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Addressing a Phanerozoic carbonate facies conundrum—sponges or clotted micrite? Evidence from Early Silurian reefs, South China Block

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ABSTRACT We describe Early Silurian carbonate reef facies containing amalgamated micritic masses, commonly layered, interpreted to have formed by bacterial processes creating clotted fabrics. However, some curved structures in these masses resemble published images of interpreted sponges, raising the question of their nature, relevant to many carbonate studies including reefs and mud mounds throughout the Phanerozoic. Many lithistid sponges are well-established but others are open to interpretation. For keratose sponges, Cambrian examples are known, but several interpreted cases in later rocks are not confirmed; one example in Devonian and Triassic rocks using 3D imaging did not lead to firm verification. Thus criteria to distinguish sponges and clotted micrites remain problematic. A careful approach to interpretation of such sponges is needed, they might instead be microbially-mediated clotted micritic masses. The difficult process of 3D reconstruction is likely needed to resolve this interesting issue of interpretation.

KEYWORDS clotted micrite; sponge; lithistid; keratose; Silurian; South China Block

INTRODUCTION AND AIM: A CONUNDRUM OF PATTERNS

Think of a pattern consisting of two components, in biogenic limestones of deep-time: a) dark-coloured ellipsoidal areas of various sizes and shapes, and b) curved light-coloured areas filling the space between the ellipses. Is the pattern made of: 1) dark ellipsoidal objects with light-coloured intervening spaces, or 2) a light-coloured complex curved framework with a dark infilling? This conundrum lies at the heart of the problem of distinguishing clotted micrite from sponges in micritic limestones. Understanding this issue is relevant for many carbonate studies in the Phanerozoic rock record, which include the widespread occurrence of reefs and mud mounds; the interpretations of presence of sponges are not necessarily always justified, affecting assessment of faunal assemblages, sedimentary processes and diagenesis. The aim of this study is to demonstrate this issue using material from Early Silurian patch reefs (Fig. 1) rich in such complex fabrics (Figs. 2 and 3), and to emphasise the need for reliable criteria to discriminate clotted micritic masses and sponges, with implications for the application of such discrimination in facies and biological interpretations. The wider implication of this study is that organic fabrics in Phanerozoic carbonates are not always easily identifiable, and it is important to maintain an open-minded approach in analysis of sedimentary rocks.

