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Table of Contents

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TSR The Sedimentary Record
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Renovation of *The Sedimentary Record*

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The Sedimentary Record (TSR) originated in 2003 as a replacement for a Society for Sedimentary Geology (SEPM) newsletter, and since then, it has housed SEPM ads, news and opinion columns with fairly minimal scientific content. Leading up to this issue, approximately one research article per quarterly issue has been published, for a total of 76 scientific papers covering various topics of sedimentology, stratigraphy, and paleontology. While the journal has been in steady production for an impressive 18 years, it is time for a rejuvenation effort, in accordance with the evolving needs and goals of our academic discipline and scientific community. This editorial will outline the changes we intend to enact for *TSR* over the coming months and years.

THE FUTURE OF *THE SEDIMENTARY RECORD*

While *TSR* has always been open access, in 2020, the SEPM Headquarters Business Committee (HBC) and Council recommended that the publication undergo an expansion, with the goal of becoming a high impact, fully open-access journal over the next 3 years. As the new editors, we have been working toward this goal for the past few months and are now pleased to share our vision for the future of the journal and our progress thus far.

Ultimately, we envision *TSR* as the premier ‘diamond’ open access journal for short format papers focused on soft rock geosciences. We recognize the demand for open access publication opportunities within our discipline, and as a society-led journal, we are well-positioned to support the publication of scientific articles with no cost to either the author or the readership. We believe this will have a positive impact on the quality and number of articles submitted to *TSR* by facilitating the inclusion of a more diverse authorship spanning academia, industry, and non-affiliated researchers around the globe, as the burden to pay fees to publish is removed.

WHAT IS DIAMOND OPEN ACCESS?

A diamond (also, ‘platinum’) open access publication does not charge readers to access content, nor are authors charged to publish. This is different from both ‘gold’ open access journals, which utilize Article Processing Charges (APCs) payable by the author to open access to articles for readers, and ‘green’ open access journals that allow authors to self-archive their articles. There are also ‘hybrid’ open access journals, which may utilize a combination of open access and subscription paywalls. Currently, SEPM publishes 2 hybrid open access journals, *Journal of Sedimentary Research (JSR)* and *PALAIOS*. With this minimum 3-year commitment to support *TSR* as a diamond open access publication, SEPM is at the forefront of the trending open access revolution within the sedimentary geoscience community.

HOW WILL THE CONTENT CHANGE?

For the time being, we plan to continue with four issues of *The Sedimentary Record* per year, but once we have a steady stream of high quality submissions, we will transition to a continuous publication format, meaning articles will be published online as they are accepted rather than batched for quarterly publication. Since *TSR* has ceased print publication, the move to continuous publication format, which is inconsequential to our operating budget, will facilitate more rapid publication and dissemination of information.

We are also removing the news and commentary content from *TSR*, in keeping with the style of other scientific publications. SEPM Executive Director Howard Harper is working to identify an alternative strategy for digital distribution of the news and commentary content that will be employed soon, if not alongside this first issue of *TSR*.

With these changes, *TSR* will be focused on timely, innovative, and provocative articles. We hope to cover topics of broad and current interest to the membership of SEPM, including all aspects of sedimentology, geomorphology,

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Comparison of Open Access Publication Models

	Green	Gold	Diamond	Hybrid
Access for readership	Regardless of access type on publisher's website, authors may self-archive in open access repositories	Fully free, immediate access for readership (full open access) available on publisher's website	Fully free, immediate access for readership (full open access) available on publisher's website	Possibility for full open access is offered to authors: mix of open and closed access articles
Fees assessed to authors	Publishing costs are generally covered by journal subscriptions; usually no fee to author	Article Publishing Charges (APCs) are payable by the authors or their institutions	No fee to publish; sponsored by external sources, e.g., professional societies	APCs may be paid by the authors or the articles may be paywalled behind journal subscriptions

sedimentary geochemistry, stratigraphy, paleontology, ichnology, paleoclimatology, paleogeography, paleoecology, and even including topics that cross from the sedimentary domain to other sciences and applications, such as sustainability and coupled natural and human systems, for example. We will offer two new article formats with a limited size for each article:

1. High quality, fully developed Research Articles
    - limited to 5000 words excluding references and figure captions
    - up to 5 full-color figures and/or tables; and
2. Early Research Advances articles, which may share preliminary results, hypotheses, or broadly reach out to the community
    - limited to 2500 words excluding references and figure captions
    - up to 2 full-color figures and/or tables.

Author guidelines are posted on our new submission platform at https://thesedimentaryrecord.scholasticahq.com.

NEW SUBMISSION PLATFORM, ONLINE ACCESS, AND DATABASES

A professional, easy-to-use online submission platform is an important step in increasing submissions to *TSR*. After testing several options, we have contracted Scholastica as the new user-friendly, manuscript submission and review platform. We evaluated the software from the perspective of both editors and authors and so far have been very impressed.

Currently, *TSR*'s online archive is available at the SEPM website and includes *TSR* issues from 2003 to the present. While all volumes, issues, and articles have DOIs and are registered with CrossRef, we hope to cross-list future *TSR* articles with other major geoscience databases in order to increase accessibility and visibility of the content. Likewise, we have submitted applications toward getting *TSR* indexed with the major impact factor metrics such as Clarivate and Scopus. Along with SEPM staff, we are working hard to accomplish this in a timely manner, acknowledging that both the databases and journal metric companies take some time to evaluate requests to be included.

