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Cambrian Reefs in the Western North China Platform, Wuhai, Inner Mongolia

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Abstract: Mid to late Cambrian thrombolites and maze-like maceriate reefs from the western North China Platform, Wuhai, Inner Mongolia, northwestern China, occur in the middle of a succession dominated by thin-bedded lime mudstone-shale/marlstone alternations, and are laterally surrounded by limestone conglomerate and/or grainstone. Thrombolite, characterized by meter-scale lenticular mounds composed of millimeter- to centimeter-scale mesoclots and wackestone matrix, occurs in the lower middle part of the sequence. Thrombolite mesoclots are composed of microstromatolites with alternating dark gray and light gray micritic laminae. The maze-like maceriate reefs occur in the middle to the upper part of the sequence, commonly forming lenticular mounds up to 1 m thick. They are characterized by centimeter- to decimeter-scale branched maze-like structures, whose biogenic portions (maceria) are selectively dolomitized. The maceriae are composed of poorly preserved microstromatolites and siliceous sponges. Inter-macerial sediments consist of lime mud and scattered bioclasts. These Wuhai reefs are generally similar to but older than various other Cambrian reefs previously reported from the Shandong region, northeastern China.

Key words: organosedimentary petrology, reefal carbonate, microbialite, siliceous sponge, Cambrian Series 3: Guzhangian, North China Platform

1 Introduction

Microbialites are organosedimentary deposits formed by microbial organisms, and occur throughout Earth's well-preserved sedimentary history (Burne and Moore, 1987; Riding, 2000, 2011; Chen and Lee, 2014). Microbialite abundance during the Phanerozoic appears to vary inversely relative to the overall rise and fall of metazoans (Riding, 2006; James and Wood, 2010). The early Paleozoic represents a transitional period in terms of reef evolution between Precambrian microbialite-dominated reefs and Phanerozoic metazoan-dominated reefs, when microbialites harbored the early reef-building metazoans (Rowland and Shapiro, 2002). During the early Cambrian (Terreneuvian and Cambrian Series 2), archaeocyaths formed reefs together with microbes. After the extinction of archaeocyaths at the end of Cambrian Series 2, it has been suggested that microbialites mainly formed reefs during the middle to late Cambrian (Series 3 to Furongian). Subsequently, as metazoans began to radiate at the onset of the Ordovician (the Great Ordovician Biodiversification Event: Webby et al., 2004), microbialites significantly declined within the reefs during the Ordovician (Webby, 2002; Adachi et al., 2011).

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On the North China Platform, previous studies of the early Paleozoic reefs mainly concentrated on the eastern regions, including Shandong, Liaoning, Jilin, Anhui, Shanxi, and Beijing in China, and the Taebaeksan Basin of Korea (Zhang et al., 1985; Gao and Zhu, 1998; Mu et al., 2003; Woo et al., 2008; Lee et al., 2010, 2012, 2014a, 2014b; Woo and Chough, 2010; Howell et al., 2011; Hong et al., 2012; Chen et al., 2014). Collectively, these reefs represent a complex evolution of reef-building constituents and organisms during the middle to late Cambrian, which cannot be explained simply as post-extinction development of microbialite (Zhuravlev, 1996; Rowland and Shapiro, 2002; Lee et al., 2015). Detailed studies of these reefs, therefore, have the potential to reveal new aspects of middle to late Cambrian reefs. In this study, we report the occurrence of Cambrian reefs in western Inner Mongolia, China, which will assist understanding of reef development within the thick Cambrian–Ordovician sequence of the western North China Platform.

2 Geological Setting and Methods

The North China Platform hosted a Cambrian–Ordovician mixed siliciclastic-carbonate succession developed on a stable craton of the Sino-Korean Block (Meng et al., 1997). The block was located near the margin (Li and Powell, 2001) or was part of Gondwana (McKenzie et al., 2011) during the early Paleozoic, and near the paleoequator (Huang et al., 2000). The block is now bounded by major suture zones on the north (Hinggan Fold Belt), east (Tanlu Fault), and south (Qinling-Dabieshan Belt). A thick Cambrian–Ordovician platform, platform-margin and deep-basinal sequence is preserved on the western margin of the block, where the Ordos Basin developed throughout the extensive (ca. 250,000 km^2) area across Shaanxi, Shanxi, Gansu, Ningxia, and Inner Mongolia, northwestern China (Yang et al., 2008) (Fig. 1a). In the northern part of the basin, a ca. 480-m thick Cambrian–Ordovician mixed siliciclastic-carbonate succession unconformably overlies Precambrian quartzose sandstone (BGMRNM, 1991) (Fig. 2).

