



Mid–Late Ordovician tetradiid–calcimicrobial–cement reef: A new, peculiar reef-building consortium recording global cooling

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ARTICLE INFO

Keywords:

Tetradium
Calcified microbe
Triple hybrid carbonate
Hirnantian glaciation
GOBE

ABSTRACT

Skeletal–microbial–cement reefs are a triple hybrid carbonate that mainly formed during the Pennsylvanian to Mid-Triassic, when a marked increase in microbial carbonate formation coincided with extensive precipitation of crystalline crusts on the seafloor. We report a new type of reef-building association from Middle–Upper Ordovician strata of western North China, in which erect thin tubes of tetradiids (coral morph) are encrusted by the calcimicrobes *Renalcis* and *Angusticellularia* and then by a large amount of early marine cement that is presumably high-Mg calcite or aragonite in composition. The resulting meter-scale mound is embedded within intraclastic–bioclastic grainstone, implying high-energy shallow-marine conditions. The thin tetradiid tubes, which would have been unable to physically withstand strong waves and currents, are interpreted to have been consolidated by encrusting calcimicrobes and then by extensive early marine cementation. Tetradiid-bearing reefs have generally been reported from muddy successions; the results of the present study suggest that consolidators were important in reef-building in high-energy environments during the later Ordovician. Considering also the coeval bivalve–sponge–microbial–cement reef reported from the same area and a sponge–microbial–cement reef from Arctic Canada, early marine cementation appears to have been at least locally important in the late Ordovician, similar to the Pennsylvanian through the Mid-Triassic. These triple hybrid carbonates may have formed by a combination of: (1) emergence of newly evolved skeletal reef-builders during the Great Ordovician Biodiversification Event; (2) development of CO₂-concentrating mechanisms in calcimicrobes induced by a decrease in atmospheric CO₂; and (3) an increase in the calcium saturation state in seawater resulting in extensive abiotic cementation as well as calcification of microbes. All of these factors might have been induced by global cooling throughout the Mid–Late Ordovician.

1. Introduction

The proportions of different carbonate-precipitating mechanisms, including biocontrolled (skeletal), bioinduced (mainly microbial), and abiotic carbonates, have changed with the evolution of organisms and environmental conditions throughout geologic history (Webb, 1996; Riding and Virgone, 2020). Precambrian bioconstructions are typically microbialitic, and contain both bioinduced microbial carbonates and significant abiotic precipitates (Grotzinger, 1990; Grotzinger and Knoll, 1999; Cantine et al., 2020). As skeletal organisms emerged in the latest Neoproterozoic, Phanerozoic reefs (mainly after the Mid-Ordovician) were often dominated by skeletal invertebrates and algae (Wood, 1999; Knoll and Fischer, 2011) augmented by sporadically occurring microbial carbonates (Kiessling, 2002; Riding and Liang, 2005; Chen

et al., 2019; Riding et al., 2019). Abiotic precipitation in open-marine environments has generally been rare throughout the Phanerozoic, except during the late Paleozoic when triple hybrid carbonates of abiotic–microbial–skeletal reefs dominated the open-marine environment (Grotzinger and Knoll, 1995; Webb, 1996; Riding and Virgone, 2020).

The early Phanerozoic marked the transition from microbially dominated Precambrian-type reefs to skeletally dominated Phanerozoic-type reefs. The Great Ordovician Biodiversification Event (GOBE), a rapid rise in taxonomic richness in the Ordovician, fundamentally changed reef communities (Lee and Riding, 2018). The microbial–skeletal reefs of the early Paleozoic – early Cambrian microbial–archaeocyath reefs and middle Cambrian–Middle Ordovician microbial–sponge reefs – were replaced by skeletal-dominant reefs in the

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<https://doi.org/10.1016/j.gloplacha.2021.103462>

Received 30 September 2020; Received in revised form 1 March 2021; Accepted 2 March 2021

Available online 6 March 2021

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Mid to Late Ordovician, as skeletal reef-builders such as stromatopora, rugose and tabulate corals, and bryozoans diversified during this time (Webby, 2002; Adachi et al., 2011; Kröger et al., 2017; Lee and Riding, 2018). Mid to Late Ordovician skeletal reef builders are generally similar to those of the Silurian and Devonian, except for peculiar “coralomorphs” such as tetradiids and *Amsassia* that are limited to the Ordovician (Webby, 2002; Kwon et al., 2012; Lee et al., 2014). These coralomorphs added diversity to Mid to Late Ordovician reef ecosystems, but their reef-building abilities are only poorly understood (e.g., Kwon et al., 2012; Lee et al., 2014; Carrera et al., 2017), and their phylogenetic affinities remain problematic (Steele-Petrovich, 2009a; Sun et al., 2014).

In this study, we report a new type of Mid–Late Ordovician reef-building association from western North China constructed by tubular tetradiids that are encrusted by the calcified microbes *Renalcis* and *Angusticellularia* with subordinate frame-building *Hedstroemia*. Together with volumetrically abundant abiotic early marine cement, these organisms formed meter-scale mounds. This find emphasizes the importance of abiotic cementation and calcimicrobes in reef-building, at least locally, during the later part of the Ordovician at the dawn of Phanerozoic-type skeletal reefs. We also discuss major changes in paleoenvironmental conditions during this time—global cooling followed by the Hirnantian glaciation—and their effects on reef-building.

2. Geological setting and methods

The Sino-Korean Craton was a microcontinent located near (Li and Powell, 2001) or at the margin (McKenzie et al., 2011) of the Gondwana Supercontinent during the Ordovician. The Ordos Basin, the second-largest sedimentary basin in China, is located on the western margin of the Sino-Korean Craton. Various Mid–Late Ordovician reefs have been reported from the southern part of the basin (Ye et al., 1995; Webby, 2002, p. 149; Wang et al., 2012). The Ordovician succession is unconformably overlain by Upper Carboniferous sedimentary rocks, and this unconformity can be recognized throughout the entire Sino-Korean Block (Zhen et al., 2016).

