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FURONGIAN (LATE CAMBRIAN) SPONGE–MICROBIAL MAZE-LIKE REEFS IN THE NORTH CHINA PLATFORM

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ABSTRACT: **During the Furongian (late Cambrian) and Early Ordovician, maze-like (maceriate) microbialites flourished in both Laurentia and Gondwana. The maze-like microbialites are characterized by centimeter- to decimeter-scale branching, complex structures. However, organisms responsible for the formation of maze-like structures are poorly known. In order to understand formational processes of maze-like microbialites, this study focuses on the Furongian microbialites of the North China Platform in which microbial components and siliceous sponges co-occur. The maze-like structures consist of microbial components such as microstromatolites, *Girvanella*, and *Renalcis*-like forms, as well as sponge spicule networks, whereas lime mud and bioclasts occupy the space between the structures. The maze-like structures developed on a relatively flat seafloor, forming low synoptic relief (<1 cm) above the sediment surface. Continuous growth of maze-like structures with balanced deposition of sediments led to meter-scale bioherms and biostromes, under the control of both microbes and siliceous sponges. This study suggests that siliceous sponges may have played an important role in the construction of maze-like structures between the end-Cambrian Series 2 extinction and the Great Ordovician Biodiversification Event.**

INTRODUCTION

Reef-building communities change with evolution and extinction of organisms throughout Earth's history (Wood 1998; Kiessling et al. 2002). During the Precambrian, most reefs (mainly stromatolites) were constructed by microbes (Grotzinger and Knoll 1999). Metazoans first appeared in the Neoproterozoic in stromatolite and thrombolite reefs (Grotzinger et al. 2000) and flourished in reefs throughout the Phanerozoic (Wood 1998). Archaeocyatha appeared in the late Terreneuvian and constructed reefs together with microbes until the end-Cambrian Series 2 extinction (Rowland and Shapiro 2002). Afterward, metazoans apparently became scarce in the Cambrian Series 3 and Furongian microbial-dominant reefs (Hong et al. 2012, table 1) until their resurgence in the Early Ordovician reefs (Webby 2002; Riding 2006).

During the Furongian and Early Ordovician, a rather unusual microbialite, characterized by centimeter- to decimeter-scale branching maze-like "maceria" structures, appeared on both Laurentia (Shapiro and Awramik 2006) and Gondwana (Lee et al. 2010). These microbialites, previously described as thrombolites (i.e., Aitken 1967), were subsequently redefined as maze-like (maceriate) microbialites (Shapiro and Awramik 2006; Lee et al. 2010). The maze-like microbialites are distinguished from thrombolites with millimeter- to centimeter-scale clotted texture; the maze-like structures may contain mesoclots within it (Shapiro 2000; Shapiro and Awramik 2006).

Although some *Girvanella* and *Renalcis*-like forms have previously been reported from maze-like microbialites (Demicco 1985; de Freitas and Mayr 1995; Hersi et al. 2002; Shapiro and Awramik 2006; Lee et al. 2010), organisms that are responsible for formation of the microbialites are still poorly known. In order to understand the constituents and formative mechanisms of maze-like microbialites, this study describes Furongian maze-like microbialites in Shandong Province, China. This study provides new insights into the components of maze-like microbialites and new information on reef evolution during the Furongian.

GEOLOGICAL SETTING AND DEPOSITIONAL ENVIRONMENTS

The North China Platform was located at the margin of Gondwana during the early Paleozoic (Golonka 2007; McKenzie et al. 2011). Sedimentation on the platform was initiated during the Cambrian Series 2 and lasted until the Middle Ordovician (Meng et al. 1997; Chough et al. 2010). The study area (Shandong Province, China) is located in the central part of the platform (Fig. 1). Furongian strata in Shandong Province are represented by the Chaomidian Formation, the uppermost Cambrian lithostratigraphic unit in the area (Chough et al. 2010) (Fig. 2A). The Chaomidian formation, which consists mainly of various carbonate lithofacies such as limestone/shale–marlstone alternation, stratified grainstone, bioturbated wackestone to packstone, microbialite, and limestone conglomerate and breccia, was deposited in a storm-dominated shallow-marine environment (Chen et al. 2011, 2012) (Fig. 2B).

Several microbialite beds are present in the Chaomidian Formation (Lee et al. 2010, 2012; Chen et al. 2011) (Fig. 2B). The Furongian microbialites occur in various locations over a 6000-km^2 area of Shandong Province (Lee et al. 2010, 2012). These microbialites occur within the *Changshania–Irvingella* and *Kaolishania* biozones, indicating a Jiangshanian age (Chough et al. 2010; Peng et al. 2012). The microbialites flourished and formed extensive bioherms and biostromes during an interval of gradually increasing relative sea level and were subsequently

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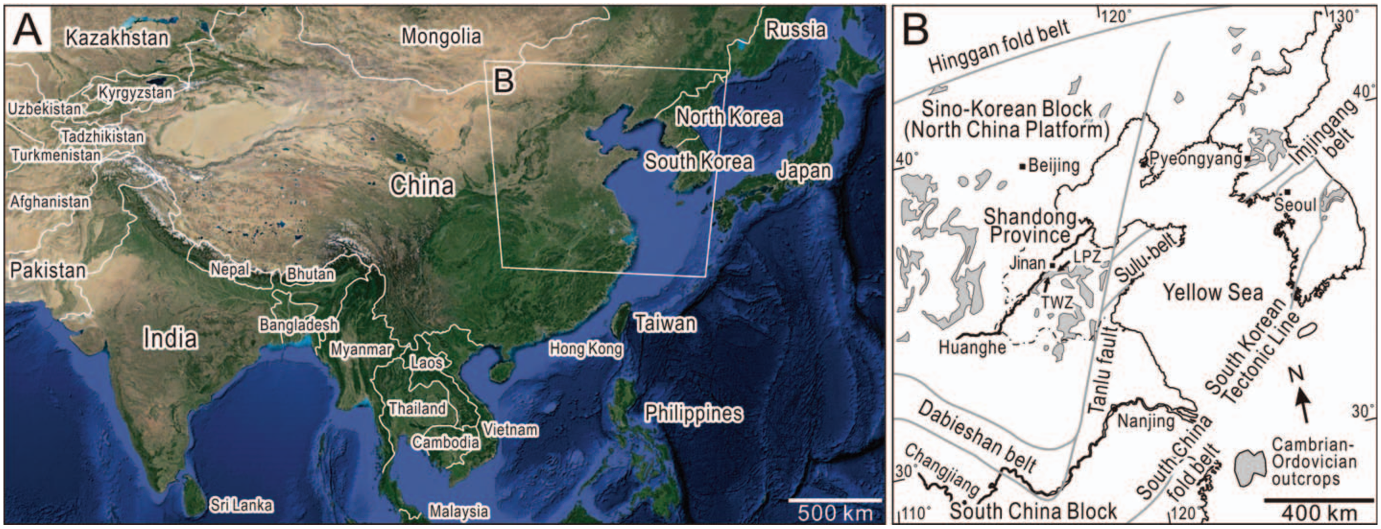


FIG. 1.—Geological setting of the study area. **A)** Satellite photograph of Asia (modified from Google Maps 2013). **B)** Cambrian–Ordovician outcrops in the North China Platform. Study areas are marked with black arrows. TWZ, Tangwangzhai section (36°30′59″N, 116°51′38″E); LPZ, Laopozhuang section (36°34′08″N, 117°04′35″E).

terminated as a result of rapid rise in relative sea level (Chen et al. 2012; Lee et al. 2012).