CLOSING THOUGHTS

We understand that sometimes change can be uncomfortable, particularly when it involves an entity like *TSR* that has been around for nearly two decades. For those who may speculate so, we do not expect *TSR* will compete with *JSR* or *PALAIOS* submissions, which cater to full-length manuscripts. To reiterate, *TSR* will be a short-format journal focused specifically on soft rock geoscience. As *TSR* editors, we will strive to maintain a high bar for the quality of accepted manuscripts, and as part of that we will be reaching out to many of you as independent reviewers. As the number of submissions increases, we may ask for additional volunteers to help with various aspects of *TSR*, and if any of you in the SEPM community have constructive comments for us, please don't hesitate to reach out via email.

A WORD OF THANKS

We would like to thank the previous editors of *TSR* that have kept the journal going for nearly two decades. Dr. Lauren Birgenheier was particularly helpful in facilitating a smooth editorship transition. Likewise, Dr. Howard Harper, SEPM's Executive Director, and Rebekah Grmela, SEPM's Digital Marketer, were both instrumental in the renovation process. We also thank the SEPM HBC and Council for approving our proposal to fund *TSR* as a diamond open access journal for (at least) the next three years. Dr. Jamie Farquharson, Editor-in-Chief at *Volcanica*, and Dr. jake Covault assisted quite a lot in the early ideation of the future of *TSR*. Finally, we are grateful to the authors that have submitted their manuscripts to our journal so far, entrusting and encouraging us to propel *TSR* toward leadership in the open access revolution.

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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

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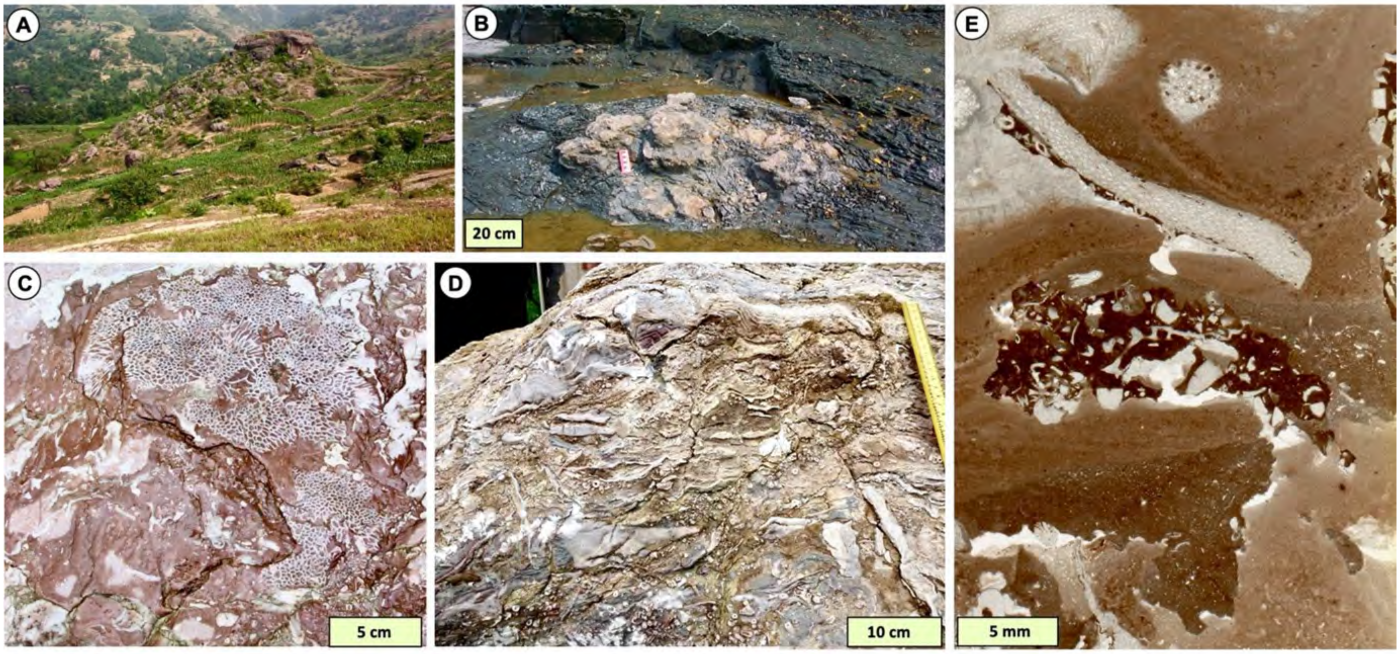

Figure 1: Features of patch reefs in the Ningqiang Formation. (A) One of the largest exposed reefs, Dashiyan reef, forming a prominent small hill, constructed on a substrate of bioclastic limestone and presumably exhumed from enclosing mudstone. (B) The smallest reef, Shizuizi reef, embedded in mudstones. (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-