Background on Sponges and Clotted Micrite

Sponges are abundant fossils throughout the Phanerozoic record. Some modern sponges have hypercalcified carbonate skeletons, represented in the fossil record as reef-building stromatoporoids and less common forms such as chaetetids and sphinctozoans; but most sponges have only their spicule-built skeleton that usually falls apart and/or dissolves soon after death, leaving either no record or incomplete indication of their presence as fossils. Of the non-calcified forms, lithistid sponges comprise tightly organised siliceous spicules of the type called desmas (Lévi, 1991)(Fig. 4C), surrounded by sponge soft tissue, and form a solid structure, hence their name, also commonly called rock sponges (Kelly, 2007). Spicules dissolve early in diagenesis but before that happens there is evidence of very early lithification of carbonate sediment enclosing the spicules, so that when spicules dissolve they may leave mouldic space that becomes infilled with sparite (e.g., Mock and Palmer, 1991). Keratose sponges are made of spongin organic proteins and no spicules (Fig. 4D); they are strong
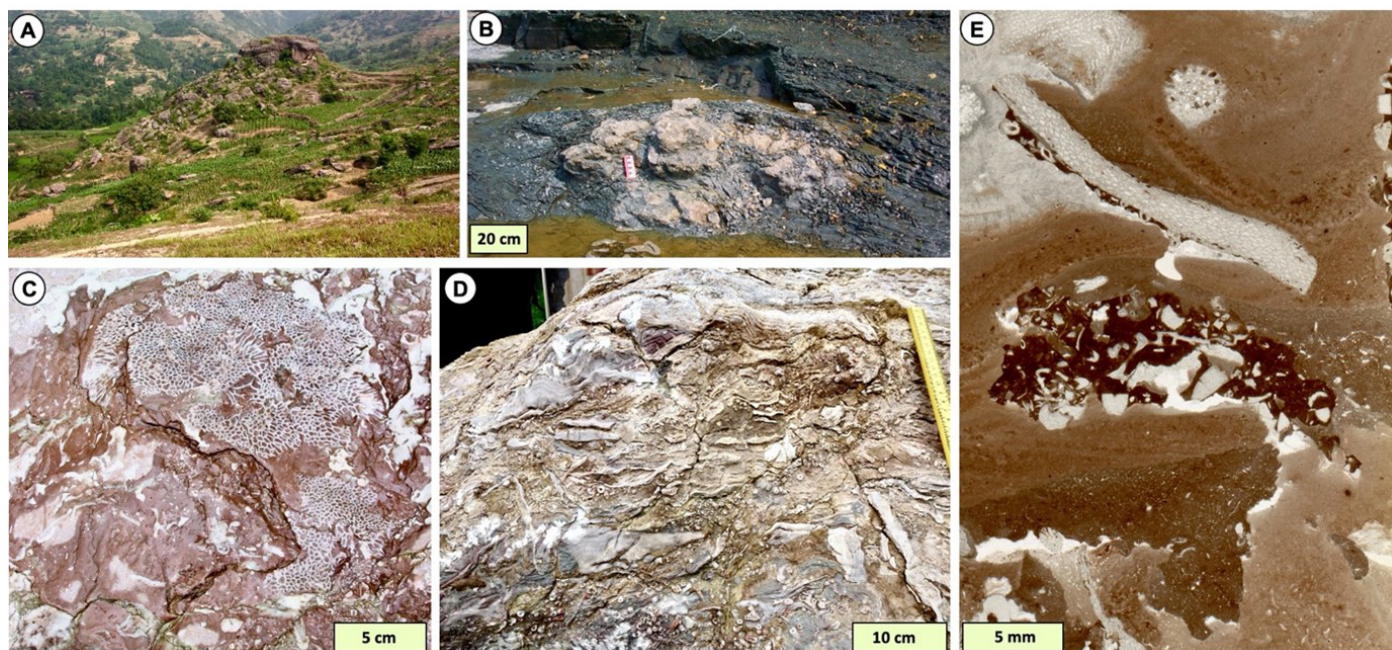
Figure 1: Features of patch reefs in the Ningqiang Formation. (A) One of the largest exposed reefs, Dashiyan reef, forming a prominent small hill, constructed on a substrate of bioclastic limestone and presumably exhumed from enclosing mudstone. (B) The smallest reef, Shizuizi reef, embedded in mudstones. (C and D) Reef fabrics comprising large corals and stromatoporoids, plus debris of a range of fossils, all embedded in micrite. (E) Large thin section view of complex irregular sediment-filled cavities that typify the Ningqiang Fm. reefs. Upper Huashitou reef, Xuanhe, Sichuan Province. (See Li et al., 2002, fig. 1) for locality details.

but lack mineralised components, hence their name (also called horny sponges, Erpenbeck et al., 2012). Preservation of lithistids is thus common, but for keratose sponges, it is more problematic. Nevertheless, many modern sponges, including some keratose sponges, actively incorporate sediments in their structures (Schönberg, 2016), so early lithification would be expected to aid sponge preservation. Luo and Reitner (2014) recounted the history of keratose sponges, and pointed out that they are uncommon, known best in Cambrian rocks (e.g., Yang et al., 2017). Luo and Reitner (2014) then described a complex procedure of 3D reconstruction of suspected keratose sponges from Devonian and Triassic examples. Their reconstructions demonstrate a filamentous network of sparite, interpreted as replacement of the tough organic structures.

Contrasting sponges, clotted micrite forms a deposit of very fine-grained calcium carbonate with curved internal surfaces, seen in thin sections as a dark mass with empty spaces (0.05–0.5 mm) subsequently filled with light-coloured sparite calcite cements. In some cases, clotted micrite is composed of peloids (0.1–0.5 mm) amalgamated into complex masses to form a heterogenous fabric. Overall the structure is commonly thrombolitic and may have involved bacterial mediation. However, a problem arises in cases where the structure is open to interpretation as either a sponge or clotted micrite, that is considered in this study, of relevance to analysis of Phanerozoic carbonate deposits, including reefs and mud mounds. Even though Luo and Reitner (2014) made a detailed 3D study of filamentous

networks, they viewed the networks as evidence of putative sponges and acknowledged they are not confirmed, therefore they are really interpreted, not putative.