The tetradiid–calcimicrobial–cement reef of this study occurs in a quarry in Chenluzhen County, Tongchuan, Shaanxi Province, China, and is the same locality described by Lee et al. (2016) (Fig. 1). The outcrop comprises a ~ 40 m-thick carbonate succession of the Pingliang Formation that is unconformably overlain by Carboniferous sedimentary rock (Fig. 2A). The overall outcrop is characterized by massive limestones that are interbedded with layers of boundstone and grainstone. The Pingliang Formation was originally described as Middle Ordovician

in age (Ye et al., 1995), but is now considered to be Upper Ordovician (Sandbian) (Wang et al., 2013, 2015; Guo et al., 2014) (see Liu et al., 2020). Xu et al. (2019) reported ages of 457.6 ± 3.8 and 454.8 ± 3.8 Ma (Sandbian) from K-bentonites in the Pingliang Formation. However, age-indicative fossils are almost absent from the outcrop sampled in this study, and litho- and biostratigraphic correlations cannot be easily performed due to the limited outcrop exposure. The unconformity overlying the Ordovician successions, a key surface for stratigraphic correlation, is often highly diachronous (Zhen et al., 2016). We tentatively identify the Chenluzhen rocks as Mid to Late Ordovician in age.

The original specimens were collected by the authors during field trips in 2012 and 2014, and prepared as slabs and thin sections in 2012–2016. We prepared two sets of serial thin sections (7.6×5.2 cm; 30 and 40 slices each) that were cut parallel to the bedding plane with a vertical spacing of ~1 mm, in addition to 10 thin sections that were cut perpendicular to the bedding. Supplementary specimens were collected by the first author during a field trip in 2019, but at that time, the outcrop was almost covered with cement, and only a small portion containing the tetradiid–calcimicrobial–cement reef of this study was exposed at the eastern margin of the quarry (Fig. 2B).

3. Tetradiid–calcimicrobial–cement reef

The reefal boundstone of this study comprises meter-scale domal mounds (~1 m high and ~3 m wide), which are laterally surrounded by intraclastic–bioclastic packstone to grainstone (Fig. 2C). Mesoscale fabrics are not clear in the field, but locally we identified tubular structures of tetradiids filled with cement and surrounded by white globular masses of *Renalcis* (Fig. 2D), in addition to some fan-shaped colonies of tetradiids (Fig. 2E). Large voids filled with cement are also identifiable in the field (Fig. 2F). The overall reef mound overlies intraclastic grainstone with fragments of tetradiid tubes surrounded by *Renalcis* (Fig. 2F). All samples were collected from tubular tetradiids that are either widely (Fig. 3A) or closely spaced (Fig. 3B).

3.1. Reef-building components

3.1.1. Tetradiids

Among the coralomorphs, tetradiids are characteristic reef-builders that are confined to the Ordovician. Tetradiids are composed of millimeter-scale thin-walled tubes that are now replaced by calcite. Cross-sections of tetradiids are square to round in shape, with septal projections causing their characteristic four-fold symmetry. Tetradiids show several growth forms, including single tubes and branching,

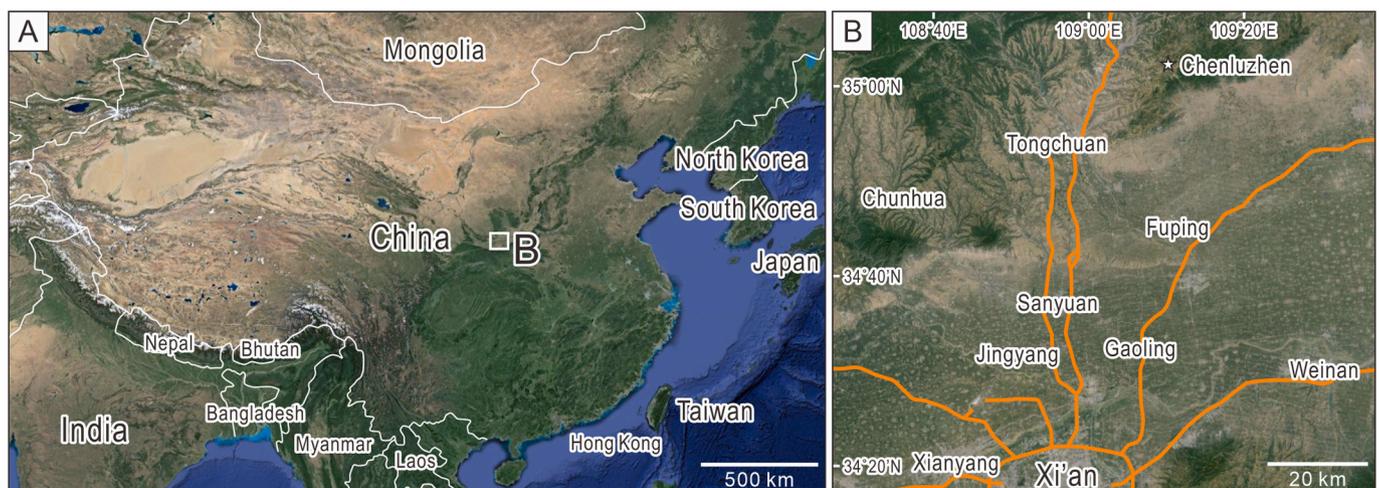


Fig. 1. (A) Satellite image of East Asia. (B) Satellite image of the study area (Shaanxi Province, China). The Chenluzhen section ($35^{\circ}02'09''\text{N}$, $109^{\circ}10'15''\text{E}$) is marked by a star. Illustration after Lee et al. (2016).