METHODS

Two outcrop sections (Tangwangzhai and Laopozhuang sections) in Shandong Province, China, were selected for this study (Fig. 1B). Among the nine microbialite beds, which were decimeters to meters thick, in the Tangwangzhai section, the third, fourth, eighth, and ninth beds can be correlated with beds in the Laopozhuang section, about 20 km distant (Fig. 2B). More than 200 samples of three types of microbialites were obtained from these four beds (Table 1). Rock slabs were cut and polished in order to clearly identify microbialite mesostructures. A total of 300 large-format (7.6 × 5.2 cm) thin sections cut in both transverse

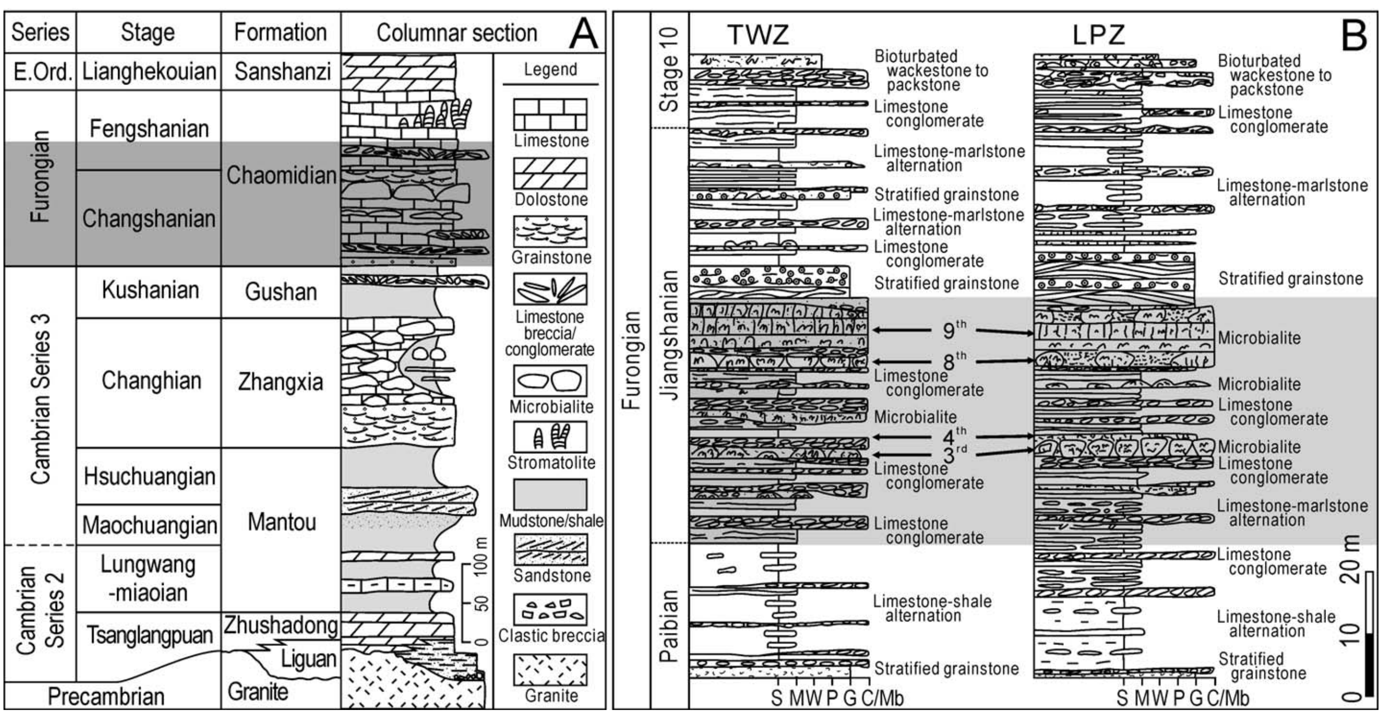
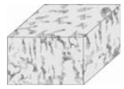
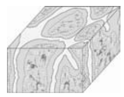
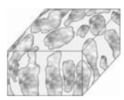


FIG. 2.—**A)** Summary of the Cambrian stratigraphy in Shandong Province, China (modified after Chough et al. 2010). Shaded interval corresponds to sedimentary logs presented in Part B. **B)** Sedimentary logs of the lower-middle part of the Chaomidian Formation in the Tangwangzhai section (left) and the Laopozhuang section (right). Reefs occur mainly in the shaded interval. Third, fourth, eighth, and ninth beds indicate studied horizons. S, Shale; M, mudstone; W, wackestone; P, packstone; G, grainstone; C, conglomerate; and Mb, microbialite. For location, see Figure 1B.

TABLE 1.—*Description and interpretation of microbialites (modified after Lee et al. 2010).*

Microbialite types	Macrostructures	Internal structures	Diagram	Macroscale and mesoscale description	Microscale description	Depositional environment
Tabular maceriate microbialite	Tabular	Maze-like structures (maceria)		Biohermal–biostromal megastructure (Fig. 3A); consists of maze-like structure and sediment in between the structure with a ragged boundary (Fig. 3C, D); chaotic texture within the maze-like structure (Fig. 4A)	Maze-like structures consist of microbial carbonates and siliceous sponges; microbial carbonates include microstromatolite, *Girvanella*, and *Renalcis*-like form; sediments in between the maze-like structures consist of mainly lime muds and bioclasts	Low-energy environment below normal wave base
Columnar maceriate microbialite	Columnar	Maze-like structures (maceria)		Columnar structure (>60 cm) within biostrome (Fig. 3E); maze-like structures occur as infrastructure, with structureless outer rim; coarse-grained intercolumnar sediments; columnar maceriate microbialite changes upward to columnar chaotic microbialite	Component of maze-like structure and sediment in between the structure similar to tabular maceriate microbialite; coarse-grained intercolumnar sediments including peloids, bioclasts, and *Girvanella* fragments	Intermediate-energy environment near normal wave base
Columnar chaotic microbialite	Columnar	Chaotic		Columnar structure (10–15 cm in diameter) (Fig. 3F); elongation ratio of columns ranges from 3:1 to 10:1; chaotic mesostructure	Mainly consist of sparite, peloid, and bioclast, with minor *Girvanella*, *Renalcis*-like form, and siliceous sponge; intercolumnar sediments consist of peloids, bioclasts, and *Girvanella* fragments	High-energy environment above normal wave base

and longitudinal directions were prepared to examine and describe microbialite components.

