

Early labechiid stromatoporoids of the Yeongheung Formation (Middle Ordovician), Yeongwol Group, mideastern Korean Peninsula: Part I. Environmental distribution

Jino Park¹, Jongsun Hong¹, Jeong-Hyun Lee², Suk-Joo Choh^{1*}, and Dong-Jin Lee³

¹Department of Earth and Environmental Sciences, Korea University, Seoul 02841, Republic of Korea

²Department of Geology and Earth Environmental Sciences, Chungnam National University, Daejeon 34134, Republic of Korea

³Department of Earth and Environmental Sciences, Andong National University, Andong 36729, Republic of Korea

ABSTRACT: This study examines depositional facies and environmental significance of early labechiid stromatoporoids in the Yeongheung Formation (late Middle Ordovician), Yeongwol Group in the mideastern part of the Korean Peninsula. The formation is composed of five depositional facies: lime mudstone to wackestone (LM/W), peloidal, intraclastic and bioclastic packstone to grainstone (P/G), laminated dolomitic lime mudstone (LMdl), algal laminite (La), and oolitic packstone to grainstone (P/Go). Three types of shallowing upward cycles in the succession are identified, including subtidal (LM/W–P/G), subtidal to peritidal (LM/W–P/G–LMdl–La), and peritidal cycles (LMdl–La). The stromatoporoids occur exclusively in the packstone to grainstone (P/G) facies of the subtidal cycle. These early labechiids inhabited on a grainy substrate under moderate- to high-energy conditions, conforming to the previous notion that stromatoporoids primarily occupied level-bottom or reefs, surrounded by grainy calcareous sediments during the Middle Ordovician.

Key words: stromatoporoid, labechiid, late Middle Ordovician, Yeongheung Formation

Manuscript received July 30, 2016; Manuscript accepted February 2, 2017

1. INTRODUCTION

Stromatoporoid, an extinct lineage of sponge similar to modern sclerosponge, first appeared in the Middle Ordovician (Stearn et al., 1999; Selden, 2015). They were shallow marine benthic organisms in the Paleozoic (Kershaw, 1998; Kershaw and Brunton, 1999; Selden, 2015) and Mesozoic (e.g., Leinfelder et al., 2005), and have been best known as an important contributor of middle Paleozoic reefs (Copper, 2002). The initial diversification of stromatoporoids is represented by labechiids, which appeared in the paleo-equatorial shallow marine realms of China, Korea, USA, Canada, Russia, Kazakhstan, and Malaysia during the late Middle Ordovician (late Darriwilian) (Webby, 2004; Nestor and Webby, 2013; Selden, 2015). In the Korean Peninsula, labechiids have been reported from the Middle

Ordovician Mandal Series of the Pyeongnam Basin (Yabe and Sugiyama, 1930), Yeongheung Formation of the Yeongwol Group (Lee and Yu, 1993; Kano et al., 1994), and Duwibong Formation of the Taebaek Group, Taebaeksan Basin (Oh et al., 2015) (Figs. 1a and b).

The diversification of labechiid stromatoporoids in the late Middle Ordovician was coincident with Ordovician radiation, particularly along with bryozoans, corals, and solenoporacean algae, which resulted in the dramatic transformation of reef type from microbial-sponge dominated reefs to metazoan-algae dominated reefs (Webby, 2002, 2004). Among the newly appeared organisms, stromatoporoids are known to occupy relatively narrower range of distribution within shallow subtidal environments, in contrast to contemporaneous sessile organisms (Webby, 2002, 2004). The labechiid stromatoporoids of the North China Platform provide a unique opportunity for a documentation of environmental distributions of the early stromatoporoids in peri-Gondwana region. In this study, we analyze depositional facies of the Yeongheung Formation (middle part; Figs. 1 and 2) and reconstruct environmental distribution of early labechiids, in order to assess substrate preference of early stromatoporoids.

