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ORIGINAL ARTICLE

Microbial reefs in eastern Yangtze Platform, South China Block: the last golden age of stromatolites in the Ordovician

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Abstract

In the eastern Yangtze Platform of South China Block, Tremadocian (Early Ordovician) stromatolites in southern Anhui Province occur along a palaeoenvironmental transect from the shallowest intra-platform setting through to deeper platform margin. The intra-platform and platform margin belts of Tremadocian rocks in the eastern platform are carbonate-dominated marine environments favourable for calcimicrobes. However, stromatolites are absent in siliciclastic-dominated slope facies. Shallower carbonate facies are represented by the upper member of the Lunshan Formation, composed of a hundred metres thickness of stromatolite-bearing carbonates. Such stromatolites at the Beigong section of Jinxian county are characterized by stratiform and dome-shaped laminations. *Girvanella* filaments are ubiquitous in thin sections. Crinoids grew on the surfaces of the microbialites. In contrast, towards the deeper carbonate platform margin, stromatolites in massive-bedded limestones of the upper member of Lunshan Formation of the Ma'anshan section at Shitai occur as dense columns of bindstones; macrofossils and bioclasts are rare in those stromatolites, indicating a lower energy and deeper marine setting. Water depth at the platform margin of the Ma'anshan section is interpreted as being above the base of the euphotic zone favorable for photosynthesis in the calcimicrobial community; however, benthic fauna notably declined. In contrast to shallower settings, in clastic-dominated locations interpreted as deposited in deeper water, stromatolites are absent, represented by the middle member of Dawuqian Formation at the Ziliqian section. This work, therefore, supports that Early Ordovician reef systems were still microbial-dominated, representing the last golden age of stromatolites.

Keywords Stromatolites · Palaeobiogeography · Tremadocian · Lower Ordovician · Eastern Yangtze Platform · South China Block

Introduction

With the rise of the Paleozoic Evolutionary Fauna and the decline of the Cambrian Evolutionary Fauna, the Ordovician records a significant transition in types of reefs (e.g., Bambach 1977; Sepkoski 1981, 1992, 1995; Jaanusson 1984; Bottjer et al. 1996; Droser et al. 1997; Droser and Finnegan 2003). Globally, the long-term (about 25 Myr) dysoxia-hypoxia marine conditions throughout the greenhouse of the mid-late Cambrian were significantly ameliorated in

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the Early Ordovician (e.g., Trotter et al. 2008), resulting in expansion of metazoan-dominated reefs formed by lithistids, stromatoporoids, bryozoa, coralomorphs and hypercalcified sponges (e.g., *Calathium*) worldwide (Webby 2002; Li et al. 2015). The Early Ordovician Period is thus viewed as an important evolutionary episode when these metazoans became key reef-builders in shallow seas (Lee and Riding 2018; Li et al. 2014, 2017). However, change from microbial- to metazoan-dominated reefs did not occur uniformly globally, with evidence of temporal and spatial variation in occurrence of both kinds of reef systems (Webby 2002; Li et al. 2019). In addition, the abundance of stromatolites achieved Neoproterozoic- to Mesoproterozoic-like prevalence by the Early Ordovician (Peters et al. 2017).

In recent decades, key Ordovician reef evolutionary stages of China have been recognized in the Yangtze Platform of the South China Block, and Ordos and Tarim blocks of northwest China (Li et al. 2004; Wang et al. 2012; Li et al. 2015). Early Tremadocian (early Early Ordovician) reefs mainly succeeded the Middle-Late Cambrian calcified microbial communities, and onward developed pioneer coral faunas. Webby (2002) recorded various microbial and metazoan combinations in these reef systems. Calcimicrobes, lithistids, bryozoans, and hypercalcified sponges (e.g., *Calathium*, *Pulchrilamina*) formed reefs from the late Tremadocian to early Darriwilian (Middle Ordovician) (Toomey and Nitecki 1979; Alerstadt et al. 1989; Zhu et al. 1993; Adachi et al. 2012; Li et al. 2017). Consistent with the global pattern (e.g., Kröger et al. 2017), corals, stromatoporoids and algae are dominant in Late Ordovician reefs on the Yangtze Platform, while the palaeogeographic variations of main reefbuilders are impressive. This paper focuses on the spatial differentiations of the late Tremadocian stromatolites along a transect from shallow to deeper marine shelf settings of the eastern Yangtze Platform of South China Block; their occurrence was just at the same time-interval as the first record of bryozoan reefs (Adachi et al. 2011) from the western Yangtze Platform. Our aim is to further explore the nature of a regional calcimicrobe-dominated marine community and reconstruct the ecological scenario of the stromatolites and their terminations in marine facies of the eastern Yangtze Platform. Thus, we pay more attention to the palaeogeographic rather than evolutionary pattern of the reefs during the Great Ordovician Biodiversification Event (GOBE).

Geological setting

The South China Block was located around 30° N in Early Ordovician time (Torsvik and Cocks 2013) and was rotated clockwise compared to its present orientation (Torsvik and Cocks 2013). During the Cambrian–Middle Ordovician, the South China Block comprises three regions documenting different paleo-environments from northwest to southeast: Yangtze Region (platform), Jiangnan Region (slope) and Zhujiang Region (basin) (Chen and Rong 1992; Chen et al. 1995). The Yangtze Platform was extensively covered by an epicontinental sea during a transgressional interval in the Early Ordovician. Shallow-marine carbonates prevailed in offshore areas. Coeval terrigenous clasts sourced from western lands were limited to near-shore belts located in the current eastern Yunnan Province (e.g., Lai 1982; Zhou et al. 1993; Zhang et al. 2002; Zhan and Jin 2007).

Detailed fossil evidence for the GOBE is mainly from the western Yangtze Platform (e.g., Lu et al. 1976; Zhou et al. 1993; Zhan et al. 2006; Zhan and Jin 2007; Zhang et al. 2010). Lower Ordovician sequences in southern Anhui Province are used to interpret a palaeogeographic corridor linking the eastern (also called lower) Yangtze Platform, Jiangnan Slope and Zhe-Wan Basin (Bureau of Geology and Mineral Resources of Anhui Province 1988). Tremadocian units are chiefly subdivided into three palaeogeographical areas; they are, respectively, documented as the carbonates of the Lunshan Formation on the eastern Yangtze Platform; interbedded deposits of siltstones and limestones of the Dawuqian Formation from the Jiangnan Slope; and dark graptolitic shales of Tanchiachiao Formation from the Zhe-Wan Basin (Fig. 1).

