aborted stromatactis). Aborted stromatactis are the main feature in Mesozoic sponge mud mounds, but occur less commonly in Palaeozoic stromatactis mud mounds.

4 With respect to siliceous sponge evolution and sediment recycling, Mesozoic sponge mud mounds represent a variation of Palaeozoic stromatactis mounds.

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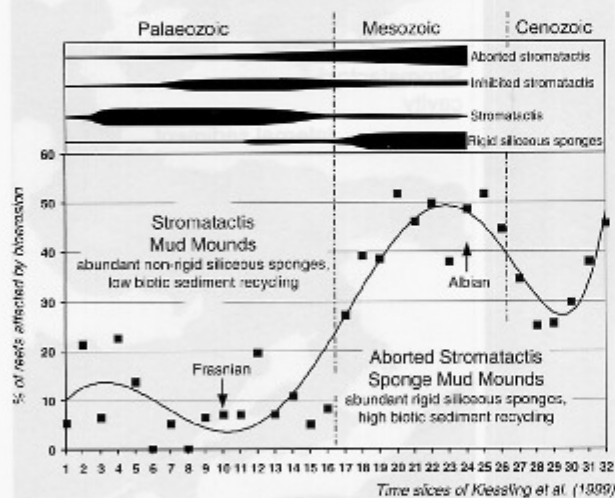


Fig. 6 Correlation of the percentage of reefs affected by bioerosion (original data taken from Kießling *et al.*, 1999) with the occurrence and relative abundance (tentative) of the different types of obturation of stromatactid cavities (stromatactis, inhibited stromatactis, aborted stromatactis) in spiculitic carbonate mud mounds. It is concluded that Mesozoic sponge mud mounds can be considered as 'aborted stromatactis mud mounds', thus representing a variation of Palaeozoic stromatactis limestones with respect to the degree of sediment recycling and the spread of siliceous sponge skeletal rigidity. Note the absence of post-Albian examples of sponge carbonate mud mounds (see short discussion in Webb, 1996).

constructive reviews. This is a contribution to IGCP 380: Biosedimentology of Microbial Buildups.

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