Fig. 2. (A) Photograph of the general outcrop facing north, taken in 2012. The tetradiid–calcimicrobial–cement reef mound of this study occurs in the eastern end of the quarry. (B) Photograph of the eastern end of the quarry, taken in 2019. Most of the outcrop was covered with cement. (C) Mound-shaped reef, outlined with yellow dotted line. (D) Close-up photograph of the reef, showing tube-shaped tetradiids (*T*) surrounded by white globular masses of *Renalcis* (*R*). Coins in (D–F) are 20.5 mm in diameter. (E) Colonial tetradiids showing fan-shaped structure, outlined with yellow dotted lines. (F) Base of the reef, located on top of intra-clastic–bioclastic grainstone with tetradiid tube fragments (white arrows). Note the occurrence of a void filled with cement within the reef (black arrow).

cateniform, columnar, and massive colonies (Webby et al., 2004). Four basic types were distinguished on the basis of their growth morphology by Bassler (1950), which are also considered to be separate genera (Sokolov, 1955): single tubes (*Tetradium syringoporoides* group; *Rhabdotetradium* Sokolov, 1955); branching stalks of 4, 16, or more closely packed tubes (*T. cellulorum* group; *Phytopsis* Hall, 1847 sensu Sokolov, 1955); one to a few tubes in wide chain-like arrays (*T. halysitoides* group; *Paratetradium* Sokolov, 1955); and densely packed tubes forming a hemispherical colony (*T. fibratum* group; *Tetradium* Dana sensu Sokolov, 1955) (Copper and Morrison, 1978; Yang and Stearn, 1990; Webby et al., 2004; Steele-Petrovich, 2009a, 2009b, 2011).

Tetradiids are often considered a type of tabulate coral (Hill and Stumm, 1956; Sokolov, 1962; Webby and Semeniuk, 1971; Hill, 1981; Young and Elias, 1995; Webby et al., 2004); however, Scrutton (1997) suggested that tetradiids are different from the rest of the tabulate

corals, and are more similar to chaetetid sponges. Riding (2004) compared *Solenopora*, which he re-classified as a chaetetid, with tetradiids in terms of their tube size and overall morphology. Steele-Petrovich (2009a, 2009b) suggested that these may be red algae, which Lee et al. (2019) agreed with. The affinity of tetradiids is beyond the scope of this article and requires further investigation, and here we tentatively assign tetradiids to the coralomorphs.

The tetradiids observed in the Chenluzhen thin sections are single tubes 0.4–0.6 mm wide and > 5 mm long (Fig. 4). The walls of each tube are 20–50 μm thick, and are now composed of sparry calcite. In cross-section, the characteristic four-fold symmetry of the tetradiids is readily recognizable, and four closely packed tubes are infrequently found (Fig. 4D). The tetradiid tubes are typically vertically to subvertically oriented. Examples of bifurcating tetradiids can be observed (Fig. 4E, F). Internal spaces within the tubes are filled with blocky sparry

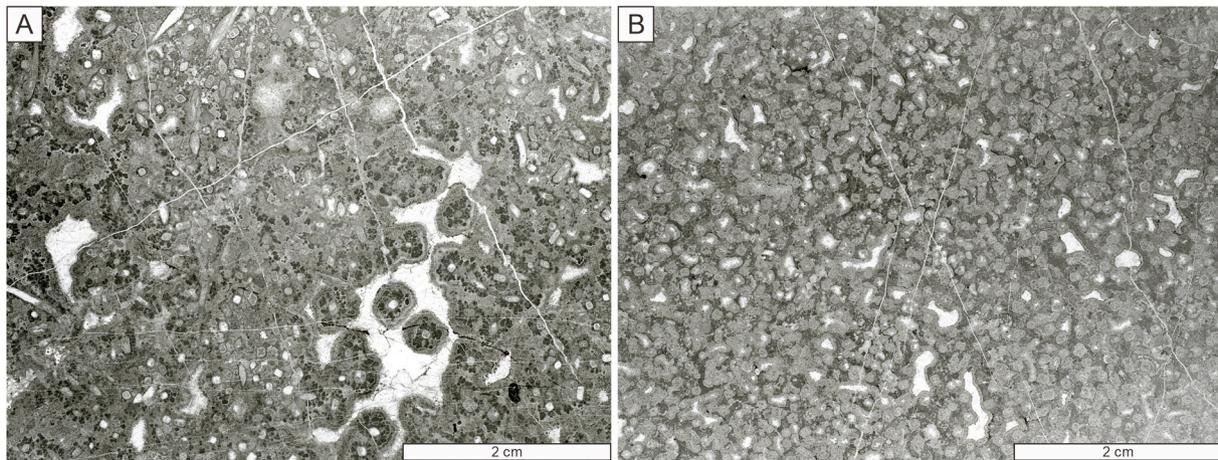


Fig. 3. Photographs of representative thin sections prepared in transverse section. Rounded to square-shaped cross-sections of tetradiid tubes are clearly visible, which are (A) closely or (B) densely spaced. Tetradiid tubes are surrounded by dark gray calcified microbes such as *Renalcis*, and then by darker gray fibrous cement and bright blocky cement.

cement or microsparite, without noticeable internal structures (e.g., tabulae).

3.1.2. *Renalcis*

Renalcis is a problematic microfossil that is characterized by rounded to lunate micritic chambers with hollow interiors filled with sparite (Riding, 1991; Liu et al., 2016). The affinity of *Renalcis* is uncertain, although it has been suggested to be cyanobacteria, red algae, or fossilized biofilms of heterotrophic bacteria (Pratt, 1984; Riding, 1991; Chafetz and Guidry, 1999; Turner et al., 2000; Stephens and Sumner, 2002; Woo et al., 2008; Luchinina, 2009; Liu et al., 2016). In the Chenluzhen reefs, these chambers are 150 to 350 μm in size, and often aggregate to form botryoidal to branching colonies with short branches (Fig. 3). Micritic chambers of *Renalcis* often grade into globular masses of micrite, probably representing tangential cuts of *Renalcis*. *Renalcis* often forms a thin micritic layer to botryoidal clusters surrounding tetradiid tubes or *Hedstroemia* colonies, growing normal to the substrate.

