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Formative mechanisms, depositional processes, and geological implications of Furongian (late Cambrian) reefs in the North China Platform

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ABSTRACT

The Cambrian Series 3–Furongian successions of the North China Platform contain various microbial–metazoan and microbial reefs. This study focuses on Furongian reefs of the platform in order to understand formative processes and the evolution of the reefs during Cambrian Epoch 3 and the Furongian. Three types of Furongian reefs were differentiated in the Shandong region, China: maceriate reefs, columnar stromatolitic reefs, and small-scale microbial reefs. Maceriate reefs show dm- to m-scale domal or flat-bedded geometry, and consist of cm-scale maze-like maceria structures made of siliceous sponges and microbial components (microstromatolites, *Girvanella*, and *Tarthinia*). Columnar stromatolitic reefs are characterized by stromatolite columns of 10–100 cm in height and 5–50 cm in diameter. They consist dominantly of *Girvanella*, with less conspicuous, poorly preserved sponge spicule networks. Small-scale microbial reefs commonly show cm- to dm-scale, domal macrostructures, and were constructed mainly by calcimicrobes, *Girvanella* and *Renalcis*. These three types of Furongian reefs were deposited in various shallow-marine settings in response to relative sea-level changes.

The Furongian reefs are markedly different, in terms of macro- and micro-fabrics, from the Cambrian Series 3 reefs that are dominated by thrombolites and dendrolites and were constructed mainly by *Epiphyton* in the Shandong region. This difference is also recognized in the Beijing region, ca. 500 km away. The abrupt transition from the Cambrian Series 3-type to Furongian-type reefs, coincidently with a decrease in calcified microbe diversity, was most likely due to global euxinic oceanic conditions and a possible eustatic sea-level drop, rather than the highly diachronous, platform-wide drowning event (i.e., drowning of the Cambrian Series 3 carbonate platform). The abundant occurrence of sponge spicule networks in the Furongian reefs suggests that metazoan reef builders (i.e., sponges) resurged and became actively involved in the reefal systems prior to the Great Ordovician Biodiversification Event. This study may provide an important basis for further investigation into the evolution of reefal systems during the middle to late Cambrian when metazoan reef-builders were known to be scarce.

1. Introduction

The evolution and extinction of organisms significantly affected Early Paleozoic reef-building communities (Wood, 1999; Rowland and Shapiro, 2002). Early Cambrian reefs were mainly constructed by archaeocyaths and diverse calcimicrobes (e.g., Rees et al., 1989; Elicki, 1999; Rowland and Shapiro, 2002). Archaeocyaths went to extinction during the end-Cambrian Epoch 2 extinction event, and many calcified microbes perished as well (Zhuravlev, 1996; Riding, 2001; Lee et al., 2014b). Metazoan reef builders participated only to a limited extent in constructing reefs until the Early Ordovician (Adachi et al., 2011; Wang et al., 2012). It is thus commonly believed that the middle to late Cambrian (Cambrian Epoch 3 to Furongian) was dominated by reefal microbialites (Wood, 1999; Riding, 2006).

The North China Platform contains various microbial and microbial–metazoan reefs that are Cambrian Epoch 3 and Furongian in age (Woo et al., 2008; Chen et al., 2009, 2011; Lee et al., 2010, 2012, 2014a; Woo and Chough, 2010; Chen and Lee, 2014). The reefs of these two intervals are, however, tremendously different with respect to their micro- and macro-scale features. The Cambrian Series 3 reefs are characterized by thrombolites and dendrolites that were constructed mainly by the calcimicrobe *Epiphyton*, with minor metazoan reef-builders (Woo et al., 2008; Woo and Chough, 2010; Park et al., 2011; Hong et al., 2012). On the other hand, the Furongian reefs mainly consist of maze-like, maceriate sponge-microbial reefs and columnar stromatolitic reefs, without any *Epiphyton* (Chen et al., 2011; Lee et al., 2014a). These Furongian reefs, on the whole, are not yet fully investigated,

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except for the maceriate reefs that were recently studied by Lee et al. (2010, 2012, 2014a).

The Furongian reefs are critical with respect to the evolution of reefal systems during the Early Paleozoic since they connect the Cambrian Series 3 reefal systems in the aftermath of end-Cambrian Series 2 extinction event with the Early Ordovician reefs that formed during the Ordovician biodiversification event. In order to examine the geological characteristics of the Furongian reefs, this study focuses on those in the central-eastern part of the North China Platform (Shandong Province, China), which are compared with coeval reefs in the northern part of the platform (Beijing region, China). The main objectives of the present study are thus to (1) illustrate various Furongian reefs and their formative processes, (2) elucidate the nature of reef development in response to relative sea-level changes, and (3) discuss the evolution of Cambrian reef systems by comparing the Furongian reefs with Cambrian Series 3 reefs of the same region.

2. Geological setting

The North China Platform was an extensive epeiric platform (1500 km east–west and 1000 km north–south) that formed on a stable craton, the North China Block (Sino-Korean Block), during the Early Paleozoic (Meyerhoff et al., 1991). It is now bounded by major suture zones, the Hinggan fold belt in the north, the Qinling–Dabieshan fold belt in the south, and a major sinistral strike-slip fault, the Tan–Lu fault, in the east (Chough et al., 2000) (Fig. 1A). Sedimentation on the North China Platform started in Cambrian Series 2 and continued until the Middle to Late Ordovician when the entire platform was subaerially exposed. This resulted in a thick (ca. 1800 m in thickness) succession of mixed carbonate and siliciclastic deposits (Meyerhoff et al., 1991; Meng et al., 1997). After a platform-wide hiatus during the middle Paleozoic (Late Ordovician to Early Carboniferous), coal-bearing, shallow marine and continental deposits accumulated on the platform during the Carboniferous and Permian (Lee and Chough, 2006; Lv and Chen, 2014). Deposition on the platform was terminated in the Early Triassic by regional uplift that resulted from the collision between the North China Block and the South China Block (Lee and Chough, 2006).

The Cambrian strata on the North China Platform contain a thick (ca. 800 m) succession of mixed siliciclastic and carbonate sediments, which were deposited in shallow-marine settings during long-term sea-level rise (Meng et al., 1997). The Cambrian succession in Shandong Province, China consists of six lithostratigraphic units (i.e., the Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian Formations in ascending order), which unconformably overlies Precambrian granitic gneiss or metasedimentary rocks and is conformably overlain by late Furongian–Early Ordovician dolostones (Sanshanzi Formation) (Meng et al., 1997; Chough et al., 2000; Lee and Chough, 2011) (Fig. 2). The dolomitization took place during Middle Ordovician subaerial exposure of the North China Platform, resulting in a highly diachronous lower boundary (Feng and Jin, 1994).

The basal Liguan Formation (laterally discontinuous, 0–30 m thick) consists mainly of quartzose sandstone and mudstone (Fig. 2). It changes both laterally and vertically into the carbonate-dominant Zhushadong Formation (15–40 m thick), which is characterized by stromatolitic and dolomitic lime mudstone, and locally bioturbated wackestone with minor microbial reefs (Lee and Chough, 2011; Lee et al., 2014b). The Mantou Formation (ca. 250 m thick) consists of mixed siliciclastic and carbonate sediments including purple mudstone, sandstone, and various carbonate deposits (Lee and Chough, 2011). The overlying Zhangxia Formation (ca. 180 m thick) is characterized by a variety of microbial-dominant reefs, carbonate deposits, and locally shaly sediments that were deposited during the Cambrian Epoch 3 Changhian Age (*Lioparia*, *Crepicephalina*, *Amphoton*–*Taitzuia*, and *Damesella*–*Yabeia* zones; late Cambrian Age 5–early Guzhangian) (Woo, 2009). The Gushan Formation (52–105 m thick) comprises shale-dominated facies deposited during the late Cambrian Epoch 3 Kushanian Age (*Blackwelderia* and *Neodrepanura* zones; late Guzhangian) (Fig. 2). The overlying Chaomidian Formation (190–260 m thick) is dominated by various carbonate facies including thin-bedded limestone-shale/marlstone alternations, wacke- to packstones, grainstones, limestone breccias and