Probably due to turbidity and salinity difference between regions, geographic variations of main reef builders are impressive on the Yangtze Platform during the Early Ordovician (e.g., Zhang et al. 2016). In Tremadocian strata of the western Yangtze Platform, small-scale stromatolites are prevalent in tidal flat settings of the Tungtzu Formation in northern Guizhou Province (Zhao et al. 2014; Jiang et al. 2015), whereas outer-shelf bryozoan-lithistid sponge-*Calathium* reefs of the Fenhsiang Formation are common in western Hubei Province (Zhu 1993; Adachi et al. 2011, 2012). In contrast to the western platform, spatial distribution and environmental character of time-equivalent reef-related stromatolites in the eastern Yangtze Platform are poorly known. Stromatolites in the Ma'anshan section at Shitai is the only reef case reported so far (Li et al. 2004; Jiang et al. 2014; Zhang et al. 2016). We employ three coeval Tremadocian sections from different palaeogeographic settings for descriptions of the stromatolite occurrence and their terminations spatially in southern Anhui Province. Two stromatolite-bearing cases of the upper member of Lunshan Formation from an intra-platform setting at Beigong section in Jingxian County and platform margin of Ma'anshan section in Shitai County are compared in aspects of morphology, biotic compositions and lithological differences. The equivalent middle member of the Dawuqian Formation at Ziliqian sections in Shitai County is an example of the

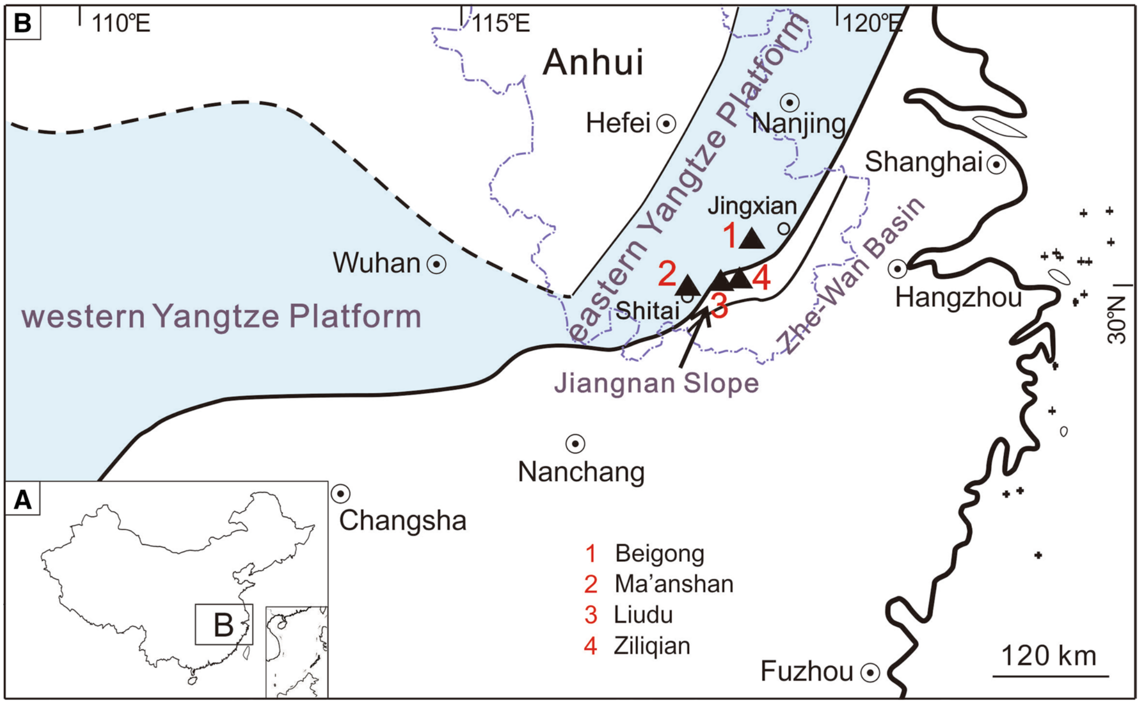


Fig. 1 **a** Location of part of the Yangtze Platform in the map of China; **b** localities of four Tremadocian sections in southern Anhui; they are, respectively, of the stromatolites of the Lunshan Formation at Beigong of intra-platform, platform margin of Ma'anshan, and the Dawuqian Formation at Liudu and Ziliqian sections of slope (base map of palaeogeographic reconstruction of the eastern Yangtze Platform after Zhou et al. 1993)

Jiangnan Slope setting and represents the limit of the spatial distribution of stromatolites of this age (Fig. 1).

Stratigraphy

The stratigraphic divisions and correlations of the Lower Ordovician units of the South China Block have been widely discussed (Mu et al. 1981; Yu et al. 1984; Zhang et al. 2002; Zhang et al. 2019). Current stratigraphic correlations of the key reef-bearing units of the Lower Ordovician of the block are shown in Fig. 2. Most of the eastern Yangtze Platform during Tremadocian time was represented by shallow-marine carbonates of the Lunshan Formation. Stromatolites of the Lunshan Formation are assigned to the initial episode of the Ordovician reef development (see Webby 2002).

Ting (1919) originally named a suite of limestones with sparse cherty beds as the "Lunshan Limestone" at the Lunshan section in Jurong county of Jiangsu Province. Lee et al. (1935) interpreted the lower part of the "Lunshan Limestones" to be Precambrian and Cambrian ages, and redefined the "Lunshan Limestone", referring to only the Lower Ordovician sequence with presence of nautiloid *Hopeioceras*. Qian et al. (1964) formally named Lunshan Formation for the basal Ordovician carbonate unit wide-spreading on the eastern Yangtze Platform, which is widely accepted. The Lunshan Formation in southern Anhui Province extends from the intra-platform area towards the platform margin with thickness of hundreds of metres. Generally, diversity of macrofossils is low and bioclasts are rich in the micritic limestones of the formation. The Lunshan Formation conformably overlies the Upper Cambrian Tangcun Formation and is overlain by the lower Floian Hunghuayuan Formation. The nautiloid *Proterocameroceras*–*Ellesmeroceras* Biozone and conodont *Psilocephalina*—*Drepanodus deltifer*–*Scandodus proteeus* Assemblage Zone in ascending order are of Lower Ordovician age (Bureau of Geology and Mineral Resources of Anhui Province 1988). The trilobite *Dactylocephalus dactyloides*–*Szechuanella szechuanensis* Biozone of the Lunshan Formation is approximately correlated to the carbonate units elsewhere on the Yangtze Platform such as Nantsinkuan and overlying Fenhsiang formations in Yichang of Hubei, and Tungtzu Formation in Sichuan and Guizhou (Wang and Xu 1966; Xu 1976; Yu et al. 1979; Zhu et al. 1986). Thus the stromatolites in eastern Yangtze platform are coeval with metazoan-dominated reefs in western Yangtze platform (Li et al. 2004). Yue et al. (1990) subdivided the Lunshan Formation into the *Cordylodus prion*-*Teriodontus gracilis* (conodont) Assemblage Zone, *Acanthodus costatus*-"*Acodus*" *oneotensis* (conodont) Assemblage Zone and *Triangulodus proteus* (conodont)-*Adelograptus* (graptolite) Assemblage Zone in ascending order. Chen et al. (1988)