MICROBIALITES

Three types of microbialites were defined in previous studies based on field descriptions of macroscale and mesoscale structures: tabular maceriate microbialites, columnar maceriate microbialites, and columnar chaotic microbialites (Lee et al. 2010, 2012) (Table 1; Fig. 3). Among these, only tabular and columnar maceriate microbialites contain maze-like structures. The three types of microbialites represent different energy conditions: tabular maceriate, columnar maceriate, and columnar chaotic microbialites formed in environments below, near, and above normal wave base, respectively (Lee et al. 2010) (Table 1). Several cyclic units of gradual upward transition from columnar maceriate microbialites to columnar chaotic microbialites are recognized, which are interpreted as shallowing-upward trends (Lee et al. 2012).

The maze-like structures (maceria) are characterized by centimeter- to decimeter-scale branching and/or converging columns in longitudinal section and maze-like complex structures in transverse section (Shapiro and Awramik 2006; Lee et al. 2010) (Fig. 3). The structures constitute the main body of the maze-like microbialites (tabular and columnar maceriate microbialites) and approximately half the microbialite volume (Lee et al. 2010, 2012) (Fig. 3B–E). The maze-like structures are chaotic in texture and light to dark gray in color. There is no evidence of clear laminae or mesoclots within the structures (Lee et al. 2010) (Fig. 4A). The space between the maze-like structures is mostly composed of lime mud, a few scattered bioclasts of trilobites and bivalves, and rare intraclasts, which are light gray in color and occasionally bioturbated (Fig. 4F). The boundary between the maze-like structures and surrounding sediments is ragged (Shapiro and Awramik 2006; Lee et al. 2010), although it is commonly indiscernible unless selectively enhanced by dolomitization (cf. Aitken 1967; Glumac and Walker 1997) (Figs. 4A, B, 5). In microscale observations, two principal components of the maze-like structures are identified: microbial components and siliceous sponges.

Microbial Components

Microbial components comprise microstromatolites, calcified *Girvanella* filaments, and *Renalcis*-like botryoid forms (Fig. 6). Microstromatolites, which are one of the most common components of the maze-like structures (Figs. 4C, D, 5B), mostly exhibit convex-up laminae composed of alternating micrite and microsparite (Fig. 6A–D). No calcified microbes have been recognized in the microstromatolites. The microstromatolites range from 1 to 10 mm in width and 1 to 20 mm in height. The laminae range from 10 to 100 μm in thickness. Columnar-shaped microstromatolites are dominant (Fig. 6A, B), although millimeter thick, relatively flat-laminated microstromatolites are also present (Fig. 6D).

The calcified microbe *Girvanella* is represented by micritic tubes (~20 μm thick in diameter and 300–500 μm long) (Fig. 6E). *Girvanella* usually forms horizontally aligned thin layers consisting of several filaments (Fig. 6A). Scarce millimeter-scale *Renalcis*-like forms are present within the maze-like structure (~1–4 mm in size). *Renalcis*-like forms are characterized by hollow chambered sparitic structures surrounded by micrite (Lee et al. 2010) (Fig. 6A). However, these *Renalcis*-like forms are different from *Renalcis*, which is composed of micrite (Riding 1991).

Siliceous Sponges

Siliceous sponges are recognized as closely spaced spicule networks embedded in light- to medium-gray micrite (Fig. 7). The spicules, which are ~20 to 60 μm in diameter and 100 to 500 μm in length, are now composed of sparry calcite. Most spicule rays meet at angles of ~120° or 180°, although determination of their original shapes is difficult. The micrite in between spicules exhibits peloidal fabric in some examples (Fig. 7D). The outlines of sponge spicule networks are usually irregular to lump shaped, although various other forms, including cylindrical, bowl-shaped, funnel-shaped, columnar, and lamellar, also occur (Fig. 7A–D). The spicule networks are generally a few millimeters in width and show maximum width of ~2 cm. Irregular millimeter-scale patches of the sponge spicule networks commonly co-occur with dark-gray micrite, the latter forming a texture similar to that of the microclots of thrombolite