Descriptions of lithistid sponges commonly give a reliable impression of sponges because casts of desmas may be recognisable in thin sections, particularly where they occur as closely organised masses indicating discrete sponge fossils in micritic limestones (e.g., Keupp et al., 1993, Adachi et al., 2009, Hong et al., 2012, Kwon et al., 2012, Hong et al., 2014, Park et al., 2015, Lee et al., 2016a,b, Park et al., 2017, Lee and Riding, 2018, 2021). However, it is important to be aware that desmas are complex curved and branching structures of variable size and shape in three dimensions (e.g., see SEM and transmitted light photos in Kelly, 2007 and Schuster et al., 2015), so their appearance in (two-dimensional) thin sections will be highly variable, depending on their orientation; thus there is potential to confuse them with clotted micrite. Also, not all spicular sponges in limestones are necessarily lithistids, so desmas may not be present. In contrast, for keratose sponges, finer curved networks of sparite cements in micrite may be convincing in some cases; Lee and Riding (2021, fig. 9) showed photos designed to illustrate the difference between lithistid and keratose fossil sponges in thin sections. However, because of the greater uncertainty of recognition of keratose sponges, a valuable approach is exemplified by Friesenbichler et al. (2018) who made clear that the structures are possible keratose sponges, but not proven.

Lee and Riding (2021) provided a good argument for ker-
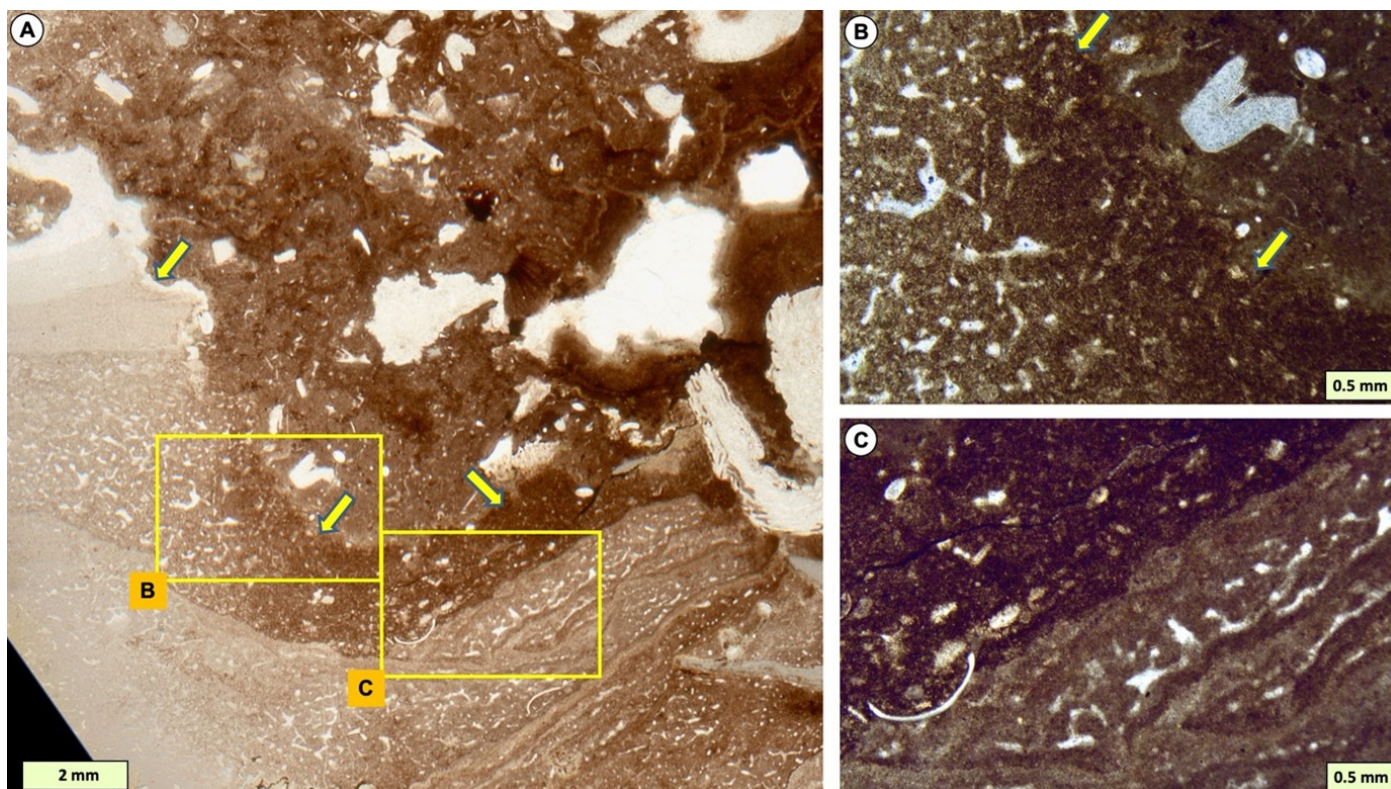
Figure 2: (A) Plane-polarised light (PPL) view of bioturbated wackestone reef fill, with margin of irregular cavity (bottom and left). Large white areas are spar-filled cavities lacking sediment. (B and C) Cross-polarised light (XPL) views of enlargements of the two boxes in (A) showing details of cavity margin and contrast between wackestone reef matrix and amalgamated micritic cavity fills, that are layered. Yellow arrows in (A) and (B) mark the cavity edge. Middle Huashitou reef, Xuanhe, Sichuan Province.