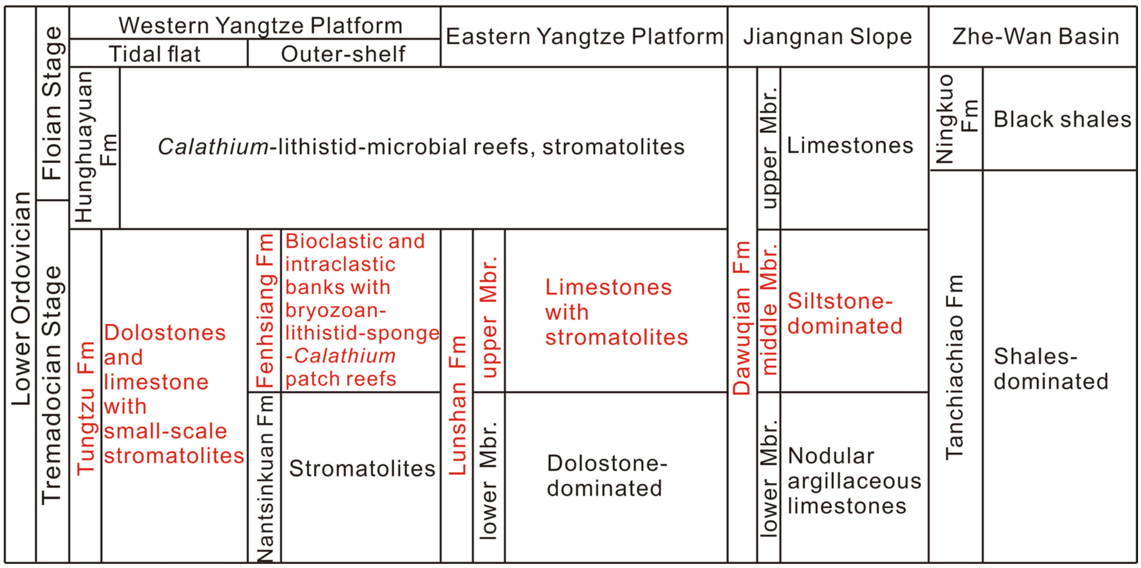


Fig. 2 Differentiations of the lithological units of the Lower Ordovician along the western Yangtze Platform, eastern Yangtze Platform, Jiangnan Slope and Zhe-Wan Basin in southern Anhui. Equivalent Tremadocian reef-bearing unts of the whole Yangtze Platform marked in red colour showing differences of reef ecosystems

assigned it to the Tremadocian. Stromatolitic units from both the Beigong and Ma'anshan sections are present in the upper member of the Lunshan Formation.

The Lower Ordovician Dawuqian Formation at Liudu section (Du and Wang 1980) (Fig. 1) contains the most typical succession, representing transitional Jiangnan Slope belt linking shallow marine carbonates of the eastern Yangtze Platform and graptolitic shales of the Zhe-Wan Basin during Early Ordovician time. Dawuqian Formation is 268 m thick and is in conformable contact with both the dark grey medium-thick bedded ribbon limestone of the uppermost Cambrian Tangcun Formation below and dark grey, grey medium-thick bedded nodular limestone and limestone of the Lower-Middle Ordovician Lishanqian Formation above. Compared to the pure carbonates of the Lower Ordovician sequences of the shallower platform, higher abundance of argillaceous clasts at the Liudu section indicate a deeper slope setting without stromatolites. At the Liudu section, Du and Wang (1980) subdivided the Dawuqian Formation into three members in ascending order:

Upper member: 98 m, grey and light grey micritic limestones, correlated to the Hunghuayuan Formation (Du and Wang 1980; Mu et al. 1980; Yu et al. 1984), the main part of the latter is assigned to the Floian (upper Lower Ordovician) (Zhan and Jin 2007).

Middle member: 35.49 m, dark grey, grey silty shales with less argillaceous limestones, and approximately correlated to the upper member of Lunshan Formation.

Lower member: 134.42 m, dark grey thin-bedded nodular argillaceous limestones yielding *Szechuanella* (trilobite) and *Obolus* (brachiopod), and approximately correlated to the lower member of the Lunshan Formation.

Middle and Upper Ordovician sequences are generally poorly exposed due to vegetation cover. Although this affects the standard section of the Dawuqian Formation erected by Du and Wang (1980) in Liudu Town, good exposure of the middle member of the Dawuqian Formation is available in another outcrop about 13 km northwest of Liudu. Lithological sequences of the platform margin of Ma'anshan and slope of Ziliqian are shown in Fig. 3 with sampling horizons for microfacies descriptions in the following text.

Biotic and lithological changes of the intra-platform, platform margin and slope

Microfacies and palaeoenvironmental features of the units containing stromatolites and those lacking stromatolites are described in this study. Terminologies of Dunham (1962), Embry and Klovan (1971) and Flügel (2004) are used for the microfacies descriptions. The thin sections were made and are housed at Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.

Stromatolites of the upper member, Lunshan Formation at the Beigong section of intra-platform setting

The Lunshan Formation at Beigong section conformably overlies carbonates of the Upper Cambrian Tangcun

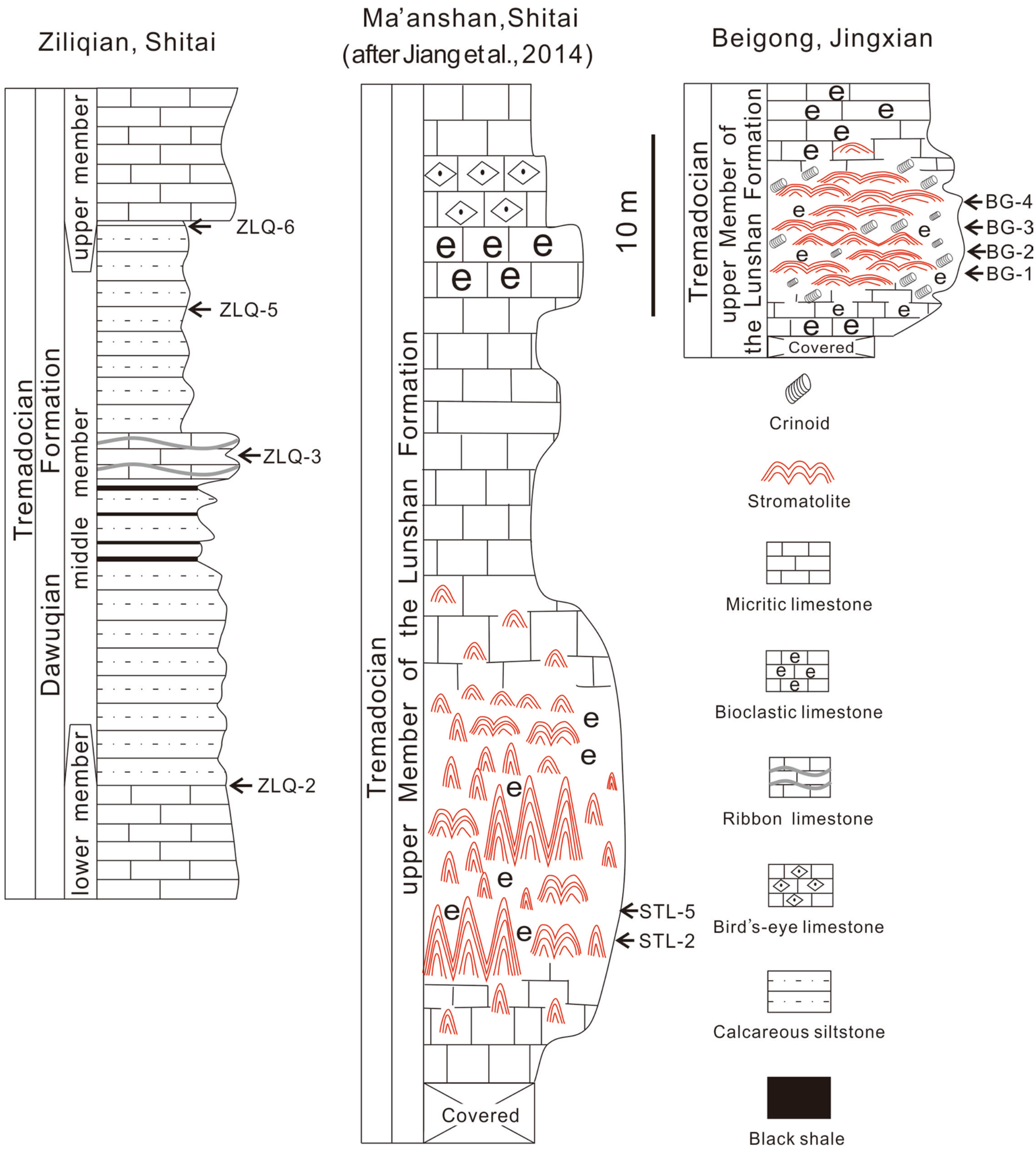


Fig. 3 Lithological logs of the Tremadocian sequences with their stratigraphic correlations from the three sections in southern Anhui Province. They are upper member of the Lunshan Formation with stromatolite-bearing at Beigong and Ma'anshan sections (marked by red colour) and middle member of the Dawuqian Formation without stromatolite at the Ziliqian section