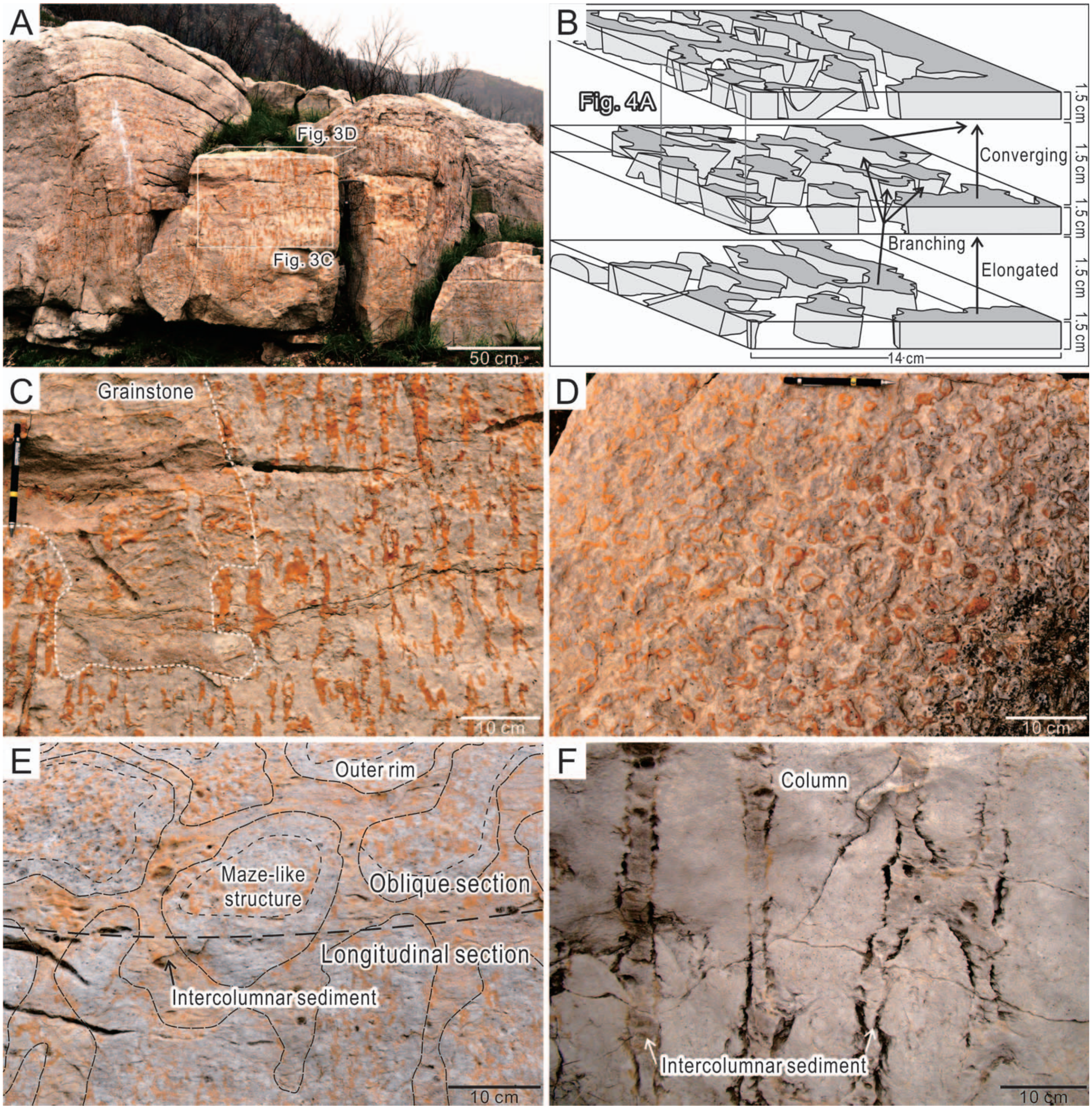


FIG. 3.—Macroscale and mesoscale descriptions of microbialites. **A)** Tabular maceriate microbialite in the middle Chaomidian Formation (Laopozhuang section). **B)** Three-dimensional reconstruction of maze-like structures (maceria). Maze-like structures show both branching-upward and converging-upward patterns (after Lee et al. 2010). **C)** Longitudinal view of maze-like structure, showing vertically branching structures; orange-colored material is dolomite, which roughly separates maze-like structures and sediments. **D)** Transverse view of the maze-like structures. **E)** Columnar maceriate microbialite. Maze-like structures are surrounded by chaotic outer rim, forming columnar macrostructure. Columns are separated by coarse-grained intercolumnar sediments. **F)** Columnar chaotic microbialite. There is no maze-like structure within this type. Intercolumnar space is filled with grainstone.

(Fig. 7E). Many of the spicule networks, however, do not show any clear margins (Fig. 7D, E). In some cases, sponges encrust other bioclasts, such as trilobite or bivalve fragments (Fig. 7C). In addition, spicule networks are also rarely found within bivalve shells or burrows (Figs. 5B, 7F). The sponges most likely belong to the class Demospongiae based on the characteristics of spicules (monaxons and tetraxons) and the occurrence of interlocking spicule networks (Rigby 1983; Hooper and Van Soest 2002).

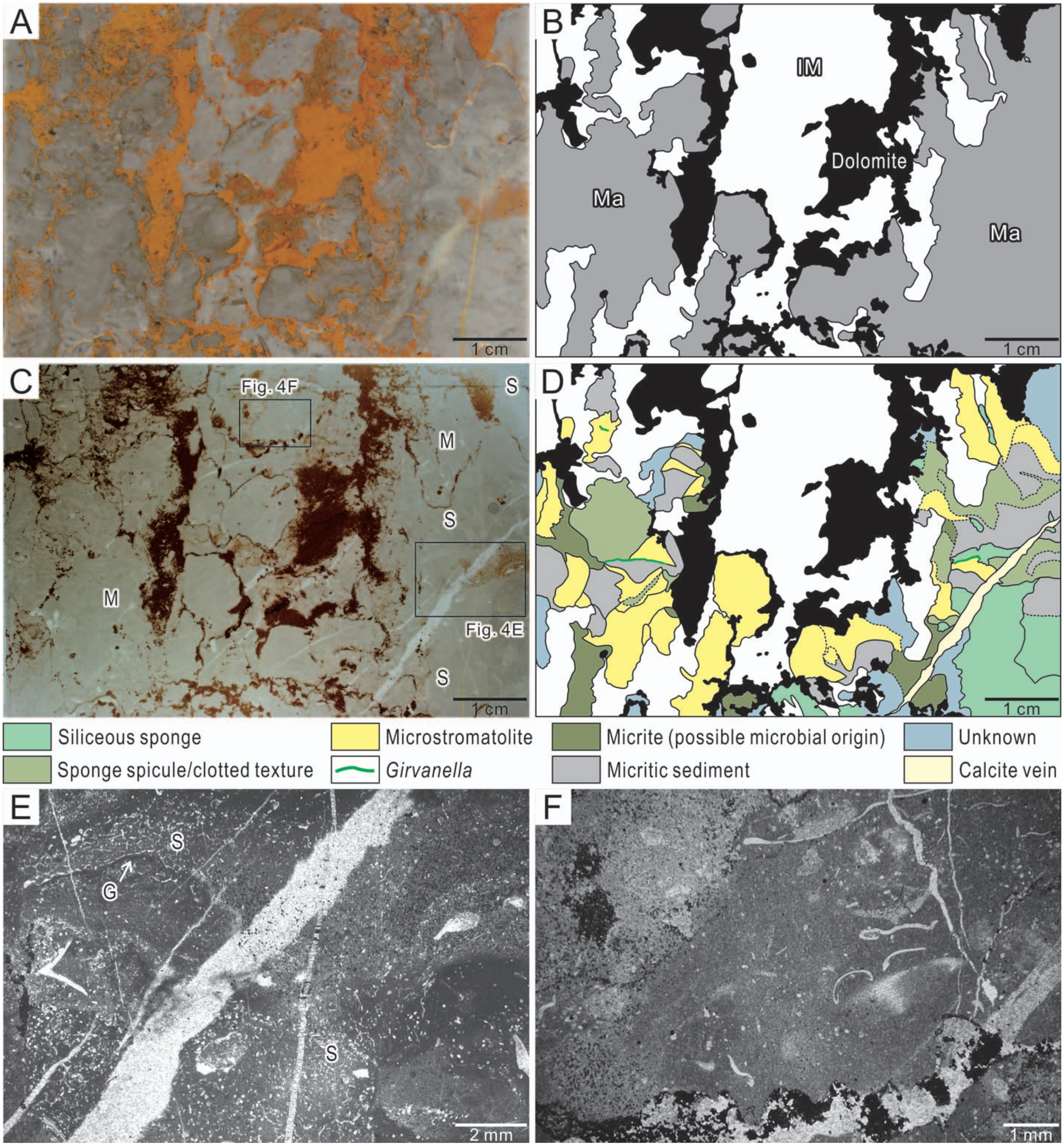


FIG. 4.—Mesoscale and microscale descriptions of maze-like microbialites. **A)** Polished rock slab showing maze-like structure (light to dark gray) and sediment in between (light gray); the boundary between the maze-like structure and sediment is usually enhanced by selective dolomitization (brown). **B)** Line drawing of Part A. Maze-like structure (Ma) and sediment in between the structure (IM) are marked by gray and white, respectively. **C)** Photograph of a thin section made from Part A. Sponge spicule networks (S) and microstromatolites (M) are recognized at various locations. **D)** Line drawing of Part C. Sponges and microbial components are mostly recognized within the maze-like structure. **E)** Photomicrograph of sponges within the maze-like structure. G, *Girvanella*. **F)** Photomicrograph of sediments between maze-like structures composed mainly of lime mud and a few bioclasts (trilobites).