3.1.3. *Hedstroemia*

Hedstroemia is a calcified microfossil composed of radially arranged clusters of tubes that have been compared with modern rivulariacean cyanobacteria (Riding and Voronova, 1985; Riding, 1991). In the Chenluzhen reefs, rarely occurring *Hedstroemia* form thalli up to 3 mm wide and high that are fan-shaped in longitudinal sections. Two different types are identified: smaller tubes (30–40 μm diameter) and larger tubes (50–70 μm diameter). Both types are polygonal in shape in transverse sections (Fig. 6A) and appear as branching/curved tubes in longitudinal sections (Fig. 6B). These two different types occur in the same thalli, suggesting that they represent the same organism (Fig. 6A). The smaller type can be classified as *Zonotrichites*, whereas the larger type is more similar to *Hedstroemia* (R. Riding, pers. comm. 2020).

Fossils similar to *Hedstroemia* include *Botomaella*, *Bija* (Cambrian), *Ortonella* (Carboniferous), and *Cayeuxia* (Triassic to Cretaceous) (Riding, 1991). Although several different genera have been identified from rocks of various ages, these fossils are very similar in general structure. They have been given different names on the basis of their shapes (tube size and branching pattern) (Liu et al., 2016) and ages (Riding, 1991), but it is possible that similar fossils could have been named differently by researchers working on rocks of various ages. In fact, their tube size ranges often overlap with one another (Liu et al., 2016), and further detailed taxonomic research is required to understand the nature of these fossils. We tentatively assign the Chenluzhen example to *Hedstroemia* on the basis of its Ordovician age.

3.1.4. *Angusticellularia*

Dark-coloured micritic masses of calcimicrobes that consist of peloids 50–300 μm in diameter, with relatively well-defined margins, are identified within the reefs (Fig. 6D). The dark masses form overall irregular to reticulate patterns with fibrous cement in between, and laterally grade into, or co-occur with, *Renalcis*. They are interpreted to be *Angusticellularia* (*Angulocellularia*) (Riding, 2011a), formed by calcification of oscillatoriacean cyanobacteria sheaths (Riding and Voronova, 1982), or poorly preserved *Renalcis*. In either case, these represent calcified remains of microbial organisms. We tentatively assign these fossils to *Angusticellularia*.

3.1.5. Microscopically clotted micrite

Microscopically clotted micrite comprises peloids 30–70 μm in diameter with poorly defined margins that are often hard to distinguish from *Angusticellularia* (Fig. 6C). These masses often co-occur with *Renalcis*, either surrounding (Fig. 6C) or surrounded by them (Fig. 5B, D). These are interpreted to be poorly preserved/calcified masses of microbial carbonates formed by sulfate-reducing bacteria (Visscher et al., 2000; Riding, 2011b; Guido et al., 2013).

3.1.6. Bioclasts

Bioclasts are rare, and are mostly surrounded by *Renalcis* colonies (Fig. 4B). These include brachiopods, bivalves, and crinoid stems. Minute ostracods or bivalve shells (0.1–0.3 mm long) are found in the *Renalcis* and in fibrous cement (Fig. 4C). Other components (e.g., lime mud) are almost absent from the boundstone.

3.1.7. Cement

A large portion of the boundstone is filled with three different generations of cement (Fig. 7). The earliest carbonate cement formed on the biogenic substrate of *Renalcis* as thin layers (mostly ~ 50 μm thick, up to 100 μm thick) of circumgranular dogtooth cement that is non-luminescent and partly altered. Isopachous, fibrous cement 100–300 μm long and 10–15 μm wide formed on the dogtooth cement. The fibrous cement is very heterogeneous, showing bright luminescence, and is highly altered, suggesting a high-Mg calcite or (less likely) an aragonite origin (J. Hendry, pers. comm. 2020). Dull-luminescent blocky cement fills the rest of the spaces. The proportions of reef-building components vary between samples, but early marine cement (dogtooth and fibrous cement) occupies about 30% of the reef volume or more (Table 1). In some cases, dogtooth, fibrous, and blocky cement altogether constitute nearly half (44.25%) of the reef volume (Fig. 3A, Table 1).