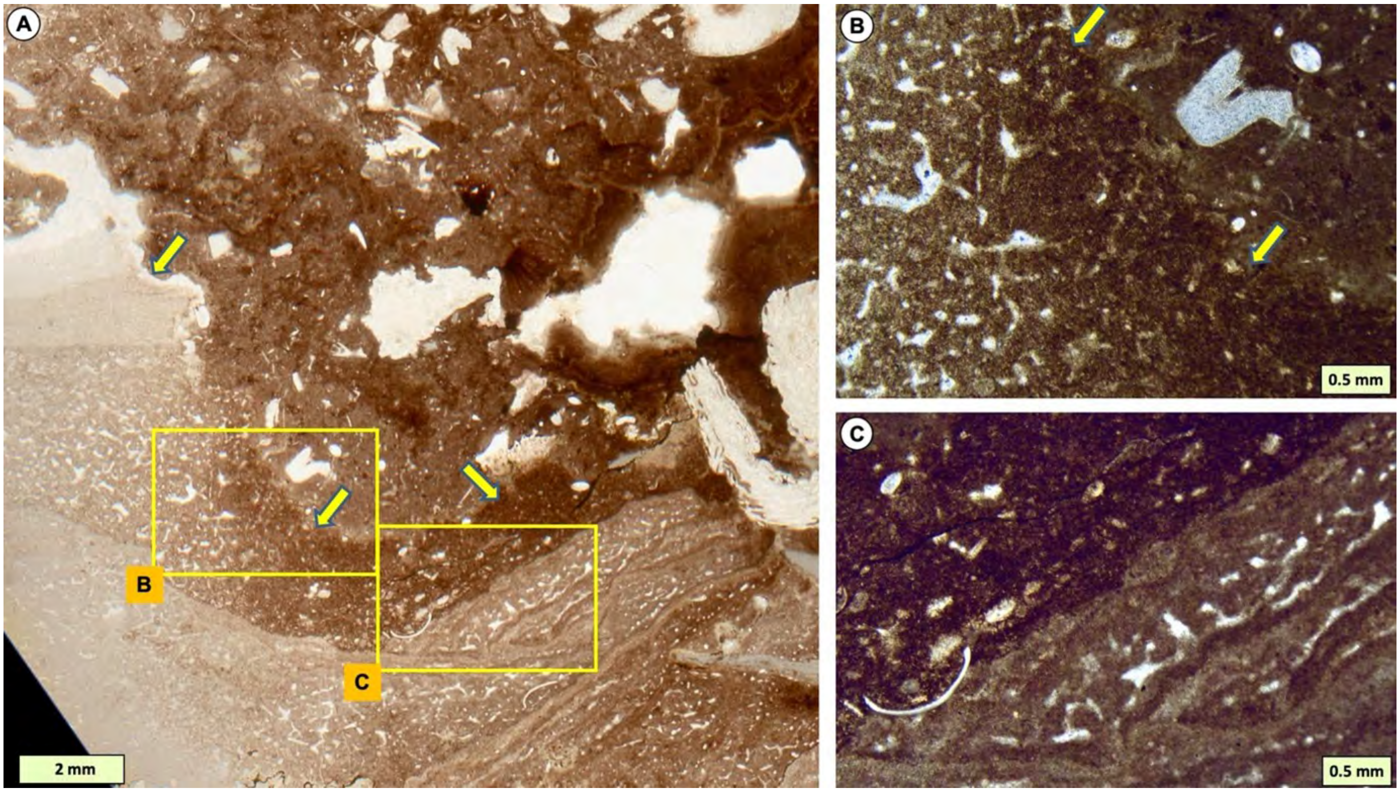

Figure 2: (A) Plane-polarised light (PPL) view of bioturbated wackestone reef fill, with margin of irregular cavity (bottom and left). Large white areas are spar-filled cavities lacking sediment. (B and C) Cross-polarised light (XPL) views of enlargements of the two boxes in (A) showing details of cavity 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 heterogeneous 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

