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Reefs in the Early Paleozoic Taebaek Group, Korea: A Review

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Abstract: Various early Paleozoic (Cambrian Series 3–Middle Ordovician) reefs are found in the Taebaek Group, eastern Korea, located in the eastern margin of the Sino-Korean Block. They occur in every carbonate-dominant lithostratigraphic unit of the group, but their morphology and composition differ markedly. The Daegi Formation (middle Cambrian: Cambrian Series 3) contains siliceous sponge-*Epiphyton* reefs formed in a shallow subtidal environment, which is one of the earliest metazoan-bearing microbial reefs after the archaeocyath extinction. The Hwajeol Formation (upper Cambrian: Furongian) encloses sporadic dendrolites consisting of *Angulocellularia*, which developed in a relatively deep subtidal environment, representing a rare deeper water example. The onset of the Ordovician radiation resulted in the formation of microbialite–*Archaeoscyphia*–calathiid patch reefs in shallow subtidal deposits of the Lower Ordovician Dumugol Formation. Subsequent late Early Ordovician relative sea-level fall established extensive peritidal environments, forming microbial mats and stromatolites of the Lower–Middle Ordovician Makgol Formation. Ensuing Ordovician radiation resulted in one of the earliest metazoan skeletal reefs of the Middle Ordovician Duwibong Formation, constructed by stromatoporoid *Cystostroma* and bryozoan *Nicholsonella*, and developed around shallow shoals. These reefs reflect ongoing evolution and sea-level change during the early Paleozoic, and exemplify a rare glimpse of peri-Gondwanan records of reef evolution, which warrant detailed investigations and comparison with their counterparts in other regions.

Key words: carbonate sedimentology, metazoans, stromatolites, Porifera, Cambrian–Ordovician, Taebaeksan Basin, Korea

1 Introduction

Reefs, "calcareous deposits created by essentially in place sessile organisms" (Riding, 2002), are one of the most diverse ecosystems on Earth. Ancient reefs often preserve various reef-building and dwelling organisms, providing critical data for paleoecological reconstruction. Reef-building biota changed along with evolution and extinction of organisms throughout the Earth history. Microbes (mainly cyanobacteria) formed reefs during the Precambrian, whereas various metazoans widely constructed reefs during the Phanerozoic (James and Wood, 2010). The early Paleozoic was a transitionary period between the Precambrian and Phanerozoic in reef evolution history. During this period, there were several fluctuations in between the microbial- and metazoan-dominated reefs, together with abundant metazoan-microbial reefs (Rowland and Shapiro, 2002; Webby, 2002; Adachi et al., 2011; Lee et al., 2015). The changes in reefal components were accompanied by major geological events, which affected not only reef-forming organisms but also global ecosystems (James and Wood, 2010; Chen and Lee, 2014). Therefore, it is important to understand the early Paleozoic reefs in order to figure out the initial evolutionary stage of Phanerozoic metazoan-dominated reefs and their relationship to global environmental change.

During the early Paleozoic, shallow carbonate platforms formed world-wide together with global eustatic sea-level

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rise (Peters and Gaines, 2012). Extensive epeiric carbonate platforms formed along the margins of Gondwana during this time. Shallow-water calcareous sediments were deposited in a vast area of epeiric sea on the Sino-Korean Block (North China Platform), which is known to be one of the oldest cratons in northeastern Asia (Meng et al., 1997) that was located at the margin of Gondwana during the early Paleozoic (McKenzie et al., 2011) (Fig. 1a). The block contains various Cambrian to Ordovician reefs (e.g., Mu et al., 2003; Wang et al., 2012), but detailed studies comprising the entire early Paleozoic succession have not yet been made. This manuscript reviews recent reports of the early Paleozoic reefs from the eastern North China Platform, in the Taebaeksan Basin of eastern Korea (Kwon et al., 2003; Hong et al., 2012, 2014, 2015; Choh et al., 2013; Oh et al., 2015), and compares them with the other early Paleozoic reefs in order to understand spatio-temporal changes of reef-building organisms and reef ecosystems during that time.

2 Geological Setting

The Cambro–Ordovician succession in the eastern part of the North China Platform, the Taebaeksan Basin, Korea, is represented by the Joseon Supergroup (Fig. 1b). Five lithostratigraphic units occur within the Joseon Supergroup, i.e., Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups (Choi, 1998). Among these five groups, this study focuses on the Taebaek Group, which is well studied in terms of sedimentology and biostratigraphy, and contains reefs of various ages. The Taebaek Group unconformably overlies Precambrian granitic gneiss and/or metasedimentary rocks, and is unconformably overlain by Carboniferous–Triassic sedimentary rocks of the Pyeongan Supergroup (Chough et al., 2000; Chough, 2013). The Taebaek Group comprises two subgroups, i.e., the Cambrian Jikdong Subgroup (Jangsan/Myeonsan, Myobong, Daegi, Sesong, and Hwajeol formations) and the latest Cambrian–Ordovician Sangdong Subgroup (Dongjeom, Dumugol, Makgol, Jigunsan, and Duwibong formations), which formed on a mixed carbonate-siliciclastic epeiric platform (Choi, 1998) (Figs. 2 and 3). Among the lithostratigraphic units in the Taebaek Group, reefs occur from every carbonate-dominant unit of the Daegi, Hwajeol, Dumugol, Makgol, and Duwibong formations (Fig. 2). Cambrian and Ordovician Stage names follow Peng et al. (2012) and Cooper et al. (2012), respectively.

3 Daegi Formation

The Cambrian Daegi Formation (ca. 150–250 m thick) is the lowermost lithostratigraphic unit dominated by carbonates in the Taebaek Group (Kwon et al., 2006) (Fig. 2). The formation consists of boundstone, bioclastic wackestone to packstone, bioclastic/oolitic packstone to grainstone, shale, and nodular packstone to grainstone in decreasing order of cumulative thickness (Hong et al., in press). Sedimentary facies analysis suggests that the formation was mainly deposited in shallow subtidal environments (Kwon et al., 2006; Sim and Lee, 2006). Trilobite biozones *Crepicephalina*, *Amphoton*, and *Jiulongshania* are recognized, indicating that the age of the Daegi Formation is late informal Stage 5 to the early Guzhangian (Kang and Choi, 2007; Park et al., 2008).

3.1 Siliceous sponge-*Epiphyton* and *Girvanella* crust-*Epiphyton* reefs

The Daegi microbial reefs were first reported as *Epiphyton-Renalcis* reef by Sim and Y.I. Lee (2006). Follow-up study by Hong et al. (2012) identified decimeter- to meter-scale reefs composed of calcified microbe *Epiphyton*, siliceous sponges, and subordinate *Girvanella* crusts, with minor stem-group cnidarian *Cambroctoconus*. These reefs are distributed in the middle part of the formation, intercalated with bioclastic wackestone to grainstone (Hong et al., in press). The reefs are subdivided into *Epiphyton*-siliceous sponge and *Girvanella* crust-*Epiphyton* reefs (Fig. 4). *Epiphyton*-siliceous sponge reefs exhibit thrombolitic textures in outcrop and slabs (Fig. 4b). Micritic clumps less than 2 mm in size composed of repeatedly bifurcating micritic filaments of *Epiphyton* thalli form reef frameworks, often encrusting on top of other *Epiphyton* thalli or sponges (Fig. 4d, e). Siliceous sponges are 0.4 to 2.7 cm in size and commonly preserved as spicule networks, tuberoids and scattered spicules (Fig. 4d). Majority of these sponges are lithistid-type, showing rectangular patterns of spicules that is probably anthaspidellid (Lee et al., in press). Some of them are characterized by straight to weakly curved spicules and spicule rays at non-perpendicular angles to one another, suggesting only probable non-lithistid demosponge affinity (Rigby, 1983). Densely populated sponges surrounded by *Epiphyton* are occasionally found in the reefs. Co-growths of *Epiphyton* clumps and siliceous sponges sometimes form growth cavities with downward-growing *Epiphyton*, whereas the rest of space is filled with micritic internal sediment and calcite cements (Hong et al., 2012, fig. 5). Decimeter-scale bodies of *Girvanella* crust–*Epiphyton* reefs occur intermittently, where arcuate *Girvanella* crusts partly encrusted by *Epiphyton* form characteristic stacked microbial sheets and tufts with narrow cavities (Fig. 4c, f). These reefs also contain minor spicule networks and scattered spicules.

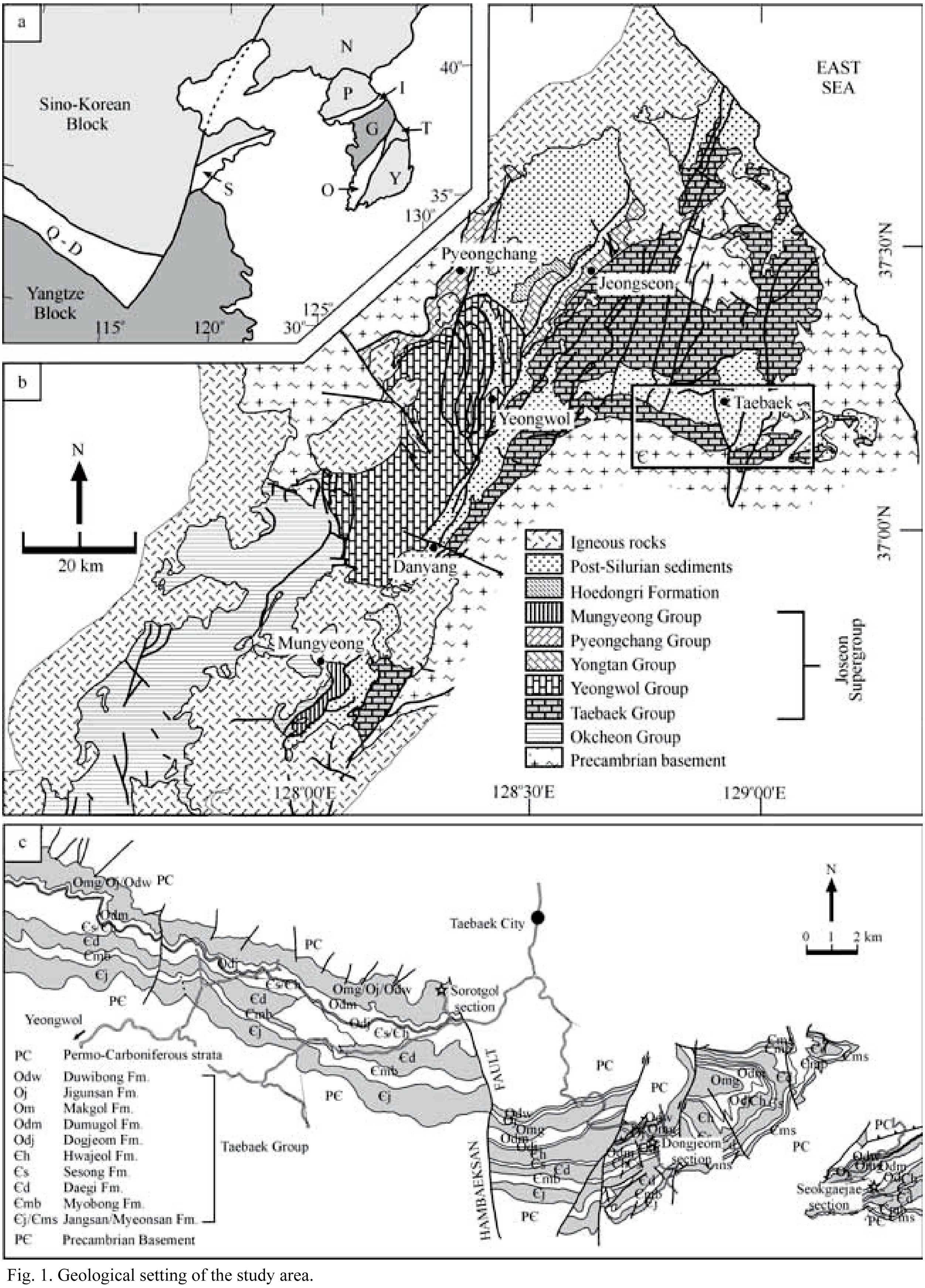

Fig. 1. Geological setting of the study area.