*Corresponding author:

Suk-Joo Choh

Department of Earth and Environmental Sciences, Korea University, Seoul 02841, Republic of Korea

Tel: +82-2-3290-3180, Fax: +82-2-3290-3189, E-mail: sjchoh@korea.ac.kr

©The Association of Korean Geoscience Societies and Springer 2017

2. GEOLOGIC BACKGROUND AND METHODS

The Taebaeksan Basin comprises a Cambrian–Ordovician succession of the Joseon Supergroup, located in mideastern Korean Peninsula (Fig. 1a). It is divided into the Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups based on their geographic distribution and lithology (Fig. 1b; Choi, 1998). Among these units, only the Taebaek and Yeongwol groups are well delineated in terms of lithostratigraphy and

biostratigraphy, whereas the rest are poorly studied, because of poor preservation of fossils, sedimentary structures and texture by strong deformation and moderate metamorphism (Choi and Chough, 2005; Chough, 2013). The Yeongwol Group consists of five lithostratigraphic units: the Sambangsan (sandstone, siltstone, and shale), Machari (limestone, dolomitic limestone, and shale), Wagok (dolostone), Mungok (limestone, dolostone and shale), and Yeongheung (limestone and dolostone) formations in ascending order (Fig. 1c; Choi, 1998; Choi and Chough, 2005).