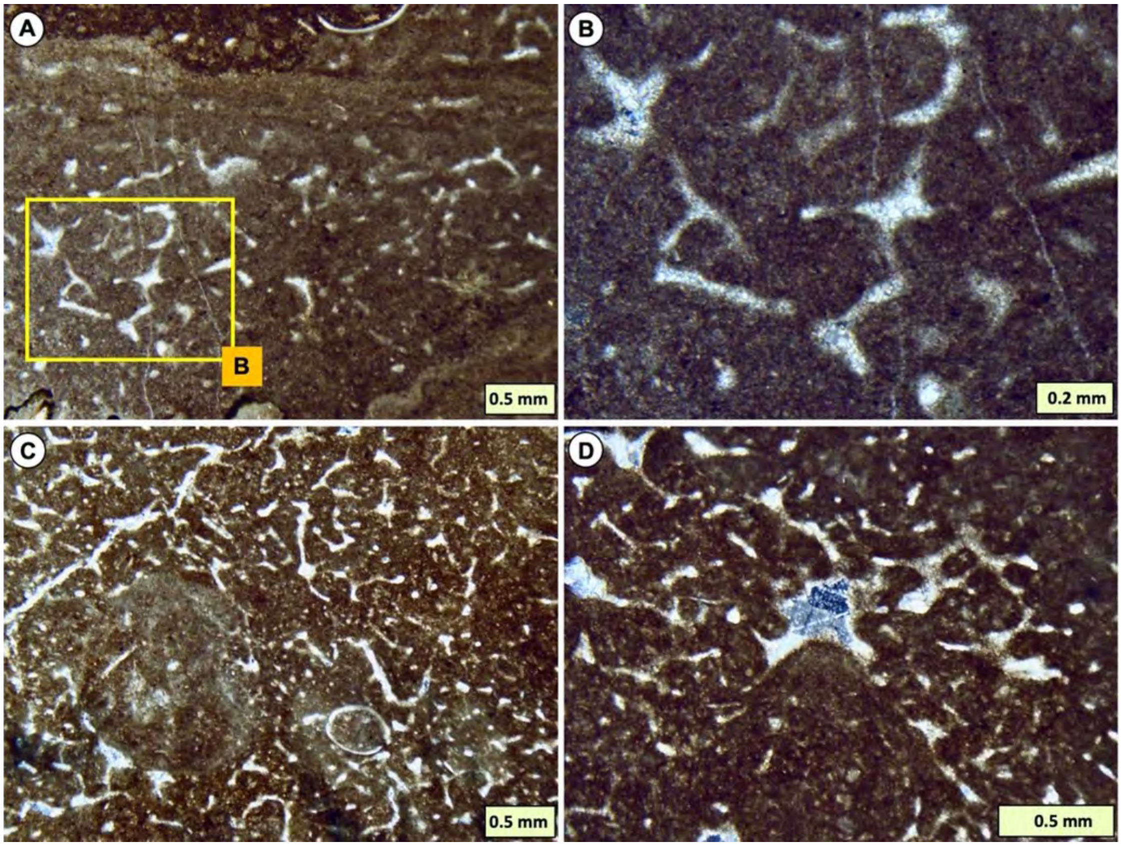

Figure 3: Enlargements of features of amalgamated micrite. (A and B) Enlargements of bottom-centre of Fig. 2A, showing detail of sparite areas, resembling lithistid sponge spicules (complex 3D objects sectioned in 2D), but in a layered material that is more consistent with clotted micrites of potential 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

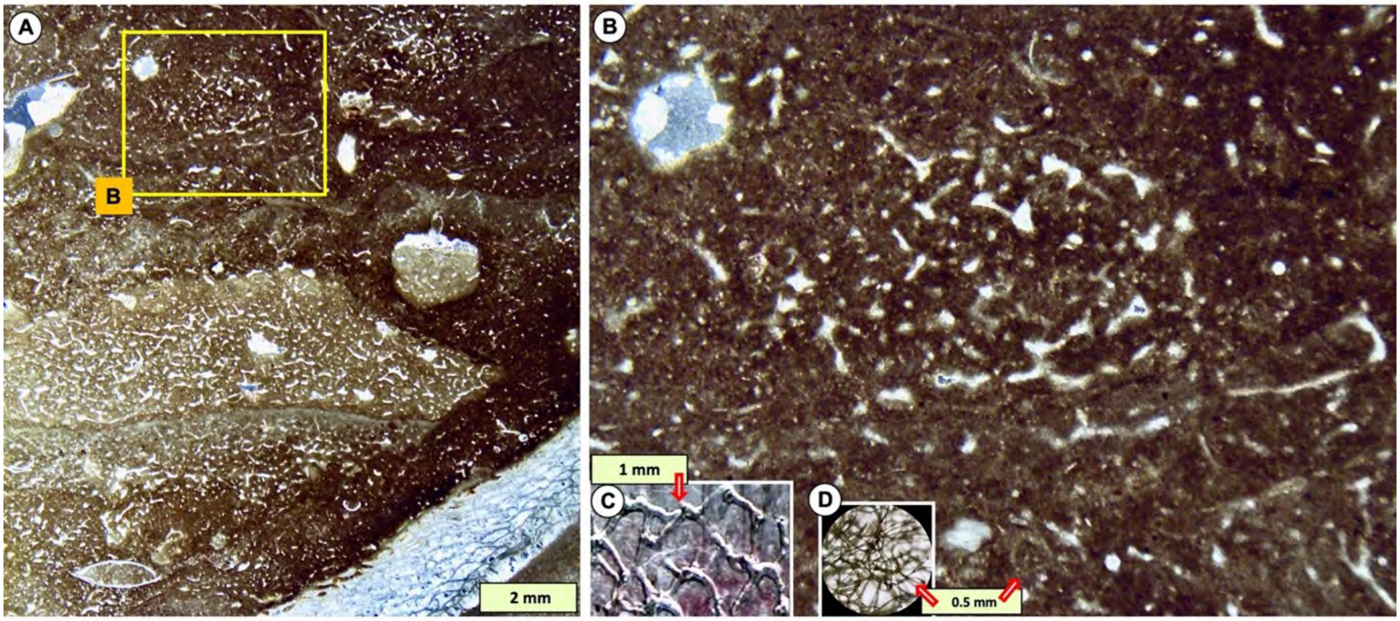

Figure 4: (A) View of amalgamated micrite with a second-generation cavity (lower centre) also filled with amalgamated micrite that is partly layered; a smaller round cavity, partly-filled, is shown centre-right. (B) Details of yellow box in (A) emphasising the round mass of sparite that might be a sponge. (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-