atose sponges in Cambrian limestones of New York State, USA; even so, they state that this is inference. The problem is how to verify the difference between sponges and heterogenous clotted micritic masses: they may have similar features but were created by entirely different processes. There is also the possibility that individual sponge spicules may be transported into clotted micrite masses that are not sponge-derived. The precise circumstances of occurrence of these features, commonly fitting the irregular shapes of cryptic spaces, also raises questions about recognition of sponges; both sponges and clotted micrites can occur in cavities.

Geological Background, Material and Methods

The Silurian reef pattern of the Yangtze Platform, part of the South China Block, is essentially controlled by the palaeogeographic background. In the first part of the Early Silurian Period, sedimentary sequences were dominated by mudstones and non-reef carbonates within the near-shoal belt, deposited during the Aeronian Epoch, until metazoan reef recovery after the end-Ordovician extinction event. Thus, in the succeeding Telychian Epoch, shallow marine limestone sequences contain well-developed metazoan patch reefs and biostromes of the Ningqiang Formation that form excellent exposures in the Sichuan–Shaanxi border area of the northwestern margin of the Yangtze Platform. The sea-floor slope was very gentle in the area where

Ningqiang Formation sediments formed because of continuation of facies over a long distance of shallow marine facies adjacent to ancient land (see Li et al., 2002, fig. 1, for locality map and palaeogeographic details). Growth of individual patch reefs was terminated by deposition of siliciclastic sediment (Li et al., 2002).

Muir et al. (2013) reviewed the global distribution of Lower Palaeozoic non-stromatoporoid sponges, noting their presence in the South China Block. Li et al. (2002) described the overall facies of the Ningqiang Formation patch reefs, with details of reef frameworks and accessory organisms, including mention of peloidal sediments and sponges in the reefs. Further study of the microfacies, presented here, demonstrates that these sediments are not simple facies, and have characteristics that might be interpreted as sponges. This study is based on field observations and thin sections only, as the material available for study; we describe petrographic features of the rocks and consider their interpretation.

RESULTS: DESCRIPTION OF REEF SEDIMENT FACIES

Ningqiang Formation patch reefs have red-colour matrices easily distinguished from their surrounding facies; they are well-exposed in stream and river sections as well as small hills, demonstrating a range in size from only 1–2 m, to
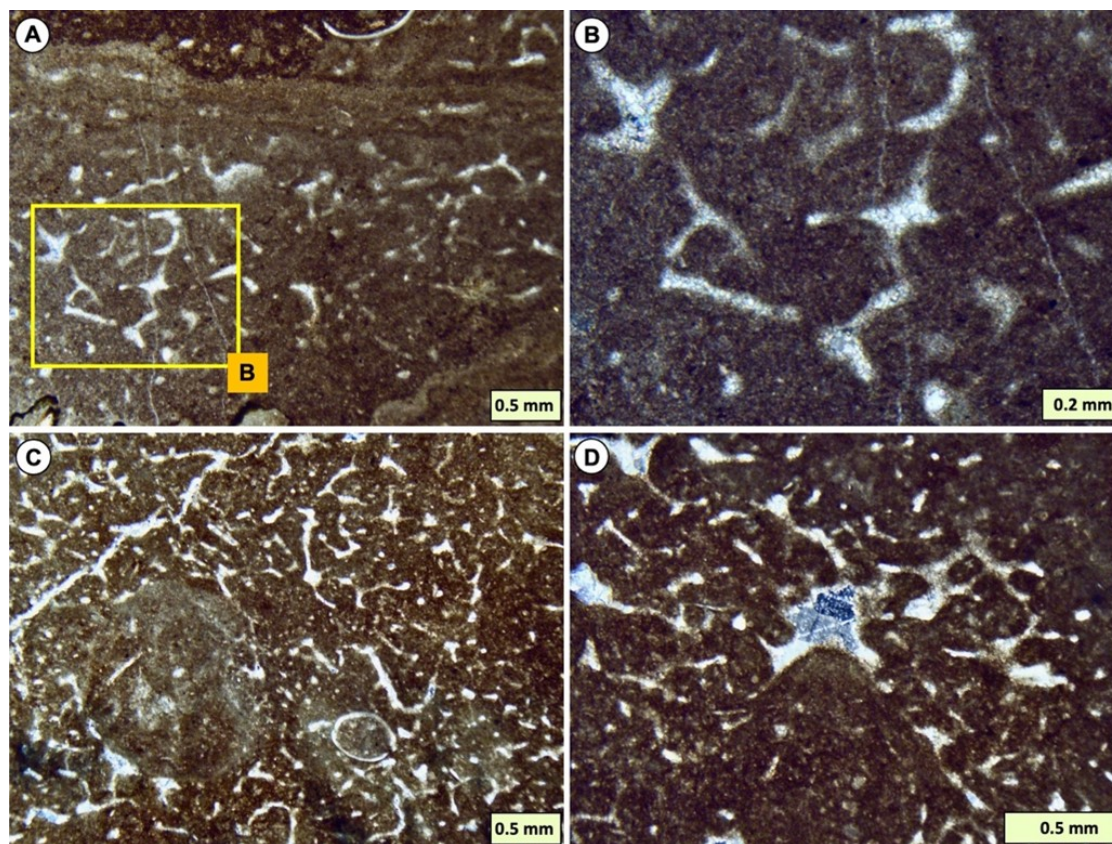
Figure 3: Enlargements of features of amalgamated micrite. (A and B) Enlargements of bottom-centre of Fig. 2A, showing detail of sparite areas, resembling lithistid sponge spicules (complex 3D objects sectioned in 2D), but in a layered material that is more consistent with clotted micrites of potential bacterial mediation. (C) Amalgamated micrite with an interpreted burrow/boring, filled with micrite (centre left). (D) Amalgamated micrite with a large cement-filled area comprising two generations of sparite. Huashitou reef; (A) and (B) middle of reef; (C) and (D) reef top part, Xuanhe, Sichuan Province.