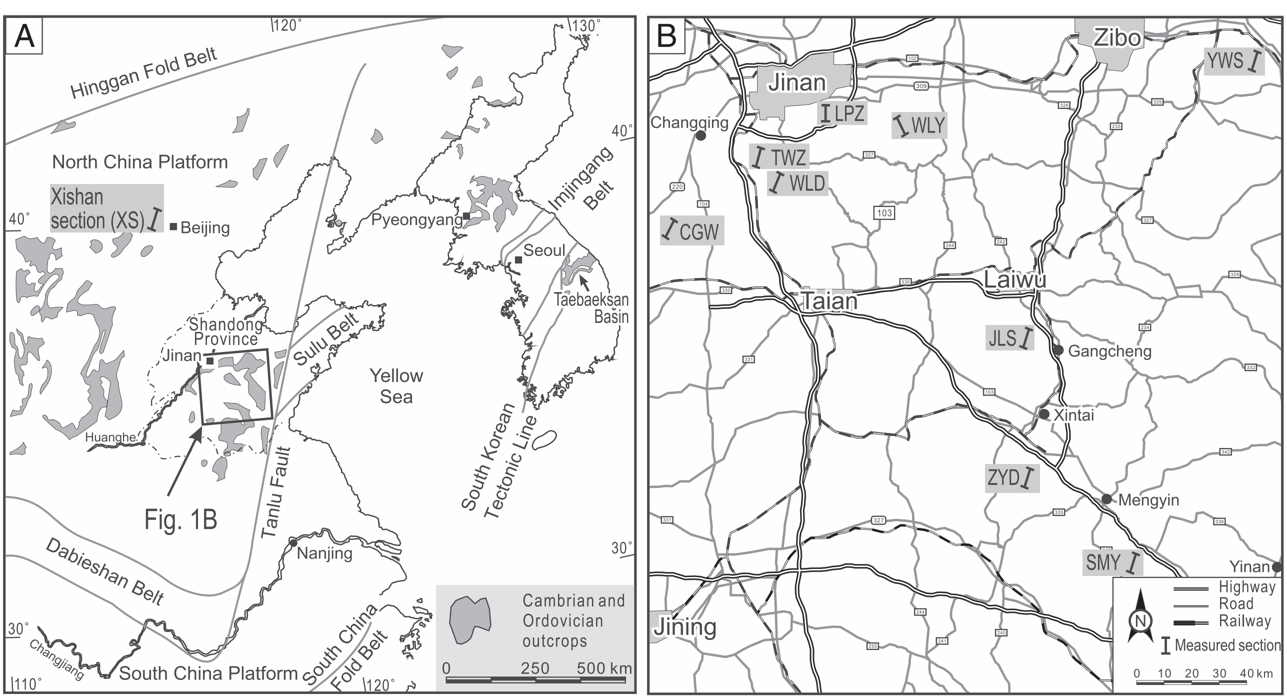

Fig. 1. Brief geological map of the North China Platform and location map of measured outcrop sections. (A) Major tectonic boundaries of the North China Platform and distribution of the Cambrian–Ordovician outcrops, with location of the Xishan section (39°59′38″N, 116°1′18″E). (B) Location map of measured outcrop sections in the Shandong region. CGW: Chengouwan section (36°22′48″N, 116°41′36″E); TWZ: Tangwangzhai section (36°31′00″N, 116°51′39″E); WLD: Wanglaoding section (35°29′5″N, 116°55′53″E); LPZ: Laopozhuang section (36°34′8″N, 117°4′34″E); WLY: Wanliangyu section (36°33′11″N, 117°16′12″E); JLS: Jiulongshan section (36°5′5″N, 117°44′58″E); ZYD: Zhaoyangdong section (35°45′18″N, 117°46′29″E); SMY: Sunmayu section (35°33′40″N, 118°2′11″E); YWS: Yaowangshan section (36°43′02″N, 118°24′58″E).

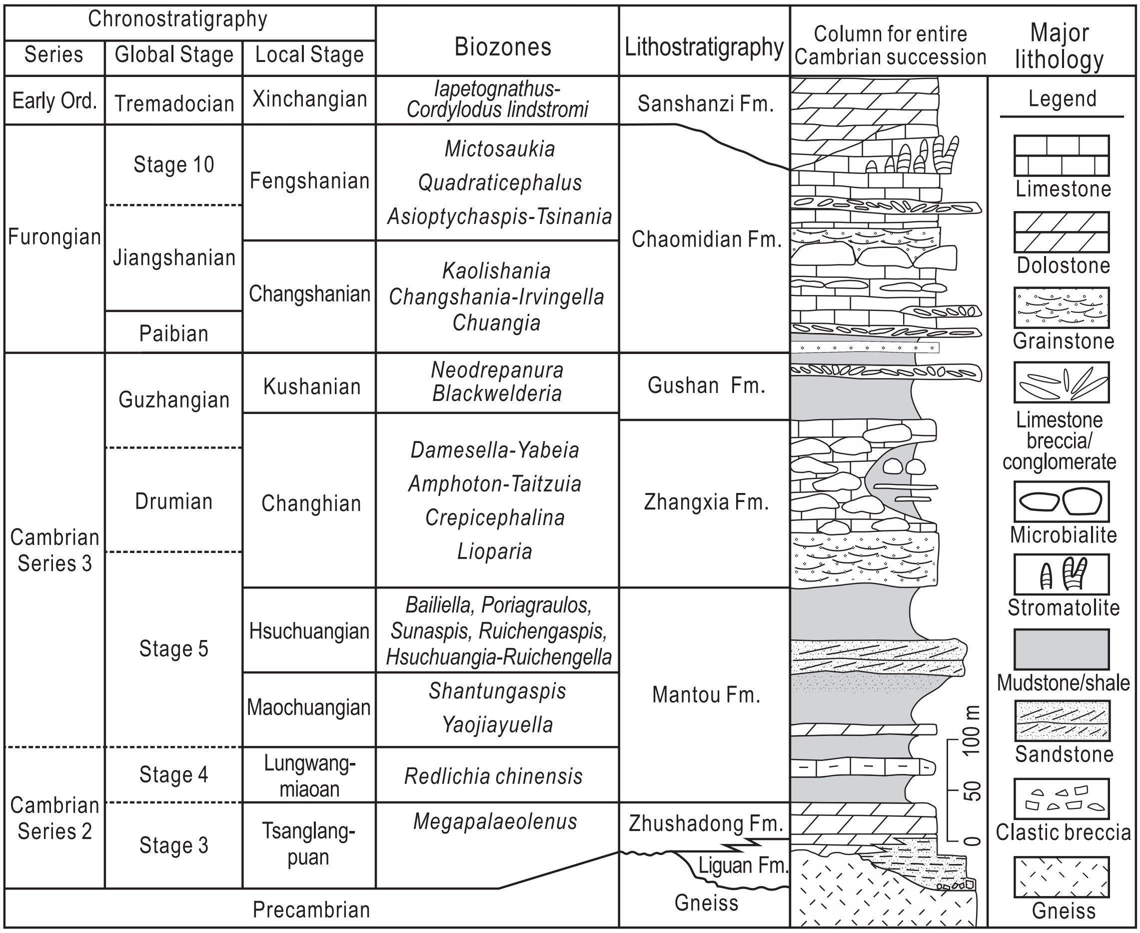

Fig. 2. Generalized chrono- and lithostratigraphy of the Cambrian succession in the North China Platform in Shandong region, China. Modified after Chough et al. (2010).

conglomerates, and various reefs (Chen et al., 2009, 2011, 2012; Lee et al., 2010, 2012, 2014a), which formed during the Furongian, including the Changshanian Age (*Chuangia*, *Changshania–Irvingella*, and *Kaolishania* zones; Paibian–early Jiangshanian) and Fengshanian Age (*Asioptychaspis–Tsinania*, *Quadraticephalus*, and *Mictosaukia* zones; late Jiangshanian–Cambrian Age 10) (Chough et al., 2010; Park et al., 2014) (Fig. 2).

3. Furongian reefs of the North China Platform

The Furongian succession in the North China Platform (Shandong Province) is well exposed in many outcrop sections in the Shandong and Beijing regions (Figs. 1 and 3). The succession contains many levels of microbial-dominant reefs as well as the recently redefined "maceriate sponge-microbial reefs" (Fig. 3), which are, in this study, collectively regarded as reefs in order to incorporate all biogenic buildups (Wood, 1999). The Furongian reefs are described in detail in terms of their microstructures, mesostructures, various orders of macrostructures, and megastructures (Chen and Lee, 2014), and are generally classified into three major categories: maceriate sponge-microbial reefs, columnar stromatolitic reefs, and small-scale microbial reefs.

3.1. Maceriate sponge-microbial reef

3.1.1. Description

Maceriate reefs are present in the middle part of the Chaomidian Formation in all studied sections (Figs. 1B and 3). They are characterized by centimeter-scale "maze-like" maceria structures (plural: maceriae), showing a branching, column-like shape in longitudinal section and a maze-like complex shape in transverse section (Shapiro and Awramik, 2006; Lee et al., 2010) (Fig. 4). The boundaries between maceriae and inter-macerial detrital carbonate sediment are commonly ragged. Based on components of maceriae and inter-macerial sediment, the maceriate reefs are classified into three types: muddy maceriate reefs (Fig. 4A, B), grainy maceriate reefs (Fig. 4C), and dolomitized maceriate reefs (Fig. 4D). The maceriate reefs display a range of macrostructures (e.g., Chen and Lee, 2014), including simple domes (a few decimeters to meters in width) (Fig. 5A), or compound domes that consist of columns (a few cm to dm in width). In outcrop scale, they show either biostromal or biohermal megastructures (Fig. 5B, C). Biostromal maceriate reefs are laterally extensive and can be correlated for several tens of kilometers (Lee et al., 2010, 2012). Biohermal maceriate reefs, which mainly consist of domal buildups, are traceable for several hundred meters. Bedded detrital carbonate sediment such as limestone-shale alternation, grainstone, and limestone conglomerate are present in between the maceriate reefs (Fig. 5B).