The study area, the Subeigo section, is located in the eastern part of Wuhai, Inner Mongolia, China (Fig. 1) (Zhang and Chen, 1982; Chi, 1987; Li et al., 2012). The Cambrian succession in the area mainly consists of thin-bedded limestone-shale/marlstone couplets interbedded with flat-pebble conglomerate, together with some wackestone and sandstone (Fig. 2). The succession was generally deposited in outer ramp settings, similar to those of the inner detrital belt of Laurentia (Myrow et al., 2015).

Reefs were described in the field, and slabs and thin sections prepared in the laboratory. Terminologies for reef description follow those of Shapiro (2000) and Chen and Lee (2014). Two types of reef are identified in the field based on macro- and mesoscale observation: thrombolites and maze-like maceriate reefs. Thrombolite occurs in the lower middle part of the succession, whereas maceriate reefs occur in the upper part of the succession, and their occurrences do not overlap (Fig. 2). Although biostratigraphic controls on the reef-bearing strata are incomplete, trilobites suggest that the thrombolites most likely formed during the Changsian Stage (late Stage 5–Drumian; Cambrian Series 3), and maceriate reefs formed during the later Changsian(?) and Kushanian stages (Guzhangian; Cambrian Series 3) (Fig. 2) (Zhang and Chen, 1982).

3 Results

3.1 Thrombolite

Description: Thrombolites constitute the lowermost microbialite unit within the succession, ca. 125 m above

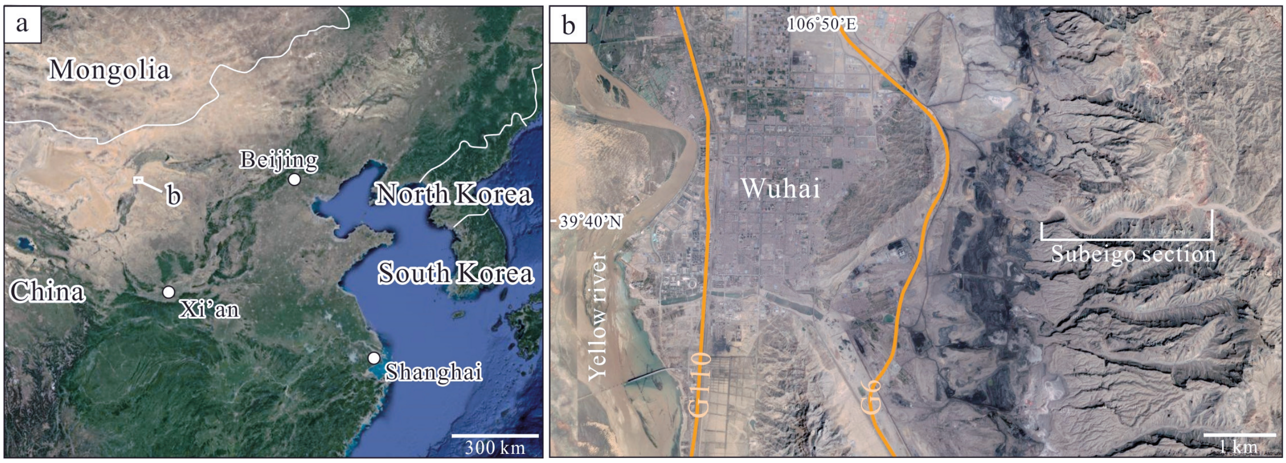

Fig. 1. Location map of the study area.
(a) Satellite photograph of Asia. The study area is marked by an arrow, (b), Satellite photograph of study area (Wuhai, Inner Mongolia, China). The studied Subeigo section is marked by a white line.