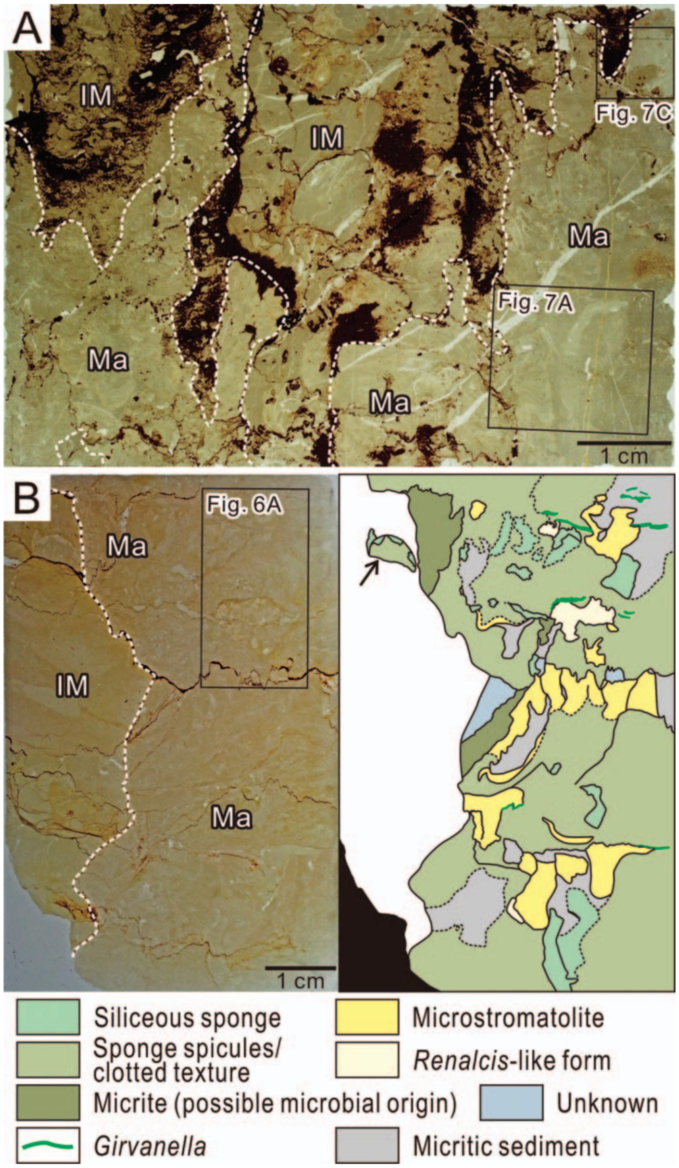


FIG. 5.—Photograph of two thin sections of maze-like microbialite (tabular maceriate microbialite). **A)** A thin section showing chaotic maze-like structure (Ma) and muddy sediments in between (IM). Maze-like structures consist mainly of sponges and microbial components; sediment in between the maze-like structures consists of lime mud and some bioclasts. **B)** A thin section and line drawing showing various components within the maze-like structure. Also note occurrence of sponge spicule network within a bivalve shell (arrow).

Occurrence of Microbial Components and Sponges

Microbial components and sponges occur mainly within maze-like microbialites (i.e., in tabular and columnar maceriate microbialites) (Table 1). Within maze-like microbialites, microbial components and siliceous sponges occur predominantly in maze-like structures (Figs. 4C–E, 5). In many cases, major portions of the maze-like structures consist of irregular patches of spicule networks, microstromatolite, and micrite (Figs. 4D, 5B). No microbial components are observed within sediments between the maze-like structures, although a few complete sponge spicule networks are present, enclosed within burrows or shells in the sediments (Figs. 5B, 7F). Reworked clasts of microbial components or sponges are also absent. On the other hand, microbial components and siliceous sponges are rarely recognized within the columnar chaotic microbialites in which maze-like structure is absent; sparite, peloid, and bioclast occur dominantly with minor *Girvanella*, *Renalcis*-like forms and siliceous sponges.

Microbial components and sponges commonly occur on top of one another or side by side (Figs. 6A–D, 7A, B). *Girvanella* filaments are aligned laterally along the margins of sponges and microstromatolites, forming thin layers (Figs. 4E, 5B, 6A–C, 7A). Lamellar-shaped sponges are often intercalated with thin *Girvanella* layers or microstromatolites (Figs. 5B, 6C). *Renalcis*-like forms are surrounded by irregular patches of sponges (Fig. 6A). Many of the cylindrical, bowl-shaped, funnel-shaped, and columnar-shaped sponges appear to be vertically aligned (Fig. 7A–C).

Interpretations

Microbial components within the maze-like structures apparently formed in situ. Convex-up laminae of microstromatolites indicate upward growth, and *Girvanella* flatly covers preexisting surfaces (tops of sponges or microstromatolites) without reworking. The upward growth patterns of microstromatolites and *Girvanella* encrusting other surfaces suggest that they were most likely formed by photosynthetic cyanobacteria (Riding 1991, 2000). The occurrences of microstromatolites in growth positions and their columnar shapes suggest that they were constructors (Fagerstrom and Weidlich 1999; Shen and Webb 2008). Flat-laminated microstromatolites and *Girvanella* would have encrusted underlying substrates (Kruse and Zhuravlev 2008; Shen and Webb 2008; Adachi et al. 2009) (Fig. 6D). *Renalcis*-like forms may represent diagenetic alteration of microbial colonies (Ezaki et al. 2003). There is no clear evidence that *Renalcis*-like forms were preserved in growth position, but it is likely that they originally formed within the maze-like structures, as they only occur within the structures.

The siliceous sponges in the Chaomidian microbialites appear to be preserved in growth position. Vertically aligned sponges (e.g., cylindrical, bowl-shaped, funnel-shaped, and columnar forms) possibly indicate their upward growth. Overall abundance of irregular-form sponges indicates either their irregular nature (Rigby 1983) or their low preservation potential (Reitner et al. 1995; Warnke 1995). Micrite and peloids of the clotted texture may be microbial in origin (Pratt and James 1989; Pratt and Haidl 2008) or may represent degraded sponge soft tissues (Reitner 1993; Reitner et al. 1995; Warnke 1995; Neuweiler et al. 2007). The occurrence of spicules within the clotted texture, however, suggests that they represent the latter (i.e., degraded sponge tissues) (Fig. 7E).