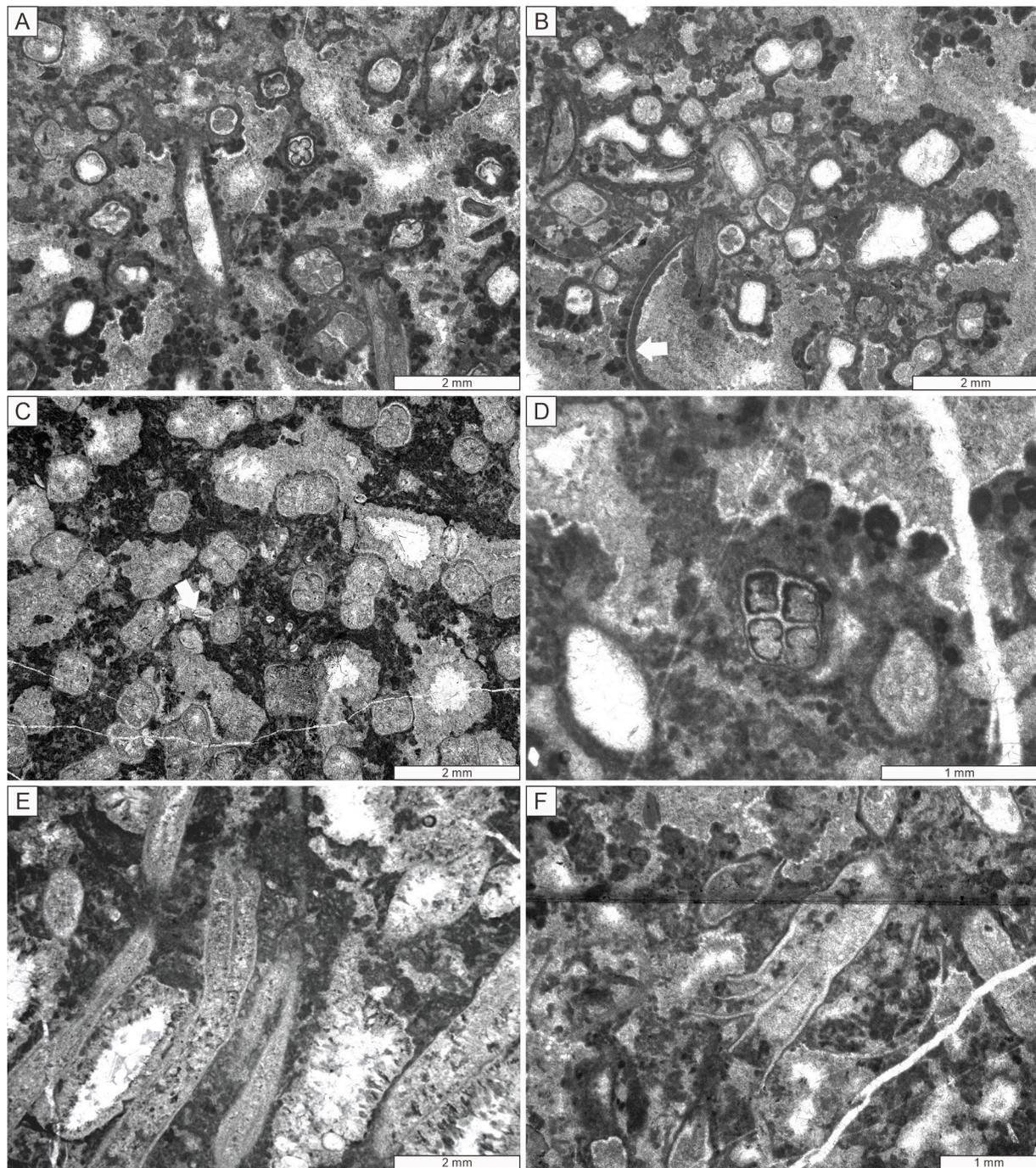


Fig. 4. Photomicrographs of tetradiid-*Renalcis* associations. (A–D, F) Transverse cut and (E) longitudinal cut. The characteristic four-fold symmetry of tetradiid tubes can be readily recognized. The tubes are surrounded by well- to poorly preserved *Renalcis* and/or microscopically clotted micrite. Other biogenic components, e.g., (B) bivalves (arrowed) or (C) ostracods? (arrowed) are also present. (D) An example of four closely packed tubes. (E, F) Bifurcating examples of longitudinal sections of tetradiid tubes. Tabulae were not found.

3.2. Reef structure

The analyzed samples exhibit the following characteristics: (1) solitary tetradiid tubes are mostly oriented vertically to subhorizontally; (2) *Renalcis*, *Angusticellularia*, and clotted micrite cover the tetradiid tubes and *Hedstroemia*; (3) all biogenic components are surrounded by dogtooth and fibrous cement; (4) the rest of the space is filled with blocky cement; and (5) allochthonous sediment is conspicuously absent throughout the reef, except for minor bioclasts.

A formative model of the Chenluzhen reef was generated based on these features. The reef frameworks were formed by vertically growing

tetradiid tubes, with subordinate *Hedstroemia*. The absence of allochthonous sediment suggests a high-energy environment where such sediments were washed out by strong waves/currents, which would have supplied seawater to the interframe space and resulted in the formation of isopachous cement (Macintyre and Marshall, 1988). Rarely occurring, but diverse, shell fragments suggest normal marine conditions. Calcified microbes (*Renalcis* and *Angusticellularia*) and clotted micrite would have encrusted the reef structure and stabilized the reef framework (Kruse et al., 1995; Webb, 1996; Shen and Webb, 2004; Adachi et al., 2007).