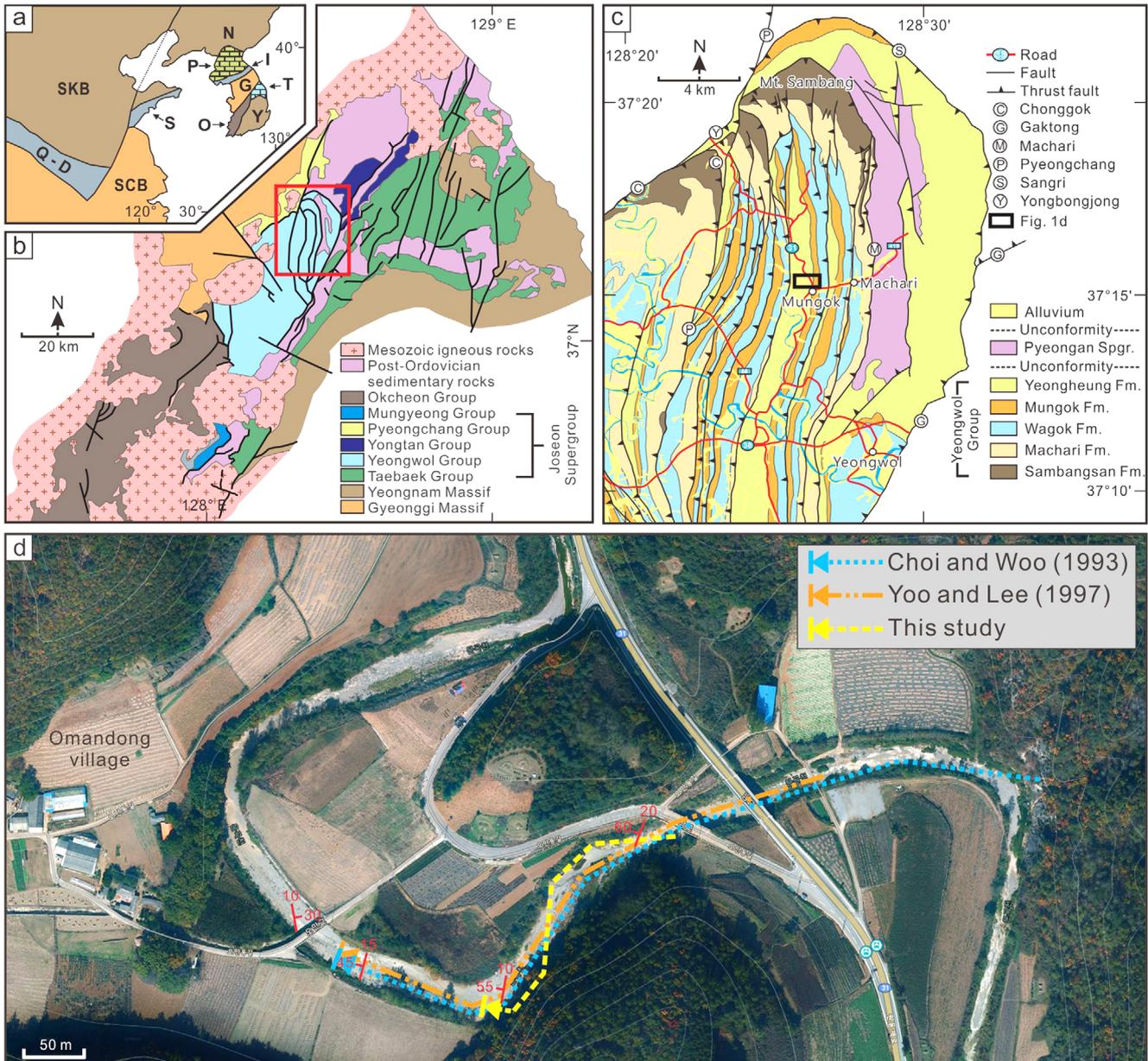


Fig. 1. (a) Tectonic elements of northeast Asia. SKB = Sino-Korean Block; SCB = South China Block; Q-D = Qinling-Dabie Belt; S = Sulong Belt; N = Nangrim Massif; P = Pyeongnam Basin; I = Imjingang Belt; G = Gyeonggi Massif; O = Okcheon Basin; T = Taebaeksan Basin; Y = Yeongnam Massif (after Chough, 2013). (b) Simplified geologic map of the Taebaeksan Basin (after Choi, 1998). Red rectangle represents the area shown in Figure 1c. (c) Distribution of the Yeongwol Group and the location of study area (modified after Choi (1998) and Kim et al. (2014)). (d) Satellite photograph of the Namgyo Section, sourced from <http://map.daum.net>. Yellow dotted line indicates a logging track of middle part of the section.