Although preservation of the sponges is generally poor, the presence of a few well-preserved in situ cylindrical, bowl-shaped, funnel-shaped, and columnar sponges suggests that they may have been constructors of the reef (Narbonne and Dixon 1984; Wendt et al. 1989; Brunton and Dixon 1994; Fagerstrom and Weidlich 1999) (Fig. 7A). Sponges would also have

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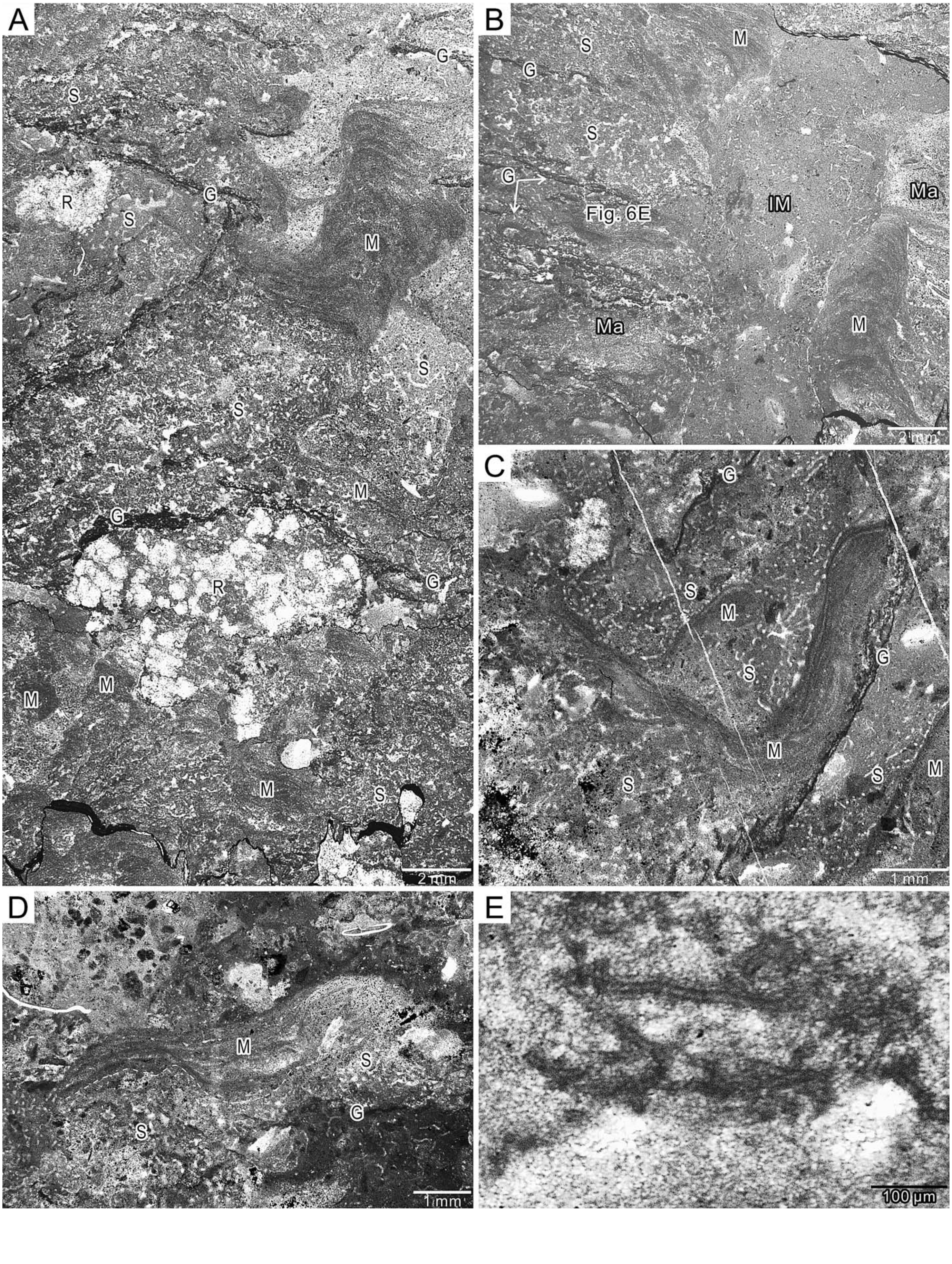
FIG. 6.—Photomicrographs of microbial components. **A)** Longitudinal section of maze-like structure, showing various relationships between microstromatolites (M), sponges (S), and *Renalcis*-like forms (R). Several *Girvanella* layers (G) intercalated between sponges or microstromatolites. **B)** A well-preserved margin between maze-like structures (Ma) and sediment in between the structures (IM), showing abundant sponges, *Girvanella* (left), and a microstromatolite (right). Sponges and *Girvanella* formed a ragged margin. **C)** Several concave-upward microstromatolites intercalated with lamellar-form sponges and *Girvanella* filaments; microstromatolites and sponges would have formed along the concave-upward surface. **D)** Thin, flat microstromatolite covering poorly preserved sponges. **E)** Close-up of *Girvanella*, showing tubular microstructure.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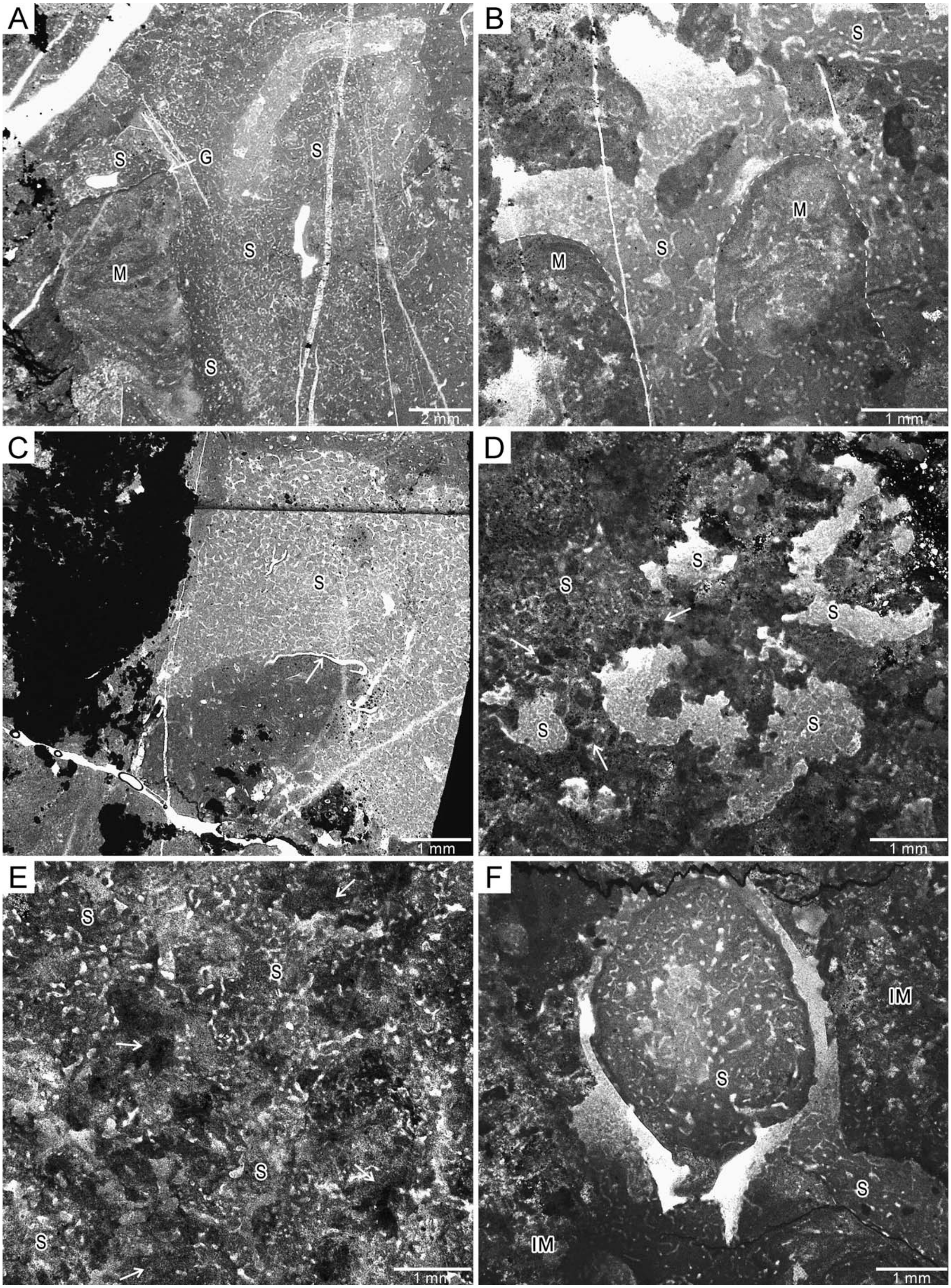
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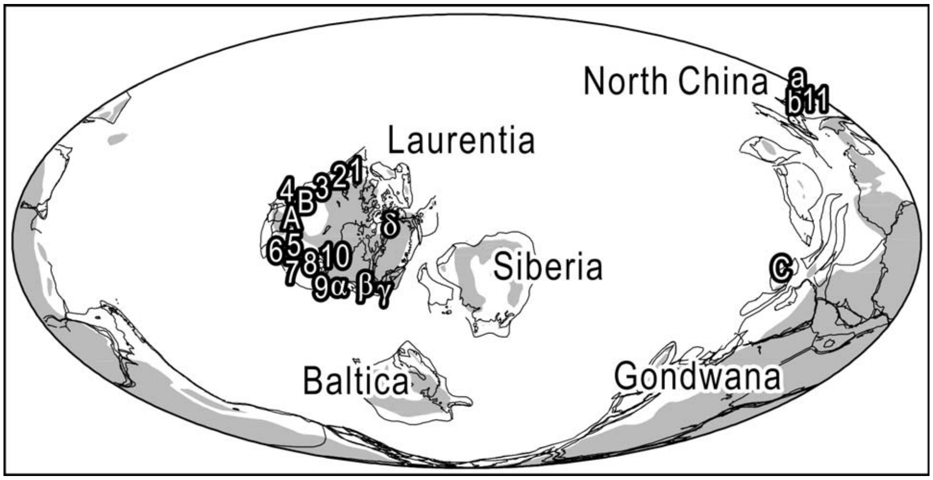