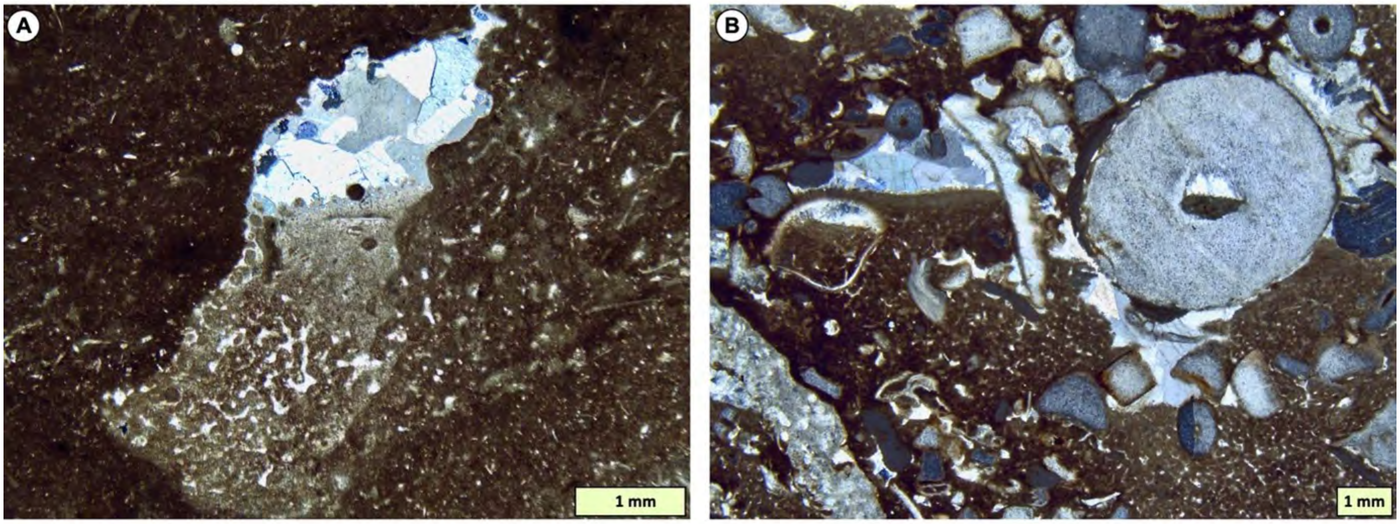

Figure 5: (A) Cavity within reef sediment showing amalgamated micrite at the bottom, passing up to peloids at the top of the fill. This is a second-generation cavity within amalgamated micrite. (B) Shelter cavity within reef sediment containing partial fill of amalgamated micrite, with an irregular margin, 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.

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Facies changes and a major negative δ^{13}C shift suggest the base of Mila Formation as the likely base of the Miaolingian Series, Alborz Mountains, northern Iran

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INTRODUCTION

The Cambrian System in the Alborz Mountains of northern Iran (Fig. 1A) consists of alternating carbonate and siliciclastic successions deposited in an extensive platform covering the length of the Cimmerian and the Arabian-Iranian plates in northeast Gondwana (e.g., Berberian and King, 1981, Lasemi, 2001). In Alborz, the lower–middle Cambrian transition (Fig. 1B) includes the siliciclastic Top Quartzite of the Lalun Formation (Assereto, 2014) and the chiefly carbonate deposits of Member 1 of the Mila Formation (Stöcklin et al., 1964). We have not applied the stratigraphic nomenclature by Geyer et al. (2014) because their approach has several shortcomings (see Lasemi and Amin-Rasouli, 2017, p. 344–345 and discussions therein). The lower–middle Cambrian transition in northern Iran is plagued by the absence of biostratigraphic criteria; here, we integrate sequence stratigraphy with δ^{13}C composition to evaluate the base of the Cambrian third series, the Miaolingian Series, in northern Iran. Our objective is to provide a valuable non-biostratigraphic criteria in the Alborz to permit chronostratigraphic correlation of this interval with other regions. This study provides evidence for the terminal early Cambrian extinction event and the resulting paleoenvironmental changes during the middle Cambrian in northern Iran.

METHODS

A composite section for the east-central Alborz Mountains comprising the Top Quartzite in the Tuyeh section and the lower part of the Mila Formation in the Shahmirzad section is placed in a sequence stratigraphic framework (Fig. 2A). For carbon isotope analysis, avoiding weathered/calcite filled cavities, 11 carbonate samples were collected to cover the basal 9 m of the Mila Formation. Because of sanctions, politico-economic reasons, and lack of funding only the basal part of Mila was sampled. Sample powders were analyzed for carbon and oxygen isotopes at the Stable Isotope Laboratory of the Institute for Geology, Leibniz University Hannover, Germany. The sample aliquots were reacted with 100% phosphoric acid at 72°C in a Thermo-Finnigan GasBench II. The produced CO_2 was transferred into a Thermo-Finnigan Delta-V advantage mass spectrometer. Repeated analysis of NBS 19, NBS 18, IAEA CO-1, and Lausan certified in-house carbonate standards produced an external reproducibility of $\leq$0.05‰ and $\leq$0.06‰ for δ^{13}C and δ^{18}O, respectively. Results are in per mil (‰) relative to the conventional V-PDB.