Muddy maceriate reefs correspond to those described by Lee et al. (2010, 2014a) (Fig. 6A, B). These reefs are characterized by maceriae and inter-macerial sediment (including lime mud and a few bioclasts) (Fig. 6A). Carbonate grains such as bioclasts are rarely present within the maceriae. Grainy maceriate reefs also show clear maceria structures, but they contain pack- to grainstone (composed of ooids and/or bioclasts) as inter-macerial sediment (Fig. 6C). Only a few carbonate grains exist within the maceriae of grainy maceriate reefs (Fig. 6C). Dolomitized maceriate reefs occur in the entirely dolomitized strata (upper Furongian–lower Ordovician Sanshanzi Formation in the North China Platform) (Fig. 6D). Maceriae and inter-macerial sediment in the dolomitized maceriate reefs can be differentiated by the color and

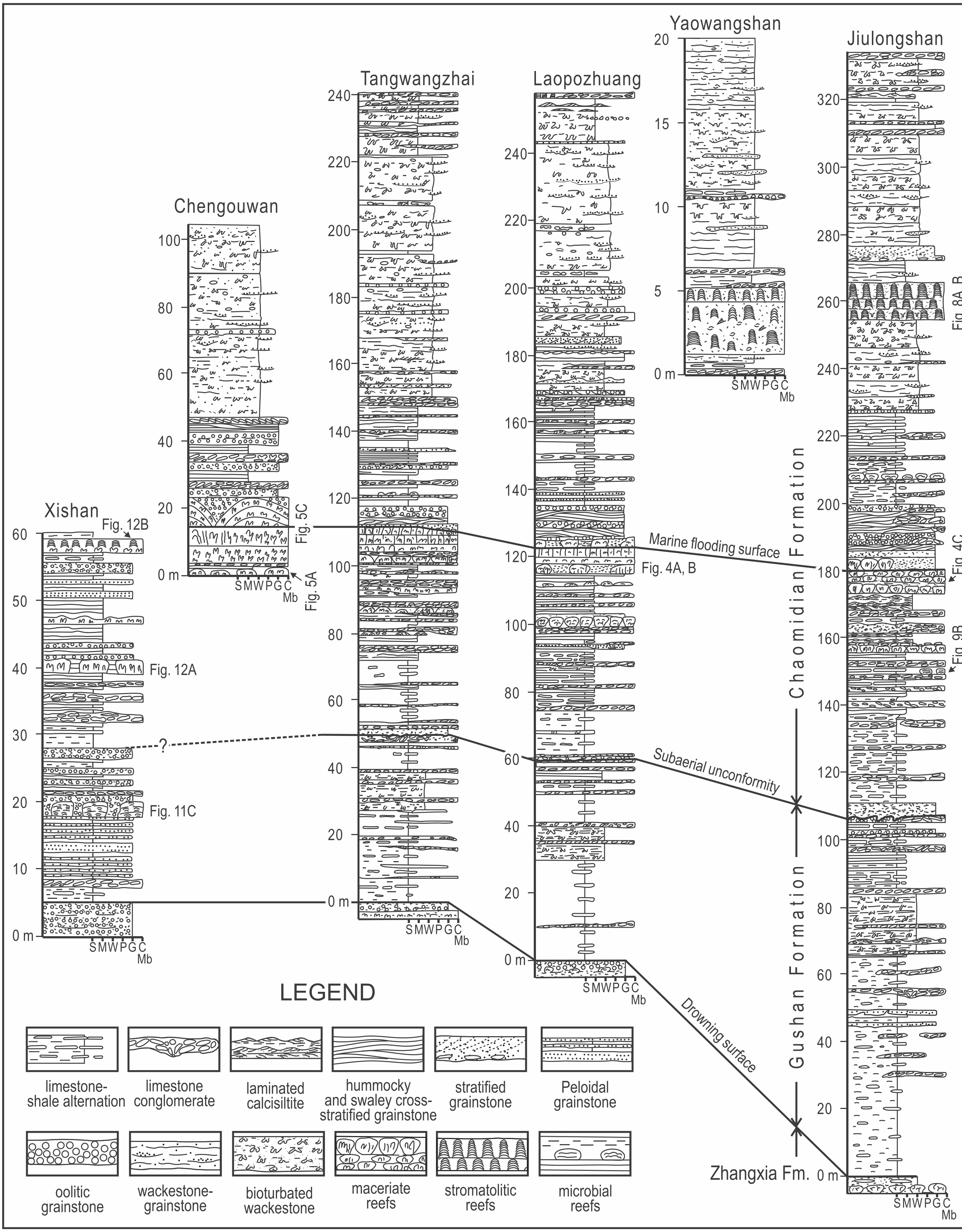

Fig. 3. Sedimentary logs (redrawn from original scale of 1:50) of the Furongian succession in representative sections of the Beijing and Shandong regions. For section location, see Fig. 1. S: shale; M: lime mudstone; W: wackestone; P: packstone; G: grainstone; C: conglomerate; Mb: microbialite.

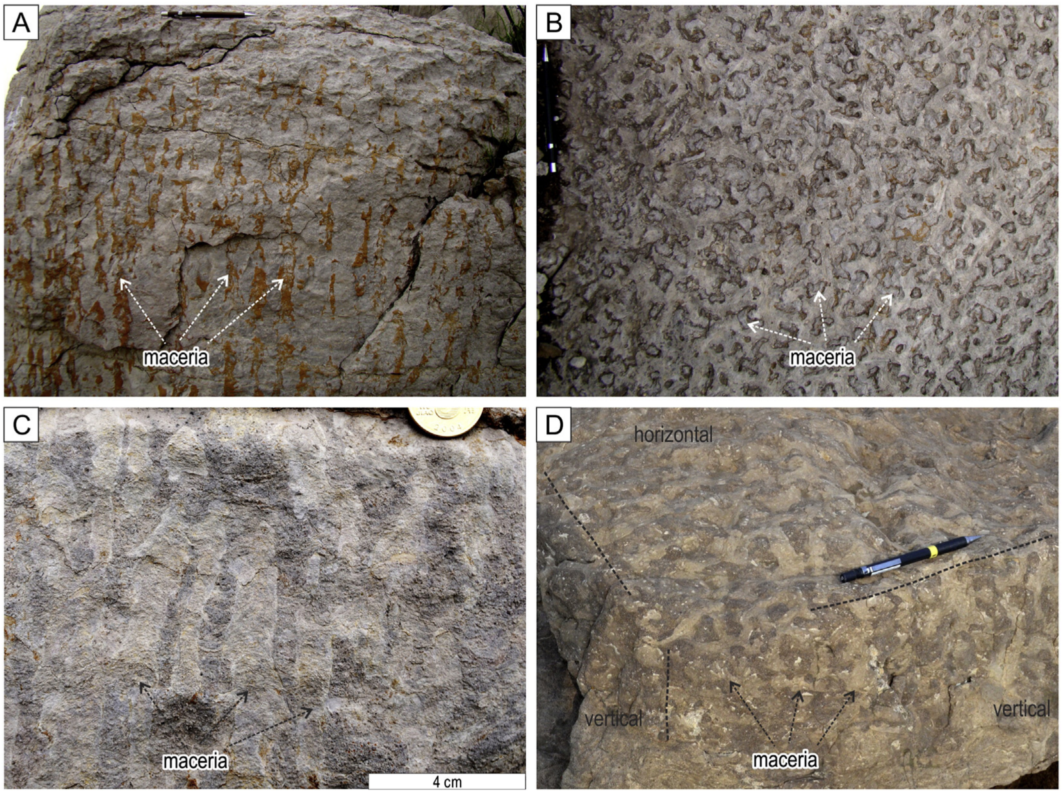

Fig. 4. Maceria structures of the maceriate reefs. (A) Vertical section of muddy maceriate reef, showing columnar or digitate features (maceria structures) which diverge or converge vertically, Laopozhuang section (for section location, see Fig. 1). (B) Differentially weathered bedding surface of muddy maceriate reef, Laopozhuang section. (C) Maceria structures with bioclasts filled in the inter-macerial space (grainy maceriate reef), Jiulongshan section. (D) Dolomitized maceriate reef showing clear maceria structures which can be recognized by different color and texture, Sunmayu section.

texture of the dolomite: maceriae are lighter in color with coarser grains, whereas the inter-macerial sediment is darker with finer grains (Figs. 4D and 6D).

In micro-scale, two major components are identified within the maceriae of the muddy and grainy maceriate reefs: siliceous sponges and microbial components (Lee et al., 2014a) (Fig. 6A–C). The siliceous sponges are characterized by mm- to cm- scale spicule networks which are barely recognizable in outcrops or polished slabs (Fig. 6A–C). Microbial components include microstromatolites, *Girvanella*, and rare *Tarthinia* (described as *Renalcis*-like form by Lee et al., 2014a). There is no clear difference between the muddy and grainy maceriate reefs in terms of the two components (Fig. 6C). On the other hand, no sponge spicules or microbial components can be identified within the dolomitized maceriate reefs. The maceriae of the dolomitized maceriate reefs consist of coarser-grained dolomite crystals of 200–500 μm in size, whereas finer-grained dolomites (50–200 μm in size) are present in the inter-macerial space together with some fossil fragments (Fig. 6D).