Formation (Qiu et al. 1985). A stromatolitic unit, described for the first time in this paper, is well-exposed at Beigong Primary School (GPS: 30°41′ 4.91″ N, 118°12′ 27.26″ E). Total thickness of the stromatolitic unit, both stratiform and dome-shaped, is about 9.5 m (Fig. 4a); below and above the stromatolitic units are thick-bedded bioclastic wackestones. Individual domes are about 0.2-0.4 m diameter and 0.05 m high (Figs. 4b, c, 5a); holdfasts of crinoids are found on the stromatolites (Fig. 5b). The microbial community is *Girvanella*-dominated (Fig. 6a–e) developing a bindstone fabric. Stromatolite laminations are clearly recognized in outcrop (Figs. 4b, c, 5a); however, boundaries between light and dark laminations are imprecise in thin section. Some laminations are poorly defined, possibly due to secondary microsparite (Fig. 6c) and dolomitization (Fig. 6g, h). Some bioclasts with borings supply space for encrustation by *Girvanella*. In contrast to green algae (which are more prominent in deeper euphotic waters), cyanobacteria tend to dominate intertidal and shallow-water carbonate-boring assemblages (Garcia-Pichel 2006). There are some small and irregular

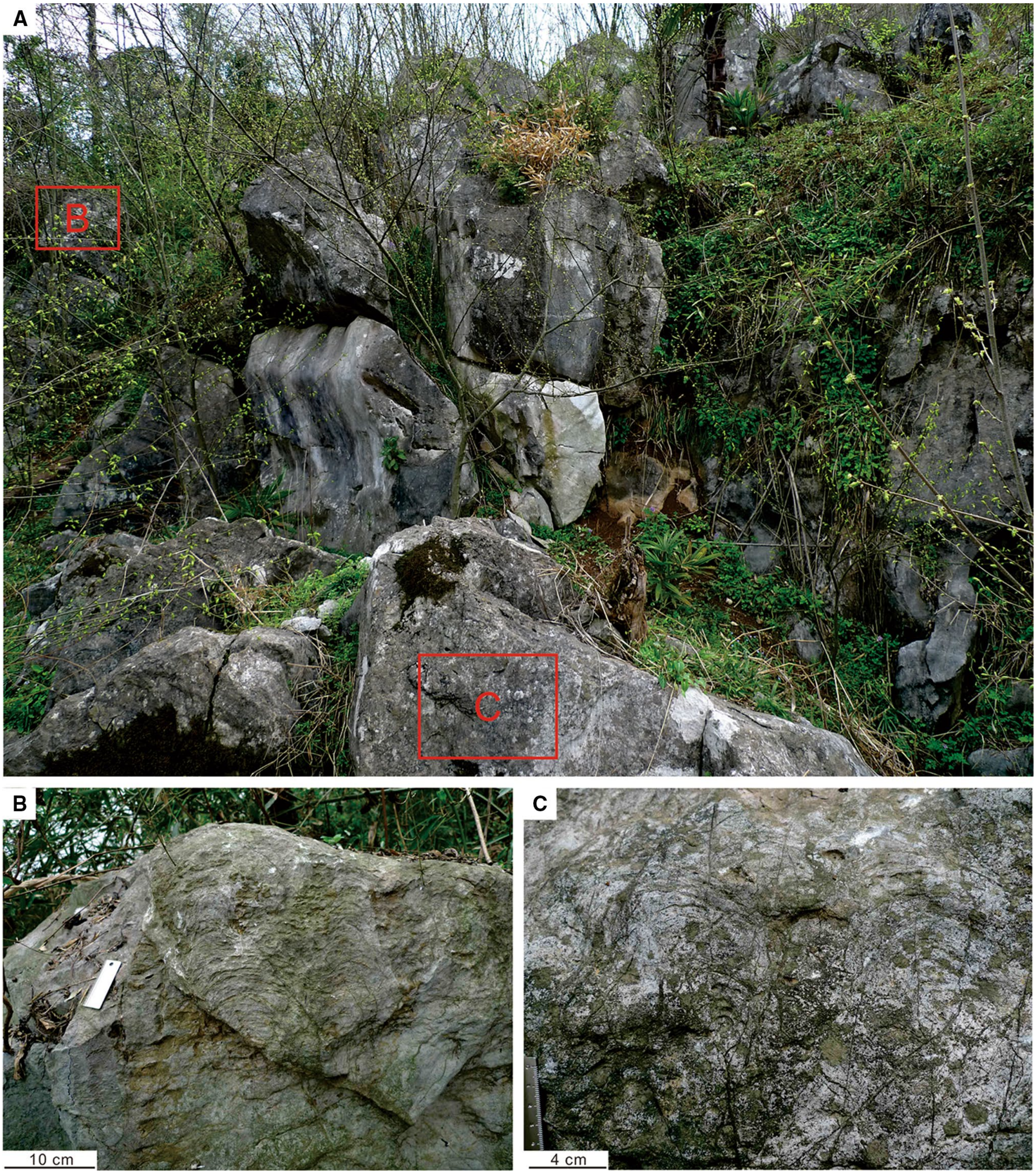


Fig. 4 **a** Thick-bedded stromatolitic sequences of the upper member of the Lunshan Formation at the Beigong section, Jinxian; **b**, **c** enlargements of red boxes in **a**: morphology of the dome-shaped stromatolites in outcrop

borings formed by unknown organisms on the surfaces of crinoid fragments and then these dwelling cavities were available for calcimicrobes (Fig. 6d). Crinoid fragments less than 1 mm to 10 mm with secondary recrystallization are concentrated in some laminations and as key components for packstones within or between the stromatolitic units (Fig. 6b, d, f). Lithoclasts, poorly sorted and rounded, occur densely locally between the dome-shaped lamination units.

Other minor bioclasts are bivalves, trilobites, sponge spicules, brachiopods, all with high level of breakage, preserved as wackestones (Fig. 6e). *Epiphyton* and *Renalcis* are key contributors of the Early Ordovician reefs in North America and other areas (e.g., Pratt and James 1982, 1989; Webby 2002) but are not present in this stromatolitic unit. Abundant bioclasts and lithoclasts are potential indicators of a depth around fair-weather wave base with effects of turbulent water masses. Recent field-intensive studies in Shark Bay suggest that coccoid cyanobacteria tend to build stromatolites in the lower intertidal to subtidal zones, in contrast to the filamentous microbial communities in the upper intertidal zone (Suosaari et al. 2016).