STRATIGRAPHIC VARIABILITY AND δ^{13}C ANALYSIS

The lower–middle Cambrian transition encompasses two depositional sequences (Fig. 2A). The Top Quartzite sequence records deposition in a shoreface system and conformably overlies the Shale unit of the Lalun Formation. Its transgressive and early highstand packages consist of interbedded gray shale and quartzose sandstone (Fig. 1C). The late highstand package is a thickening upward cross-bedded to planar-bedded upper shoreface sandstone that unconformably underlies the Mila Formation (Fig. 1D, E). The basal Mila sequence is a shallow marine succession and comprises a transgressive package (2.5 m) the lower part of which (~70 cm) is characterized by varicolored calcareous mudstone and/or argillaceous limestone/dolostone tidal rhythmites (Fig. 1D) grading upward to distal open marine thin-bedded, dark gray rhythmic shale and micritic limestone (Fig. 1E). This interval thickens upward in the early highstand package and grades to dolostone containing a thrombolite reef zone (~3 m) in which domical bioherms become larger upward (Fig. 1e) and encompass well-preserved clotted fabric (Fig. 2B). The early highstand package underlies the unconformity capped late highstand ramp margin ooid grainstone and peritidal facies (Fig. 2A).

Carbonate carbon isotopic analysis records a large-magnitude negative δ^{13}C shift (-3.86‰) in the lowest sampled layer ~70 cm above the base of the Mila Formation. The δ^{13}C values increase upward to -0.05‰ in the upper part of the thrombolite reef zone and change to +0.31‰ in the ooid grainstone bed at about 9 m from the base of

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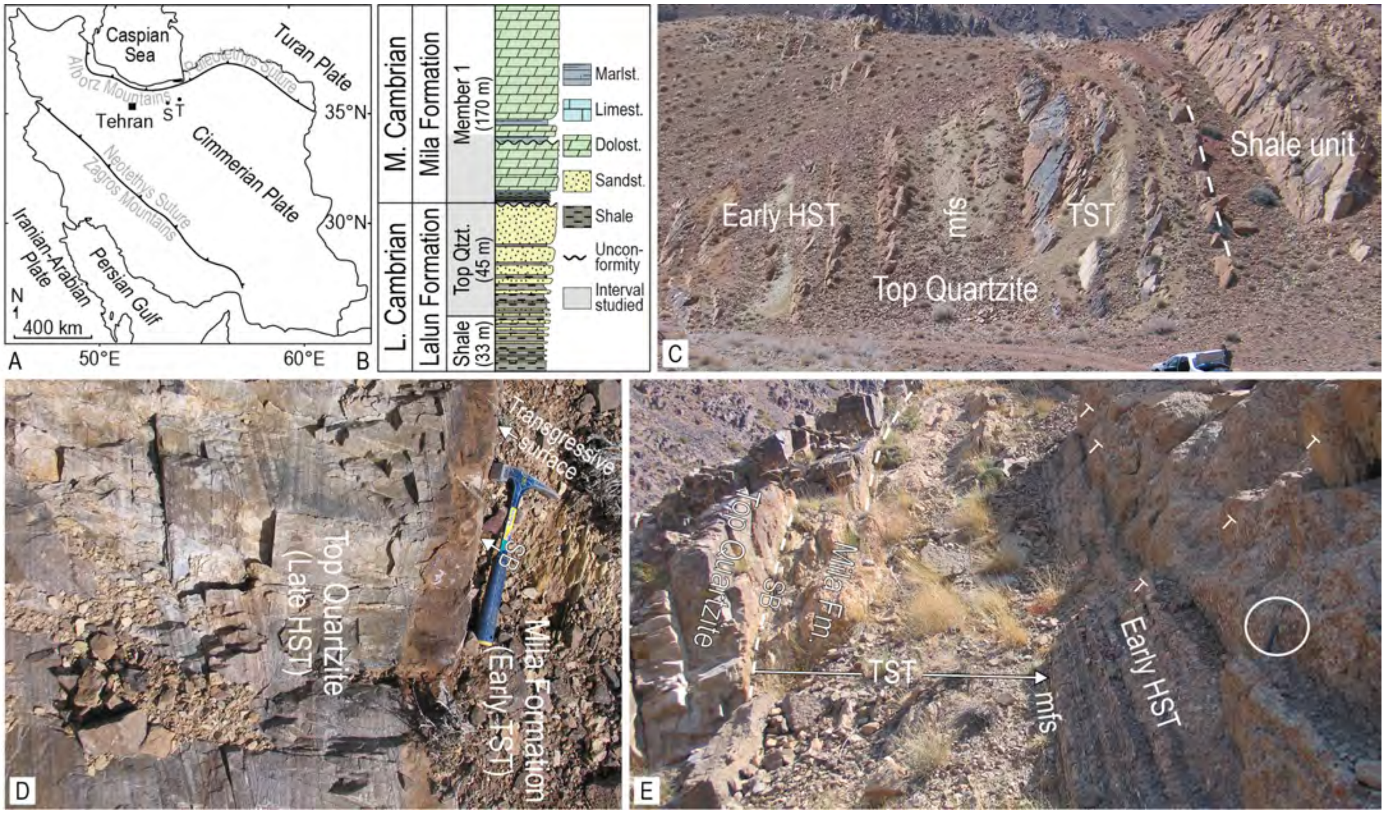