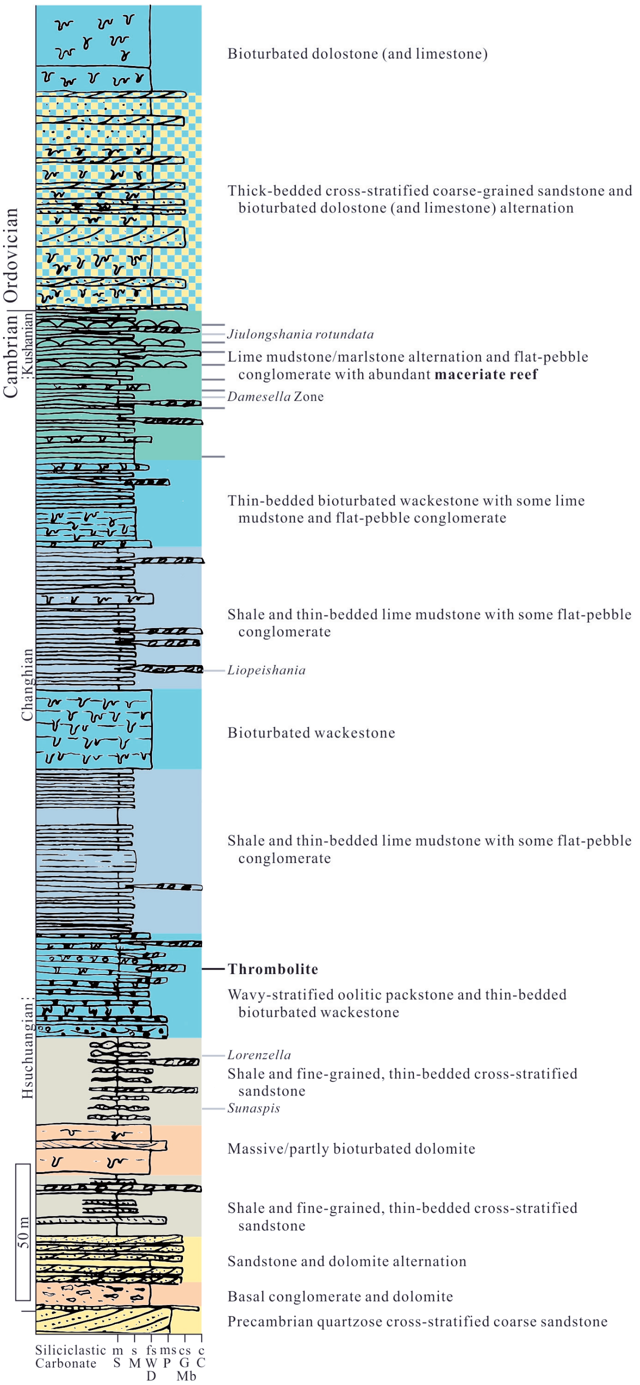

Fig. 2. Sedimentological log of the Subeigo section.
Occurrences of thrombolite (black line), maceriate reef (dark gray line), and trilobites (light gray line with name) found in this study are marked in the figure. m=mudstone, s=siltstone, fs=fine sandstone, ms=medium sandstone, cs=coarse sandstone, c=conglomerate, S=shale, M=lime mudstone, W=wackestone, P=packstone, G=grainstone, C=limestone conglomerate, D=dolomite, Mb=microbialite.

the Precambrian–Cambrian unconformity (Fig. 2). They are represented by ca. 60-cm thick mounds within thin-bedded limestone shale alternations (Fig. 3a). The mounds have abrupt contacts with limestone conglomerates that occur between the mounds, which partly cover the upper parts of the mounds. The limestone conglomerates consist of ellipsoidal to irregular micritic limestone intraclasts in bioclastic grainstone matrix. Several bulbous masses, 20–30 cm in height and width, occur within the mounds and are separated from one another by bioclastic wackestone (Fig. 3b). These bulbous masses consist of mesoclots ~1 cm in width and surrounding wackestone matrix (Fig. 3c). The mesoclots are dark gray in color and form irregular small columns, sometimes containing faint convex-up lamination.

In microscale, the mesoclots consist mainly of microstromatolites characterized by alternating dark and light gray micritic laminae (Fig. 3d). The mesoclots sometimes display clotted microstructure, with micritic clotted fabrics (ca. 200 μm in size) separated by sparite (50–80 μm in width) (Fig. 3e). This clotted microstructure resembles partly degraded sponge fabrics (cf. Lee et al., 2014a). Mesoclot boundaries are often enhanced by minor dolomitization. Bioturbated micrites that occupy spaces between the mesoclots contain trilobite fragments. Three types of bioturbation are recognized (Fig. 3f). The first type, characterized by relatively large size (0.4–0.6 mm in diameter) and gradational margins, is filled with fairly light gray micrite. The second type shows thick tubular shapes (80–120 μm in diameter), with relatively sharp margins and lighter gray micrite infill, and occurs either within the first type of burrow or within micrite. The third burrow type consists of bifurcating tubular structures that form X- or Y-shapes ca. 30 μm in diameter, with relatively clear margins.