(a) Tectonic map of eastern Asia. N, Nangrim Massif; P, Pyeongnam Basin; I, Imjingang Belt; G, Gyeonggi Massif; O, Okcheon Basin; T, Taebaeksan Basin; Y, Yeongnam Massif; S, Sulu Belt; Q-D, Qinling–Dabie Belt. (b) Geologic map of Taebaek area where a thick Cambrian–Ordovician succession (Joseon Supergroup) occurs. (c) Detailed geologic map of the Taebaek Group in the Taebaek area. Studied Dongjeom, Seokgaejae and Sorotgol sections are marked by stars.

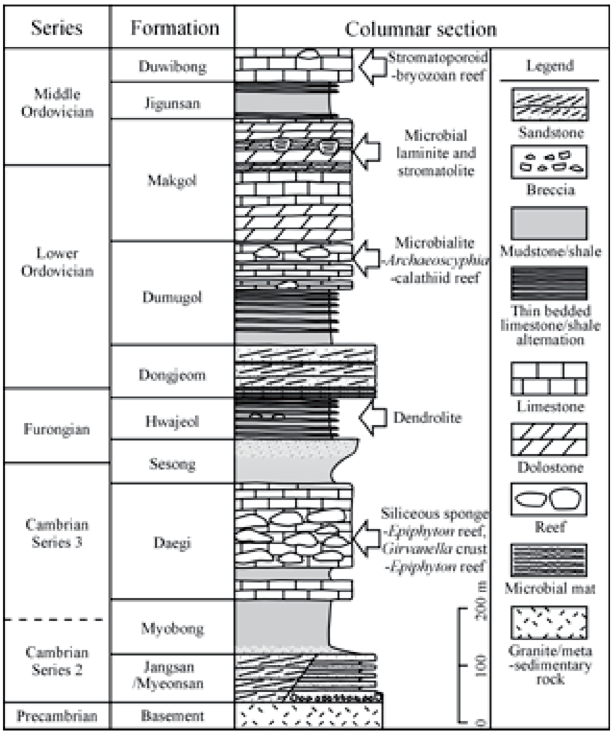

Fig. 2. Summary of the lithostratigraphy of the Taebaek Group. Occurrences of reefs are marked on the schematic sedimentologic log.

3.2 Implications of the Daegi reef

The Cambrian Series 3 to Furongian reefs have largely been regarded to be microbialite-dominated and devoid of reef-building metazoans because of the end-early Cambrian reef crisis (Rowland and Shapiro, 2002; Adachi et al., 2011). On the other hand, recent studies report a few reefs with anthaspidellid sponges from Australia, China, Iran, and USA (Hamdi et al., 1995; Shapiro and Rigby, 2004; Johns et al., 2007; Kruse and Zhuravlev, 2008; Kruse and Reitner, 2014; Lee et al., in press). The Cambrian Series 3 Daegi reefs containing siliceous sponges and stem-group cnidarians, which represent an early phase of reef-building metazoan recovery, where the reef frameworks were mainly formed by *Epiphyton* and sponges (Hong et al., 2012; Park et al., 2016). Thus, the Daegi microbial-siliceous sponge reefs record one of the earliest resurgences of reef-building metazoans during the middle to late Cambrian. Understanding of constituents and constructional modes of this "precursor" type is thus critical for deciphering overall spatio-temporal evolutionary patterns in the early Paleozoic reefs.

Reefs containing fabrics similar to those of the Daegi *Girvanella* crust–*Epiphyton* reefs occur in early and middle Cambrian successions around the world (James, 1981; Rowland and Gangloff, 1988; Debrenne et al., 1989; Wood et al., 1993; Debrenne et al., 2002; Gandin et al., 2007). However, their environmental controls and growth strategies are still unclear, and thus further investigations on the Daegi *Girvanella* crust-*Epiphyton* reefs are necessary to resolve the origin of these enigmatic Cambrian reef types.

4 Hwajeol Formation

The Cambrian Hwajeol Formation comprises mainly cyclic successions of meter-scale shallowing-upward units that consist of shale, lime mudstone, and wackestone to grainstone with abundant flat-pebble conglomerates, interpreted to be deposited in deep to shallow subtidal environments (Kwon et al., 2006). Trilobite biozones *Asioptychaspis*, *Quadraticephalus*, and *Eosaukia* (Sohn and Choi, 2005, 2007; Park and Kihm, 2015), and conodont biozones *Proconodontus tenuiserratus*, *Proconodontus posterocostatus*, *Proconodontus muelleri*, *Eoconodontus notchpeakensis*, *Cambrooistodus minutus*, *Cordylodus proavus*, and *Fryellodontus inornatus*–*Monocostodus sevierensis*–*Semiacontiodus lavadamensis* (Jeong and Lee, 2000; Lee B.-S. and Seo, 2008; Lee B.-S., 2014) are recognized from the formation, indicating late Jiangshanian to Stage 10 in age.

4.1 Dendrolite mound

Decimeter-scale dendrolite mounds are found mainly on top of flat-pebble conglomerate beds in the middle part of the Hwajeol Formation and are overlain by nodule-bearing shale (Fig. 5a). The dendrolites are characterized by millimeter- to centimeter-scale upward-widening and bifurcating clots, i.e., dendroids (Howell et al., 2011), collectively forming branch-like gross morphology. These dendroids stack on top of each other and extend vertically rather than laterally. The dendroids frequently terminate with a flat upper boundary that then becomes a new surface on which the next dendroids start growing (Fig. 5b, c). A mixture of lime mud and trilobite fragments occurs between these clots (Fig. 5b). In microscale, the dendroids are composed of dense micrite, which can be regarded as the calcified microbe *Angulocellularia* (Fig. 5c).

4.2 Significance of Hwajeol dendrolites

The Hwajeol dendrolites have not yet been studied in detail, and they require further investigation in order to understand their formational processes and depositional environments. These dendrolites are similar in shape to other dendrolites reported from Cambrian Series 3 succession of Shandong Province, China (Howell et al., 2011) and early Furongian succession of Great Basin, USA (Shapiro and Awramik, 2000; Shapiro and Rigby, 2004), potentially implying their wide occurrence during Cambrian Series 3 to the Furongian time span. It is noteworthy that the Hwajeol dendrolite mounds occur

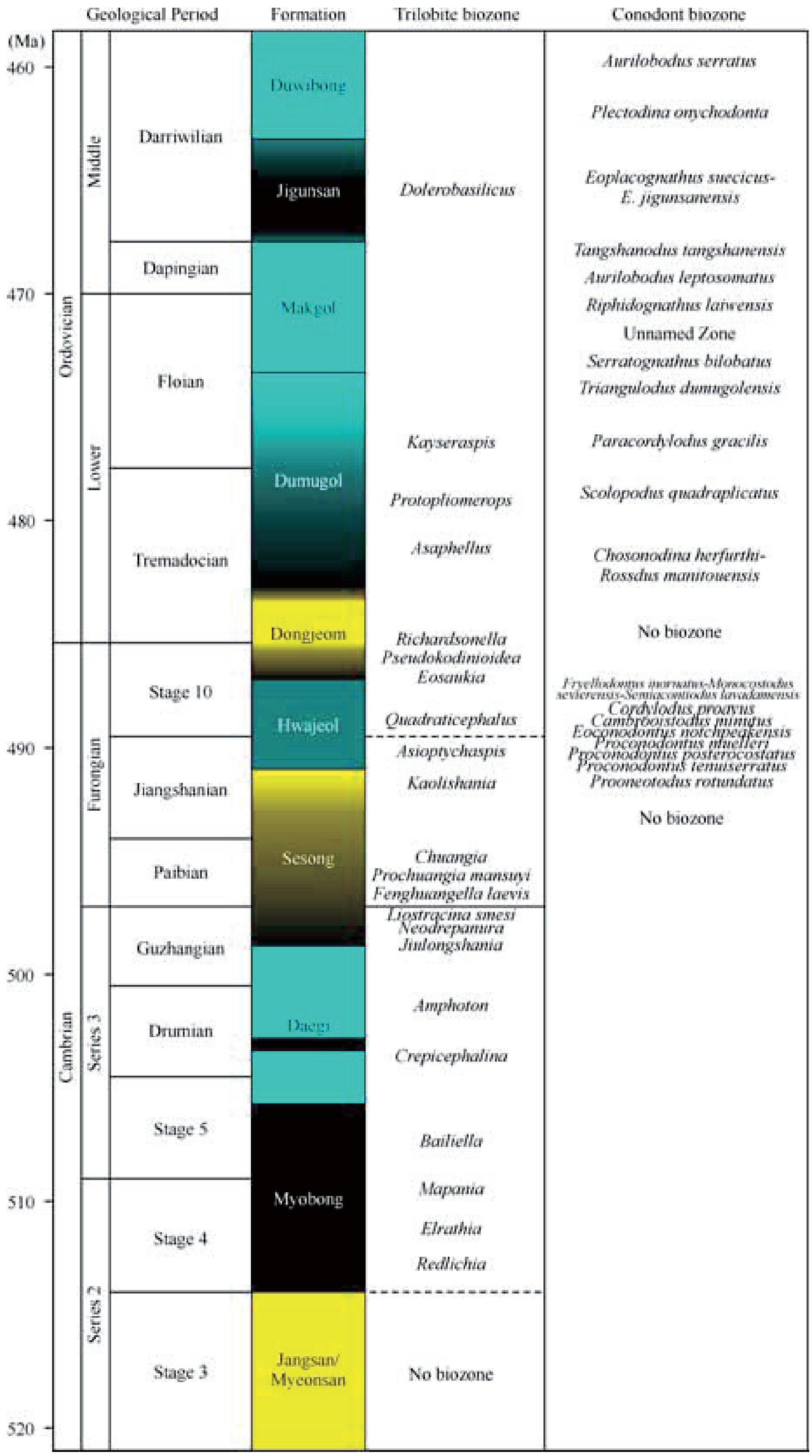

Fig. 3. Summary of the biostratigraphy of the Taebaek Group.
Blue: limestone, yellow: sandstone, black: shale.