several 10s of metres diameter and thickness (Fig. 1). There is no notable reef succession from the base to top of each reef, with the sedimentary facies similar throughout their thickness and lateral dimensions irrespective of reef size. Thin sections from all the reefs show a common pattern of microfacies, consisting of four fabrics: 1) micrite with bioclasts filling much space between frame-building metazoa (Figs. 1E and 2A); 2) laminated micrite (Fig. 1E); 3) peloids (Fig. 5B); and 4) amalgamated micrite that includes curved and angular areas of sparite (Figs. 2–5), in some cases forming layers (Figs. 2, 3A, and 4A); the fourth category is the main topic of this study.

Red micrite with bioclasts, forming a wackestone-packstone texture, is the initial reef sediment and is unlaminated; instead it is bioturbated (Fig. 2), presumably indicating early disturbance of unconsolidated micrite. However, small (a few mm to several cm wide) irregular sharp-edged cavities (Figs. 2, 4, and 5) developed in the wackestone-packstone; some are shelter cavities below skeletal components (Fig. 5B), but others are secondary. The cause of many cavities is not clear, candidates are: a) secondary cavities formed by either erosion (including bioerosion) or dissolution; and b) moulds left by sponges which disappeared in early diagenesis. Nevertheless, cavities containing sediment indicate that these carbonate materials became lithified on the sea floor. Cavities are occupied by geopetal fabrics in almost all cases; only a few cavities are completely filled.

In most cases, cavity infills comprise fabrics we interpret to be clotted micrite masses, and the layering (Figs. 2–5) presumably represents multiple events of infilling of open cavities, perhaps as microbial micrites. Some cavities contain undoubted peloids (Fig. 5A) that are not amalgamated. In some cases cavity fills contain a second generation of cavities within the amalgamated material, filled with similar fabric (Fig. 4). Most of the sparite within the amalgamated masses has two generations of cement, seen clearly in larger spaces (Fig. 3D). Figure 4 includes comparative images of modern lithistid desmas and keratose fibres and show that the size of lithistid desmas is comparable to the curved sparitic features in the Ningqiang Formation sediments, although keratose fibres are much smaller.

DISCUSSION: CLOTTED MICRITE OR SPONGES?