Interpretation: Occurrence of the thrombolites within a succession dominated by thin-bedded limestone and shale suggests deposition in a relatively deep environment, possibly near or below storm wave base (Pfeil and Read, 1980; Kwon et al., 2006; Chen et al., 2011; Myrow et al., 2015). This is consistent with lack of wave- or current-induced sedimentary structures within the thin-bedded lime mudstone and shale. The thrombolites could have been formed by microbes that produced alternation of dark- and light-colored laminae via trapping and binding of sediments or precipitation/ calcification of microbes forming micritic laminae (cf. Riding, 2000, 2011). Lime muds could have been supplied via suspension and settling during mound growth, and subsequently burrowed by infauna. Absence of intraclasts within the mound, as well as occurrence of micritic matrix between the mesoclot-like structures, suggest that the mounds were not severely affected by storms during their growth. These features collectively indicate that the thrombolites mainly formed in relatively deep, low-energy environments, which, however, were shallow enough to receive sunlight. Occurrence of limestone conglomerates between the mounds, and sharp mound margins, suggest that storm events might have

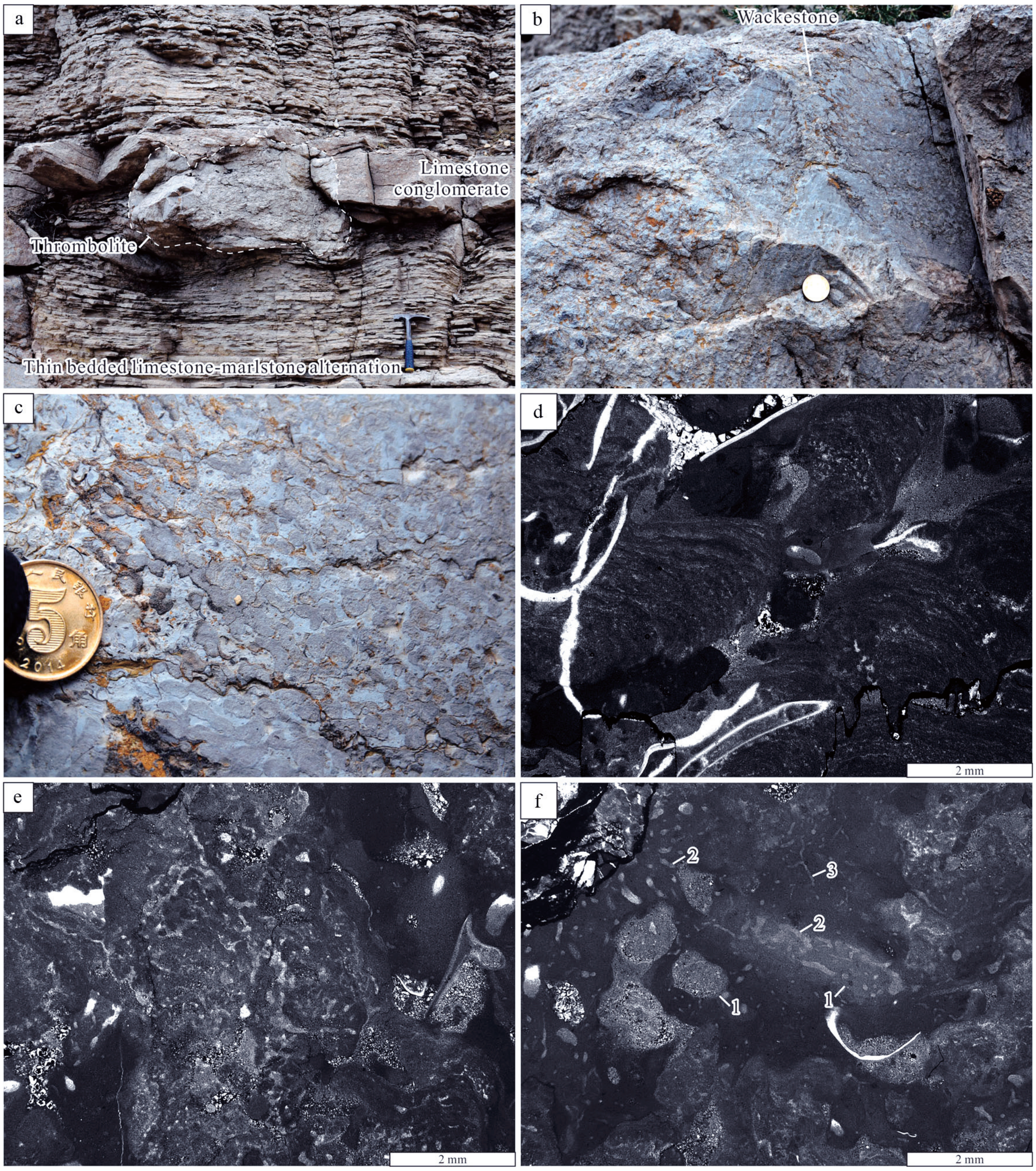

Fig. 3. Thrombolite.
(a) Thrombolite mound (white dashed line) and associated facies. Hammer for scale is 27 cm in length. (b) A close-up photograph showing two bulbous structures with wackestone. Coin for scale in (b) and (c) is 2 cm in diameter. (c) Mesoclots within the thrombolite. Note faint lamination within the mesoclots. (d) Photomicrograph of the mesoclots showing microstromatolitic lamination made by alternation of dark and light gray micritic laminae. Micrite fills space between mesoclots. (e) Mesoclot showing clotted microstructure. (f) Bioturbations within micrite. Note occurrence of three different types of burrows (marked by arrows with numbers 1, 2, and 3).

terminated mound growth (Lee et al., 2012).

3.2 Maze-like maceriate reef