Stromatolites of the upper member, Lunshan Formation at Ma'anshan section of platform margin

Massive-bedded limestones bearing rich stromatolites and rare macrofossils of the upper member of the Lunshan Formation are well exposed in the cliff of Ma'anshan Park (GPS: 30°12′ 47.34″ N, 117°29′ 10.35″ E) beside the Shitai Middle School, downtown area of Shitai County town (Fig. 7a). Stromatolites grew in the grey thick-bedded micritic limestones. Li et al. (2004) first interpreted this stromatolite as a reef deposit in the eastern Yangtze Platform margin. Wang et al. (2012) and Zhang et al. (2016) further cited the stromatolites for temporal and spatial reconstructions of the Early Ordovician reefs of the Yangtze Platform. The total thickness of the stromatolitic units is 23 m and subdivided into lower dense stromatolitic unit (20 m thick), and upper sparse stromatolitic unit (3 m thick). Above the stromatolitic units is grey thick-bedded micritic limestones and bioclastic wackestones with dissolution sutures. Dolostone close to the top of the Lunshan Formation may represent a dolomitic tidal flat, a regional regressional tract (Jiang et al. 2014).

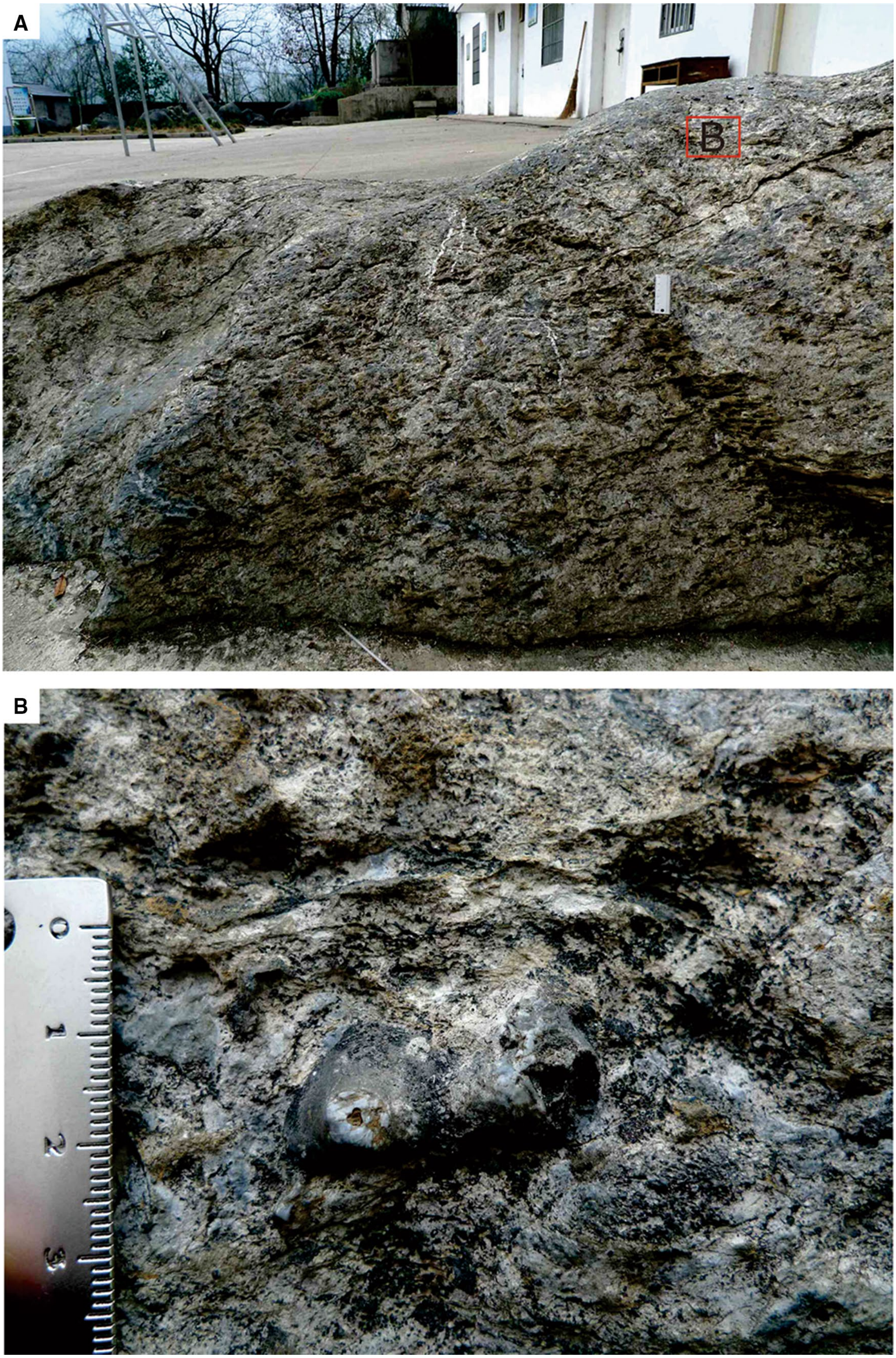
Morphological differences of stromatolites between Beigong and Ma'anshan sections are distinct. Stromatolites abundant in the lower dense unit at Ma'anshan are mostly columnar in contrast to the stratiform and dome-shaped at Beigong (Fig. 7b). Stromatolites occupy nearly 80% of the rocks in the lower dense stromatolitic unit; some individual columns are more than 1 m high. Macrofossils are rare except a few nautiloids between stromatolitic columns (Fig. 7c). Thin bright and thick dark laminations are basic structures of the bindstones (Fig. 7d). In the dark laminations, micro-clots are distinct. However, *Girvanella* filaments have not been recognized, implying that coccoid cyanobacteria predominate in the stromatolites here. No microbial boring can be confirmed in the thin sections. The space between stromatolitic columns is filled mainly by micritic components, and occasionally by some brachiopod fragments (Fig. 7e) and sand-sized intraclasts. Fragmented bioclasts might reflect distal transport by storms from other areas of the shallow platform. In a few cases, these grains interrupted the growth of the stromatolitic laminations. Bioturbation shown as yellow muddy mottling is uncommonly present on the surfaces of calcimicrobial-mats. Spaces between columns of stromatolites are usually filled by lime mud. We deduce that column-shaped stromatolites kept their relief above marine-floor with maximum depth around storm-wave base. Narrow spaces between stromatolitic columns were not ideal for reef-attached shelly fauna.

Terrigenous debris-dominated sequences of the middle member, Dawuqian Formation at Ziliqian section, a slope setting

The middle member of the Dawuqian Formation along the path of the Ziliqian village (GPS: 30°20′ 3.228″ N, 117°53′ 42.98″ E) is almost vertically dipping with thickness about 31 m. The lithological sequence is quite different from the equivalent upper member of Lunshan Formation showing distinctive increasing contains of the darkish grey siltstones and shales (Fig. 3). Thin-medium bedded limestones with yellow ribbon structures from the middle part of the middle member of the Dawuqian Formation is about 3.5 m in thickness (Figs. 3, 8a). Sedimentary structures of typical shallow turbulent environments are missing. Gravity-controlled sediment derived from shallower platform with such features as graded bedding, erosional and slumping structures has not been recognized. Angular and well-sorted quartz grains are present in siltstones (Fig. 8b, e), and also in thin-bedded micritic limestones (Fig. 8d). Marls (Fig. 8c) are thick-bedded and sparse in quartz clasts. Bioclasts of macrofossils are extremely low in abundance both in carbonates and terrigenous rocks, so no packstone and wackestone occur, only carbonate mudstones. We interpret these features of the slope setting of the Ziliqian section as a dark, even anoxic, environment below major-wave base, unfavorable for inhabitation of calcimicrobes and benthic shelly faunas.