As stated above, the structure of the amalgamated micrite of the Ningqiang Formation reefs illustrated here seems to overlap with many published images interpreted to contain sponges, widespread in Phanerozoic carbonate facies. The
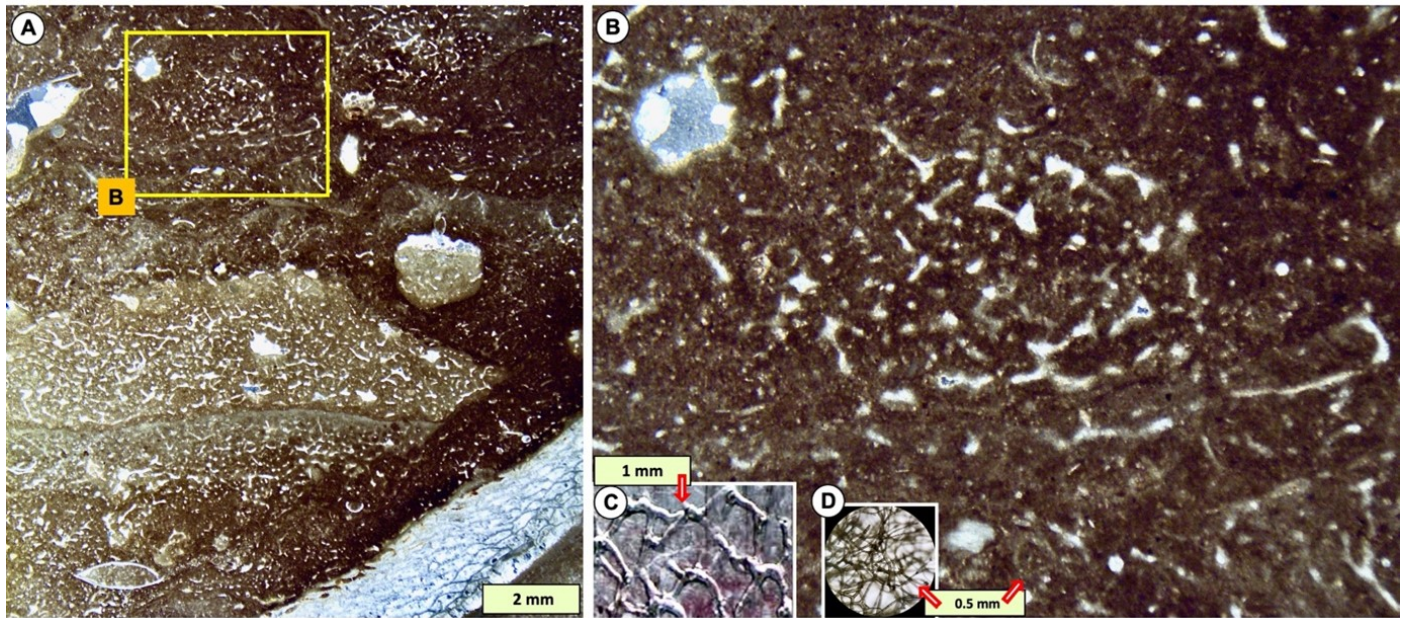
Figure 4: (A) View of amalgamated micrite with a second-generation cavity (lower centre) also filled with amalgamated micrite that is partly layered; a smaller round cavity, partly-filled, is shown centre-right. (B) Details of yellow box in (A) emphasising the round mass of sparite that might be a sponge. (C) Modern lithistid sponge desmas in transmitted light, from Schuster et al. (2015, Fig. 4o); note the difference in scale. (D) Modern keratose sponge fibres, at the same scale as the main picture, from an unidentified sponge, Bahamas; note the sponge fibres have much smaller diameters than the sparite areas of (B); also they are much smaller than the interpreted keratose sponges reported by Luo and Reitner (2014); see also Manconi et al. (2013) for a range of keratose sponge fibre illustrations. (A) and (B) are from top part of Huashitou reef, Xuanhe, Sichuan Province.

issue discussed here focusses on variability of appearance and confidence of identification as sponges in these South China Block sequences, and thus the wider problem of criteria for verifying sponges in carbonate studies.

The Ningqiang Formation facies described in this study are strikingly similar to those illustrated for Carboniferous and Triassic material, by Luo and Reitner (2016), who interpreted their samples to be sponge-microbe associations building stromatolites. Some of their material is described as automicrite with filaments (Luo and Reitner, 2016, their fig. 5), which they interpreted as keratose filaments. However, in the Ningqiang Formation these features, together with larger sparite areas that may be recrystallised lithistid desmas or clotted micrites, are in cavities, in some cases completely filling the cavity space, fitting its shape. To explain these as sponges requires them to be consistent with a cryptic habitat where the sponges tightly fit the space they occupy. Sponges may have grown in cavities; for example, sponges are abundant in modern reef cavities (e.g., Kobluk and Van Soest, 1989), and sponges in cavities in Ordovician limestones are described by Park et al. (2017). However, in the Ningqiang Formation some of the fabrics are layered (Fig. 2), so at least in those cases we consider that a sponge interpretation is problematic. Nevertheless, it is possible that the filled cavities in the Ningqiang Formation reefs represent moulds of sponges. A potential example from the literature, quite similar to our Fig. 5A is shown by Lee et al. (2014, their fig. 7D) and interpreted as an irregular