Description: The term "maze-like maceriate reef" indicates reefs with characteristic centimeter- to decimeter-scale branching structures that form maze-like structures in transverse section (Shapiro and Awramik, 2006; Lee et al., 2010). The Wuhai maze-like maceriate reefs mainly occur within a 55-m thick interval in the upper part of the Cambrian succession, ca. 310 m above the basement, in which more than ten horizons of maceriate reefs occur (Fig. 2). Many of these reefs are lenticular in shape and less than 20 cm thick, showing circular shape on the bedding surface; some mounds are up to 1 m thick (Fig. 4a, b, c). Partly dolomitized grainstones and some lime mudstones commonly occur between the mounds (Fig. 4a). Most of the maceriate reefs occur within a succession of thin-bedded limestone-shale/

marlstone alternation. They laterally co-occur with grainstones, limestone conglomerates, and lime mudstone and marlstone. Selective dolomitization along the margins of maceria structures enhance their shape in outcrop (Fig. 4a, d). On the other hand, dolomitization overprints reef constituents in microscale, and only some poorly preserved remains of siliceous sponges together with microstromatolites are identifiable (Fig. 4e, f). The siliceous sponge remains are composed of spicule networks with irregular outlines (Fig. 4e), and are generally similar to those recently identified from Furongian maceriate reefs in the Shandong region, northeastern China (Lee et al., 2014a). On the other hand, unlike the Shandong maceriate reefs, no calcified microbes can be recognized. Micrites containing some trilobite fragments fill interspace between maceria structures.

Interpretation: The occurrence of maceriate reefs within thin-bedded limestone and shale/marlstone suggests deposition in a relatively deep environment (Pfeil and Read, 1980; Kwon et al., 2006; Lee et al., 2010; Chen et al., 2011; Myrow et al., 2015). In contrast, grainstones within and between the mounds suggest that high-energy processes (e.g., storms) occasionally affected growth of these maceriate reefs and in some cases might have buried mounds. Overall similarities between these maceriate reefs and those in Shandong indicate that they could have been formed by similar organisms, i.e., siliceous sponges and microbes (Chen et al., 2014; Lee et al., 2014a). Recent study on similar sponges from Devonian and Triassic strata suggests that these siliceous sponge remains may be fibrous skeletons of non-spicular "keratose" demosponge (Luo and Reitner, 2014). Apparent lack of calcified microbes in the Wuhai area, in contrast to those identified in the Shandong maceriate reefs, is likely due to their poor preservation and dolomitization.