Rapid early marine cementation would also have provided strength

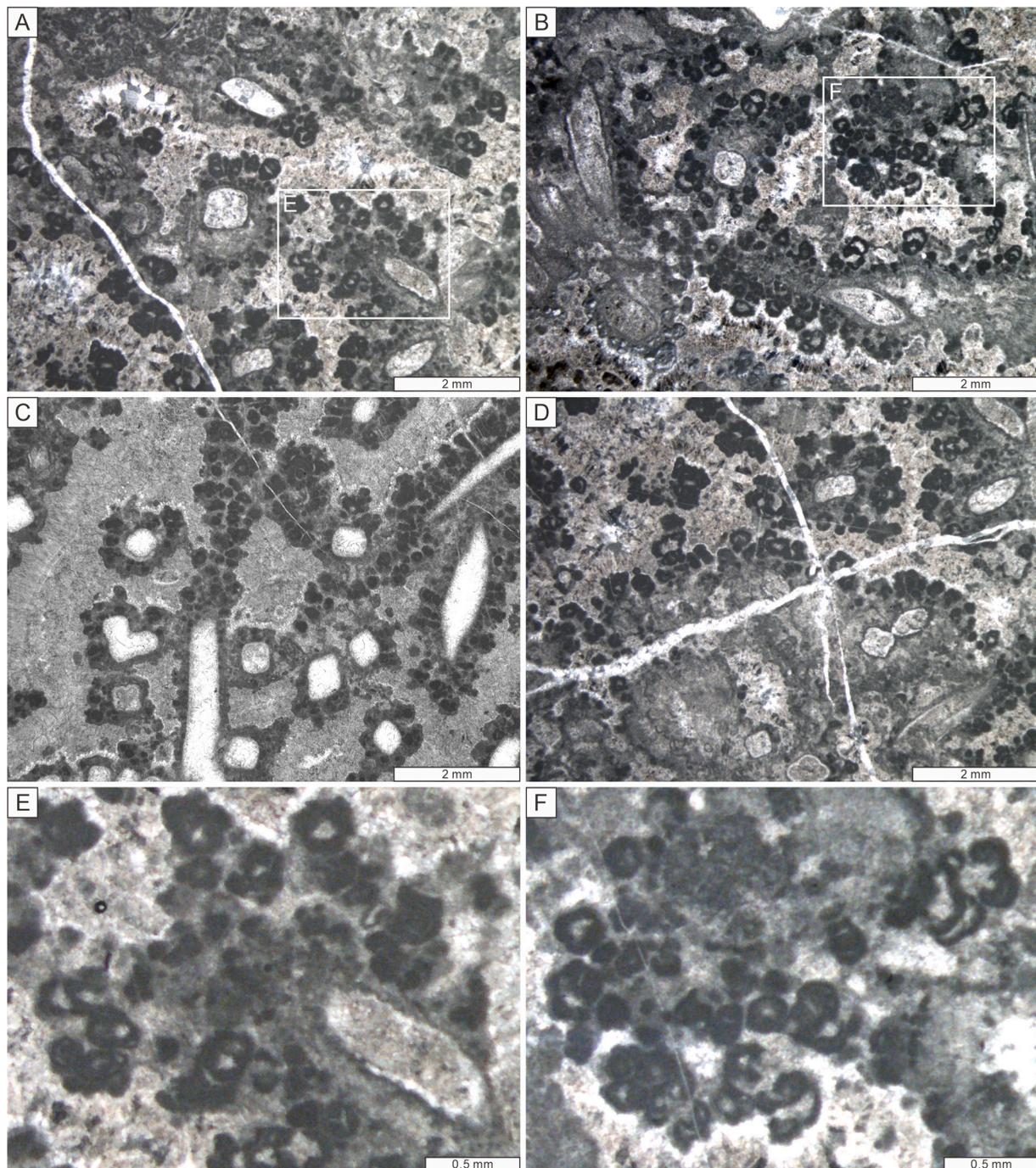


Fig. 5. Photomicrographs of *Renalcis*. (A–D) *Renalcis* colonies surrounding tetradiid tubes and/or poorly preserved microbes. (E–F) Detailed photomicrographs of *Renalcis*. All photomicrographs are from transverse-cut thin sections.

to the reef framework (Fagerstrom, 1987, p. 5; Riding, 2002), as in the bivalve–sponge–microbial reef from the same area (Lee et al., 2016) and in Early Permian and Late Triassic (Flügel, 1981), Permian (Grotzinger and Knoll, 1995), and modern (Land and Goreau, 1970; Macintyre, 1977) reefs. Interestingly, the tetradiid–calcimicrobe–cement reef of this study differs greatly in composition from the bivalve–sponge–microbial reef from the same area (Lee et al., 2016). Tetradiids and calcimicrobes are both minor components of the bivalve–sponge–microbial reef, whereas bivalves and sponges are conspicuously absent from the tetradiid–calcimicrobe–cement reef. This difference may indicate differentiation of ecological niches among reef-builders in nearby environments during the later Ordovician. Abiotic cement is a major component in both cases, suggesting that early marine cementation was important in

reef-building in the Chenluzhen area (and possibly across a wider region).

4. Discussion

4.1. Reef-building ability of tetradiids in the Ordovician

Tetradiids are commonly found as centimeter- to decimeter-scale colonies (Elias and Young, 1998; Webby et al., 2004; Steele-Petrovich, 2009a), but are known to form small mounds (Kwon et al., 2012), biostromes (Webby, 2002), and microatolls (Webb, 1997; Webby et al., 1997). The Chenluzhen reef is the largest tetradiid-associated reef ever reported; most others are decimeter-scale tiny reefs, including