within deep to shallow subtidal facies (Kwon et al., 2006), whereas other previously reported dendrolites are from lithofacies deposited in open or restricted shallow subtidal platforms (Shapiro and Awramik, 2000; Shapiro and Rigby, 2004; Howell et al., 2011). The Hwajeol dendrolite mounds therefore suggest that dendrolites might have

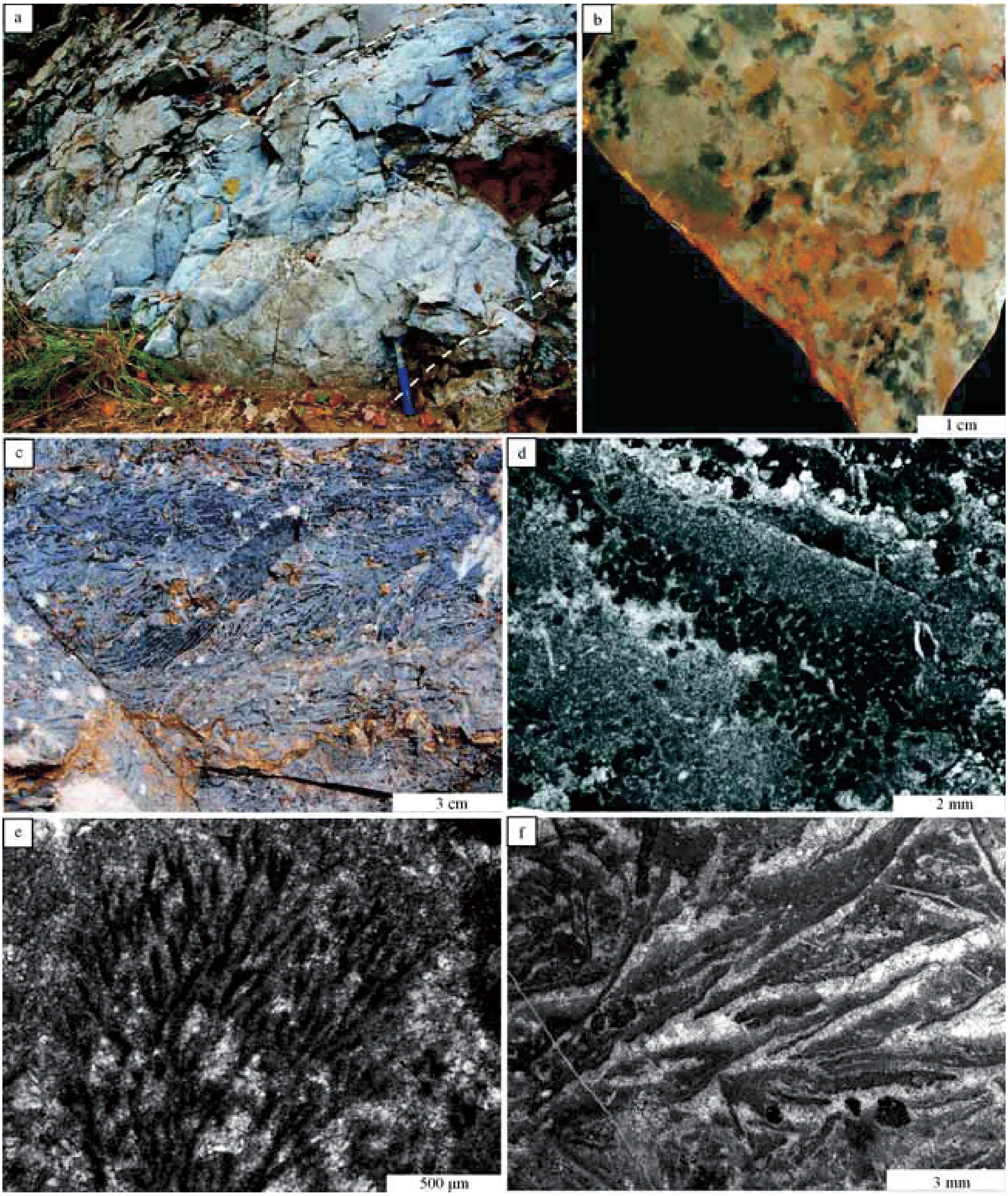

Fig. 4. Reefs in the Daegi Formation at the Seokgaejae section.
(a) Photograph of outcrop of the Daegi Formation, yielding siliceous sponge–*Epiphyton* reef and *Girvanella* crust–*Epiphyton* reef. Hammer for scale is 28 cm; (b) slab of siliceous sponge–*Epiphyton* reef showing thrombolitic texture; (c) outcrop photograph of *Girvanella* crust–*Epiphyton* reef; (d) photomicrograph of siliceous sponge; (e) photomicrograph of *Epiphyton* showing branching structure; (f) photomicrograph of *Girvanella* crust-*Epiphyton* reef.

inhabited a rather wide spectrum of environments during the Cambrian, and the subtle variation in their structure in different habitats should be considered. Deep-water reefs were uncommon prior to the Middle Ordovician, and there is no known example of dendrolite among them (Pratt, 1989, 1995). The Hwajeol dendrolites therefore warrant further study in order to understand the depositional spectrum of Cambrian reefs as well as the evolutionary pathway and diversity of deep-water reefs.

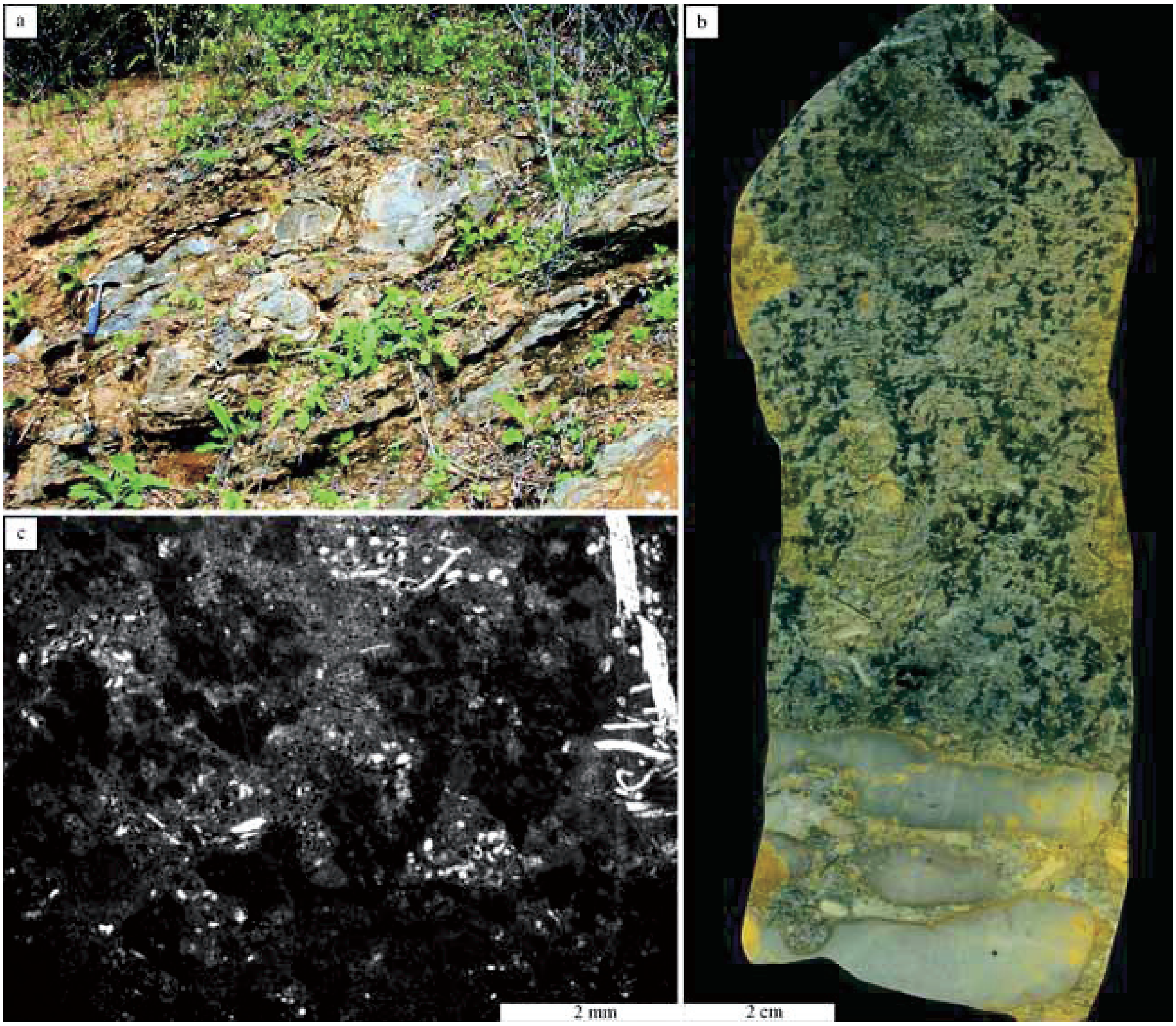

Fig. 5. Dendrolite in the Hwajeol Formation at the Seokgaejae section.
(a) Photograph of outcrop of dendrolite, showing lenticular shape. Hammer for scale is 27 cm; (b) slab of dendrolite. Dendrolite develops on limestone conglomerate. Note characteristic dendritic, upward-widening clots; (c) photomicrograph showing micritic microbes (*Angulocellularia*) forming dendritic clots and bioclasts between the clots.

5 Dumugol Formation

The Ordovician Dumugol Formation is characterized by meter-scale upward-shallowing limestone-shale cycles with numerous intercalating limestone conglomerates. The formation is interpreted to have been deposited in outer to inner ramp environments with common storm-induced currents (Kwon and Chough, 2005). Three trilobite biozones, *Asaphellus*, *Protopliomerops*, and *Kayseraspis* (Choi et al., 2001), and four conodont biozones, *Chosonodina herfurthi–Rossdus manitouensis*, *Scolopodus quadraplicatus*, *Paracordylodus gracilis*, and *Triangulodus dumugolensis* (Kim et al., 1991; Lee B.-S. et al., 1991, 1998; Lee B.-S. and Seo, 2004; Seo and Lee, B.-S., 2010) are recognized, indicating the age of the Dumugol Formation is middle Tremadocian to early Floian.