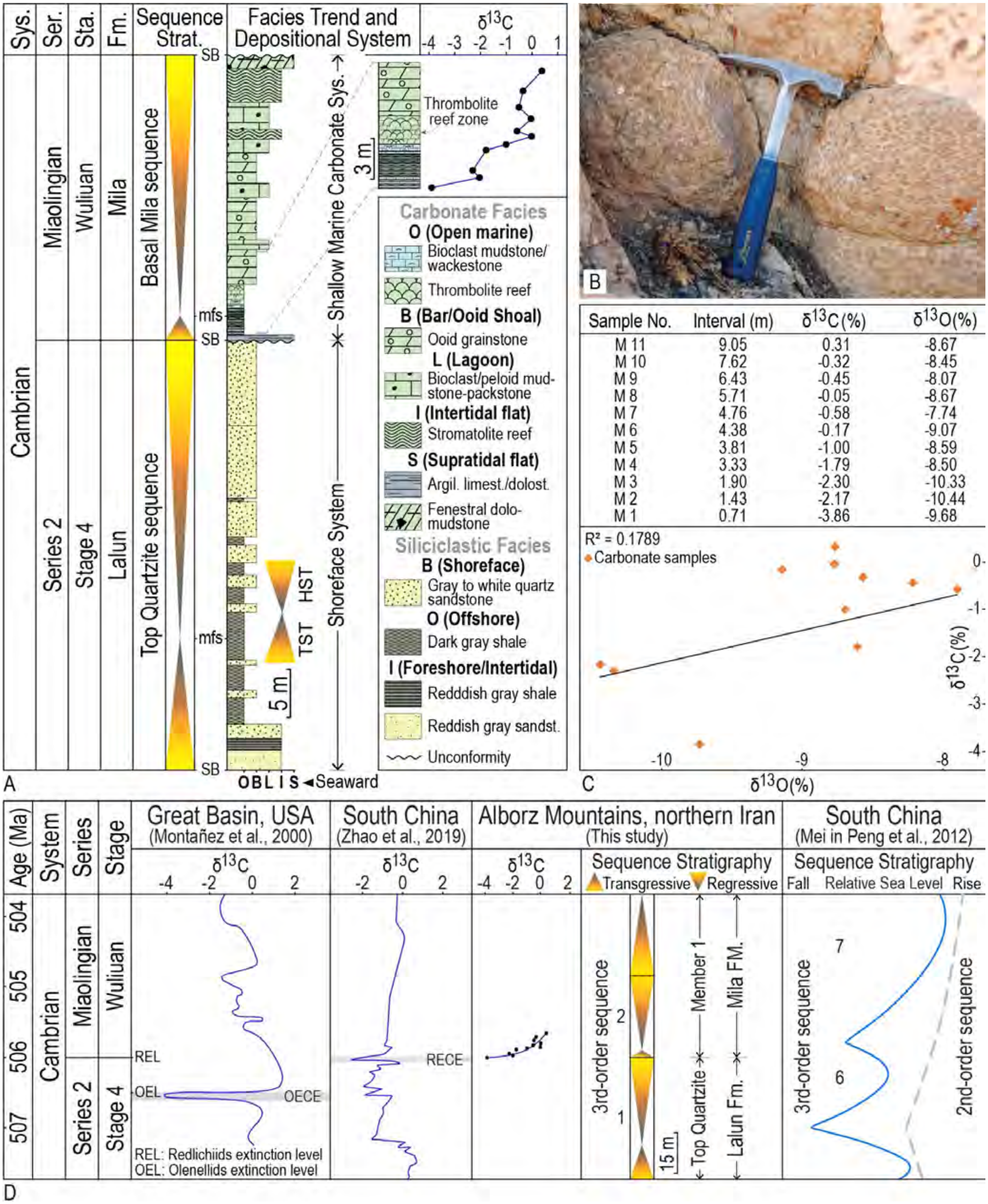
Figure 1: (A) Map of Iran showing tectonic plates and the location of Shahmirzad (S) and Tuyeh (T) sections (from Lasemi and Amin-Rasouli, 2017). (B) Stratigraphic nomenclature and composite section of the lower–middle Cambrian transition comprising the upper part of the Shale unit and the Top Quartzite unit of Lalun in Tuyeh and Member 1 of the Mila Formation in Shahmirzad. (C) The lower portion of the Lalun Top Quartzite sequence that conformably overlies the Shale unit (Tuyeh section, stratigraphic top to the left and view to the southeast). Note that sandstone layers thin upward in the TST but thicken upward in the early HST. (D) The unconformity capped Top Quartzite late highstand package that underlies the tidal rhythmites of the lowermost transgressive package of the basal Mila sequence. (E) The upper part of the Top Quartzite that unconformably underlies the lower part of the basal Mila sequence (Shahmirzad section, view to the NE and stratigraphic top to the right). Note very thin-bedded rhythmic shale and micritic limestone that thickens upward in the early highstand package containing thrombolite bioherms (T). Abbreviations: HST: Highstand systems tract; mfs: Maximum flooding surface; SB: Sequence boundary; TST: Transgressive systems tract.