FIG. 8.—Paleogeographic map of the late Cambrian (after Golonka 2007). Known distributions of Cambrian Series 3 sponge–microbial reefs (a–b), Furongian maze-like reefs (1–11) and sponge–microbial reefs (A–C), and Early Ordovician maze-like reefs (α–δ). a = Daegi Formation, Taebaeksan Basin, Korea (Hong et al. 2012). b = Zhangxia Formation, Shandong Province, China (Hong et al. 2012). 1–3 = Sullivan, Waterfowl, and Bison Creek formations, respectively, Canadian Rockies (Aitken 1967). 4 = Nopah Formation, Great Basin, USA (Shapiro and Awramik 2006). 5 = Potosi Formation, Upper Mississippi Valley, USA (Howe 1966). 6 = La Flecha Formation, Argentine Precordillera (Armella 1994; Raviolo et al. 2010). 7–8 = Gatesburg Formation (Taylor et al. 1999) and Conococheague Limestone (Demicco 1985), respectively, southern Appalachians, USA. 9 = Little Falls Formation, northern Appalachians, USA (Mazzullo and Friedman 1977). 10 = Strites Pond Formation, Quebec, Canada (Hersi et al. 2002). 11 = Chaomidian Formation, Shandong Province, China (Lee et al. 2010, 2012; this study). A = Wilberns Formation, Texas, USA (Johns et al. 2007). B = Gallatin and Bonanza King formations, Great Basin, USA (Shapiro and Rigby 2004). C = Mila Formation, Iran (Hamdi et al. 1995; Kruse and Zhuravlev 2008). α = Tribes Hill Formation, northern Appalachians, USA (Mazzullo and Friedman 1977). β = St. George Group, Newfoundland, Canada (Pratt and James 1982). γ = Sangomore Formation, Scotland (Herringshaw and Raine 2007), δ = Bulleys Lump and other formations, Arctic Canada (de Freitas and Mayr 1995).

encrusted bioclasts or microstromatolites (Narbonne and Dixon 1984; Webb 1987) (Fig. 7B, C). Rare occurrence of undisturbed sponge spicule networks within shells or burrows indicates their presence in cryptic microhabitats outside of the maze-like structures (Kobluk 1988) (Figs. 5B, 7F).

The maze-like structures in the Chaomidian microbialites resulted from cogrowth of microbes and siliceous sponges. The growth of microbes and sponges was accompanied by deposition of lime mud and bioclasts among the maze-like structures. The growth rate of the maze-like structures (i.e., microbe–sponge complexes) was likely balanced with the rate of background sedimentation (of lime mud and bioclasts). The ragged margins likely indicate a low synoptic relief (possibly <1 cm) above the sediment–water interface (Pratt and James 1982; Shapiro and Awramik 2006; Lee et al. 2010).

The contemporaneous deposition of biogenic maze-like frameworks and the surrounding sediments resulted in the formation of meter-scale domal, tabular, and columnar macrostructures (Shapiro and Awramik 2006; Lee et al. 2010). The presence of muddy sediments in between the maze-like structures suggests that the maze-like microbialites formed on a low-energy seafloor near or below the wave base (Lee et al. 2010), in which environmental conditions would have been favorable for siliceous sponges and microstromatolites (Reitner et al. 1995). On the other hand, high-energy environments above the normal wave base, in which the columnar chaotic microbialites formed (Lee et al. 2010), would have been unfavorable for the growth of siliceous sponges and microstromatolites.