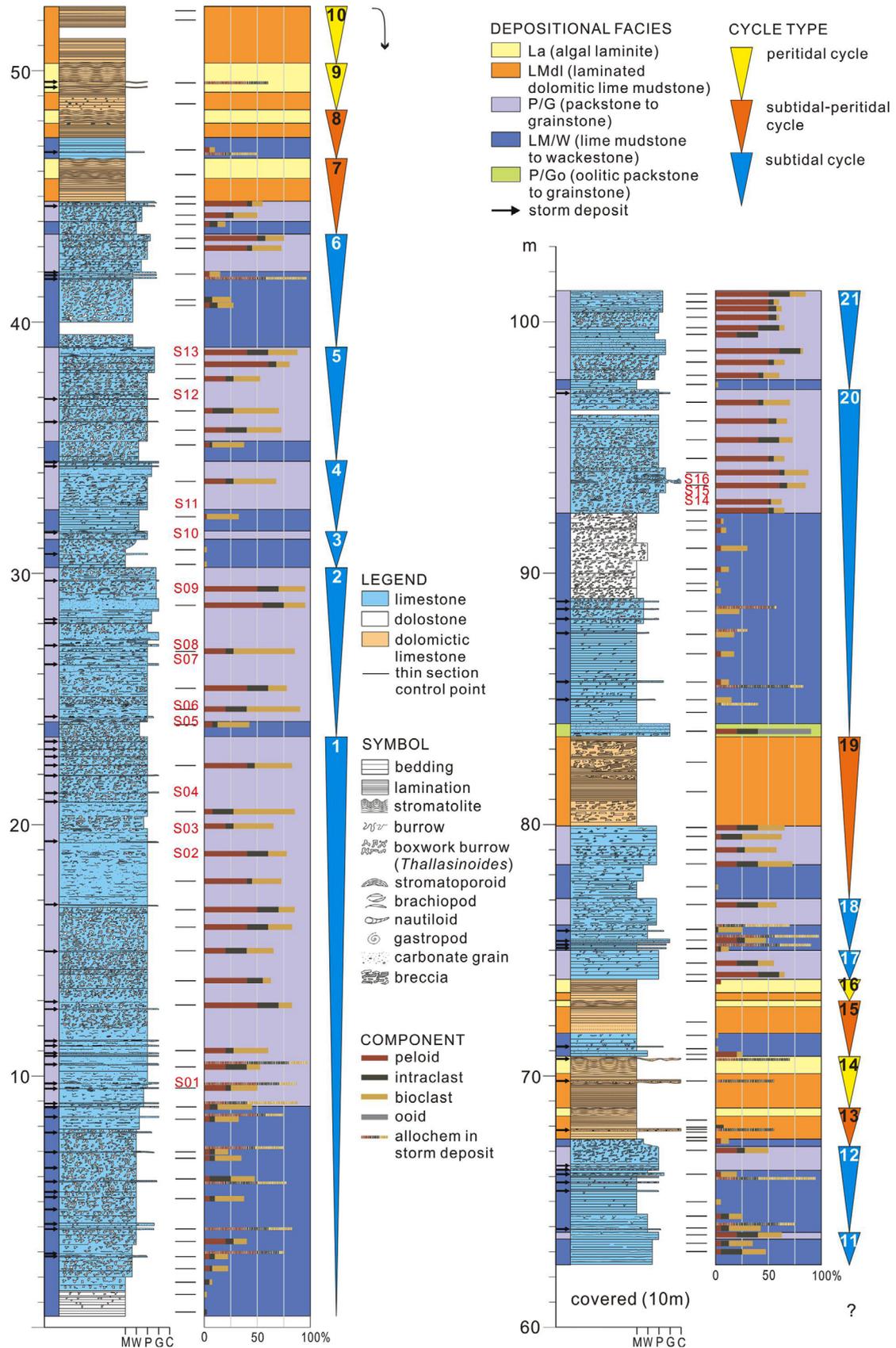


Fig. 2. Measured section of the middle Yeongheung Formation in the study area. Stromatoporoid occurrences (S1–S16) are marked at right of the columns. M = lime mudstone, W = wackestone, P = packstone, G = grainstone, C = limestone conglomerate.

The entire succession was affected by N-S trending and eastward-stacking thrust faults and associated folds (Fig. 1c). The base of the Sambangsan Formation and the top of the Yeongheung Formation are missing due to these thrust faults (Choi, 1998). The Yeongheung Formation is composed of dark to bluish grey, thin- to very thick-bedded limestone and dolostone, interpreted as the deposits of sabkha-type peritidal to shallow subtidal environments overprinted by penecontemporaneous dolomitization (Choi and Woo, 1993; Woo and Choi, 1993; Yoo and Lee, 1997, 1998). Lee and Yu (1993) and Kano et al. (1994) have suggested that the middle part of the Yeongheung Formation is representative of the late Llanvirnian (late Darriwilian) based on the studies of trilobite *Basiliella*, actinoceratoid cephalopod (Kobayashi, 1966), and conodont *Plectodina* (Lee, 1979).

The Namgyo section crops out along a streambed near the Omandong village, 8.5 km north-northwest of Yeongwol city (Fig. 1c). Choi and Woo (1993) and Yoo and Lee (1997) described approximately 280 m and 200 m of the Yeongheung Formation in the vicinity, respectively (Fig. 1d). Because the lower and upper parts of the section are covered by river sediments, about 100-m thick middle part of the formation was measured (Figs. 1d and 2). Sixteen stromatoporoid-bearing stratigraphic intervals have been recognized in the Namgyo section (Fig. 2). Rock samples were collected at a vertical interval of 0.1 to 2 m depending on the sedimentary facies (Fig. 2). 117 large-format (54 × 76 mm) and 5 standard (28 × 48 mm) thin sections were cut perpendicular to bedding; texture and relative proportion of non-skeletal and skeletal grains, micrite matrix, and cements are described, complemented by visual estimation chart by Matthew et al. (1991) (Flügel, 2004). The white card technique (Folk, 1987) of superimposing thin section on white paper and projecting oblique reflected light was employed for the description of original texture of partly to completely dolomitized specimens. The systematic description of the labechiid stromatoporoids and their geologic implications are dealt separately in a companion paper in this volume (Jeon et al., 2017).

3. RESULTS

3.1. Constituents

Two major types of carbonate grains are recognized in the Yeongheung Formation: non-skeletal grains and skeletal grains. Non-skeletal grains include peloids, intraclasts, and rare ooids. Rounded to sub-angular and poorly sorted peloids up to 2 mm in diameter commonly occur with micritic granular intraclasts less than 5 mm in size. Well-rounded to angular intraclasts up to 50 mm long are mostly micritic in composition,

and subordinate peloidal and bioclastic wackestone to grainstone intraclasts are also present. Their shapes include spheroidal to sub-spheroidal, oval, and flat to irregular.