Palaeoenvironmental pattern of the stromatolites

During the Tremadocian, shallow carbonates in southern Anhui Province are characterised by stromatolites. Other microbial fabrics, such as thrombolites (described by Shapiro 2000; Harwood and Sumner 2016), have not been recognized in the cases here. Their occurrence and distribution provide insight into the palaeoenvironmental patterns of the eastern Yangtze Platform (Fig. 9). Shallow, oxygenated, normal salinity, high-clarity and turbulent water at the sea floor in the Beigong section was favourable for metazoans such as crinoids, brachiopods, bivalves and trilobites. Moreover, an interpreted well-lit euphotic zone promoted photosynthesis of *Girvanella*. The growth habit of calcimicrobes shows lateral expansion resulting in abundant stratiform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◂**Fig. 5** **a** Stratiform to dome-shaped stromatolite beside classroom of the Beigong Primary School at the Beigong section, Jinxian; **b** Holdfasts of crinoid on the stromatolitic substrata

and dome-shaped stromatolites. Metazoans, especially shelly fauna, are of extremely low abundance and diversity in the stromatolites at Ma'anshan section at the platform margin indicating a deeper, calmer, even possible anoxic marine floor below major wave-base. Light intensity is interpreted to have been relatively weak due to the deeper water. Overall, stromatolites are largely column-shaped; vertical growth was likely more necessary for photosynthetic advantage. This

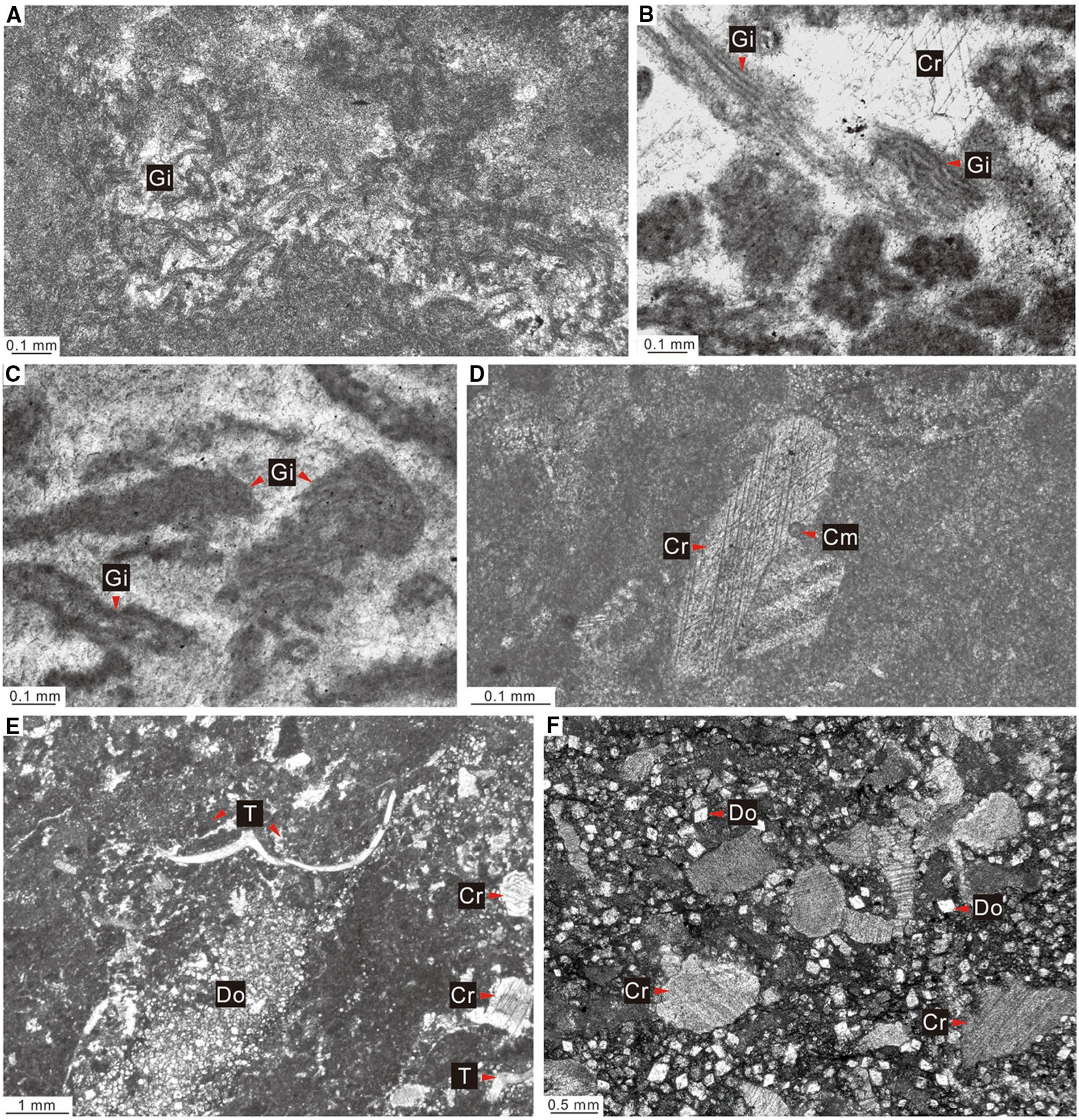


Fig. 6 Microfacies of the lithological types of the stromatolitic units, upper member of the Lunshan Formation at Beigong section of Jinxian; their sampling horizons shown in Fig. 3. **a** Tangled filaments of *Girvanella* (Gi), BG-3; **b** Linear and tangled filaments of *Girvanella* (Gi) and crinoidal fragment (Cr), BG-3; **c** tangled filaments of *Girvanella*, some filaments are recrystallized as spars, BG-3; **d** calcimicrobial (Cm) encrusts on the borings of crinoid (Cr) fragments, BG-4; **e** bioclastics of trilobite (T) and crinoid (Cr) fragments surrounding stromatolites, BG-3; **f** crinoidal fragments (Cr) within stromatolitic laminations, limemud partly dolomitization (Do), BG-2

ecological strategy was favorable for calcimicrobes surviving above the photic zone. In contrast, the slope belt of the Ziliqian section (with siltstone and marl) is interpreted to have been low-clarity water. Litho- and biofacies of the Tremadocian sequences along the Beigong, Ma'anshan and Liudu sections described above likely represent a gradient

Fig. 8 **a** Outcrop of the thin-medium bedded ribbon limestone (location of sampling number of the ZLQ-5 in the logging of Fig. 3) from the middle member of the Dawuqian Formation at Ziliqian section, the strata are nearly vertical dip by deformation; **b–e** microfacies of the lithological types; their sampling horizons shown in Fig. 3. **b** Siltstone with fine quartz grains, ZLQ-1; **c** Marls, ZLQ-5; **d** Micritic limestone with sparse quartz grains, ZLQ-3; **e** siltstone with rich and quartz grains, ZLQ-6 ▸