5.1 Microbialite–*Archaeoscyphia*–calathiid reef

Decimeter- to meter-scale patch reefs composed of microbialite characterized by thrombolitic or stromatolitic fabric, the anthaspidellid sponge *Archaeoscyphia*, the calcified microbe *Epiphyton*, “receptaculitid” calathiids, and minor non-lithistid demosponges of unknown affinity occur in eight horizons of the middle and upper Dumugol Formation (Lee Y.I. and Choi, 1987; Kwon et al., 2003; Choh et al., 2013) (Fig. 6). These reefs are further subdivided into two types: microbialite-siliceous sponge (with or without calathiids) and thrombolites with minor *Archaeoscyphia* (Choh et al., 2013). The former type is commonly surrounded by intraclastic-bioclastic packstone to grainstone and overlain and underlain by either lime mudstone or shale, whereas the latter type, which only occurs in the middle part of the formation, is underlain and

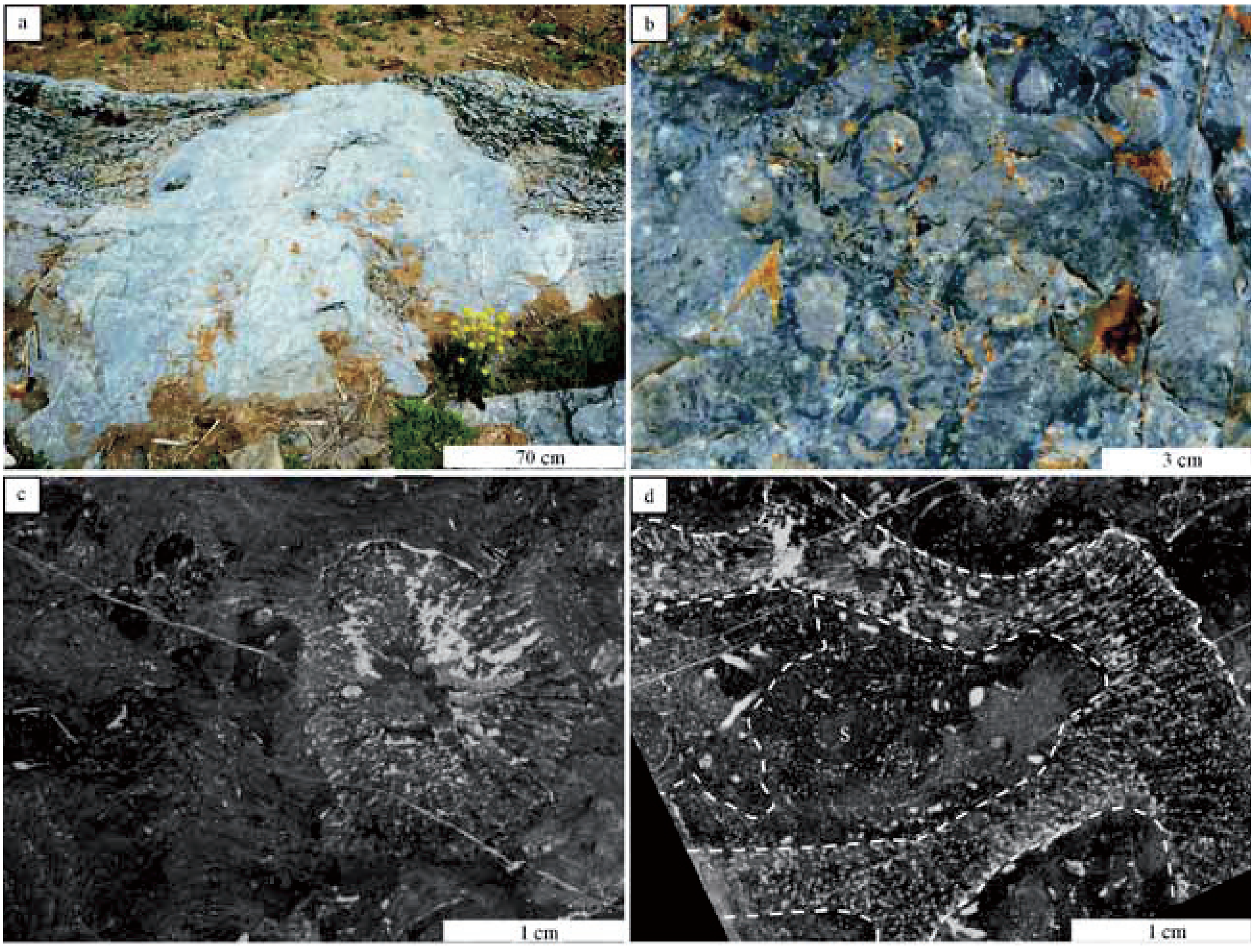

Fig. 6. Microbialite–*Archaeoscyphia*–calathiid reef in the Dumugol Formation.
(a) Photograph of outcrop of a patch reef in Dongjeom section; (b) transverse cut of *Archaeoscyphia* within the reef, showing circular shape (Dongjeom section); (c) photomicrograph of microbial-siliceous sponge reef, showing microstromatolite (left) and *Archaeoscyphia* (right), Seokgaejae section; (d) non-lithistid demosponge (S) within spongocoel of *Archaeoscyphia* (A), Seokgaejae section.

overlain by bioturbated wackestone and limestone nodule-bearing shale, respectively.

The microbial-siliceous sponge reefs are mainly composed of centimeter-scale siliceous sponge-microbial and microbial-dominated boundstones, which are occasionally truncated by erosive surfaces (Hong et al., 2015). These boundstones are primarily constructed by microbialites that encrust micritic substrates and siliceous sponges (*Archaeoscyphia* and non-lithistid demosponge), or are repeatedly stacked to form reef frameworks (Fig. 6c). *Archaeoscyphia* up to 3–5 cm in diameter and 5–10 cm in length are commonly scattered throughout the reefs. Smaller (ca. 1 cm in diameter) *Archaeoscyphia* occasionally attach to one another and form limited sponge-dominated framestone up to 5 cm in height and length. They also provide intraskeletal, shelter and rare growth cavities up to a few centimeters in size, within (spongocoel), beneath, and between *Archaeoscyphia* skeletons, respectively. Part of these cryptic spaces is occupied by non-lithistid demosponges and microbialites, though they constitute a much smaller portion of the reefs than siliceous sponges in the open surface (Fig. 6d) (Hong et al., 2014).

5.2 Implications of the Dumugol metazoan-microbial reefs

Sessile organisms including lithistid sponges, calathiids, the stromatoporoid *Pulchrilamina*, bryozoans, the tabulate coral *Lichenaria*, and pelmatozoans increasingly appeared in Early Ordovician microbial-dominant reefs (Webby, 2002; James and Wood, 2010; Adachi et al., 2011). Among these, lithistid sponges were the most prominent reef-building organisms, which occurred widely around the world (Adachi et al., 2009; Li Q. et al., 2014). The Dumugol reefs were mainly formed by microbialite and the lithistid sponge *Archaeoscyphia* and are therefore comparable to coeval reefs in Laurentia, the Argentine Precordillera, and South China (Church, 1974; Toomey and Nitecki, 1979; Cañas and Carrera, 1993; Adachi et al., 2011). Lithistid sponges within these reefs have been regarded as needing microbial bindings for development of the reef framework (Adachi et al., 2011). However, the occurrence of limited sponge-dominated framestone within the Dumugol reefs, as well as the skeletal bioconstruction by other sessile organisms documented in various regions (Toomey and Nitecki, 1979; Pratt and James, 1982; Adachi et al., 2011; Cuffey et al., 2013; Li Q. et al., 2014), indicate the beginning of the transition from microbial- to metazoan-dominated reefs (Hong et al., 2015).

In addition, these limited metazoan frameworks harbored cryptic habitats that have often been overlooked. The cavity-dwelling metazoans first appeared in the Proterozoic reefs (Wood and Curtis, 2015) and became remarkably diversified within the early Cambrian archaeocyath-microbial reefs (Kobluk, 1988; Wood, 1999; Gandin and Debrenne, 2010). However, cryptic habitat has generally been regarded to be greatly subdued during Cambrian Series 3 to the Furongian due to the absence of true framework constructors after the end-early Cambrian extinction (Klappa and James, 1980; Kobluk, 1988; Wood, 1999). The Dumugol non-lithistid demosponges within the reef cavities represent one of the earliest cryptic metazoans after the extinction of archaeocyaths. This seems to indicate that epibenthic metazoans transiently exploited cryptic spaces before the eventual establishment of obligate cryptic forms, potentially hinting at how cryptic organisms initially adapted to these habitats (Hong et al., 2014).

6 Makgol Formation

The Ordovician Makgol Formation conformably overlies the Dumugol Formation and is overlain by the shale-dominated Jigunsan Formation. The formation comprises peritidal cyclic successions with various shallow-water sedimentary structures such as stromatolites, mudcracks, ripples, and salt and gypsum casts, which were deposited in sabkha-type peritidal to subtidal environments (Paik, 1987; Woo K.S., 1999; Ryu et al., 2002; Kwon et al., 2006) (Fig. 7). Conodont biozones including *Serratognathus bilobatus*, *Riphidognathus laiwensis*, *Aurilobodus leptosomatus*, and *Tangshanodus tangshanensis* zones that indicate the age of the Makgol Formation to be from the middle Floian to Dapingian (Lee B.-S. et al., 1997; Lee B.-S. and Seo, 2004).

Microbial laminites (formed by microbial mats) and stromatolites are the main type of reefs in the Makgol Formation (Fig. 7a, b), where no skeletal- or skeletal-microbial reefs have been reported as yet (Paik, 1987; Woo K.S., 1999; Ryu et al., 2002). On the other hand, calathiids, which formed reefs in the earlier Dumugol Formation, was reported from the middle part of the Makgol Formation within mud- to wackestone facies (Lee D.-J., 2000). Re-examination of the materials studied by D.-J. Lee (2000) shows that siliceous sponges (anthaspidellid and an unidentifiable non-lithistid demosponge) co-occur with calathiids, forming boundstone fabric (Fig. 7c). The occurrence of such facies within the Makgol Formation suggests that further studies are required to find evidence of skeletal-microbial reefs.

6.1 Microbial mats and stromatolite

Two forms of microbial-induced structures are identified from the Makgol Formation, i.e., microbial laminite and stromatolite (Fig. 7a, b). Microbial laminites are characterized by thin, planar and undulatory laminae, partly changing into cm-scale laterally linked hemispheroid (LLH)-type stromatolite (Fig. 7b). Laminae of the microbial laminite are characterized by intercalation of 0.5–2 mm-thick fine-grained, dolomitized muddy layers containing euhedral dolomite crystals less than 10 μm in size and relatively coarse-grained sediment-rich layers (Woo K.S., 1999). Stromatolites in the Makgol Formation are generally similar to microbial laminite in mesostructure. However, they generally form upward-widening domal geometry, and some of them are surrounded by limestone conglomerate (Fig. 7a). The stromatolites are commonly associated with bird's eye structures, gypsum and salt casts, and desiccation cracks.

6.2 Implications of the Makgol stromatolite

Microbial laminites and LLH-type stromatolites of the Makgol Formation formed in intertidal to supratidal environments, and are seen together with mudcracks and casts of evaporite minerals (Paik, 1987; Woo K.S., 1999; Ryu et al., 2002; Kwon et al., 2006). The microbial laminites and stromatolites constitute an integral part of the meter-scale peritidal cycles that composed of the lower bioturbated wackestone to grainstone, middle stromatolitic lime mudstone or wavy/lenticular grainstone/lime mudstone, and upper microbial laminite (Woo K.S., 1999; Kwon et al., 2006). Stromatolites occurring with conglomerates would have formed within abandoned tidal channels (Feldmann and McKenzie, 1998; Andres and Reid, 2006). Extensive occurrence of the microbial laminites and stromatolites of the Makgol Formation deposited in shallow marine environments would have resulted from the relative sea-level fall that occurred across the entire North China Platform (Meng et al., 1997; Kwon et al., 2006).