Skeletal grains larger than 1 cm across include stromatoporoids, mollusks and brachiopods. Bivalves and gastropods are up to 2 cm in length, and spiral and orthoconic nautiloids are up to 3 cm in diameter and 15 cm in length, respectively. Disarticulated brachiopods are up to 2 cm long. Disarticulated crinoids (up to 0.2 cm in length) are the most common skeletal grains, followed by mollusk fragments with common micritic envelope. Trilobite fragments are up to 1 cm across. Although the overall contribution to the carbonate fractions is minor, ostracods (up to 1 mm across) are common in certain intervals. Scattered monaxial and triaxial sponge spicules (up to 0.1 mm in diameter and 1 mm in length) and partial “spicular” networks of non-lithistid demosponges (see Park et al., 2015, Fig. 8b) locally occur in the wackestone to packstone. Other rare fossils include a trepostome bryozoan *Dianulites*, calcimicrobes (*Ortonella*- and *Girvanella*-like filamentous bundles), and probable *Amsassia*, a modular organism with red alga affinity.

3.2. Depositional Facies

Five sedimentary facies are described, based on composition (constituents), texture and sedimentary structures: lime mudstone to wackestone (LM/W), peloidal, intraclastic, and skeletal packstone to grainstone (P/G), laminated dolomitic lime mudstone (LMdl), algal laminite (stromatolite) (La), and oolitic packstone to grainstone (P/Go).

3.2.1. Lime mudstone to wackestone (LM/W)

This facies consists of thin- to thick-bedded dark gray mudstone to wackestone bounded by stylolites or dissolution seams (Figs. 3a and b). Peloids and smaller micritic intraclasts are locally present in bioturbated lime mudstone to wackestone. Isolated and bifurcating horizontal to vertical burrows often grade upward into a mottled fabric with frequent overlap of boxwork-type burrows (*Thalassinoides*), filled with light gray micritic sediments and cement, or preferentially dolomitized (Fig. 3a). This facies is gradationally overlain by P/G or LMdl facies (Fig. 2). Graded wackestone laminae consist of light micrite, peloids and skeletal grains and grade upward into dark homogeneous micrite and thin beds of graded wackestone to packstone, which are composed of light micrite, peloids, smaller rounded micritic intraclasts, and subordinate crinoid fragments, trilobites, ostracods, mollusks, and rare calcimicrobes (Figs. 2 and 3c). The skeletal grains are best preserved in this facies (Fig. 3b).