DISCUSSION

During the Cambrian, reef ecosystems experienced a drastic changeover (Wood 1998). Archaeocyatha and associated metazoans with microbes formed the initial Paleozoic reef systems during the Terreneuvian and Cambrian Series 2 (Wood et al. 1993; Riding and Zhuravlev 1995; Álvaro et al. 2006). After the extinction of metazoans at the end of Cambrian Series 2, calcified microbes played an important role in the reefs of Cambrian Series 3 and Furongian with a few siliceous sponges (Sheehan 1985; Rowland and Shapiro 2002; Shapiro and Rigby 2004; Riding 2006; Johns et al. 2007; Kruse and Zhuravlev 2008; Hong et al. 2012) (Fig. 8). Diverse metazoans, such as sponges, corals, stromatoporoids, pelmatozoans, and bryozoans, began to participate widely in reefs during the Early to Middle Ordovician (Webby 2002). Most of the Early Ordovician metazoans could not, however, construct reefs independently; rather, they required the binding activities of microbes to stabilize the reef framework (Webby 2002; Adachi et al. 2011). Metazoan-dominated reefs eventually replaced these metazoan–microbial reefs during the middle–late Middle Ordovician (Webby 2002).

During the Furongian and Early Ordovician, maze-like microbialites were distributed worldwide (Howe 1966; Aitken 1967; Mazzullo and Friedman 1977; Pratt and James 1982; Demicco 1985; Armella 1994; de Freitas and Mayr 1995; Taylor et al. 1999; Hersi et al. 2002; Shapiro and Awramik 2006; Herringshaw and Raine 2007; Lee et al. 2010; Raviolo et al. 2010) (Fig. 8; Table 2). However, reports on the constituents of the maze-like microbialites are scarce (e.g., Mazzullo and Friedman 1977; Taylor et al. 1999; Herringshaw and Raine 2007), partly because of dolomitization and recrystallization (Howe 1966; Shapiro and Awramik

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FIG. 7.—Photomicrographs of siliceous sponges. **A)** Cylinder-shaped sponge (S) beside a microstromatolite (M); microstromatolite is overlain by a thin layer of *Girvanella* (G) and a lump-shaped sponge. **B)** Sponge covering microstromatolite. **C)** Sponge overlying a trilobite shell (white arrow). **D)** Irregularly shaped sponges surrounded by disarticulated sponge spicules. Some disarticulated sponges contain peloids (arrow) within it. **E)** Irregular sponge spicule networks and dark-gray micrite (arrow) forming texture similar to microclots. **F)** Cryptic sponge in a bivalve shell; the shell occurs within the sediment in between the maze-like structures (IM).

TABLE 2.—*Summary of worldwide occurrence of the Furongian to Early Ordovician maze-like microbialites.*

Location	Formation	Age	Component of maze-like structure	Component occurring outside of maze-like structure	Reference
Shandong Province, China	Chaomidian Formation	Furongian	Siliceous sponge, microstromatolite, *Girvanella*, *Renalcis*-like forms		Lee et al. (2010, 2012), this study
Canadian Rockies	Sullivan Formation	Furongian	no data		Aitken (1967)
Canadian Rockies	Waterfowl Formation	Furongian	no data		Aitken (1967)
Canadian Rockies	Bison Creek Formation	Furongian	no data		Aitken (1967)
Great Basin, USA	Nopah Formation	Furongian	Dolomitized		Shapiro and Awramik (2006)
Upper Mississippi Valley, USA	Potosi Formation	Furongian	Dolomitized		Howe (1966)
Quebec, Canada	Strites Pond Formation	Furongian	*Renalcis*-like clusters, clotted fabric		Hersi et al. (2002)
Precordillera, Argentina	La Flecha Formation	Furongian	Peloid, clotted micrite	*Nuia*	Armella (1994), Raviolo et al. (2010)
Southern Appalachians, USA	Gatesburg Formation	Furongian	no data		Taylor et al. (1999)
Southern Appalachians, USA	Conococheague Limestone	Furongian	*Renalcis* or *Renalcis*-like forms, *Girvanella*		Demicco (1985)
Northern Appalachians, USA	Little Falls Formation	Furongian	no data		Mazzullo and Friedman (1977)
Northern Appalachians, USA	Tribes Hill Formation	Early Ordovician	no data		Mazzullo and Friedman (1977)
Northwest Scotland	Sangomore Formation	Early Ordovician	no data		Herringshaw and Raine (2007)
Newfoundland, Canada	St. George Group	Early Ordovician	Peloid, fenestrae	*Lichenaria*, *Renalcis*, Archaeoscyphiid sponges, *Calathium*, *Pulchrilamina*	Pratt and James (1982)
Arctic Canada	Bulleys Lump and other formations	Early Ordovician	Peloid, fenestrae, *Girvanella*	*Renalcis*, lithistid sponges	de Freitas and Mayr (1995)

2006). In previous studies, peloids and clotted micrite with minor *Girvanella* and *Renalcis*-like forms were reported from maze-like structures (Table 2). Although metazoans, including lithistid sponges, occur in some Ordovician maze-like microbialites, they occur outside of the maze-like structures and thus are possibly not closely related to the formation of the structures (Pratt and James 1982; de Freitas and Mayr 1995). Thus, it is first demonstrated herein that intergrowth of microbes and siliceous sponges within maze-like structures occurred prior to the Ordovician.

Although the organisms responsible for the formation of maze-like structures are poorly known, it has been suggested that biological processes controlled the formation of maze-like microbialites, on account of their limited range (Furongian–Early Ordovician) and occurrence in various depositional environments (Shapiro and Awramik 2006). The co-occurrence of microbial components and siliceous sponges within maze-like structures, as reported in this study, indicates that both microbes and siliceous sponges contributed to the formation of Chaomidian maze-like structures. This finding raises the possibility that similar processes may have contributed to the construction of maze-like microbialites elsewhere during the Furongian and Early Ordovician. The finding further suggests that siliceous sponges were pervasive components of Furongian reefs (Johns et al. 2007; Hong et al. 2012). In fact, sponges within the reefs can be easily overlooked unless recognizable structures are present in macroscale or mesoscale. Other early Paleozoic sponges are also not visible in macroscale or mesoscale but are observed in microscale (Hong et al. 2012; Kwon et al. 2012). This study suggests that further petrographic examination of the maze-like microbialites may potentially provide additional clues as to evolutionary trends of the early Paleozoic reefal faunas.

CONCLUSIONS

Maze-like microbialites, constructed by microbes and siliceous sponges, were widely developed on the central North China Platform during the Furongian. Microbes and sponges played various roles within the reef, as constructors and binders. The accumulative growth of maze-like structures with balanced deposition of lime mud and bioclasts formed meter-scale bioherms and biostromes. The temporal restriction of the maze-like microbialites and their occurrence in various depositional environments suggests that specific organisms (microbes and siliceous sponges) could have constructed characteristic maze-like structures elsewhere during the Furongian and Early Ordovician.

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