3.1.2. Interpretation

The occurrence of sponges and microbial components within maceriae suggests that they are essential for the formation of maceriae (Fig. 7). The absence of sponge spicules and microbial components in dolomitized maceriate reefs indicates that dolomitization could have obscured maceria-forming organisms (cf. Shapiro and Awramik, 2006). The maceria structures were constructed by framework-building siliceous sponges and microstromatolites, together with encrusting sponges and *Girvanella* (Lee et al., 2014a) (Fig. 7A). The general absence of detrital carbonate sediment (e.g., lime mud, ooids, and bioclasts) within maceriae suggests that trapping and binding processes by sponges and microbes were not active during their growth. The deposition rate of inter-macerial sediment was most likely balanced with the growth rate of maceriae, sustaining a low synoptic relief of less than a centimeter, forming a ragged boundary between maceriae and inter-macerial sediment (Pratt and James, 1982; Shapiro and Awramik, 2006; Lee et al., 2014a). Continued growth of biogenic maceriae and deposition of detrital carbonate sediment formed the maze-like maceria structures (Fig. 7B). Eventually, meter-scale bioherms and biostromes were formed (Fig. 7C).

Two mechanisms have been proposed for the formation of maceriate reefs (Shapiro and Awramik, 2006; Lee et al., 2010). Shapiro and Awramik (2006) suggested that specific organisms were responsible for the formation of maceriate reefs, based on the temporal restriction (late Cambrian to early Ordovician) of the maceriate reefs and their occurrence in various depositional environments. However, they were unable to identify the specific organisms involved, due mainly to recrystallization and dolomitization of the strata. On the other hand, Lee et al. (2010) proposed that global paleoenvironmental factors (e.g., sea-water chemistry, carbonate production, and lack of metazoan reef builders) were critical to the formation of maceriate reefs, based on the occurrence of abundant lime mud between the maceriae and the absence of specific organisms responsible for the formation of maceria structures. Recently, however, Lee et al. (2014a) reported siliceous sponges and microbial components from the maceriate reefs of the Shandong region, and they proposed that these organisms were responsible for the formation of the characteristic maze-like maceria structures, lending support to the Shapiro and Awramik (2006) hypothesis.

The occurrence of ooids and bioclasts in the inter-macerial space (in grainy maceriate reefs) suggests that a large input of lime mud is not necessary for the formation of maceriae. The siliceous sponges and microbial components that constructed maceriae are greatly affected by post-depositional processes. For example, dolomitization can completely destroy microfabrics of maceriate reefs, while preserving the characteristic, maze-like maceriae (Figs. 4D and 6D) (cf. Shapiro and Awramik, 2006). On the other hand, when sponge spicules are not well preserved,

Fig. 5. Macro- and megastructures of the maceriate reefs. (A) Small-scale domal maceriate reef. Scale bar in cm, Chengouwan section. (B) Flat-bedded maceriate reefs overlain by grainstones, Wanglaoding section. Note occurrence of bedded detrital carbonate strata in between two reefs. (C) Flat-bedded (biostromal) and domal (biohermal) maceriate reefs, separated by a marine flooding surface, Chengouwan section.

they mainly show structures similar to a vermiform or clotted texture (Kwon et al., 2012; Lee et al., 2014a), which are not easy to recognize. This study suggests that the maceriate reefs reported elsewhere, but not studied in detail in terms of microfacies, may also contain siliceous sponges as well as microbial components.

3.2. Columnar stromatolitic reefs

3.2.1. Description

The columnar stromatolitic reefs are mainly present in the upper part of the Chaomidian Formation and only in the eastern sections (Yaowangshan, Jiulongshan, Zhaoyangdong, and Sunmayu sections) (Figs. 1B and 3). In outcrop scale, columnar stromatolitic reefs show biostromal megastructures (as extensive as several km to tens of km) (Fig. 8A). They are constructed of vertically stacked columnar stromatolites with locally intercalated bioturbated wackestones and bioclastic grainstones (Fig. 8B). Stromatolite columns are commonly 30 to 100 cm in height and 10 to 50 cm in diameter, partly bifurcating or branching upward. The transverse surfaces of stromatolite columns display a circular shape. Small-scale (cm to dm) columnar stromatolites are often overlain by bioclastic grainstones, whereas larger columns (a few decimeters to meters) are overlain by bioturbated wackestones (Fig. 8B). Small columns are sometimes inclined or even laid down horizontally. The stromatolites are locally extensively bioturbated. The shells of various organisms, such as cephalopods, brachiopods, trilobites, and gastropods, are present within the stromatolites.

The stromatolites are crudely laminated, with discontinuous and coarse convex-up laminae. The stromatolites consist of fine-grained, light gray laminae alternating with grain-rich laminae (1–2 mm in thickness). Lamination is often enhanced by extensive stylolites (Fig. 8B). Inter-columnar space is often filled by peloids and microbialite clasts, as well as fossil fragments. Stromatolites are composed dominantly of *Girvanella* colonies, fragments of fossils (trilobites, algae, cephalopods, brachiopods, and gastropods), peloids, rhombic dolomite, and cement of sparry calcite (Fig. 8C, D). Poorly preserved siliceous sponge-spicule networks are also recognized within the columnar stromatolitic reefs (Fig. 8C).

3.2.2. Interpretation

Columnar stromatolites commonly form in intertidal to subtidal environments with sufficient water depth and hydrodynamic conditions for their formation and accumulation (Campbell, 1976; Rees et al., 1976; Dravis, 1983; Riding et al., 1991; Andres and Reid, 2006; Jahnert and Collins, 2011; Jahnert et al., 2013). The complete absence of supratidal features (e.g., desiccation cracks, fenestral cavities, and tepee structures) suggests that the columnar stromatolites from the Chaomidian Formation were possibly formed in either intertidal or subtidal settings. The presence of pervasive bioturbation and various fossil fragments associated with the stromatolites is, however, indicative of a more subtidal setting. The columnar stromatolitic reefs probably formed in relatively high-energy settings, which is evinced by coarse-grained inter-columnar sediment. Alternation of laminae resulted from trapping and binding of detrital carbonate sediment and calcification of cyanobacteria, *Girvanella* (Riding, 1999, 2000). The presence of patches of spicules (Fig. 8C) indicates that sponges might have played a minor role in the construction of the stromatolite reefs together with *Girvanella*.

The smaller stromatolite columns and upward branching columns resulted from rapid deposition of coarse sediment which interrupted and/or terminated the growth of microbes. Fallen small columns were caused by strong hydrodynamic conditions that broke the cemented, rigid columns. Bioturbated wackestone might have been deposited during low-energy conditions after the formation of stromatolite columns.

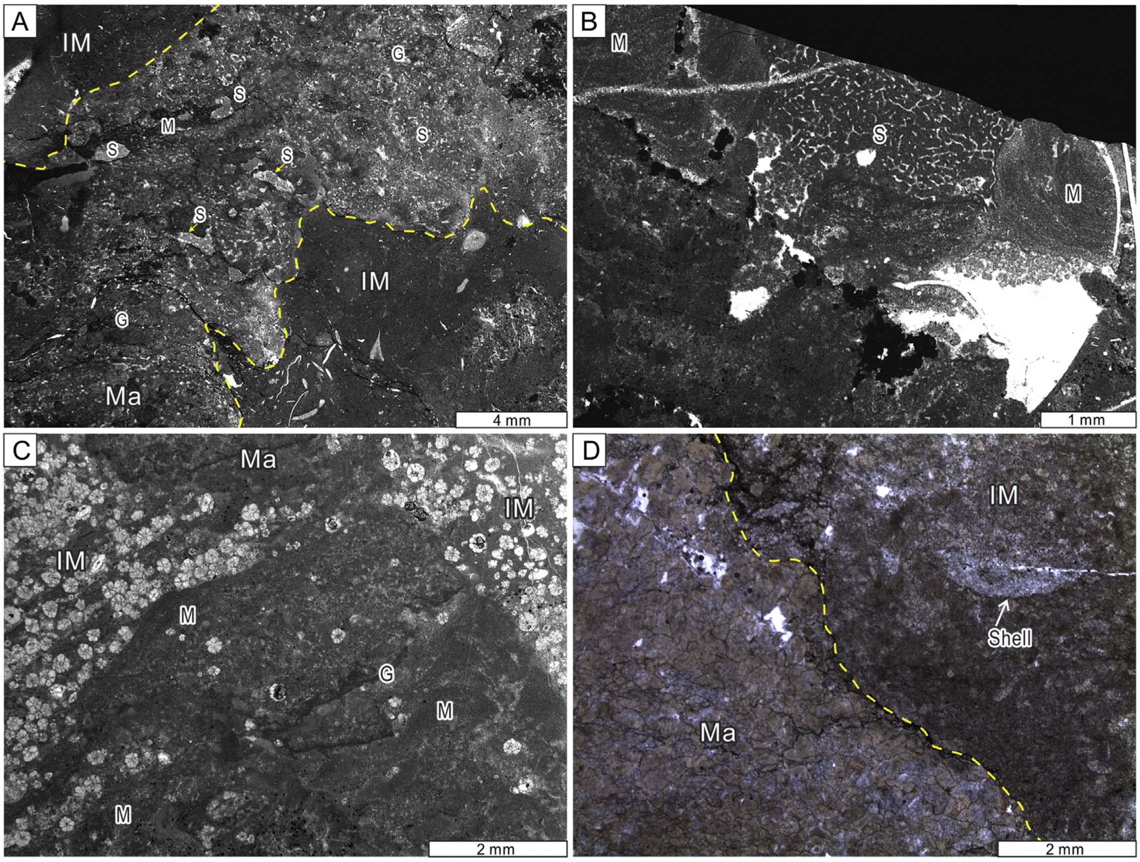

Fig. 6. Micro-structures of the maceriate reefs. (A) Photomicrograph of a muddy maceriate reef, showing sponge spicule networks (S), microstromatolites (M), and *Girvanella* (G) in the maceria structures (Ma), and inter-macerial sediment (IM) including micrite with a few fossil fragments, Tangwangzhai section. (B) A sponge and two microstromatolites exist side by side, Tangwangzhai section. (C) Photomicrograph of a grainy (oolitic) maceriate reef. Maceria mainly consists of sponge spicule networks and microbial components, within only minor grains, Sunmayu section. (D) Photomicrograph of a dolomitized maceriate reef. Maceria is characterized by coarse-grained dolomite, whereas inter-macerial sediment by fine-grained dolomite, Sunmayu section.