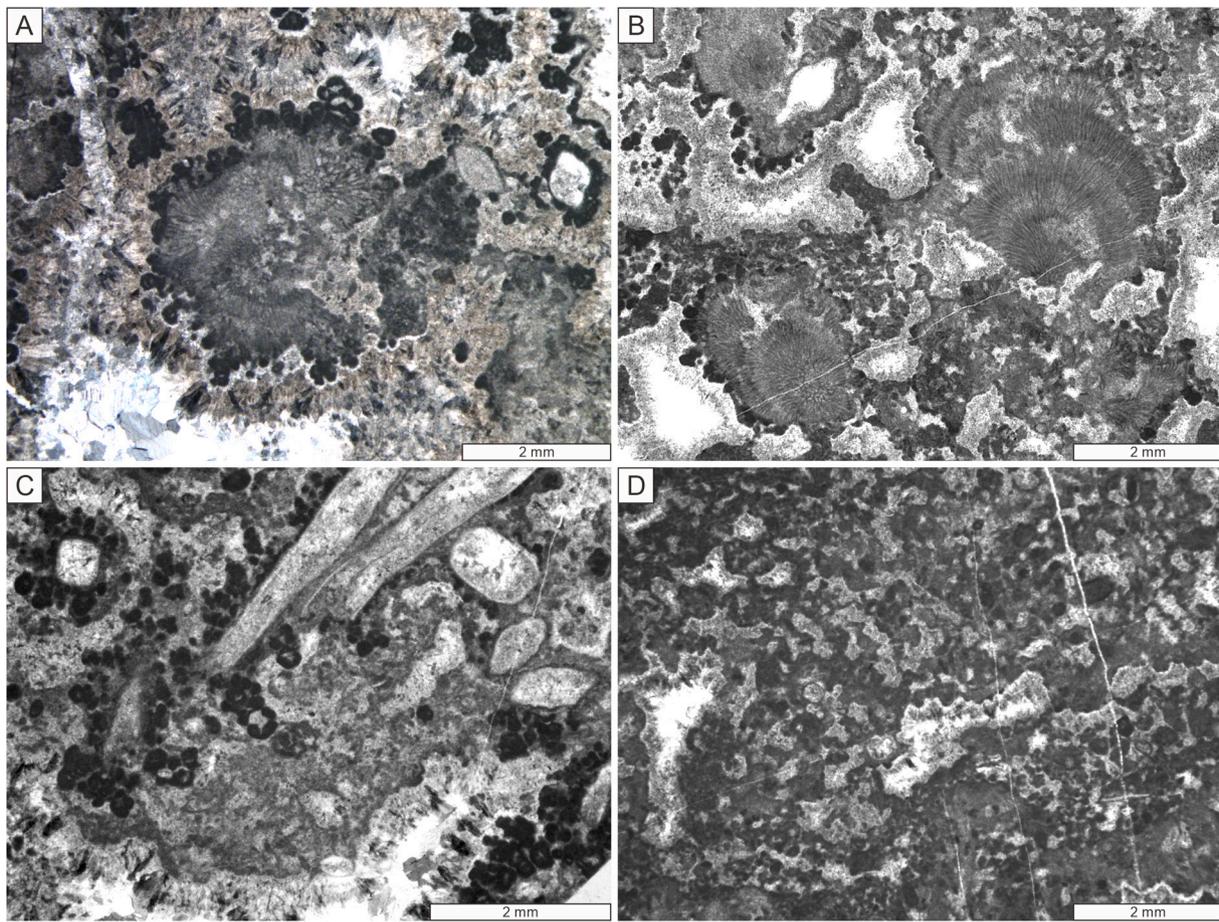


Fig. 6. Photomicrographs of *Hedstroemia* and microscopically clotted micrite. (A) Transverse cut of *Hedstroemia*, surrounded by *Renalcis*. (B) Longitudinal cut of *Hedstroemia*, surrounded by poorly preserved *Renalcis* or *Angusticellularia*. (C) Microscopically clotted micrites surrounding a tetradiid-*Renalcis* association, surrounded in turn by fibrous cement. (D) An example of microscopically clotted micrite, presumably *Angusticellularia*.

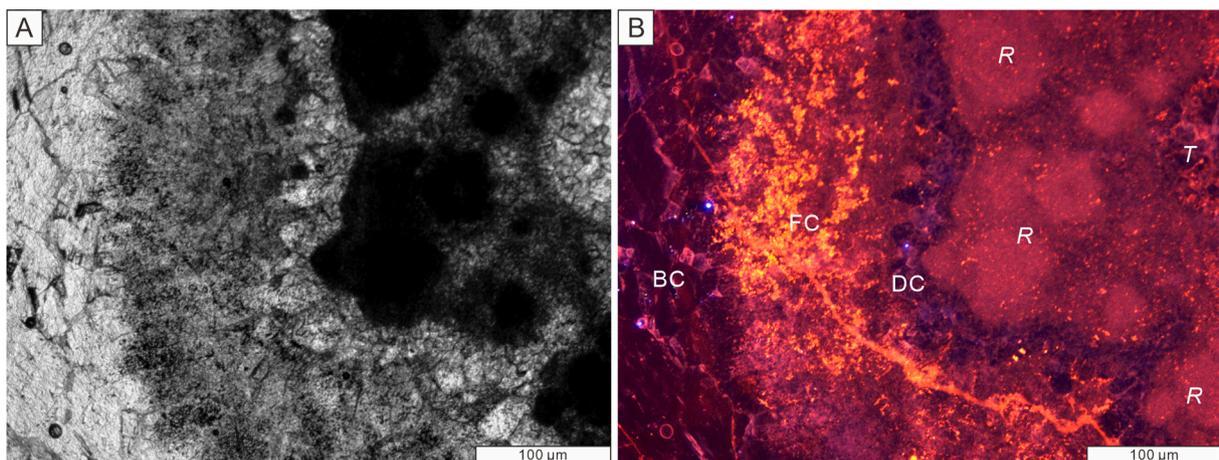


Fig. 7. Details of abiotic cements, taken under (A) stereomicroscope and (B) cathodoluminescence microscope. T: tetradiid, R: *Renalcis*, DC: dogtooth cement, FC: fibrous cement, BC: blocky cement.

tetradiid-sponge reefs (Kwon et al., 2012), stromatoporoid-coral-tetradiid reefs (Alberstadt et al., 1974), tetradiid-algae/bryozoan-coral reefs (Harland et al., 1985), and tetradiid-bryozoan reefs (Walker, 1972). The Chenluzhen reef differs from other tetradiid reefs in size and depositional environment. Although a sedimentological study of the study area was not conducted, associated coarse-grained sediments, the absence of allochthonous sediments within the reef

fabric, and abundant early marine cement in reef interframe spaces collectively suggest that the Chenluzhen reef formed under high-energy shallow-water conditions. However, previously reported tetradiids were mostly found in low-energy shallow subtidal or protected lagoonal settings with muddy sediments (e.g., Young, 1995; Webb, 1997; Steele-Petrovich, 2009a), except for some examples where domical tetradiids are interpreted to have formed a wave-baffle community, which was

Table 1

Proportions of reef-building components in the Chenluzhen reef. Samples 1 and 2 are from Fig. 3A and B, respectively. A total of 400 points were counted for each sample.

	Sample 1	Sample 2
Tetradiid	9.75%	29.5%
<i>Renalcis</i>	21.25%	10.75%
Clotted micrite (+ <i>Angusticellularia</i>)	22.5%	27.75%
<i>Hedstroemia</i>	0.25%	0%
Fibrous/dogtooth cement	33.75%	27.25%
Blocky cement	10.5%	4%
Unknown	2%	0.75%

also embedded within a muddy matrix (Walker, 1972; Copper and Grawbarger, 1978).

Compared with other Ordovician corals (Webby, 2002) and coralomorphs (e.g., *Amsassia*) (Lee et al., 2014; Carrera et al., 2017), it seems that tetradiids are ineffective reef builders, especially under high-energy conditions. We postulate that erect thin tubes of tetradiids would have been unstable under such high-energy conditions, and required encrusters and/or extensive early marine cementation to be stabilized. This result emphasizes that reef-building calcified microbes persisted in the Mid–Late Ordovician (Liu et al., 2020), when various skeletal reef-builders such as tabulate and rugose corals, stromatoporoids, bryozoans, and other organisms began to form reefs during the peak of the GOBE (Lee and Riding, 2018). The calcified microbes would have encrusted tetradiid tubes, stabilizing the primary reef framework, and critically contributed to reef-building. The upward-growing tetradiids would have been suitable substrates for calcimicrobes high above the seafloor; this location may have provided sunlight as well as dissolved organic matter and CO₂ to calcimicrobes.