7 Duwibong Formation

The Duwibong Formation, the uppermost unit of the

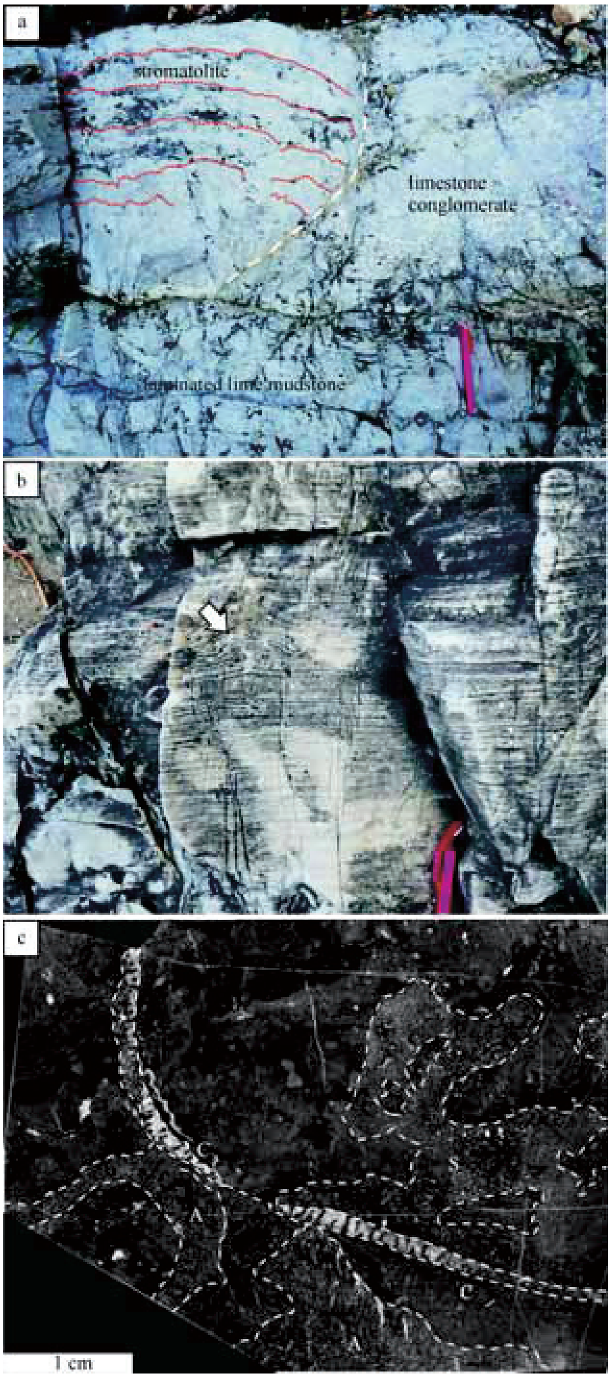

Fig. 7. Reefs in the Makgol Formation at the Dongjeom section.
(a) Stromatolite developing within the limestone conglomerate. Note relatively sharp and inclined margin in between stromatolite and conglomerate. (b) Microbial laminites consisting alternation of light- and dark-colored laminae. Note occurrence of convex-up lamination (arrow). (c) Boundstone facies formed by calathiid (C), anthaspidellid sponge (A), and unidentifiable siliceous sponge (S).

Taebaek Group, conformably overlies the shale-dominated Jigunsan Formation. The formation consists mainly of various carbonate facies from mudstone to grainstone, deposited in shallow subtidal environments (Lee Y.I., 1988; Lee Y.I. et al., 2001; Kwon et al., 2006). Biozones established from the formation based on conodonts (*Plectodina onychodonta* and *Aurilobodus serratus*) (Lee Y.N. and Lee H.-Y., 1986; Lee K. and Lee H.-Y., 1990) and cephalopods (*Actinoceroids*) (Yun, 2000) indicate a late Llanvirnian to early Llandeilian (mid- to late Darriwilian) age.

7.1 Stromatoporoid–bryozoan reef

The occurrence of reef in the Ordovician Duwibong Formation is very restricted; until now, reef is reported from only one locality (Fig. 8) (Oh et al., 2015). The stromatoporoid–bryozoan reef in the formation occurs as ca. 30 cm-thick bioherms, which overlie bioclastic, ramose bryozoan-rich packstone and is overlain by bioturbated dolo-mudstone (Fig. 8a). In outcrop, the reef consists of columnar to globular structures of less than 5 cm in width, composed of convex-upward laminations resembling stromatolites. In microscale observation, the reef mainly comprises the stromatoporoid *Cystostroma* and bryozoan *Nicholsonella*, with minor unknown tubular organisms and siliceous sponges (Oh et al., in preparation) (Fig. 8b, c). Alternation of encrusting stromatoporoids and bryozoans formed thin laminae in the reef (Fig. 8b). Minor siliceous sponges and tubular organisms occur as patches or thin layers in between laminae. Based on the areal distribution and relationship of reef-building organisms in the frameworks, stromatoporoids and bryozoans are interpreted to be the main frame-builders, and the rest are encrusters that cover the surface of other organisms. Some siliceous sponges also occur as cryptic dwellers living inside of cavities between frameworks or borings. The reef was initiated by stromatoporoids and bryozoans growing on siliceous sponges or fragments of ramose bryozoans. Continual encrustation by these organisms resulted in the formation of columnar to bulbous reef frameworks.

7.2 Implications of the Duwibong stromatoporoid–bryozoan reef

The Duwibong reef represents the first metazoan-dominated skeletal reef on the North China Platform. Its presence coincides with the worldwide emergence of metazoan-dominated reefs composed of corals, stromatoporoids and bryozoans during the late Middle Ordovician (late Darriwilian) (Pitcher, 1964; Ross, 1981; Cuffey et al., 2000; Webby, 2002). However, reefs mainly consisting of alternation of stromatoporoids and bryozoans have not previously been reported from Ordovician strata (Webby, 2002). Therefore, the Duwibong stromatoporoid–bryozoan reef represents one of the earliest reports of such a consortium, and indicates that these organisms could have lived together and formed reefs much earlier than previously known (Oh et al., in preparation).

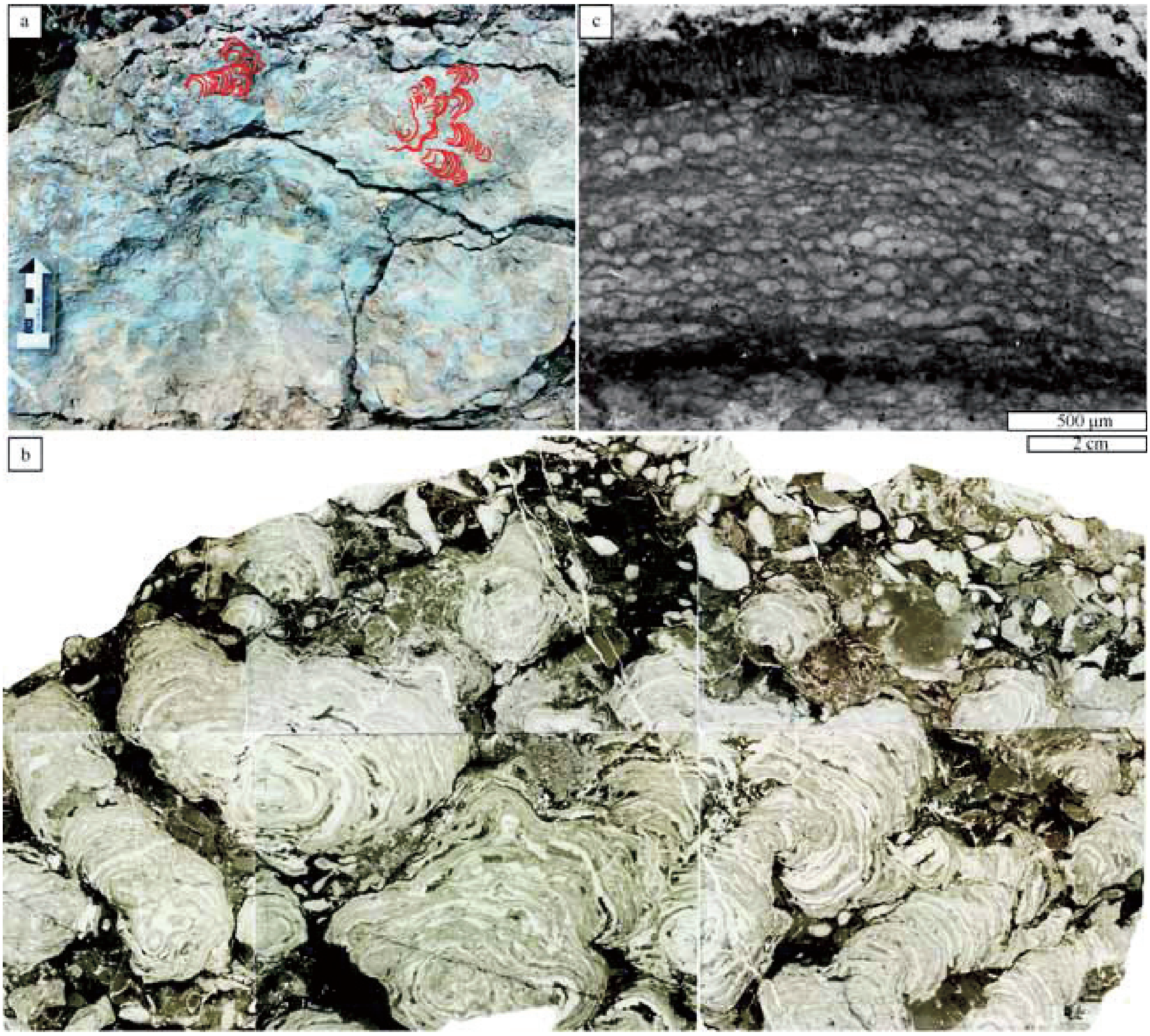

Fig. 8. Stromatoporoid-bryozoan reef in the Duwibong Formation at the Sorotgol section.
(a) Outcrop photograph showing stromatolite-like morphology. Modified after Oh et al. (2015); (b) Photograph of thin sections, showing columnar to globular structures with alternating lighter and darker colored laminae; (c) Photomicrograph of stromatoporoid *Cystostroma*, showing stacked convex-upward cysts without denticles.

Cystostroma within the Duwibong reef is a primitive stromatoporoid and one of the earliest examples, together with an example from the coeval succession in the Chazy Group of Laurentia (Galloway, 1957; Galloway and St. Jean, 1961; Stock et al., 2012; Nestor and Webby, 2013; Oh et al., 2015). Although the North China Platform has many records of early stromatoporoids (Dong, 2001), this is the first report of the genus from the region. Current findings of primitive stromatoporoids suggest that the North China Platform might have been closely related to the origin of stromatoporoids (Oh et al., 2015).