4 Comparison with Cambrian reefs in Shandong Province, China

Numerous studies of Cambrian reefs have been conducted in the eastern North China Platform, Shandong Province (Fig. 5) (Woo et al., 2008; Woo, 2009; Lee et al., 2010, 2014a, 2014b; Woo and Chough, 2010; Howell et al., 2011; Chen et al., 2014; Adachi et al., 2015). Many of these reefs are microbial-dominated, although recent studies reveal co-occurrence of reef-building metazoans within these reefs (Woo, 2009; Chen et al., 2014; Lee et al., 2014a). Cambrian Series 2 reefs, the oldest Paleozoic reefs known from the North China Platform, occur in eastern Shandong (Lee et al., 2014b). These are small mound-shaped thrombolites consisting of various calcified microbes locally formed within grainstone facies. During Cambrian Series 3, reefs developed throughout the Shandong region, forming the ca. 200-m thick carbonate-dominated Zhangxia Formation. Various microbial reefs including *Epiphyton* framestone, thrombolite, dendrolite, leiolite, and stromatolite are present in this succession (Fig. 5a, b) (Woo et al., 2008; Woo, 2009; Woo and Chough, 2010; Howell et al., 2011; Park et al., 2011). Some lithistid sponges (anthaspidellid sponge *Rankenella zhangxianensis*) and stem-group cnidarians (*Cambroctoconus orientalis*) occur within the reefs (Woo, 2009; Park et al., 2011; Adachi et al., 2015; Lee et al., 2016). The Zhangxia reefs were terminated by rapid sea-level rise during late Cambrian Series 3 (Chen et al., 2011). When carbonate platform conditions were reestablished during the Furongian, maze-like maceriate reefs forming meter-scale bioherms and biostromes developed widely in the Chaomidian Formation (Lee et al., 2010; Lee et al., 2012, 2014a). These maceriate reefs were previously described as "microbialite" because of the absence of recognizable features in outcrop, but detailed microfacies study has revealed that these maceriate reefs consist of siliceous sponges and microbial carbonates including microstromatolite, *Girvanella* and *Tarthinia* (Fig. 5c, d) (Lee et al., 2014a). During the late Furongian, decimetric columnar stromatolites consisted of *Girvanella* and some siliceous sponges flourished within the lagoonal environment (Chen et al., 2011, 2014).

The thrombolite and maze-like maceriate reefs of the Wuhai region are comparable with thrombolites in the Zhangxia Formation and the maceriate reefs in the Chaomidian Formation in the Shandong region, respectively. Zhangxia thrombolites are subdivided into type A, consisting of mesoclots with poorly preserved microstructures and dolomitic fine matrix, and type B, characterized by mesoclots composed mainly of coccoidal microbial remains, fine-branched *Epiphyton* and some siliceous sponges, surrounded by micritic matrix (Fig. 5a, b) (Woo, 2009). Although mesoclots in Cambrian thrombolites are commonly micritic or microcrystalline in texture, lacking original fabrics (Kennard and James, 1986; Kennard et al., 1989), the different microstructures preserved in the Wuhai and Zhangxia thrombolites suggest that there might have been multiple origins for these thrombolites. Further studies are required in order to understand the origin of Cambrian thrombolites.

Maceriate reefs in the Wuhai area are generally similar to those in Shandong (Figs. 4 and 5c, d). Both show characteristic maceria structure, composed of siliceous sponges and microbial carbonates. Although more maceriate reef-bearing beds occur in Wuhai than in Shandong, they are generally thinner and volumetrically