Dark gray micrite and wackestone are suggestive of deposition

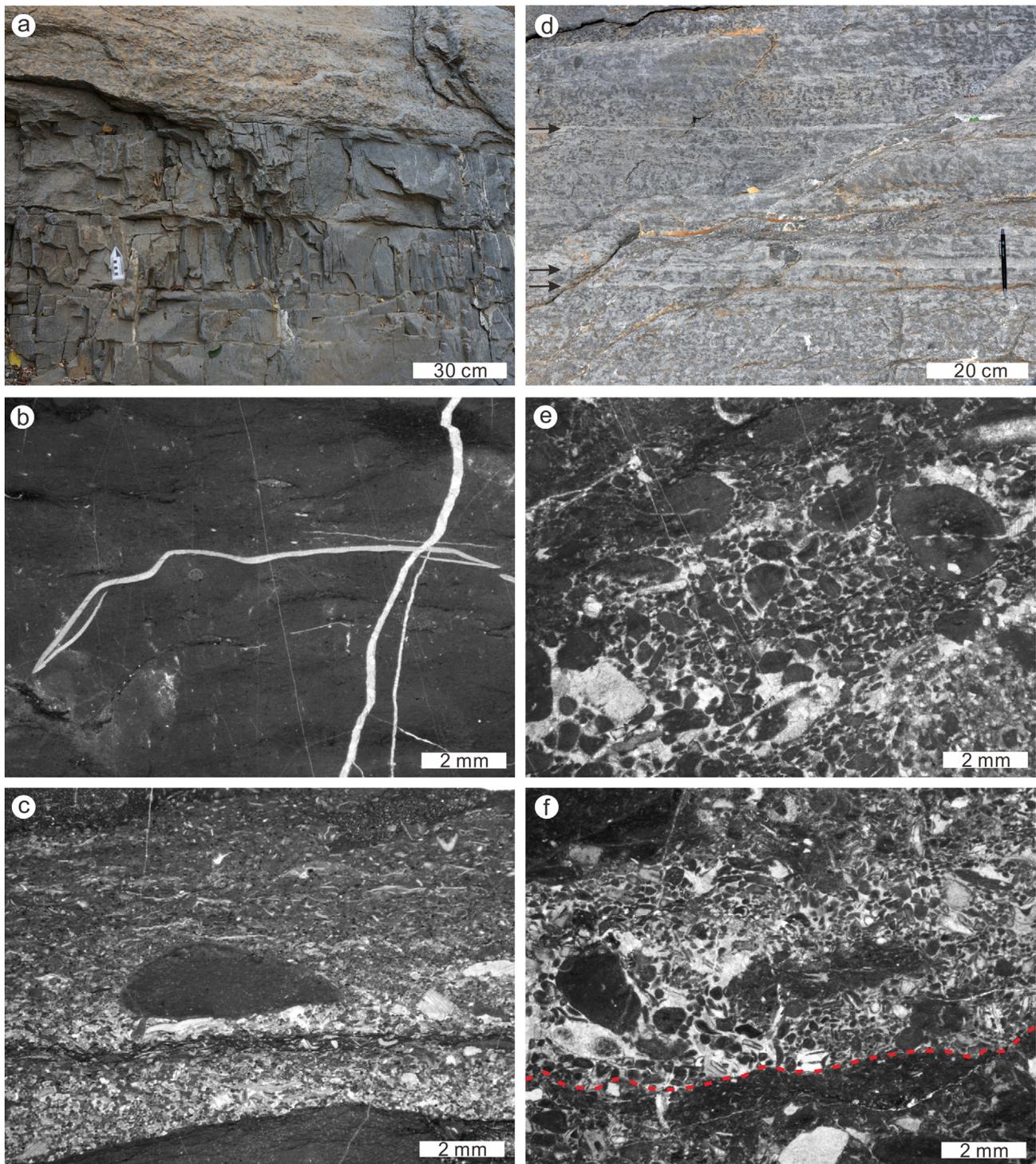


Fig. 3. (a) Photograph of thin- to thick-bedded lime mudstone to wackestone (LM/W facies), showing a vertical increase of selectively dolomitized burrows. (b) Photomicrograph of lime mudstone to wackestone with a trilobite skeleton. (c) Photomicrograph of amalgamated, thin bed of graded peloidal and bioclastic wackestone to packstone within the LM/W facies. (d) Photograph of packstone to grainstone (P/G facies) with boxwork-type (*Thalassinoides*) burrows, and intercalated thin beds of packstone to grainstone (arrows). (e) Photomicrograph of packstone to grainstone composed of peloids and rounded micritic intraclasts. (f) Photomicrograph of intercalated thin bed of grainstone with undulatory erosional base (red dotted line).

from suspension of lime muds in middle to outer platform environments, most likely below wave base (Burchette and Wright, 1992). Bioturbations and intact fossils indicate well-

oxygenated normal marine conditions. Millimeter-scale laminae and thin beds of wackestone to packstone are indicative of offshore-directed transportation of intraclasts and skeletal grains probably

derived from shallower subtidal environments (P/G facies) by storm-induced currents (Aigner, 1985).

3.2.2. Peloidal, intraclastic, and skeletal packstone to grainstone (P/G)

This facies is composed of mottled, medium- to very thick-bedded gray to dark gray packstone to grainstone (Figs. 2 and 3d). Well- to poorly sorted peloids and well-rounded small micritic intraclasts are the main constituents (Figs. 2 and 3e). Less bioturbated intervals contain low-angle cross stratifications and intraclasts of peloidal and bioclastic wackestone to grainstone. Mottled burrows are commonly dolomitized. Stromatoporoids, bryozoans, calcimicrobes, *Amsassia* and several stromatoporoid patch reefs exclusively occur in this facies. Whole to fragmented crinoid ossicles, ostracods, trilobites, brachiopods, gastropods, bivalves, orthoconic nautiloids, sponge spicules, and “spicular” networks are also present. This facies unit gradationally overlies and is overlain by LM/W facies or abruptly by LMdl facies (Fig. 2). Non-graded, lenticular to laterally continuous, single thin bed to amalgamated, cm-thick packstone to grainstone with erosional base are frequently intercalated (Figs. 3d and f). Well-rounded lime mudstone to wackestone intraclasts and sub-angular to rounded packstone to grainstone intraclasts are similar to those of adjacent or underlying sediments (Fig. 3f). Disarticulated crinoid ossicles, trilobite, ostracod, mollusks, brachiopod, bryozoan, calcimicrobes and dislocated stromatoporoids are also present within the interbeds.