8 Conclusion

The early Paleozoic reef-building biota rose and declined throughout the Cambrian to Ordovician. Archaeocyaths are one of the first reef-building metazoans that dominated reefal ecosystem during the Terreneuvian and Cambrian Series 2. As these forms and various calcified microbes declined at the end of Series 2, reefs of Cambrian Series 3 and the Furongian became dominated by calcified microbes, a time considered as the longest “metazoan reef gap” in the Phanerozoic (Boucot, 1990; Zhuravlev, 1996; Kiessling, 2009). On the other hand, it is noteworthy that Cambrian Series 3 and Furongian reefs are different in texture and constituents, and warrant further study to understand their importance in reef evolution (Lee et al., 2015).

It has been generally considered that together with the Great Ordovician Biodiversification Event, the metazoan reef-builders resurge in reefal environments during the Early Ordovician (Webby, 2002; Adachi et al., 2011). Various metazoan reef-builders including *Archaeoscyphia* (lithistid sponge), *Lichenaria* (tabulate coral), *Pulchrilamina* (stromatoporoid), and possible algal calathiids formed reefs together with microbes. Early Ordovician reefs are thought to have required microbes in order to bind and stabilize metazoan reef frameworks (Adachi et al., 2011). As metazoans flourish in reefs during the Middle Ordovician, metazoan-dominated skeletal reefs became widespread as microbial reefs decline (Webby, 2002). After the Middle Ordovician, microbial reefs became only minor component throughout the Phanerozoic, although they occasionally flourished shortly after mass extinction events (Riding, 2006; James and Wood, 2010).

The reefs in the Taebaek Group generally follow this trend, although there are differences in detail (Fig. 9). The siliceous sponge-*Epiphyton* reef of the Daegi Formation (Cambrian Series 3) is one of the earliest metazoan-microbial reef to form after the archaeocyath extinction. The dendrolite in the Furongian Hwajeol Formation represents a rare example of an early Paleozoic deep-water dendrolite that formed during the period when microbialites were known to be dominant. The Dumugol microbialite–*Archaeoscyphia*–calathiid reefs are similar in composition to other coeval reefs, but they contain siliceous sponges that have not yet been identified compared to others. The occurrence of lithistid sponge-dominated framestone and non-lithistid demosponges within cryptic habitats is also noteworthy. Microbial mats and stromatolites in the Makgol Formation that formed in the intertidal to supratidal environments represent relative sea-level fall that affected the entire North China Platform in the middle Floian to Dapingian. The stromatoporoid–bryozoan reef of the Duwibong Formation is one of the earliest skeletal reefs and previously had not been known from the region.

These Taebaek reefs are comparable to those reported from other areas in the North China Platform (Fig. 9). During Cambrian Series 2, reefs only develop locally as small mound-shaped thrombolites with various calcified microbes, which occur within the grainstone and conglomerates of the Zhushadong Formation (Lee et al., 2014b). Reefs flourished on an extensive area of platform during Cambrian Series 3, consisting major portion of a ca. 200-m-thick carbonate-dominant succession (Zhangxia Formation) (Zhang et al., 1985; Gao and Zhu, 1998; Mu et al., 2003; Woo J. et al., 2008). The Zhangxia reefs are characterized by *Epiphyton* framestone, thrombolite, dendrolite, leiolite, and stromatolite, which mainly consist of calcified microbes *Epiphyton*, *Renalcis*, and *Girvanella*, together with lithistid sponges (*Rankenella zhangxianensis* Lee et al., in press) and stem-group cnidarians (*Cambroctoconus orientalis* Park et al., 2011) (Woo et al., 2008; Woo, 2009; Woo and Chough, 2010; Howell et al., 2011; Park et al., 2011; Adachi et al., 2015; Lee et al. in press). During the Furongian, maze-like maceriate reefs that consist of siliceous sponges and microbes flourished, forming several meter-scale bioherms and biostromes in Shandong region, China (Lee et al., 2010, 2012, 2014a). Together with maceriate reefs, columnar stromatolites that consist of calcified microbe *Girvanella* and some siliceous sponges also flourished in the shallower environments (Chen et al., 2011, 2014). The Early Ordovician reefs in the North China Platform are generally represented by microbialite–*Archaeoscyphia*–calathiid reef, which are similar in composition with those of the Taebaek Group (Li S.M. and Zhu, 1995; Liu and Zhan, 2009; Choh et al., 2013). The Middle–Late Ordovician reefs are only identified from the western North China Platform, where various skeletal-dominated and skeletal-microbial reefs formed by coral, stromatoporoid, *Amsassia*, algae, and calcified microbe developed (Wang et al., 2012; Lee M. et al., 2014; Sun et al., 2014).

The reefs in the Taebaek Group and the North China Platform represent part of the early Paleozoic reef development in the peri-Gondwanan region. Further studies on these reefs and comparison with coeval structures from peri-Gondwana, including Australia, Iran,

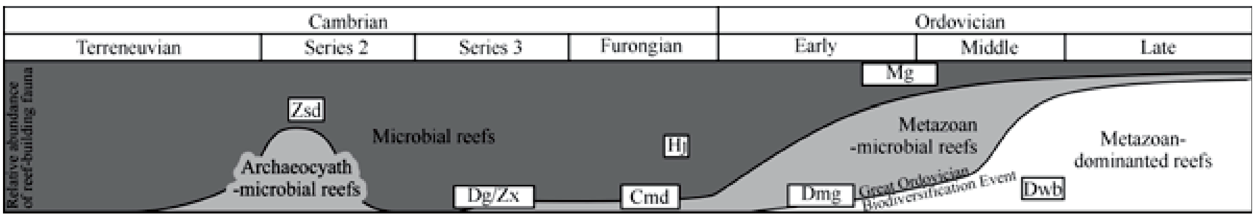

Fig. 9. Schematic diagram of reef evolution during the Cambrian and Ordovician.
During the Terreneuvian and Series 2, archaeocyath-microbial reefs and microbial reefs were the sole reef types. After archaeocyathid extinction, a few sponge-microbial reefs appeared during Cambrian Series 3 (represented by metazoan–microbial reefs). Metazoan–microbial reefs flourished during the Early to mid-Ordovician then with the Great Ordovician Biodiversification Event, microbial reefs declined. Early Ordovician reefs gradually evolved into metazoan-dominated reefs by the mid- to Late Ordovician. Reefs reviewed in this study marked by white rectangles. Taebaek reefs: Dg=Daegi, Hj=Hwajeol, Dmg=Dumugol, Mg=Makgol, Dwb=Duwibong. Shandong reefs: Zsd=Zhushadong, Zx=Zhangxia, Cmd=Chaomidian. The vertical distribution of reefs at any given time indicates the relative proportions of each reef type.

South China, and Tarim will enable us to understand regional variation in early Paleozoic reef development and how this reflects global evolution in the organisms as well as environmental changes and local environmental differences. Understanding these reefs may help expand our knowledge of early Paleozoic reef development, which has mainly been constructed based on Laurentian examples (e.g., Rowland and Shapiro, 2002).

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References

Adachi, N., Ezaki, Y., and Liu, J., 2011. Early Ordovician shift in reef construction from microbial to metazoan reefs. *Palaios*, 26: 106–114.

Adachi, N., Ezaki, Y., Liu, J., and Cao, J., 2009. Early Ordovician reef construction in Anhui Province, South China: A geobiological transition from microbial- to metazoan-dominant reefs. *Sedimentary Geology*, 220: 1–11.

Adachi, N., Kotani, A., Ezaki, Y., and Liu, J., 2015. Cambrian Series 3 lithistid sponge–microbial reefs in Shandong Province, North China: reef development after the disappearance of archaeocyaths. *Lethaia*, 48: 405–416.

Andres, M.S., and Reid, R.P., 2006. Growth morphologies of modern marine stromatolites: A case study from Highborne Cay, Bahamas. *Sedimentary Geology*, 185: 319–328.

Boucot, A., 1990. Phanerozoic extinctions: how similar are they to each other? In: Kauffman, E.G., and Walliser, O.H. (eds.). *Extinction Events in Earth History*. Berlin: Springer, 5–30.

Cañas, F., and Carrera, M., 1993. Early Ordovician microbial-sponge-receptaculitid bioherms of the Precordillera, Western Argentina. *Facies*, 29: 169–178.

Chen, J., Chough, S.K., Han, Z., and Lee, J.-H., 2011. An extensive erosion surface of a strongly deformed limestone bed in the Gushan and Chaomidian formations (late Middle Cambrian to Furongian), Shandong Province, China: Sequence–stratigraphic implications. *Sedimentary Geology*, 233: 129–149.

Chen, J., and Lee, J.-H., 2014. Current progress on the geological record of microbialites and microbial carbonates. *Acta Geologica Sinica* (English edition), 88(1): 260–275.

Chen, J., Lee, J.-H., and Woo, J., 2014. Formative mechanisms, depositional processes, and geological implications of Furongian (late Cambrian) reefs in the North China Platform. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 414: 246–259.

Choh, S.-J., Hong, J., Sun, N., Kwon, S.-W., Park, T.-Y., Woo, J., Kwon, Y.K., Lee, D.-C., and Lee, D.-J., 2013. Early Ordovician reefs from the Taebaek Group, Korea: constituents, types, and geological implications. *Geosciences Journal*, 17: 139–149.

Choi, D.K., 1998. The Yongwol Group (Cambrian-Ordovician) redefined: a proposal for the stratigraphic nomenclature of the Choson Supergroup. *Geosciences Journal*, 2: 220–234.

Choi, D.K., Kim, D.H., and Sohn, J.W., 2001. Ordovician trilobite faunas and depositional history of the Taebaeksan Basin, Korea: implications for palaeogeography. *Alcheringa*, 25: 53–68.

Chough, S.K., 2013. *Geology and Sedimentology of Korean Peninsula*. Amsterdam: Elsevier, 363.

Chough, S.K., Kwon, S.T., Ree, J.-H., and Choi, D.K., 2000. Tectonic and sedimentary evolution of the Korean peninsula: a review and new view. *Earth-Science Reviews*, 52: 175–235.

Church, S.B., 1974. Lower Ordovician patch reefs in western Utah. *Brigham Young University Geology Studies*, 21: 41–62.

Cooper, R.A., Sadler, P.M., Hammer, O., and Gradstein, F.M., 2012. *The Ordovician Period*. In: Gradstein , F.M., Ogg, J.G., Schmitz, M. and Ogg, G. (eds.), *The Geologic Time Scale 2012*. Amsterdam: Elsevier, 489–523.

Cuffey, R.J., Cawley, J.C., Lane, J.A., Bernarsky-Remington, S.M., Ansari, S.L., McClain, M.D., Ross-Phillips, T.L., and Savill, A.C., 2000. Bryozoan reefs and bryozoan-rich limestones in the Ordovician of Virginia. In: *Proceedings of the 9th international coral reef symposium*, 205–210, Bali, Indonesia.