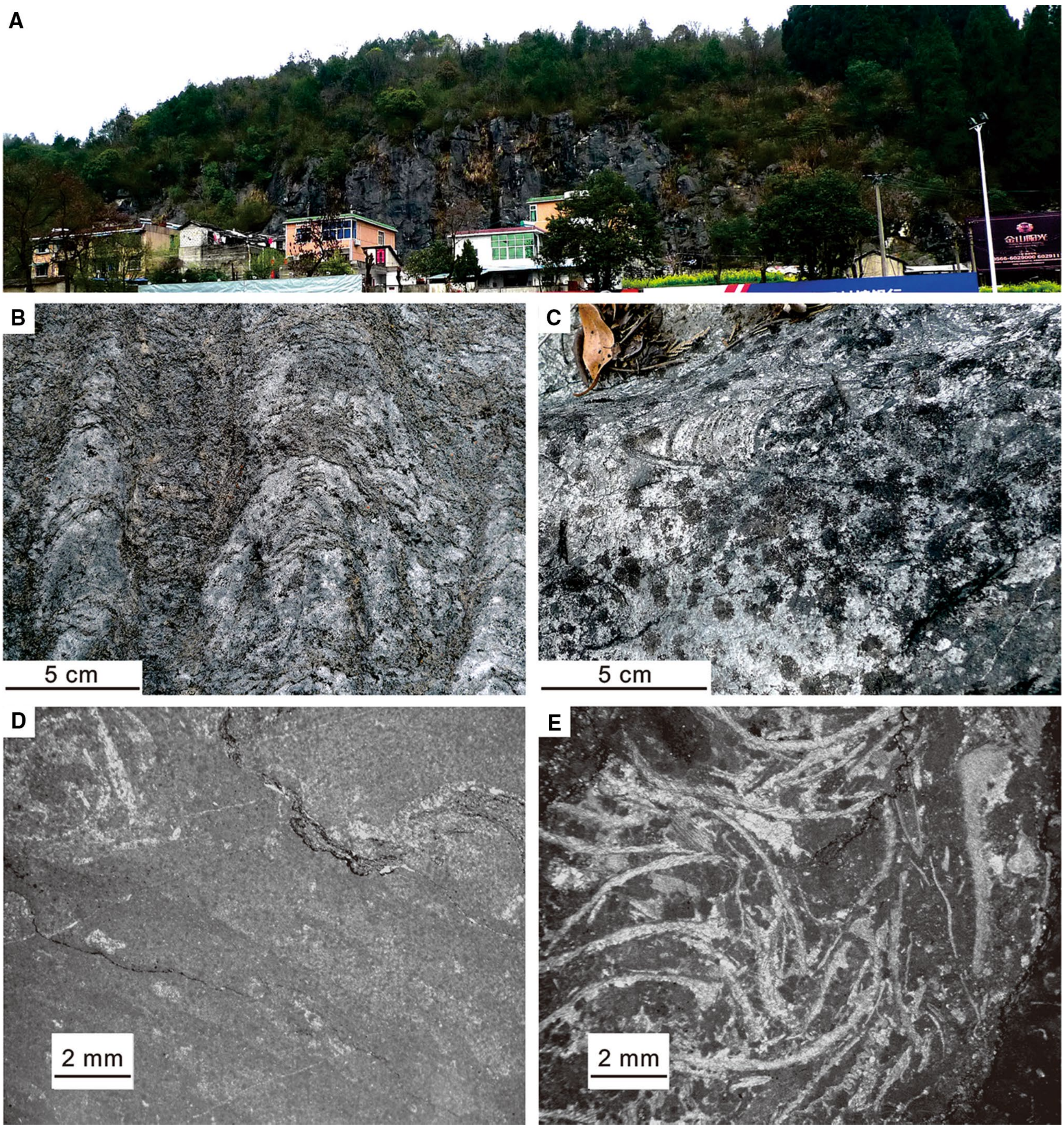
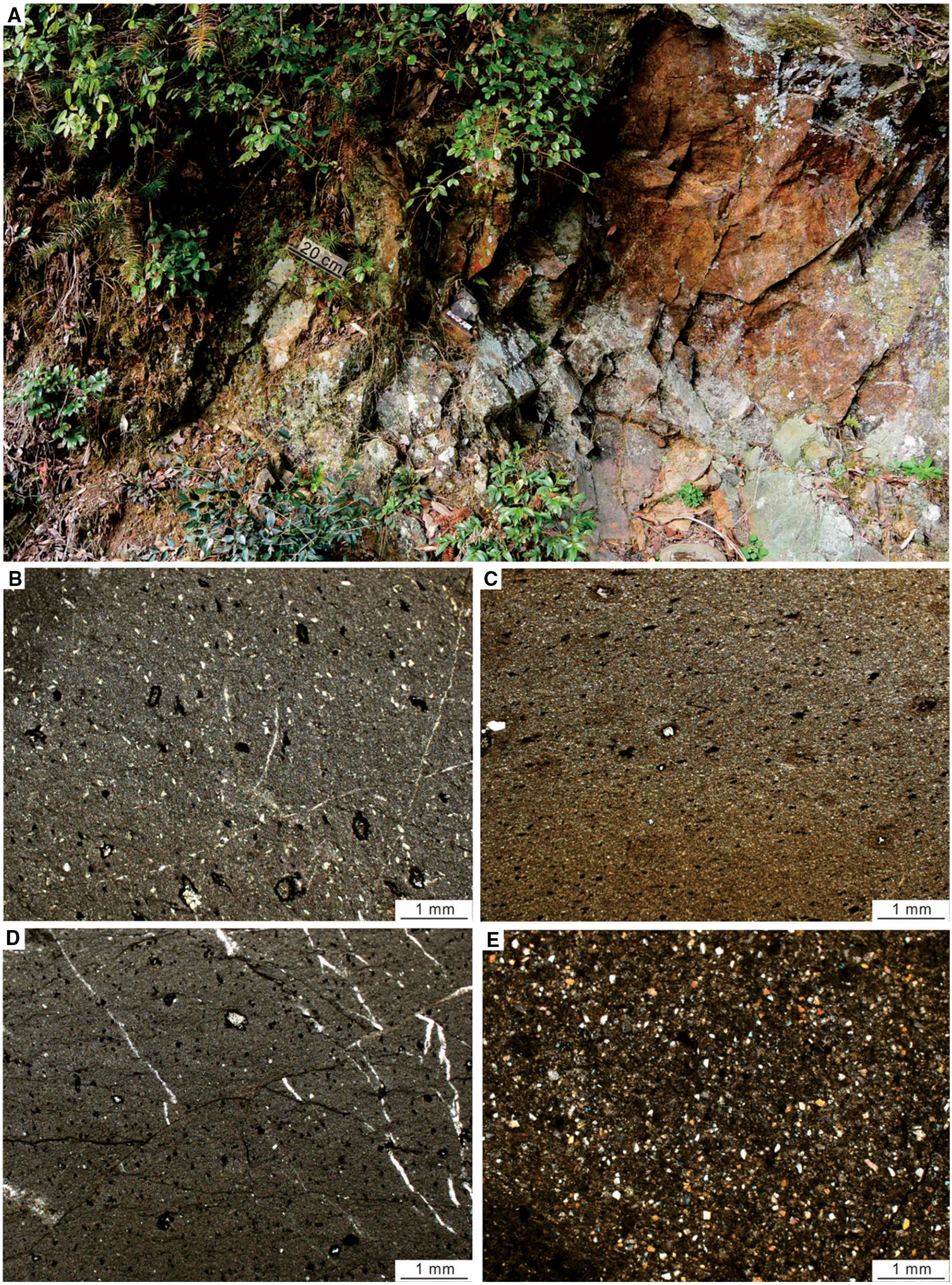