The co-occurrence of various fossils within the stromatolites suggests that the stromatolites formed in normal-salinity water conditions where animals thrived (cf. Runnegar et al., 1979; Taylor et al., 1999; Stinchcomb and Angeli, 2002; Loch and Taylor, 2004; Vendrasco and Runnegar, 2004). The relatively limited distribution of these columnar stromatolitic reefs indicates that they most likely formed an elongate barrier reef along the eastern part of the platform during the late Furongian (cf. de Freitas and Mayr, 1995).

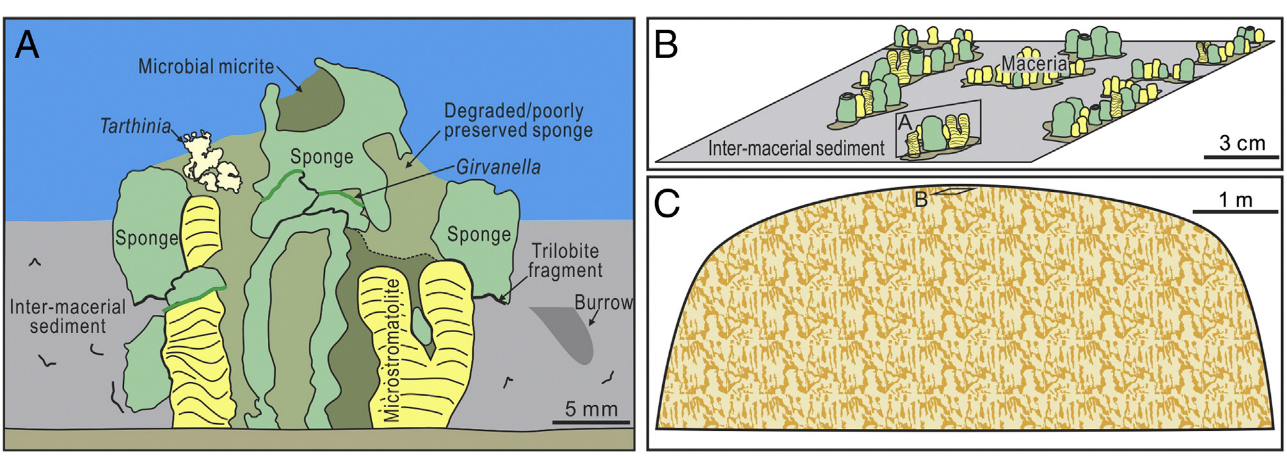

Fig. 7. Schematic model for the formation of maceriate reefs. (A) Maceria structures formed by sponges and microbial components. Frameworks were constructed by sponges and microstromatolites, which are encrusted and stabilized by sponges and *Girvanella*. *Tarthinia* rarely exist within the maceria structure. (B) Maze-like, biogenic maceria structures were formed by growth of sponges and microbes. (C) Continuous growth of maceria structures together with balanced deposition of detrital carbonate sediment eventually formed domal, tabular or columnar maceriate reefs.

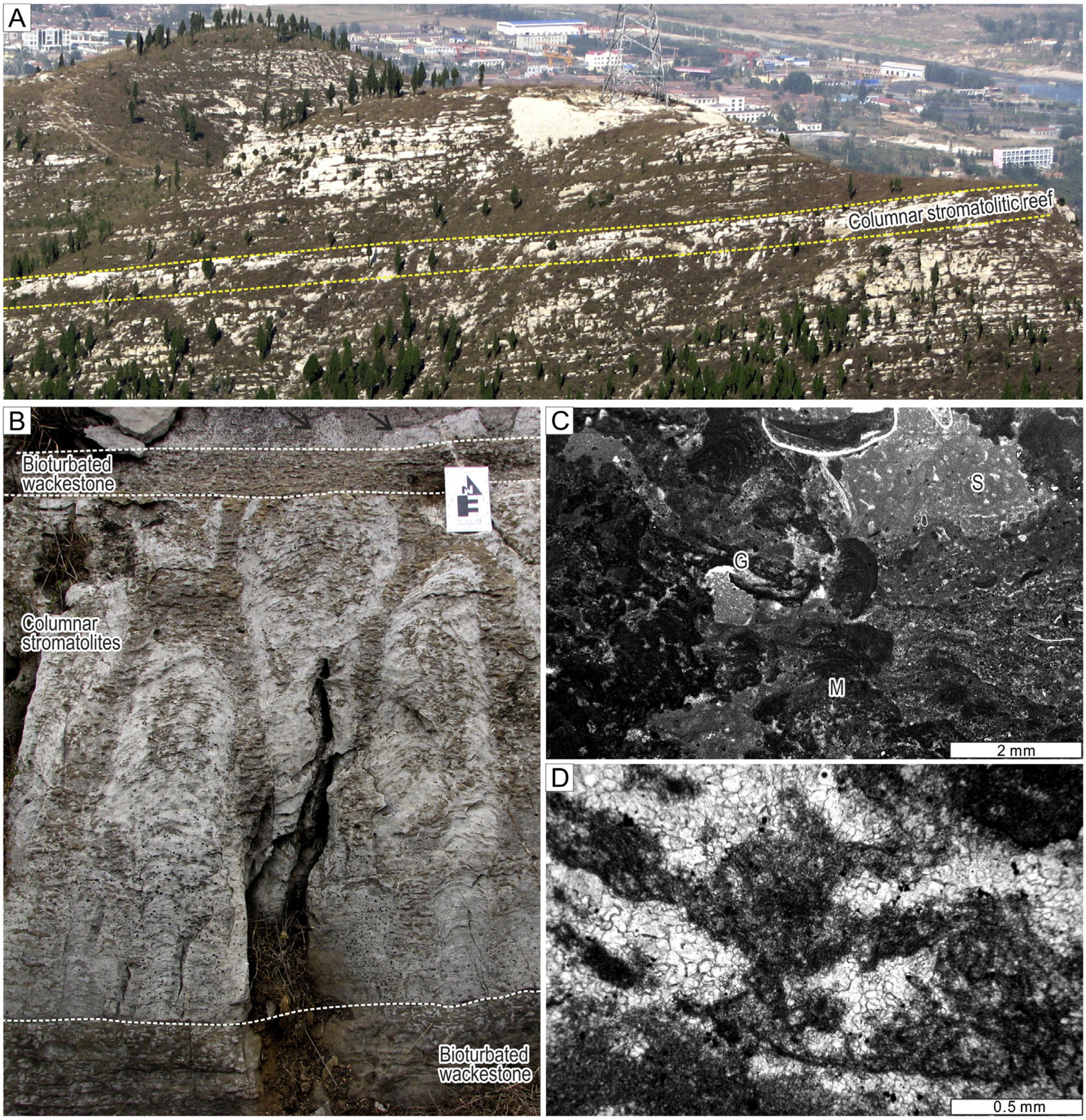

Fig. 8. Columnar stromatolitic reefs, Jiulongshan section. (A) Columnar stromatolitic reefs forming ~10 m thick biostrome in the upper part of the Chaomidian Formation, which can be correlated for several kilometers in the outcrop, Jiulongshan section. (B) Meter-scale columnar stromatolitic reefs underlain and overlain by bioturbated wackestone. Note cm-scale columns (arrows) are overlain by bioclastic grainstone. Scale bar is 15 cm. (C) Complex microstructure, consisting of microstromatolites (M), *Girvanella* (G), and sponge spicule network (S). (D) *Girvanella* showing tubular structures within sparry calcite cement.

3.3. Small-scale microbial reefs

3.3.1. Description

There are several horizons of small-scale microbial reefs in the Furongian Chaomidian Formation (Fig. 3). They vary in size from a few cm to a few dm, and generally show domal macrostructure with either crudely clotted and laminated structures, or aphanitic and chaotic texture (Fig. 9). These small-scale microbial reefs can be again categorized into five types according to the associated facies, which are described underneath.