Cuffey, R.J., Chuantao, X., Zhu, Z., Spjeldnaes, N., and Hu, Z.-X., 2013. The world's oldest-known bryozoan reefs: Late Tremadocian, mid-Early Ordovician; Yichang, Central China. In: Ernst, A., Schäfer, P. and Scholz, J. (eds.), *Bryozoan Studies 2010*. Berlin/Heidelberg: Springer-Verlag, 13–27.

Debrenne, F., Gandin, A., and Courjault-Radé, P., 2002. Facies and depositional setting of the Lower Cambrian archeocyath-bearing limestones of southern Montagne Noire (Massif Central, France). *Bulletin de la Société Géologique de France*, 173: 533–546.

Debrenne, F., Gandin, A., and Rowland, S.M., 1989. Lower Cambrian bioconstructions in Northwestern Mexico (Sonora). Depositional setting, paleoecology and systematics of Archaeocyaths. *Geobios*, 22: 137–195.

Dong, D.Y., 2001. *Stromatoporoids of China*. Beijing: Science Press, 423 (in Chinese with English abstract).

Feldmann, M., and McKenzie, J.A., 1998. Stromatolite-thrombolite association in a modern environment, Lee Stocking Island, Bahamas. *Palaios*, 13: 201–212.

Galloway, J.J., 1957. Structure and classification of the Stromatoporoidea. *Bulletin of American Paleontology*, 37: 345–480.

Galloway, J.J., and St. Jean, J., 1961. Ordovician Stromatoporoidea of North America. *Bulletin of American Paleontology*, 43: 1–111.

Gandin, A., and Debrenne, F., 2010. Distribution of the archaeocyath-calcimicrobial bioconstructions on the Early Cambrian shelves. *Palaeoworld*, 19: 222–241.

Gandin, A., Debrenne, F., and Debrenne, M., 2007. Anatomy of the Early Cambrian 'La Sentinella'reef complex, Serra Scoris, SW Sardinia, Italy. In: Álvaro, J.J., Aretz, M., Boulvain, F., Munnecke, A., Vachard, D., and Vennin, E. (eds.), *Palaeozoic reefs and bioaccumulations: climatic and evolutionary controls Geological Society of London Special Publications*. London: Geological Society of London, 29–50.

Gao, J., and Zhu, S., 1998. Cambrian microbialites from the northeastern Shanxi Province and their relation to sedimentary environments. *Acta Micropalaeontologica Sinica*, 15: 166–177 (in Chinese with English abstract).

Hamdi, B., Rozanov, A.Y., and Zhuravlev, A.Y., 1995. Latest Middle Cambrian metazoan reef from northern Iran. *Geological Magazine*, 132: 367–373.

Hong, J., Cho, S.-H., Choh, S.-J., Woo, J., and Lee, D.-J., 2012. Middle Cambrian siliceous sponge-calcimicrobe buildups (Daegi Formation, Korea): Metazoan buildup constituents in the aftermath of the Early Cambrian extinction event. *Sedimentary Geology*, 253–254: 47–57.

Hong, J., Choh, S.-J., and Lee, D.-J., 2014. Tales from the crypt: early adaptation of cryptobiontic sessile metazoans. *Palaios*, 29: 95–100.

Hong, J., Choh, S.-J., and Lee, D.-J., 2015. Untangling intricate microbial–sponge frameworks: The contributions of sponges to Early Ordovician reefs. *Sedimentary Geology*, 318: 75–84.

Hong, J., Choh, S.-J., and Lee, D.-J., (in press). Distribution of chancelloriid in middle Cambrian carbonate platform of the Taebaek Group, Korea and its geologic implications. *Acta Geologica Sinica* (English edition).

Howell, J., Woo, J., and Chough, S.K., 2011. Dendroid morphology and growth patterns: 3-D computed tomographic reconstruction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 299: 335–347.

James, N.P., 1981. Megablocks of calcified algae in the Cow Head Breccia, western Newfoundland: Vestiges of a Cambro-Ordovician platform margin. *Geological Society of America Bulletin*, 92: 799–811.

James, N.P., and Wood, R., 2010. Reefs. In: James, N.P., and Dalrymple, R.W. (eds.), *Facies Models 4*. St. John's: Geological Association of Canada, 421–447.

Jeong, H., and Lee, Y.I., 2000. Late Cambrian biogeography: conodont bioprovinces from Korea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 162: 119–136.

Johns, R.A., Dattilo, B.F., and Spincer, B., 2007. Neotype and redescription of the Upper Cambrian anthaspidellid sponge, *Wilbernicyathus donegani* Wilson, 1950. *Journal of Paleontology*, 81: 435–444.

Kang, I., and Choi, D., 2007. Middle Cambrian trilobites and biostratigraphy of the Daegi Formation (Taebaek Group) in the Seokgaejae section, Taebaeksan Basin, Korea. *Geosciences Journal*, 11: 279–296.

Kiessling, W., 2009. Geologic and Biologic Controls on the Evolution of Reefs. *Annual Review of Ecology, Evolution, and Systematics*, 40: 173–192.

Kim, K.H., Choi, D.K., and Lee, C.Z., 1991. Trilobite biostratigraphy of the Dumugol Formation (Lower Ordovician) of Dongjeom Area, Korea. *Journal of the Paleontological Society of Korea*, 7: 106–116.

Klappa, C.F., and James, N.P., 1980. Small lithistid sponge bioherms, early Middle Ordovician Table Head Group, western Newfoundland. *Bulletin of Canadian Petroleum Geology*, 28: 425–451.

Kobluk, D.R., 1988. Pre-Cenozoic Fossil Record of Cryptobionts and their Presence in Early Reefs and Mounds. *Palaios*, 3: 243–250.

Kruse, P.D., and Reitner, J.R., 2014. Northern Australian microbial-metazoan reefs after the mid-Cambrian mass extinction. *Memoirs of the Association of Australasian Palaeontologists*, 45: 31–53.

Kruse, P.D., and Zhuravlev, A.Y., 2008. Middle-Late Cambrian *Rankenella*-*Girvanella* reefs of the Mila Formation, northern Iran. *Canadian Journal of Earth Sciences*, 45: 619–639.

Kwon, Y.K., and Chough, S.K., 2005. Sequence stratigraphy of the cyclic successions in the Dumugol Formation (Lower Ordovician), mideast Korea. *Geosciences Journal*, 9: 305–324.

Kwon, Y.K., Chough, S.K., Choi, D.K., and Lee, D.J., 2006. Sequence stratigraphy of the Taebaek Group (Cambrian-Ordovician), mideast Korea. *Sedimentary Geology*, 192: 19–55.

Kwon, Y.K., Lee, D.J., Choi, D.K., and Chough, S.K., 2003. Lower Ordovician sponge bioherms in the Makkol Formation, Taebaeksan Basin, Mideast Korea. *Facies*, 48: 79–90.

Lee, B.-S., 2014. Conodonts from the Sesong Slate and Hwajeol Formation (Guzhangian to Furongian) in the Taebaeksan Basin, Korea. *Acta Geologica Sinica* (English editon), 88(1): 35–45.

Lee, B.-S., Lee, J.-D., and Bak, Y.-S., 1997. Ordovician Conodont Biostratigraphy of the Maggol Limestone in the Ogdong-Yeongchun Area. *Journal of the Paleontological Society of Korea*, 13: 37–50 (in Korean with English abstract).

Lee, B.-S., Lee, J.-D., and Chun, H.Y., 1998. Conodont biostratigraphy of the Dumugol Shale (Lower Ordovician) in Ogdong, Yeongweol-gun and Yeongchun, Danyang-gun, Korea. *Journal of the Paleontological Society of Korea*, 14: 147–164 (in Korean with English abstract).

Lee, B.-S., and Seo, K.-S., 2004. Lower Paleozoic conodonts of Korea. *Journal of the Paleontological Society of Korea*, S7: 189-215 (in Korean with English abstract).

Lee, B.-S., and Seo, K.-S., 2008. Conodonts from the Hwajeol Formation (Upper Cambrian) in the Seokgaejae area, southeast margin of the Taebaeksan Basin. *Geosciences Journal*, 12: 233–242.

Lee, B.-S., Seo, K.-S., and Lee, B.-S., 1991. Conodonts from the lower Dumugol Shale (Lower Ordovician) of the Cheungsan-Sabuk area, Jeongseon-Gun, Kangweon-Do. *Journal of the Paleontological Society of Korea*, 7: 63–75.

Lee, D.-J., 2000. Occurrence of calathids from the Makkol Formation (Middle Ordovician), Taebaek, Korea. *Journal of the Paleontological Society of Korea*, 16: 37–44 (in Korean with English abstract).

Lee, J.-H., Chen, J., Choh, S.-J., Lee, D.-J., Han, Z., and Chough, S.K., 2014a. Furongian (late Cambrian) sponge-microbial maze-like reefs in the North China Platform. *Palaios*, 29: 27–37.

Lee, J.-H., Chen, J., and Chough, S.K., 2010. Paleoenvironmental implications of an extensive maceriate microbialite bed in the Furongian Chaomidian Formation, Shandong Province, China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 297: 621–632.

Lee, J.-H., Chen, J., and Chough, S.K., 2012. Demise of an extensive biostromal microbialite in the Furongian (late Cambrian) Chaomidian Formation, Shandong Province, China. *Geosciences Journal*, 16: 275–287.

Lee, J.-H., Chen, J., and Chough, S.K., 2015. The middle–late Cambrian reef transition and related geological events: a review and new view. *Earth-Science Reviews*, 145: 66–84.

Lee, J.-H., Lee, H.S., Chen, J., Woo, J., and Chough, S.K., 2014b. Calcified microbial reefs in the Cambrian Series 2 of the North China Platform: implications for the evolution of Cambrian calcified microbes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 403: 30–42.

Lee, J.-H., Woo, J., and Lee, D.-J., in press. The earliest reef-building anthaspidellid sponge *Rankenella zhangxianensis* n. sp. from the Zhangxia Formation (Cambrian Series 3), Shandong Province, China. *Journal of Paleontology*.

Lee, K., and Lee, H.-Y., 1990. Conodont biostratigraphy of the upper Choseon Supergroup in Jangseong-Dongjeom area, Gangweon-Do. *Journal of the Paleontological Society of Korea*, 6: 188–210.

Lee, M., Sun, N., Choh, S.-J., and Lee, D.-J., 2014. A new Middle Ordovician reef assemblage from north-central China and its palaeobiogeographical implications. *Sedimentary Geology*, 310: 30–40.

Lee, Y.I., 1988. Storm Sedimentation in the Middle Ordovician Duwibong Formation, southern Taebaeg City. *Journal of the Geological Society of Korea*, 24: 234–242.

Lee, Y.I., and Choi, D.K., 1987. Sedimentology of the Dumugol Formation (Lower Ordovician) in the Vicinity of the Dongjeom Station, Taebaeg City: a preliminary study. *Journal of the Geological Society of Korea*, 23: 331–337 (in Korean with English abstract).

Lee, Y.I., Hyeong, K., and Yoo, C.M., 2001. Cyclic sedimentation across a Middle Ordovician carbonate ramp (Duwibong Formation), Korea. *Facies*, 44: 61–74.