Mila Formation (Fig. 2A). Field and petrographic studies indicate that influence of diagenesis was minimal because the sampled dense micritic limestone and dolostone could inhibit movement of diagenetic fluids. Lack of correlation between carbon and oxygen isotope values (Fig. 2C) suggests the primary carbon isotope signature of original seawater (e.g., Azmy et al., 2014). Furthermore, unlike the δ^{18}O, influence of diagenesis and burial temperature on δ^{13}C values of carbonates is insignificant (e.g., Swart, 2015).

DISCUSSION AND CONCLUSIONS

The terminal early Cambrian in Laurentia and south China is marked by the mass extinction of trilobites associated with a large-magnitude negative carbon isotope excursion (e.g., Lin et al., 2019). Montañez et al. (2000) first reported a major short-term (∼100 k.y.) negative δ^{13}C shift ($\geq$4‰) in the terminal early Cambrian in Laurentia, just prior to the extinction of olenellid trilobites. A rather large negative δ^{13}C shift is also recognized at the base of the middle Cambrian boundary in south China preceding the extinction level of Redlichiid trilobites, the base of the recently defined Miaolingian Series (Zhao et al., 2019). Zhu et al. (2006) named the foregoing exertions Redlichiid Olenellid Extinction Carbon Isotope Excursion (ROECE). Recent studies, however, have questioned the ROECE definition documenting that the extinction level of olenellids and redlichiids and their associated δ^{13}C excursions, here referred to as “RECE” and “OECE” (Fig. 2D), are not synchronous (Lin et al., 2019, Geyer, 2019, Sundberg et al., 2020).

The major negative δ^{13}C shift ∼70 cm above the base of Mila unconformable boundary, like south China (e.g., Zhao et al., 2019), occurs within the transgressive phase of a major global eustatic event and likely corresponds to the “RECE” excursion (Fig. 2D) and may define the Series 2-Miaolingian boundary in northern Iran. The Mila thrombolites (Fig. 2A, B), like the basal Famennian (e.g., Whalen et al., 2002) and the basal Triassic (e.g., Kershaw et al., 2012), appear in a very short stratigraphic interval close to the unconformity and could represent a post-extinction boundary thrombolite. As the consequence of post-extinction



Sample No.	Interval (m)	δ13C(%)	δ13O(%)
M 11	9.05	0.31	-8.67
M 10	7.62	-0.32	-8.45
M 9	6.43	-0.45	-8.07
M 8	5.71	-0.05	-8.67
M 7	4.76	-0.58	-7.74
M 6	4.38	-0.17	-9.07
M 5	3.81	-1.00	-8.59
M 4	3.33	-1.79	-8.50
M 3	1.90	-2.30	-10.33
M 2	1.43	-2.17	-10.44
M 1	0.71	-3.86	-9.68

Figure 2: (A) Vertical facies trend and $\delta^{13}C$ composition of the Series 2-Miaolingian transition comprising the Top Quartzite and the basal Mila sequences in the Tuyeh and Shahmirzad composite section. (B) Close up view of domal thrombolite bioherms in Fig. 1E showing clotted fabric (from Lasemi and Amin-Rasouli, 2017). (C) Geochemical data and $\delta^{18}O$ vs $\delta^{13}C$ crossplot. (D) Correlation of the base of Mila $\delta^{13}C$ shift with those in Laurentia and south China, as well as correlation of the 3rd-order sequences in the Alborz with the sequences recorded at the Series 2-Miaolingian transition in south China (time scale and extinction level after Sundberg et al., 2020).

environmental stress and metazoan reef crisis (e.g., Mata and Bottjer, 2012) owing to sea level rise and low marine oxygenation (Lee and Riding, 2018), the middle Cambrian rocks in Iran are microbial carbonates dominated by stromatolites, oncoids, and ooids (e.g., Lasemi, 2001). The lower–middle Cambrian transition in northern Iran records a major transformation in depositional regime from the regressive Top Quartzite siliciclastics to the transgressive base of Mila carbonates. The Top Quartzite and the basal Mila sequences (sequences 1 and 2), using the current time scale (Sundberg et al., 2020), correlate with the south China third-order sequences (sequences 6 and 7 of Mei et al., 2007 in Peng et al., 2012) at the Series 2-Miaolingian transition (Fig. 2D). Results of this study suggest that the base of the Miaolingian is likely to be placed at the base of Mila Formation in northern Iran. Future work should test this interpretation by focusing on facies and carbon isotope studies covering the entire middle–upper Cambrian succession.

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The Sedimentary Record (TSR) is published quarterly by SEPM. It contains peer-reviewed science articles on topics of broad and current interest to the membership of SEPM, including all aspects of sedimentology, stratigraphy, geomorphology, sedimentary geochemistry, paleontology, paleoclimatology, paleogeography, etc. We welcome high-quality, short-format scientific contributions from members of the sedimentary geoscience community.