(1) At the basal Chaomidian Formation (Furongian), some small-scale microbial reefs exist sporadically on an extensive erosion surface (subaerial unconformity) below a laterally traceable deformed limestone bed of Cambrian Series 3 (Chen et al., 2011). They are mainly present on the topographic highs of the erosion surface, encrusting the relief (Figs. 9A and 10). They show sharp irregular margins and are covered by crudely cross-stratified bioclastic grainstones (Fig. 9A). These reefs display a crudely laminated or clotted texture. (2) In the lower Chaomidian Formation, some microbial reefs are present on top of channelized limestone conglomerate imbedded in limestone-shale alternations (Figs. 9B and 10). The reefs contain cm-scale digitate columns that show crude lamination. Abundant rounded flat pebbles (a few mm to cm in long axis) are present in the buildups. The microbial buildups are overlain by lime mudstone and shale alternations (Fig. 9B). (3) In the middle Chaomidian Formation, small-scale microbial reefs are sporadically embedded within grainstones and show sharp, erosional margins (Fig. 10). These reefs have crude lamination and contain small amounts of ooids and fossil fragments. (4) Above the grainstone interval of the middle–upper Chaomidian Formation, small microbial reefs encrust hard ground surfaces on top of flat-pebble

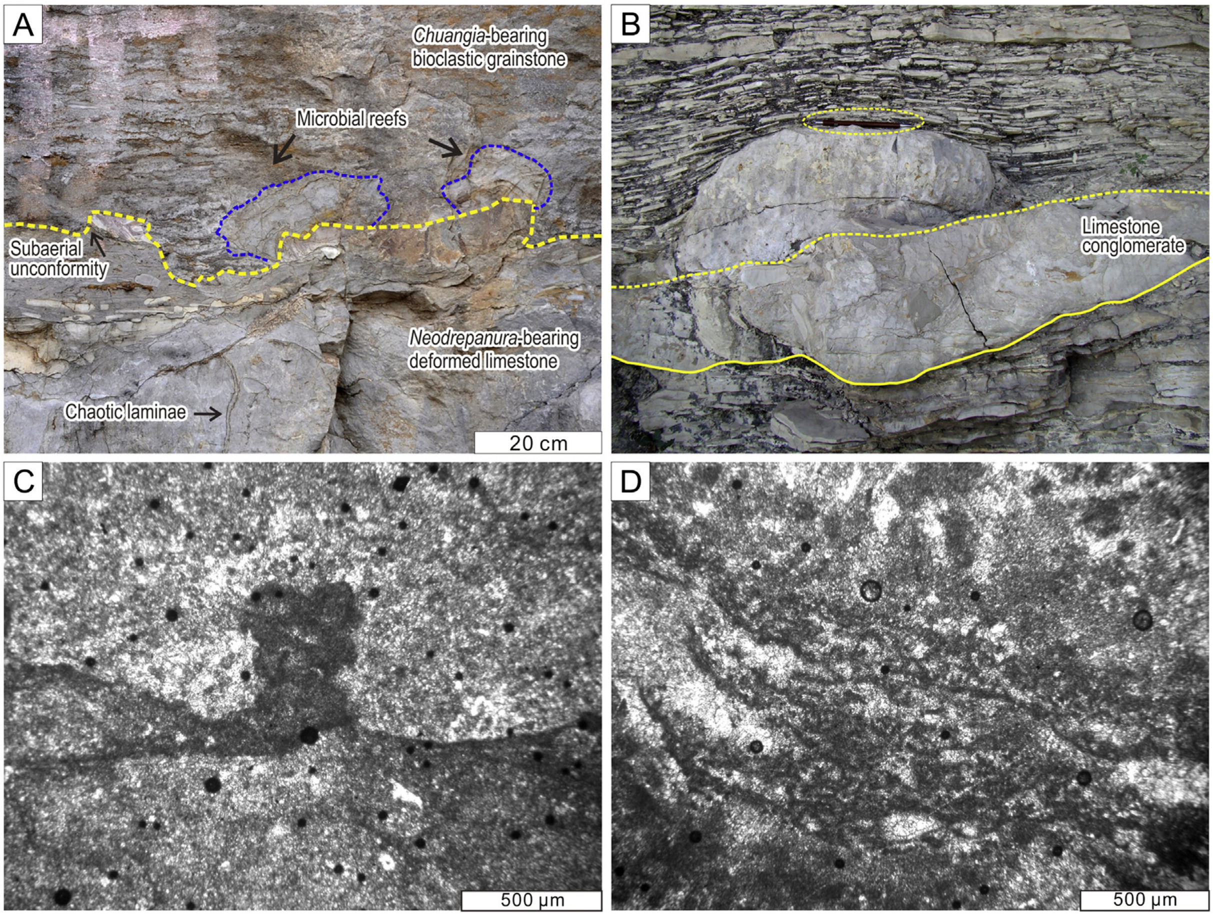

Fig. 9. Small-scale microbial reefs. (A) Small microbial reefs on a subaerial unconformity represented by an irregular truncation surface on a laterally extensive deformed limestone bed (uppermost Cambrian Series 3), Wanliangyu section. (B) Small isolated microbial reefs on channelized limestone conglomerate embedded within limestone and shale alternations, Jiulongshan section. (C) Upward growth of calcimicrobes, possibly *Renalcis*, Wanliangyu section. (D) Laminae formed by *Girvanella*, Wanliangyu section.

conglomerate beds and are commonly overlain by shale and lime mudstone (Fig. 10). They show either laminated or clotted mesostructures. (5) In the upper Chaomidian Formation, sporadic microbial reefs are present in a thick monotonous succession of mostly bioturbated wackestone and bioclastic wackestone to grainstone (Fig. 10). The reefs show aphanitic and chaotic texture. They are commonly underlain by thin-bedded lime mudstone or bioturbated wackestone, and overlain by bioclastic wackestone to grainstone. These small-scale microbial reefs consist mainly of the calcimicrobes *Girvanella* and *Renalcis* forming microbial laminae and clots (Fig. 9C, D).

3.3.2. Interpretation

Small-scale microbial reefs commonly developed in stressed environments where continuous growth was hampered (e.g., Whalen et al., 2002). Most of the small microbial reefs in the Chaomidian Formation initiated their growth on hard/firm ground surfaces which were suitable for colonization by microbial communities (e.g., Myrow et al., 2012), although they could also develop on soft substrates. Microbial reefs likely formed by calcification of cyanobacteria, and trapping and binding of lesser carbonate sediment (Riding, 2000). Favorable conditions (e.g., low sedimentation rate, transparent waters, and adequate nutrient) for the growth of calcimicrobes were temporary, limiting the size of the microbial reefs. Growth of microbial reefs was terminated by strong hydrodynamic conditions, excessive input of coarse grained sediment, or deepened waters.

4. Reef development in response to sea-level changes

Most reef builders, including both metazoans and cyanobacteria, require sunlight (dependent on water depth and clarity) and nutrients (riverine influx and oceanographic perturbation) to grow and construct reefs. In addition, reef growth and demise are significantly affected by drowning of the carbonate factory, subaerial exposure, siliciclastic input, and submarine erosion (Tucker, 1977; Sami and James, 1994; Kershaw et al., 1999; Whalen et al., 2002; Adams et al., 2005; Grotzinger et al., 2005; Chen et al., 2012; Lee et al., 2012). All of the above-mentioned factors indicate that reef development is closely related to relative sea-level changes (Fig. 10).

The Cambrian series 3 Zhangxia Formation represents a broad oolitic-microbial platform that developed over an extensive area of the North China Platform (Meng et al., 1997; Chough et al., 2010) (Figs. 3, 5B, and 10). High catch-up and keep-up ability of the carbonate platform in response to sea-level rise resulted in a ~180-m-thick succession of oolite and various microbial reefs (Zhang et al., 1985; Mu et al., 2003; Woo et al., 2008; Woo, 2009) (Fig. 11A, B). The Zhangxia platform was then drowned during the late Cambrian Epoch 3 due to rapid relative sea-level rise on most parts of the North China Platform, including the Shandong and Beijing regions (Mei et al., 2005; Chen et al., 2012) (Figs. 1 and 3). The drowning event is recorded in the abrupt change in lithofacies from the underlying carbonate strata of the Zhangxia Formation to the overlying shales of the Gushan Formation (Figs. 3, 5B, and 10). The drowning event was, however, highly diachronous. In