Lee, Y.N., and Lee, H.-Y., 1986. Conodont biostratigraphy of the Jigunsan Shale and Duwibong Limestone in the Nokjeon-Sangdong area, Yeongweol-Gun, Kangweondo, Korea. *Journal of the Paleontological Society of Korea*, 2: 114–136.

Li, Q., Li, Y., and Kiessling, W., 2014. Early Ordovician sponge-*Calathium*-microbial reefs on the Yangtze Platform margin of the South China Block. *Gff*, 136: 157–161.

Li, S.M., and Zhu, Z., 1995. Discovery of Lower Ordovician reefs from North China Platform. *Oil and Gas Geology*, 16: 202 (in Chinese).

Liu, J., and Zhan, R., 2009. Temporal distribution of diagnostic biofabrics in the Lower and Middle Ordovician in North China: clues to the geobiology of the Great Ordovician Biodiversification Event. *Acta Geologica Sinica* (English edition), 83: 513–523.

McKenzie, N.R., Hughes, N.C., Myrow, P.M., Choi, D.K., and Park, T.y., 2011. Trilobites and zircons link north China with the eastern Himalaya during the Cambrian. *Geology*, 39: 591–594.

Meng, X., Ge, M., and Tucker, M.E., 1997. Sequence stratigraphy, sea-level changes and depositional systems in the Cambro-Ordovician of the North China carbonate platform. *Sedimentary Geology*, 114: 189–222.

Mu, X., Yan, H., Li, Y., Yuan, J., and Zhang, J., 2003. Temporal and spatial distribution of microbiolitic reefs of Middle Cambrian, eastern North China Craton. *Acta Micropalaeontologica Sinica*, 20: 279–285 (in Chinese with English abstract).

Nestor, H., and Webby, B.D., 2013. Biogeography of the Ordovician and Silurian Stromatoporoidea. In: Harper, D.A.T. and Servais, T. (eds.), *Early Palaeozoic biogeography and palaeogeography.* Geological Society of London Memoir. London, 67–79.

Oh, J.-R., Choh, S.-J., and Lee, D.-J., 2015. First report of *Cystostroma* (Stromatoporoidea; Ordovician) from Sino-Korean Craton. *Geosciences Journal*, 19: 25–31.

Paik, I.S., 1987. Depositional environments of the Middle Ordovician Maggol Formation, southern part of the Baegunsan syncline area. *Journal of the Geological Society of Korea*, 23: 360–373.

Park, T.-Y., Han, Z., Bai, Z., and Choi, D., 2008. Two middle Cambrian trilobite genera, *Cyclolorenzella* Kobayashi, 1960 and *Jiulongshania* gen. nov., from Korea and China. *Alcheringa*, 32: 247–269.

Park, T.-Y., Woo, J., Lee, D.-J., Lee, D.-C., Lee, S.-b., Han, Z., Chough, S.K., and Choi, D.K., 2011. A stem-group cnidarian described from the mid-Cambrian of China and its significance for cnidarian evolution. *Nature Communications*, 2: 442.

Park, T.-Y.S., and Kihm, J.-H., 2015. Furongian (late Cambrian) trilobites from the *Asioptychaspis subglobosa* Zone of the Hwajeol Formation, Korea. *Alcheringa*, 39: 181–199.

Park, T.-Y.S., Kihm, J.-H., Woo, J., Zhen, Y.-Y., Engelbretsen, M., Hong, J., Choh, S.-J., and Lee, D.-J., 2016. Cambrian stem-group cnidarians and a new species of stem-group cnidarian from the Cambrian Series 3 of the Taebaeksan Basin, Korea. *Acta Geologica Sinica* (English edition), (in press).

Peng, S., Babcock, L.E., and Cooper, R.A., 2012. The Cambrian Period. In: Gradstein , F.M., Ogg, J.G., Schmitz, M., and Ogg, G.. (eds.), *The Geologic Time Scale 2012*. Amsterdam: Elsevier, 437–488.

Peters, S.E., and Gaines, R.R., 2012. Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion. *Nature*, 484: 363–366.

Pitcher, M., 1964. Evolution of Chazyan (Ordovician) reefs of eastern United States and Canada. *Bulletin of Canadian Petroleum Geology*, 12: 632–691.

Pratt, B.R., 1989. Deep-water *Girvanella-Epiphyton* reef on a mid-Cambrian continental slope, Rockslide Formation, MacKenzie Mountains, Northwest Territories. In: Geldsetzer, H.H.J., James, N.P., and Tebbutt, G.E. (eds.), *Reefs: Canada and adjacent areas.* Canadian Society of Petroleum Geologists Memoir, 13: Canadian Society of Petroleum Geologists, 161–164.

Pratt, B.R., 1995. The origin, biota and evolution of deep-water mud-mounds. In: Monty, C.L.V., Bosence, D.W.J., Bridges, P.H. and Pratt, B.R.(eds.), *Carbonate Mud-Mounds: Their Origin and Evolution*. International Association of Sedimentologists Special Publication: Blackwell Science, 49–123.

Pratt, B.R., and James, N.P., 1982. Cryptalgal-metazoan bioherms of early Ordovician age in the St George Group, western Newfoundland. *Sedimentology*, 29: 543–569.

Riding, R., 2002. Structure and composition of organic reefs and carbonate mud mounds: concepts and categories. *Earth-Science Reviews*, 58: 163–231.

Riding, R., 2006. Microbial carbonate abundance compared with fluctuations in metazoan diversity over geological time. *Sedimentary Geology*, 185: 229–238.

Rigby, J.K., 1983. Fossil Demospongia. In: Broadhead, T.W. (ed.), *Sponges and Spongiomorphs: Notes for a Short Course Studies in Geology*. Knoxville: University of Tennessee, 12–39.

Ross, J.R.P., 1981. Ordovician environmental heterogeneity and community organization. In: Gray, J., Boucot, A.J., and Berry, W.B.N. (eds.), *Communities of the past*. Stroudsburg: Hutchinson Ross, 1–33.

Rowland, S.M., and Gangloff, R.A., 1988. Structure and paleoecology of Lower Cambrian reefs. *Palaios*, 3: 111–135.

Rowland, S.M., and Shapiro, R.S., 2002. Reef patterns and environmental influences in the Cambrian and earliest Ordovician. In: Kiessling, W., Flügel, E., and Golonka, J. (eds.), *Phanerozoic Reef Patterns SEPM Special Publication*. Tulsa: SEPM, 95–128.

Ryu, I.-C., Doh, S.-J., and Choi, S.-G., 2002. Carbonate breccias in the Lower-Middle Ordovician Maggol Limestone (Taebacksan Basin, South Korea): implications for regional tectonism. *Facies*, 46: 35–56.

Seo, K.-S., and Lee, B.-S., 2010. Conodonts from the Early Ordovician Dumugol Formation in Seokgaejae area, Bonghwagun, Kyungsangbukdo, Korea. *Journal of the Paleontological Society of Korea*, 26: 59–69 (in Korean with English abstract).

Shapiro, R.S., and Awramik, S.M., 2000. Microbialite morphostratigraphy as a tool for correlating Late Cambrian–Early Ordovician sequences. *The Journal of Geology*, 108: 171–180.

Shapiro, R.S., and Rigby, J.K., 2004. First occurrence of an in situ anthaspidellid sponge in a dendrolite mound (Upper Cambrian; Great Basin, USA). *Journal of Paleontology*, 78: 645–650.

Sim, M.S., and Lee, Y.I., 2006. Sequence stratigraphy of the Middle Cambrian Daegi Formation (Korea), and its bearing on the regional stratigraphic correlation. *Sedimentary Geology*, 191: 151–169.

Sohn, J.W., and Choi, D.K., 2005. Revision of the Upper Cambrian trilobite biostratigraphy of the Sesong and Hwajeol formations, Taebaek Group, Korea. *Journal of the Paleontological Society of Korea*, 21: 195–200 (in Korean with English abstract).

Sohn, J.W., and Choi, D.K., 2007. Furongian trilobites from the *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea. *Geosciences Journal*, 11: 297–314.

Stock, C.W., Nestor, H., and Webby, B.D., 2012. Part E, Revised, Volume 4, Chapter 14: Paleobiogeography of the Paleozoic Stromatoporoidea. *Treatise Online*, 34: 1–44.

Sun, N., Elias, R.J., and Lee, D.-J., 2014. The biological affinity of *Amsassia*: new evidence from the Ordovician of North China. *Palaeontology*, 57: 1067–1089.

Toomey, D.F., and Nitecki, M.H., 1979. *Organic buildups in the Lower Ordovician (Canadian) of Texas and Oklahoma*. Field Museum of Natural History, 181.

Wang, J., Deng, X., Wang, G., and Li, Y., 2012. Types and biotic successions of Ordovician reefs in China. *Chinese Science Bulletin*, 57: 1160–1168.

Webby, B.D., 2002. Patterns of Ordovician reef development. In: Kiessling, W., Flügel, E.. and Golonka, J. (eds.), *Phanerozoic Reef Patterns*. SEPM Special Publication. Tulsa: SEPM, 129–179.

Woo, J., 2009. *The Middle Cambrian Zhangxia Formation, Shandong Province, China: Depositional Environments and Microbial Sedimentation*. Ph.D. Thesis, Seoul National University, Seoul, 243.

Woo, J., and Chough, S.K., 2010. Growth patterns of the Cambrian microbialite: Phototropism and speciation of *Epiphyton*. *Sedimentary Geology*, 229: 1–8.

Woo, J., Chough, S.K., and Han, Z., 2008. Chambers of *Epiphyton* thalli in microbial buildups, Zhangxia Formation (Middle Cambrian), Shandong Province, China. *Palaios*, 23: 55–64.

Woo, K.S., 1999. Cyclic tidal successions of the Middle Ordovician Maggol Formation in the Taebaeg area, Kangwondo, Korea. *Geosciences Journal*, 3: 123–140.

Wood, R., 1999. *Reef Evolution*. Oxford: Oxford University Press, 414.

Wood, R., and Curtis, A., 2015. Extensive metazoan reefs from the Ediacaran Nama Group, Namibia: the rise of benthic suspension feeding. *Geobiology*, 13: 112–122.

Wood, R., Zhuravlev, A.Y., and Anaaz, C.T., 1993. The ecology of Lower Cambrian buildups from Zuune Arts, Mongolia: implications for early metazoan reef evolution. *Sedimentology*, 40: 829–858.

Yun, C.-S., 2000. Actinoceroid cephalopods from the Duwibong Formation (Middle Ordovician), Taebaek-Yeongwol area, Korea. *Journal of the Paleontological Society of Korea*, 16: 67–92.

Zhang, J., Zhou, Y., and Wang, Z., 1985. *Epiphyton* boundstone and palaeogeography of the Middle Cambrian Zhangxia Formation in the east of North China Platform. *Acta Sedimentologica Sinica*, 3: 63–71 (in Chinese with English abstract).

Zhuravlev, A.Y., 1996. Reef ecosystem recovery after the Early Cambrian extinction. In: Hart, M.B. (ed.), *Biotic Recovery from Mass Extinction Events*. Geological Society, London Special Publications, 102: 79–96.

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