4.2. Triple hybrid carbonates: Skeletal–microbial–cement reefs and global environmental changes

The tetradiid–calcimicrobe–cement reef reported in this study is a peculiar reef-building association, because it has an extensive amount of in situ marine cement. The Chenluzhen reef can be classified as a skeleton–cement reef (sensu Riding, 2002) or a triple hybrid carbonate of skeleton–microbial–abiotic components (sensu Riding and Virgone, 2020), which dominantly occur in lower Pennsylvanian to Mid-Triassic strata (e.g., Mazzullo and Cys, 1979; Wood et al., 1994, 1996; Kershaw et al., 2007). Permian reefs formed of bryozoan and sponges often contain anomalously large volumes of cement and microbial carbonates, as demonstrated in the famous Capitan Reef in Texas, USA (Wood et al., 1994, 1996; Grotzinger and Knoll, 1995; Weidlich, 2002). The Waulsortian mud mounds, Mississippian deep-water mounds composed of lime muds, various skeletal components, and cements, are also noticeable (Rodríguez-Martínez, 2011). These late Paleozoic triple hybrid carbonates resulted from the widespread precipitation of reef-associated sparry seafloor crusts (Grotzinger and Knoll, 1995). Some early Cambrian microbial–archaeocyath reefs with extensive syndimentary cements are comparable to these triple hybrid carbonates (e.g., Wood et al., 1993; Gandin et al., 2007; Gandin and Debrenne, 2010). To our knowledge, there are two Ordovician examples of similar skeletal–microbial–cement reefs: a bivalve–sponge–microbial–cement reef from North China (Lee et al., 2016) and a sponge–microbial–cement reef from Arctic Canada (Castagner et al., 2016). Coeval *Xianella* calcimicrobial boundstone from the slope successions of North China also dominantly comprises early marine cements (Lee and Riding, 2016).

Grotzinger and Knoll (1995) suggested that the carbonate saturation state in seawater would have increased during the late Paleozoic due to the reduced extent of shallow carbonate platform induced by eustatic sea-level fall, an increase in continental erosion that provided calcium and alkalinity to the ocean, and anoxic bottom water with elevated alkalinities that mixed with the surface water by upwelling. All of these

factors also affected the Mid–Late Ordovician ocean, marked by the end-Ordovician (Hirnantian) glaciation and accompanying eustatic sea-level fall (Haq and Schutter, 2008). The sea-level fall, which was associated with the Taconic orogeny, would have increased continental weathering and thereby provided calcium and alkalinity to the ocean (Kump et al., 1999; Saltzman and Young, 2005; Young et al., 2009; Swanson-Hysell and Macdonald, 2017). The evolution and radiation of land plants in the Ordovician would have enhanced this process (Lenton et al., 2012; Servais et al., 2019). Widespread development of bottom water anoxia associated with coastal upwelling during the Middle to Late Ordovician would have provided alkalinity to the shallow carbonate platform (Pope and Steffen, 2003; Young et al., 2008; Challands et al., 2009; Kanygin et al., 2010; Melchin et al., 2013; Pohl et al., 2017; Bartlett et al., 2018; Jin et al., 2018).

These changes collectively suggest the possibility of an increase in the calcite saturation state, at least locally, in the Mid–Late Ordovician that might have promoted abiotic marine cementation. Calculations suggest that calcite saturation state was elevated ($\Omega = \sim 15$) throughout the Ordovician (Riding and Liang, 2005; Liu et al., 2020). Calcite saturation state in the modern ocean is much lower ($\Omega = 3\text{--}5$) and varies greatly with temperature as well as with upwelling patterns (Carter et al., 2014; Jiang et al., 2015). In addition, a decrease in atmospheric CO₂ in the later Ordovician could have induced the development of carbon-dioxide-concentrating mechanisms in cyanobacteria, resulting in the extensive occurrence of calcified microbes (Liu et al., 2020). These conditions coincided with the emergence of new skeletal reef-builders during the Great Ordovician Biodiversification Event, inferred to have been induced by progressive global cooling during the Ordovician (Trotter et al., 2008; Lee and Riding, 2018). A combination of these three unique conditions – appearance of new skeletal reef-builders, extensive occurrence of calcified microbes, and increase in calcite saturation state – would have resulted in the occurrence of triple hybrid carbonates in the Mid–Late Ordovician. This study thus suggests that there were some similarities in reef building between the Ordovician cooling and late Paleozoic glaciation events.

5. Conclusions

1. A Mid–Late Ordovician tetradiid–calcimicrobial–cement reef from western North China was formed by vertically growing tubular tetradiids that were encrusted by the calcimicrobes *Renalcis* and *Angusticellularia*, and poorly preserved microbial carbonates, with minor *Hedstroemia*. The overall organic reef framework was stabilized by extensive early marine cementation by high-Mg calcite or aragonite.

2. Tetradiids, coralomorphs that are confined to the Ordovician, generally inhabited low-energy shallow-marine environments and were not effective reef builders. Intensive calcimicrobial encrustation accompanied by extensive early marine cementation would have enabled tetradiids to form meter-scale mounds in high-energy environments.

3. Triple hybrid carbonates of skeletal–microbial–cement reefs formed locally during the Mid–Late Ordovician, when there was a unique combination of three different events: emergence of skeletal reef-builders as part of the Great Ordovician Biodiversification Event; development of CO₂-concentrating mechanisms in cyanobacteria induced by decreased atmospheric CO₂; and a possible increase in the calcium saturation state in seawater. These characteristic conditions would have resulted from global cooling throughout the Mid–Late Ordovician.

Declaration of Competing Interest

None.

Acknowledgments

The authors thank R. Riding for discussion of the Chenluzhen reefs, J. Hendry for discussion of cement, L. Liang for discussion of seawater chemistry, X. Yuan for logistic support during fieldwork, H. Park for preparing thin sections, and M.A. Henderson for obtaining cathodoluminescence images. Comments from M.G. Carrera and two anonymous reviewers are greatly appreciated. This study was supported by grants from the National Research Foundation of Korea to JHL (2019R1A2C4069278) and DJL (2018R1A2B2005578). This study is a contribution to IGCP Project 653 ‘The onset of the Great Ordovician Biodiversification Event’.

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