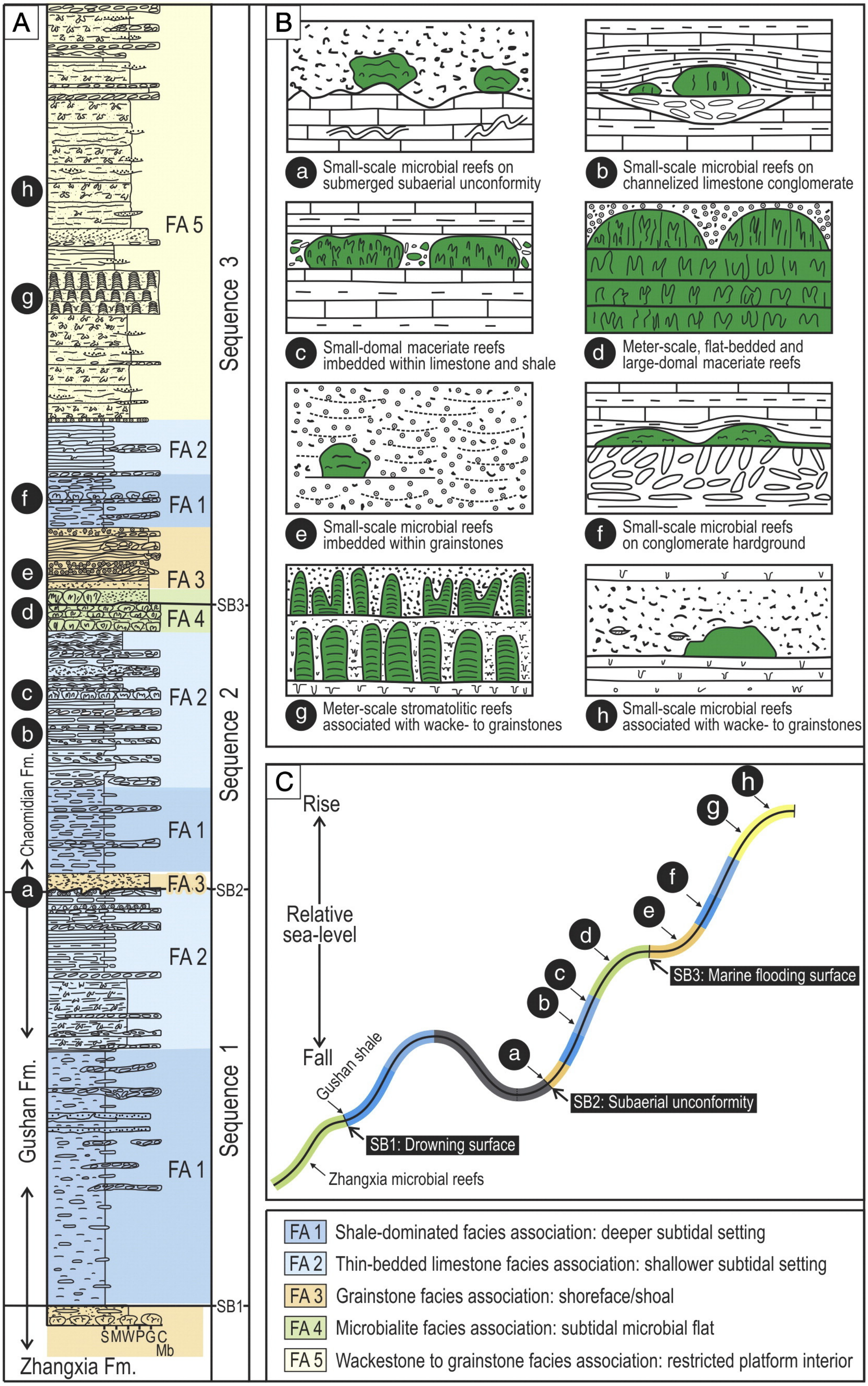

Fig. 10. Reef development in response to sea-level changes. (A) A representative stratigraphic columns of the Gushan and Chaomidian Formations (upper Cambrian Series 3 to Furongian), Jiulongshan section (for location, see Fig. 1B). Modified after Chen et al. (2011). (B) Schematic model of the Furongian reefs and associated lithofacies. (C) Relative sea-level curve of the Gushan and Chaomidian Formations, with occurrence of different types of reefs.

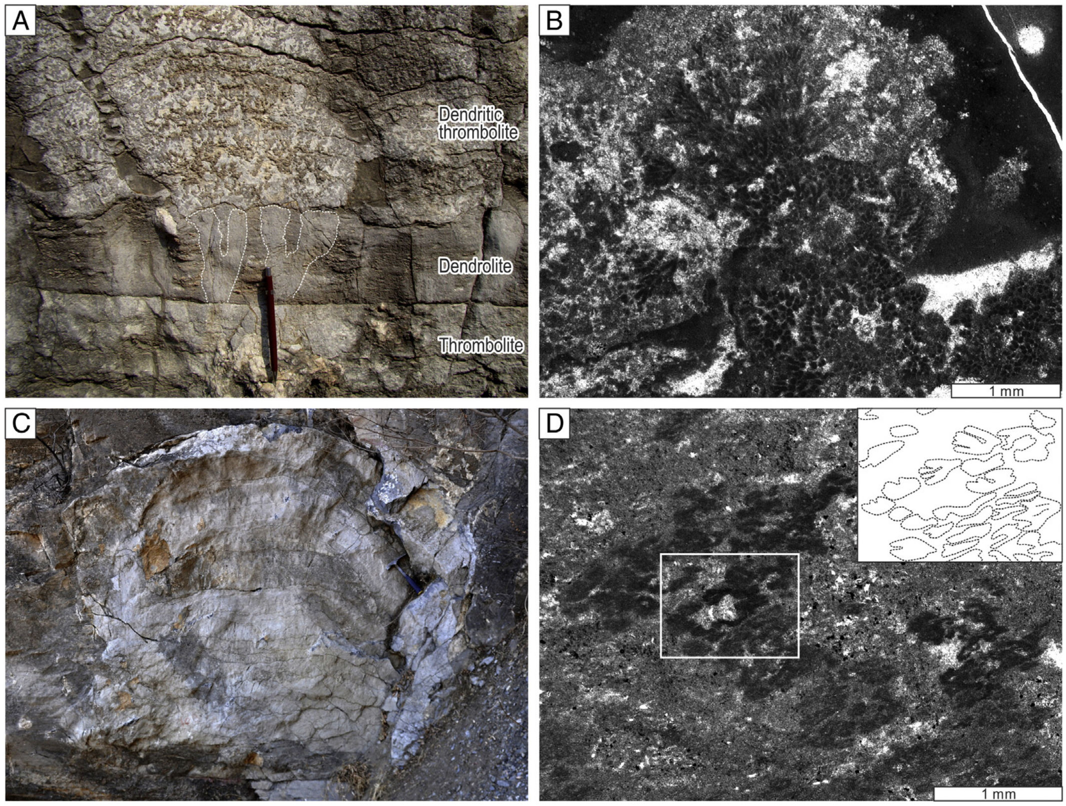

Fig. 11. Microbialites in the Cambrian Series 3 of the North China Platform. (A) Typical microbialites of the Cambrian Series 3 Zhangxia Formation, Laopozhuang section. (B) Photomicrograph well-preserved *Epiphyton* within the Zhangxia *Epiphyton* framestone, Wanglaoding section. (C). Stromatolitic–thrombolitic reef in the Gushan Formation (late Cambrian Series 3), Xishan section, Beijing region, China, showing domal macrostructures. (D) Poorly preserved *Epiphyton* from the Gushan reefs, Xishan section, Beijing region.

the easternmost part of the North China Platform (Taebaeksan Basin, South Korea, Fig. 1A), the drowning occurred much later than in the Shandong region, as revealed by detailed sequence- and biostratigraphic investigations (Chen et al., 2012; Park et al., 2013).

Overlying the drowned Zhangxia carbonate platform is the deeper-water facies of the lower Gushan Formation which is characterized by shales with nodular to thin-bedded lime mudstones, and an absence of reefs (Chen et al., 2012) (Fig. 10). As sea-level rise slowed, shallow-water carbonate sediments (e.g., bioturbated wackestone, oolite, and flat-pebble conglomerate) were deposited in the upper part of the Gushan Formation, in both the Shandong and Beijing regions (Fig. 3). Some microbial reefs formed in the upper Gushan Formation in the Beijing region, reflecting shallower water depth there (Mei et al., 2005) (Fig. 11C, D). During the latest Cambrian Epoch 3, the platform was subaerially exposed in the Shandong region as a result of a sea-level fall, forming a subaerial unconformity on a laterally traceable (over 100 km), deformed limestone bed (Chen et al., 2011).

With resumed rise in sea-level, small-scale microbial reefs grew on the submerged subaerial unconformity during the early Furongian (Chen et al., 2011) (Figs. 9A and 10). The microbial reefs could not, however, catch up with sea-level rise; they were eroded by transgressive ravinement and eventually buried by transgressive lag deposits (bioclastic grainstone) (Chen et al., 2011). Extensive microbial reefs could not resurge under deepened waters indicated by the shale-dominated facies in the lower part of the Chaomidian Formation (Fig. 3). However, small-scale microbial reefs locally developed on suitable substrate such as channelized limestone conglomerates (Figs. 9B and 10). These small microbial reefs could not catch up to sea-level rise, and they were eventually terminated and buried under limestone and shale alternations.

As the carbonate platform became re-established during the sea level highstand, maceriate sponge-microbial reefs began to form in both Shandong and Beijing regions (Figs. 5, 10, and 12). Some of these reefs are decimeter-scale and could not flourish, but most of them formed meter- to several-meter-scale biostromes (Fig. 5B, C) (Lee et al., 2010, 2012). These biostromal reefs can be correlated over 100 km, covering an extensive area of the Shandong region. The biostromal reefs were terminated due to the rapid rise in sea level, forming a marine flooding surface on its top (Lee et al., 2012). Above the flooding surface, reefs with domal megastructures formed by high catch-up ability relative to sea-level rise. The domal reefs were then buried by grainstones with sea-level rise. Small microbial reefs sporadically developed in grainstone shoreface or shoal. Continued sea-level rise terminated carbonate production, resulting in the deposition of shales with nodular lime mudstone, within which small microbial reefs developed on hard ground surfaces. Maceriate reefs only locally resurged (e.g., Jiulongshan section), forming m-scale, domal-tabular structures.

Overlying the shale-dominated interval, the upper part of the Chaomidian Formation is characterized by a thick succession of bioturbated wackestone to grainstone, indicating restricted platform interior or protected lagoonal settings (Chen et al., 2011). Columnar stromatolitic reefs developed along the eastern margin of the platform (Fig. 3), most likely forming a barrier reef. Small microbial reefs sporadically formed within the lagoonal environments, in the form of patch reefs. Above the carbonate-dominated interval, up to 50-m-thick, dolomitized, maceriate reefs were recognized at various locations within the Shandong region (e.g., Sunmayu section), suggesting resurgence of maceriate reefs during the latest Cambrian to early Ordovician. These dolomitized reefs have not, however, been studied in detail due to pervasive dolomitization.