sponge surrounded by micrite, but an alternative interpretation turns that idea around. It is possible to imagine that the interpreted irregular sponges are instead clotted micrites inside an irregular cavity in the limestone, noting that the micrites in the example of Lee et al. (2014, fig. 7D) are geopetals. A further issue is that if they were sponges growing in cavities, whether keratose or lithistid, did they grow tightly fitting inside these cavities? Figure 2 (with details in Fig. 3A and B) shows layered amalgamated micrite, representing repeated events of cavity infilling of micrite, with sparite shapes that could be interpreted as sponge spicules, but the entire deposit in the cavity may be better interpreted as a bacterially-mediated clotted micrite. Figure 3C and D show potential filamentous structures that may be sponge components, but those two images also contain components that fit a clotted micrite description. Fig. 5A shows an example where amalgamated micrite at the base of the cavity passes upwards to definite peloids at the top of the cavity sediment, seemingly problematic to interpret this as a sponge; if it is a sponge, what are the defining criteria? Fig. 5B displays a shelter cavity partially filled with geopetal fabrics, an assembly that we view is better explained as clotted micrite than sponges. In modern reefs, as light intensity decreases with depth, the amount of cavity-filling automicrites increases (Reitner et al., 1995), that may have a parallel in the Ningqiang reefs.

The size and shape of sparite-filled areas is relevant, in relation to the known dimensions of keratose fibres, lithis-
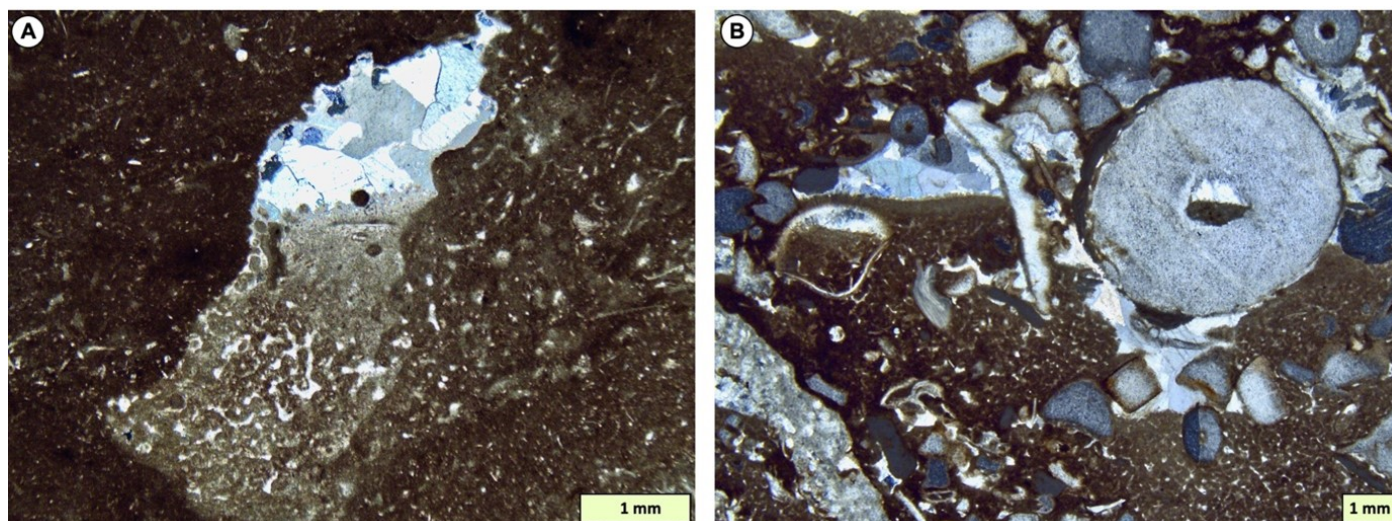
Figure 5: (A) Cavity within reef sediment showing amalgamated micrite at the bottom, passing up to peloids at the top of the fill. This is a second-generation cavity within amalgamated micrite. (B) Shelter cavity within reef sediment containing partial fill of amalgamated micrite, with an irregular margin, indicating the micrite may have been constructed as bound sediment, possibly under microbial influence. Lower Huashitou reef, Xuanhe, Sichuan Province.

tid desmas and clotted micrite interstices. The images displayed in Figs. 2–5 demonstrate the problem of discriminating these disparate structures based on their dimensions and shapes, because they overlap (also compare images in Manconi et al. (2013, for keratose sponges); Kelly (2007, for lithistids); Luo and Reitner (2016, for automicrites, that also contain evidence of sponges)). Lithistid desmas in particular have widely varying shapes, diameters and lengths. The interpreted fossil keratose sponge 3D networks illustrated by Luo and Reitner (2014) are much larger in scale than those illustrated in Fig. 4D, but are consistent with the large size range of modern keratose sponge fibres (Manconi et al., 2013).