Fig. 7 **a** Lunshan Formation outcrop in the cliff at Ma'anshan behind Shitai Middle School, Shitai, containing stromatolites illustrated; **b** detail of outcrop showing column-shape stromatolites; **c** nautiloid between stromatolite columns; **d**, **e** show microfacies of the lithological types; their sampling horizons shown in Fig. 3. **d** Microfacies showing stromatolite dominantly formed by dark laminations, STL-2; **e** brachiopod shells deposited between column-shape stromatolites, STL-5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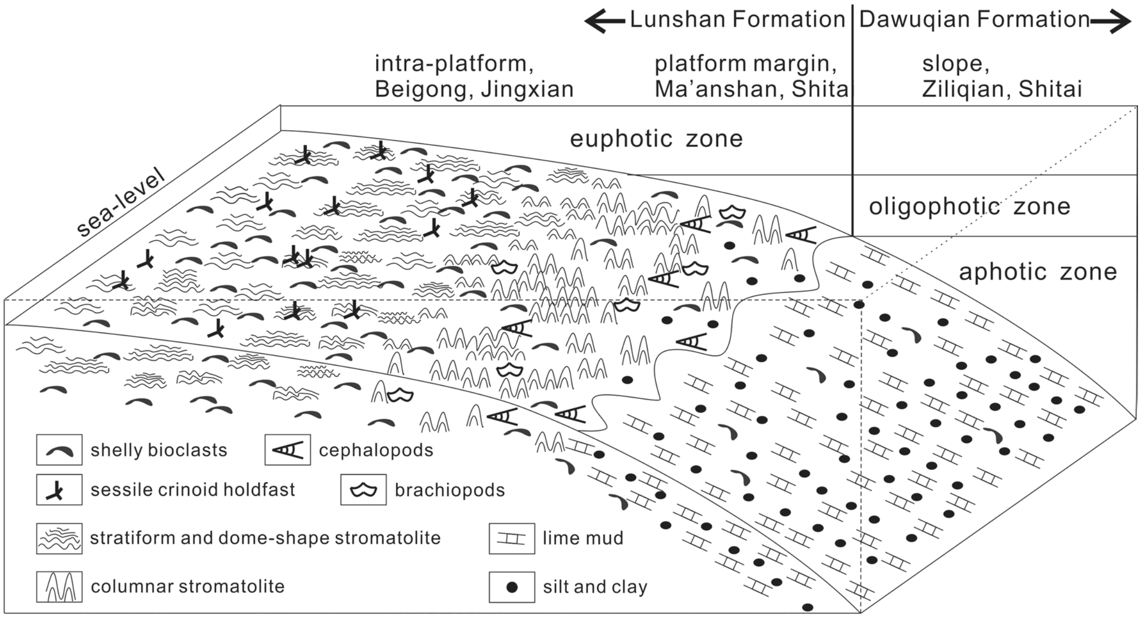

Fig. 9 Environmental reconstruction interpreting the biotic and lithological facies changes controlled by bathymetric deeping and decreased photosynthesis of marine-floor along the transition between the Lunshan and Dawuqian formations in the Tremadocian, southern Anhui

of environmental setting due to the increasing depth of the water column along the ramp of the platform and slope.

Discussion

Stratification of water column and vertical temperature gradient of marine-water in the Ordovician System have been considered as important factors in configuration of biogeographic patterns (e.g., Skevington 1974; Kaljo 1978; Jaanusson 1984; Brett et al. 1984; Yu et al. 2018); these hypotheses are supported by the bio- and lithofacies changes of the Tremadocian sequences of the present paper. Interpretations of oceanographic patterns characterized by vertical gradients, sluggish circulation and poorly ventilated marine water in the Early-Middle Ordovician (Fisher and Arthur 1977; Matin 1995, 1996; Berry and Wilder 1978) are supported by the present case of the Dawuqian Formation at Liudu section, where anoxic conditions in the lower parts of the shelf slope might are interpreted to have reduced the diversity and abundance of benthic fauna. The present case emphasizes that the late Tremadocian was an episode in the Palaeozoic when stromatolites still occupied a variety of normal marine shelf facies of the eastern Yangtze Platform.

Microbial reefs in shallow marine settings were quite common in the Tremadocian time globally (Webby 2002). Nevertheless, reefs formed by sessile metazoan were also reported from shallow marine floor of intra-platforms; they form associations together with calcimicrobes such as in the case of the bryozoa reef in St. George Group, Newfoundland (Pratt and James 1989). Tremadocian metazoan reefs formed by bryozoan-lithistid sponge communities occurred in the Fenhsiang Formation, outer-shelf of the western Yangtze Platform (Li et al. 2004; Adachi et al. 2011). Metazoan-calcimicrobial communities are also diverse in the Tremadocian of Argentina (Cañas 1999; Cañas and Carrera 1993, 2003 or Carrera et al. 2017); and also in North America (Cecile 1989; Rigby and Desrochers 1995). After this period, with the increased development of skeletal reef-builders, stromatolites sharply declined in the mid-Ordovician (Garrett 1970; Pratt 1982; Riding 2006; Peters et al. 2017). Webby (2002) summarized that both calcimicrobial reefs and metazoan reefs were present throughout the eight reef development episodes of the Ordovician time, indicating that the evolutionary transition from microbial- to metazoan-dominated was a complex process. Thus, while development of Ordovician metazoan reefs is evidence of the major changes, the GOBE was not isochronous; stromatolites and other calcimicrobial reefs did occupy carbonate platforms locally (Webby 2002; Adachi et al. 2009). Therefore, stromatolites, of which the present case are excellent examples of facies-controlled systems, demonstrate microbial reefs continued to occupy ecological niches unsuitable for metazoan builders. Absence of metazoan reefs in southern Anhui demonstrates stenotopic and narrow biogeographic realms of sessile fauna.

Conclusions

1. Spatial distributions of the Tremadocian stromatolites in the eastern Yangtze Platform were essentially controlled by the depth of the sea floor rather than variation of turbidity.
2. Stromatolites, as the only reef type in the Tremadocian time in the study area in the eastern Yangtze Platform, thrived from intra-platform to platform margin palaeogeographically in southern Anhui. Biodiversities of reef-dwelling fauna were low, corresponding to the increasing depth of the water column.
3. Benthic communities of both calcimicrobes and metazoans have limited distribution from intra-platform of the Beigong section to platform margin Ma'anshan section, where the depth of sea floor is interpreted to have been around the oligophotic zone.
4. Neither stromatolites or benthic fauna occur in slope facies, where the depth of the sea floor was below the euphotic zone and might become anoxic.
5. The shift from microbial- to metazoan-dominated reefs shown substantial geographic variation during the GOBE, demonstrating facies controls on these shallow marine ecosystems.

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