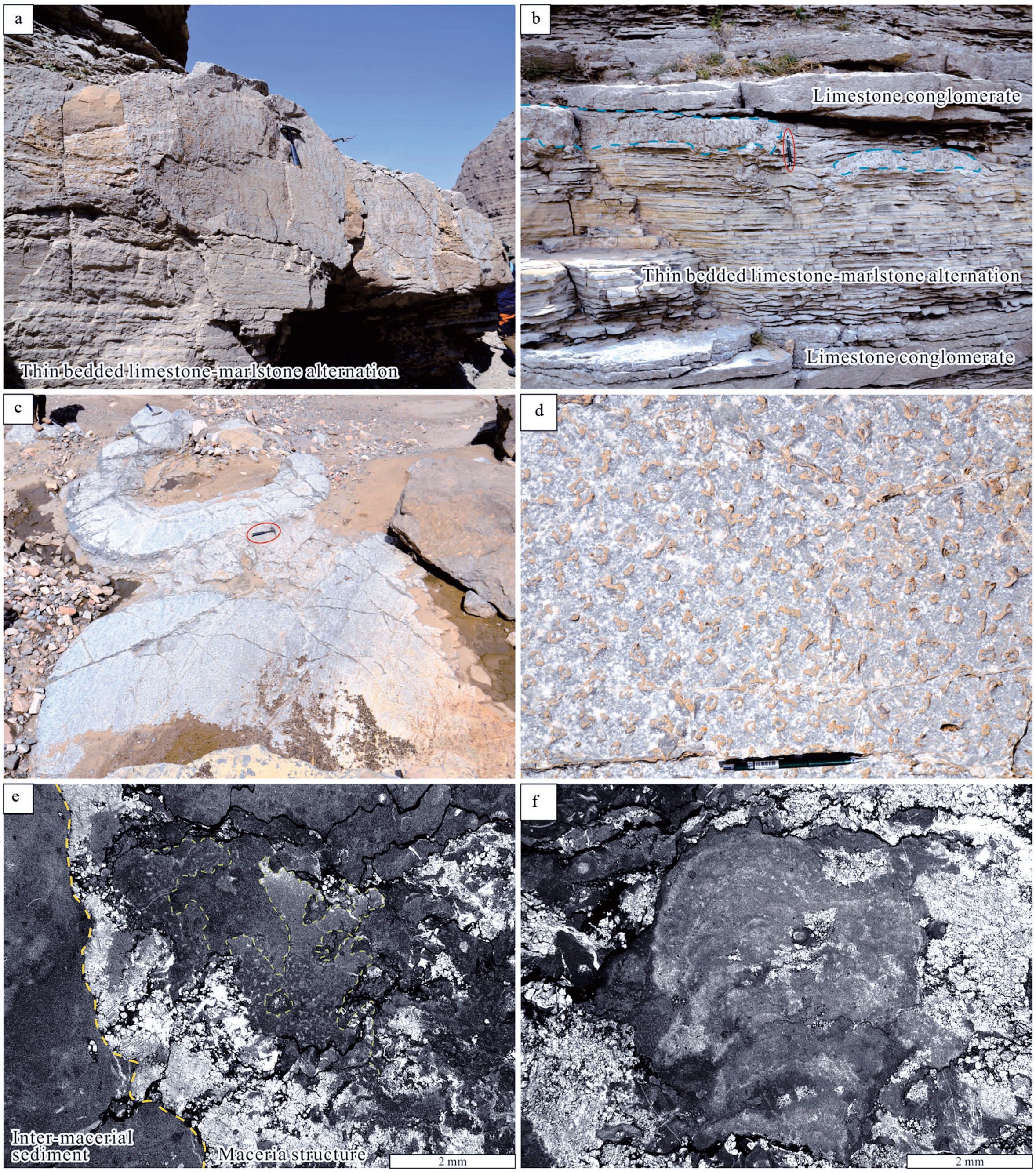

Fig. 4. Maze-like maceriate reef.
(a) Maceriate reef showing mound-shape geometry. Hammer for scale in (a) and (c) is 27 cm in length. (b) Photograph of two thin lenticular maceriate reefs (blue dashed line) occurring within the alternation of thin-bedded lime mudstone and marlstone. Pencil for scale in (b) and (d) is 14.5 cm in length. (c) Bedding surface of maceriate reef, showing circular shape. (d). Close-up of (c), showing maze-like complex structures on the upper surface. (e) Photomicrograph showing maceria structure and inter-macerial sediment. Note occurrence of poorly preserved sponges (green dashed line). (f) Photomicrograph of microstromatolite.

much smaller, possibly due to different depositional environments, i.e., a shallow carbonate platform in Shandong (Woo et al., 2008; Lee et al., 2010) and a deep-water environment in Wuhai (Myrow et al., 2015). It is also noteworthy that the Wuhai maceriate reefs occurred earlier (Guzhangian) than the Shandong maceriate reefs (Jiangshanian). Considering that maceriate reefs are generally limited to the Furongian and Early Ordovician (Shapiro and Awramik, 2006), the Wuhai examples may represent one of the earliest occurrences of maceriate reefs. Since the transition from thrombolite-dominated Cambrian Series 3 reefs to maceriate-dominated Furongian reefs is a global phenomenon that might reflect global-scale geological events, the Wuhai macerate reefs are important for understanding the Cambrian Series 3–Furongian reef transition (Lee et al., 2015).