It was noted above that lithistid sponges may form discrete objects. An example is given by Coulson and Brand (2016, fig. 6), who illustrated thin sections of areas containing interpreted sponge spicules, including desma-like structures (presumably therefore lithistid), that are very similar to the structures illustrated in this paper. Coulson and Brand (2016)'s specimens show the interpreted spicular structures to occur in clusters with sharp margins, appropriate to a sponge interpretation, as also seen in many of the papers on Ordovician rocks cited earlier. A further illustration of problems of sponge recognition is indicated by Lee and Riding (2021) who questioned whether those illustrated by Coulson and Brand (2016) as lithistids might instead be keratose sponges. In the Ningqiang Formation only a few areas of such features have sharp margins, and they are quite small (Fig. 4). Alternatively, it may be possible in the case of lithistid sponges that the structure disaggregated after death, before lithification, leading to individual spicules scattered in clotted micritic sediment, thus another potential explanation of the Ningqiang Formation structures, which overall resemble the automicritic

clumps reported in some Ordovician microbialites (e.g., Li et al., 2019, fig. 8). Such an interpretation could not apply to keratose sponges, composed of only a spongin skeleton, lacking spicules. As noted above, Mock and Palmer (1991, p. 683) observed that in Jurassic sponges from Normandy, spicules were replaced by calcite sparite, but the space between spicules was previously filled with peloidal cements that have cement-filled pores (0.05–0.2 mm) between cement peloids. In the Ningqiang Formation material illustrated here, the amalgamated micrite is mottled rather than being made of peloidal cements, and is more consistent with a bacterially mediated depositional process rather than a diagenetic one. Individual peloids occur in only a few of the fills.

Peloidal fills are well known as microbial structures in cavities, for example in Quaternary reefs (Reitner, 1993, Kazmierczak et al., 1996), and observed in Holocene material from the Mediterranean (Kershaw, 2000, Kershaw et al., 2005). The interpretation that these Quaternary forms are cyanobacterial cryptic fills is robust (Reitner, 1993) but in modern environments there is a complex association between microbia and other organisms, that also includes sponges. The issue of presence of sponges in cavities is explored in detail by Park et al. (2017), although we note that their illustrations lack the layered structures in the Ningqiang Formation (Fig. 2). One area of difficulty in ancient material is recognising separated desmas in thin sections, given their complex 3D curved and branching structure (Kelly, 2007); potential examples are in Fig. 3, which remain unconfirmed.

Overall, we interpret the amalgamated fabrics in cavities of the Ningqiang Formation reefs as bacterially-mediated clotted micrites, but note some similarity with spicules of sponges so that it is important to recognise the possibility

that sponges may also exist in these amalgamated micritic carbonates. The implication of this work is that studies reporting lithistid and keratose sponges in limestones in the Phanerozoic records may warrant careful consideration of the interpretation of presence of sponges, that may have an impact on discussions of sedimentology and diagenesis, and of sponge palaeobiology and evolution. The attempt by Luo and Reitner (2014) to identify keratose sponges, using 3D reconstruction that involved destructive grinding, is difficult to achieve, but may be necessary for confirmation. The arguments presented in this study have potential wider implications for the analysis of other carbonate structures, such as mud mounds, and an example is provided by Zhou and Pratt (2019) in Devonian mounds that include fabrics interpreted as sponges.

CONCLUSIONS

1. There is a lot of potential confusion about criteria for recognition of sponges in fine-grained limestones, in comparison to amalgamated, clotted micritic, material, leading to difficulty of discrimination between sponges and clotted micrites.

2. In the case of the Early Silurian reefs of the Ningqiang Formation, South China Block, the majority of the amalgamated facies is interpreted here as bacterially (perhaps cyanobacterially) mediated clotted micrite, but the possibility remains open that a sponge component is present.

3. It is likely that 3D reconstruction methods are needed in order to verify the extent to which lithistid and possible keratose sponges are represented in these facies.

4. Assessment of Phanerozoic limestone sequences containing interpreted non-calcified sponges, involving sedimentary and diagenetic processes, sponge palaeobiology and even their evolution may be affected by the ideas presented in this study.

ACKNOWLEDGMENTS

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