5. Discussion: insight into the evolution of Cambrian reefs

It has been suggested that the Cambrian Epoch 3–Furongian interval was a time of microbialites, between the extinction of archaeocyaths

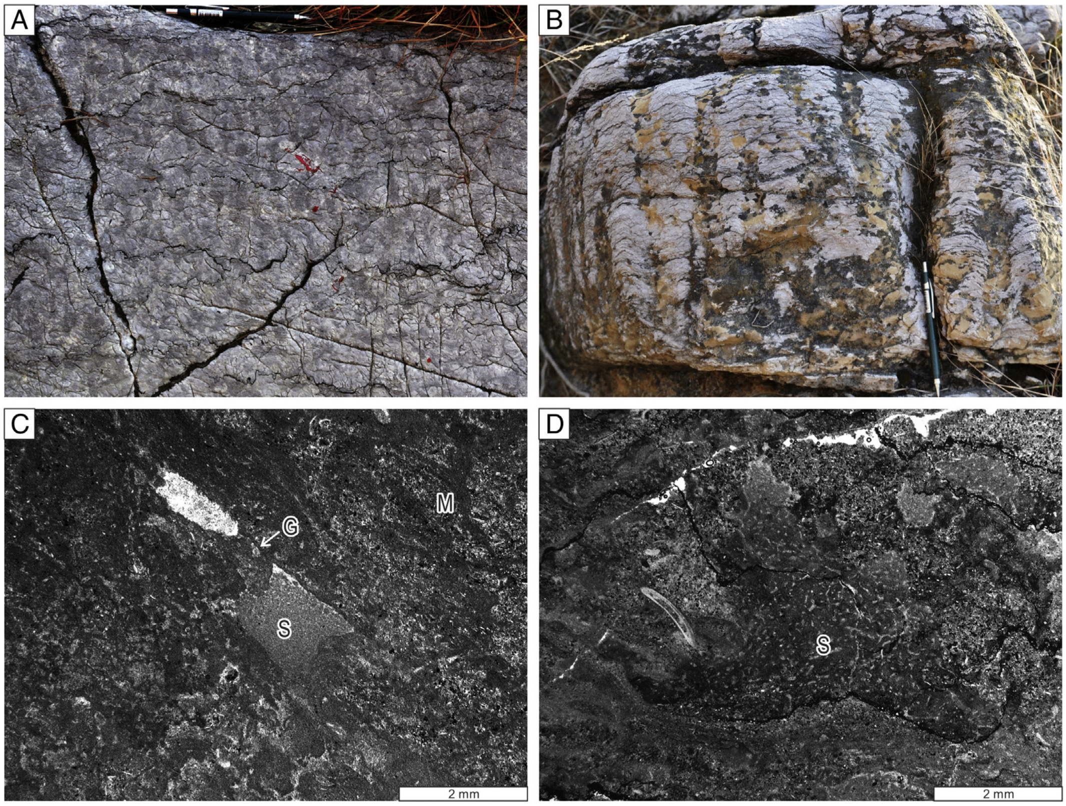

Fig. 12. Furongian reefs in the Beijing region (Xishan section), China (for location, see Fig. 1A). (A) A maceriate reef, showing typical maceria structures. (B) A thick biostromal columnar stromatolitic reef, showing crude lamination. (C) Photomicrograph of maceriate reef, showing poorly preserved sponge spicule networks (S), microstromatolite (M), and *Girvanella* (G). (D) Photomicrograph of columnar stromatolitic reef, showing poorly preserved sponge spicule networks.

(end Cambrian Epoch 2) and the Early Ordovician diversification event (Rowland and Shapiro, 2002; Adachi et al., 2011). During Cambrian Epoch 3 (Zhangxia Formation), the North China Platform was dominated by various reefal microbialites, including *Epiphyton* framestone, thrombolite, dendrolite, and minor stromatolite and leiolite (Zhang et al., 1985; Gao and Zhu, 1998; Mu et al., 2003; Woo et al., 2008; Woo, 2009; Woo and Chough, 2010; Howell et al., 2011; Chen and Lee, 2014) (Fig. 11A). Within these microbialites, the branching calcified microbe *Epiphyton* is dominant, with minor amounts of the chambered *Renalcis* and filamentous *Girvanella* (Woo et al., 2008; Woo and Chough, 2010; Howell et al., 2011) (Fig. 11B). These reefal microbialites are significantly different from the Furongian reefs of the North China Platform, which is represented by the following aspects: (1) *Epiphyton* is abundant in the Zhangxia reefal microbialites, whereas it is completely absent in the Furongian reefs of the North China Platform (Figs. 6, 8, 9, and 12); and (2) maceriate sponge-microbial reefs occurred characteristically in the Furongian, together with siliceous-sponge-containing columnar stromatolitic reefs (Figs. 6, 8C, and 12C, D), whereas the Zhangxia reefs are constructed by diverse microbialites (Fig. 11A, B), except for some occurrence of metazoan reef builders (e.g., lithistid sponges and the stem-group cnidarian *Cambroctoconus*) (Woo, 2009; Park et al., 2011; Hong et al., 2012). What could have caused these differences?

The abrupt transition in reefal components the Cambrian Series 3 to the Furongian could have been caused by the platform-wide drowning event during Cambrian Epoch 3 (see Section 4). Indeed, the flourishing and decline of reefs are closely related to not only global perturbations (e.g., major extinction events) but also local changes (e.g., catch-up ability, topography, relative sea level, and hydrodynamics) (Turner et al., 1997; Chen et al., 2012; Lee et al., 2012). It is possible to think that the overturn of reef-building organisms took place coincidently with the local changes in depositional environments (i.e., the drowning event). The highly diachronous drowning event (Chen et al., 2012; Park et al., 2013) was, however, unlikely to induce a platform-wide overturn in biofacies. In fact, microbial reefs that resurged after the drowning event (Cambrian Epoch 3) in the Beijing region (Mei et al., 2005) still contain *Epiphyton*, although poorly preserved due to diagenetic alteration (Fig. 11C, D). Therefore, the drowning event was most likely not the primary driving mechanism for the demise of *Epiphyton* on the North China Platform.

The transition of reefal systems from *Epiphyton*-dominated microbial reefs in Cambrian Epoch 3 to *Epiphyton*-less/free reefs in the Furongian is well recorded in the Shandong and Beijing regions of the North China Platform. This transition is not yet recognized elsewhere, but it coincides with an abrupt decrease in calcified microbe diversity across the Cambrian Epoch 3–Furongian boundary (Zhuravlev, 1996; Riding, 2001). It might have been related to a global extinction event (i.e., the Dresbachian extinction event) that occurred across the Cambrian Series 3–Furongian boundary (Saltzman et al., 2000; Chen et al., 2011). This event was most likely caused by euxinic oceanic conditions and a possible eustatic sea-level drop, concurrently with a global carbon isotope excursion event (SPICE) (Saltzman et al., 2004; Chen et al., 2011; Gill et al., 2011; Bayet-Goll et al., 2014), which led to the demise of *Epiphyton* by the end of Cambrian Epoch 3. New reef-building organisms such as siliceous sponges and other calcified microbes, including *Girvanella* and *Tarthinia*, would have replaced *Epiphyton*, and flourished in the Furongian reefal system. Further integrative sedimentological, geochemical, and geobiological studies are, however, required in order to test this hypothesis.

On the other hand, maceriate reefs and columnar stromatolitic reefs occurred worldwide during the late Cambrian to early Ordovician (e.g., Aitken, 1967; Campbell, 1976; Pratt and James, 1982; de Freitas and Mayr, 1995; Taylor et al., 1999; Myrow et al., 2003; Chen et al., 2011; Lee et al., 2014a). If previously reported maceriate reefs and stromatolitic reefs elsewhere (e.g., those in Laurentia) are also sponge-microbial reefs (i.e., a worldwide phenomenon), it may suggest that metazoan-reef builders were actively involved in reefs before the Early Ordovician Biodiversification Event, which challenges the traditional views on the middle–late Cambrian microbialite-dominant period.

6. Conclusions

The Furongian succession (Chaomidian Formation) of the North China Platform contains various well preserved microbial and microbial–metazoan reefs. These reefs were classified into three categories according to various textures and structures. Maceriate sponge-microbial reefs are characterized by cm- to dm-scale, maceriate (maze-like) structures, and form either biohermal or biostromal geometry. Columnar stromatolitic reefs consist of dm-wide, m-thick stromatolitic columns that were constructed by microbial laminae with a small component of siliceous sponges. Small-scale microbial reefs are cm- to m-scale, isolated microbial buildups that were mainly constructed by calcimicrobes. They are associated with various lithofacies (limestone and shale alternation, limestone conglomerate, and wacke- to grainstone) and formed in a wide range of depositional settings. Growth and termination of these Furongian reefs were strongly controlled by relative sea-level changes. An abrupt transition in reefal components from Cambrian Series 3 reefs to Furongian reefs indicates that reef construction might have been affected by global events such as a eustatic sea-level drop and global euxinic conditions during the latest Cambrian Epoch 3 to the early Furongian. Further integrated studies on Cambrian reefs would certainly help understand the evolution of reefs and their relationship to major geological events during the Early Paleozoic.

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