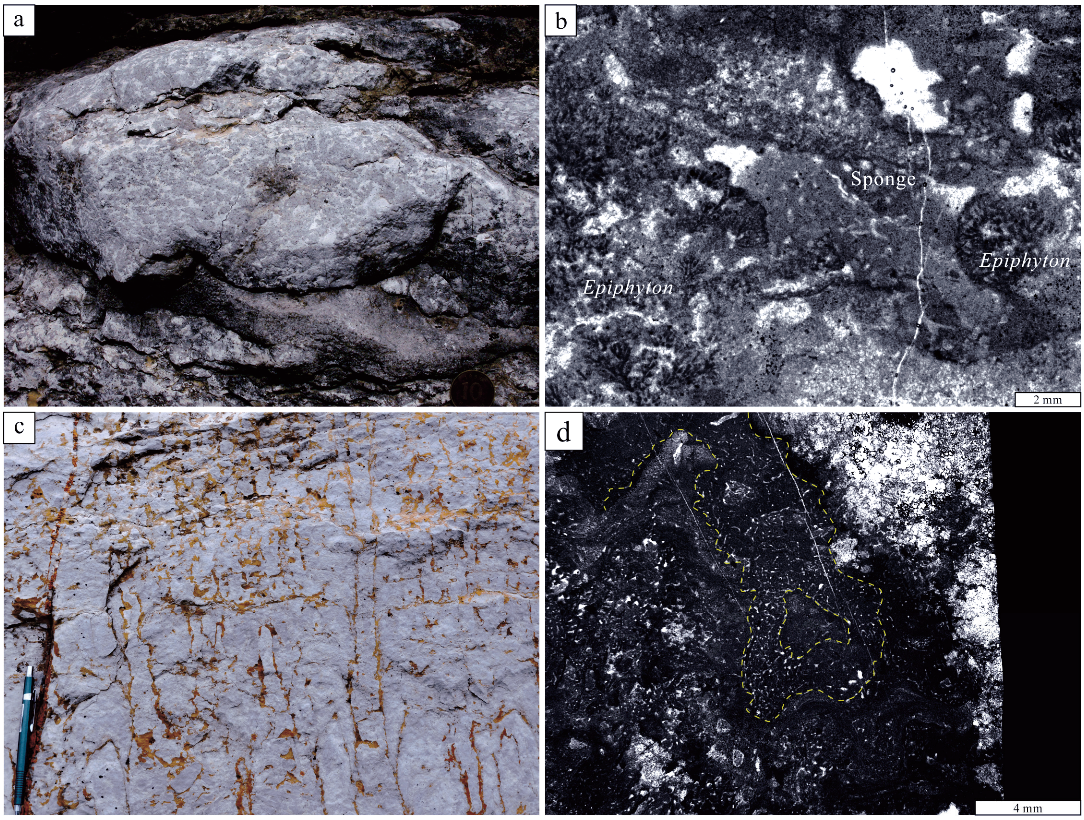

Fig. 5. Cambrian reefs in Shandong Province, China.
(a) Type B thrombolite in the Zhangxia Formation (Drumian). Coin for scale is 2.3 cm in diameter. (b) Photomicrograph of type B thrombolite, showing calcified microbe *Epiphyton* and siliceous sponge remains. (c) Longitudinal view of maceriate reef in the Chaomidian Formation (Jiangshanian). Pencil for scale is 14.5 cm in length. (d) Photomicrograph showing siliceous sponges (green dashed line) within maceriate reef.

5 Conclusions

Two types of Cambrian reef, thrombolite and maze-like maceriate reef, are recognized from the Subeigo section, Wuhai, Inner Mongolia, northwest China. Although both types occur in similar depositional settings and form similar macrostructures, their meso- and microscale structures differ greatly. These reefs occur in the middle of successions dominated by thin-bedded lime mudstone-shale/marlstone alternations, indicating deposition in relatively deep environments, and laterally co-occur with grainstone/conglomerate, suggesting occasional storm influence. Thrombolite, occurring in the lower middle part of the sequence, is characterized by millimetric to centimetric mesoclots that consist of microstromatolite. On the other hand, maze-like maceriate reefs occur in the upper part of the sequence and consist of centimetric to decimetric maze-like maceria structures composed of siliceous sponges and microstromatolites. These reefs are generally similar to those previously reported from Shandong. Although Wuhai thrombolites are similar to those in Shandong in terms of mesostructure, their microstructures differ. Macerate reefs are also generally similar to the Shandong maceriate reefs, but the Wuhai maceriate reefs are much smaller in size and predate Shandong maceriate reefs.

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