Diverse skeletal grains and common bioturbations indicate well-oxygenated, normal shallow marine conditions. Micritic intraclasts might have formed by reworking of semi-consolidated lime muds. Peloidal and bioclastic wackestone to grainstone intraclasts are also indicative of reworking of semi-consolidated contemporaneous sediments. Packstone to grainstone texture is interpreted as the result of winnowing of lime muds above the wave base in shallow subtidal environments (Burchette and Wright, 1992; Flügel, 2004). Similar to LM/W facies, intervening erosional-based, non-graded thin beds of packstone to grainstone are interpreted as storm reworking by combined waves and currents and lag deposition during waning of storm (Aigner, 1985; Brookfield and Brett, 1988; Liang et al., 1993).

3.2.3. Laminated dolomitic lime mudstone (LMdl)

This facies is composed of thin-bedded parallel laminated dolomitic lime mudstone with millimeter-scale alternation of graded light gray silty dolomitic and dark gray homogeneous micritic laminae (Figs. 4a and b). Silt-sized peloidal packstone to grainstone lenses or laminae are intercalated within laminated dolomitic lime mudstone. Low angle cross-laminations, gypsum pseudomorphs filled with calcite cements, and tepee-like

desiccation structures are occasionally present. Skeletal grains and bioturbations are absent. This facies is commonly overlain by algal laminite (La) facies (Figs. 2 and 4a). Rarely intercalated conglomerates (a few cm to more than 10 cm-thick) with uneven erosive base consist of angular to rounded, granule- to pebble-sized flat clasts (Figs. 2 and 4c). Multidirectional clast imbrications are present (Fig. 4c). Two types of clasts are dominant: intraclasts with millimeter-scale lighter silty and darker micrite alternations and organic-rich intraclasts with some poorly preserved filamentous microbial remains: both are indicative of derivation from the LMdl or La facies.

This facies is interpreted as tidal bundle deposit consisting of planar graded laminae formed by tidal currents and deposition of suspended lime muds under the slack water conditions (Pratt, 2010). Unlike common grainstone and mudstone couplets in shallow subtidal to intertidal environments, the alternating muddy laminae with rare coarse-grained lenticular thin beds are most likely indicative of deposition under low-energy tidal currents (Demicco, 1983; Pratt and James, 1986; Demicco and Hardie, 1994; Pratt, 2010). Absence of skeletal grains and bioturbations, presence of evaporite pseudomorphs and tepee-like features suggest deposition in arid intertidal to supratidal conditions (Pratt and James, 1986; Demicco and Hardie, 1994; Pratt, 2002, 2010). Intercalated thin conglomerates are interpreted as deposits of episodic high-energy currents of probable storm origin (Aigner, 1985; Liang et al., 1993; Demicco and Hardie, 1994).

3.2.4. Algal laminite (stromatolite) (La)

This facies consists of wrinkled to wavy laminated lime mudstone (Figs. 4a and d) with bundles of relatively thicker organic-rich dark gray micritic and light gray dolomitic laminae (Fig. 4e). Relatively continuous, parallel laminated bundles grade upward to less continuous, wrinkled, and wavy laminae, which often form laterally linked hemispheroidal (LLH-C type) stromatolite (Fig. 4a). Gypsum pseudomorphs and fenestral fabrics are locally present. Tepees, laterally discontinuous brecciated thin layers, and desiccation cracks are common toward the top of the facies (Fig. 4d). The facies is devoid of skeletal grains and burrows, and some poorly preserved calcified filamentous microbial remains are present in dark gray laminae. The facies gradationally overlies LMdl facies, and is sharply overlain by LMdl or LM/W facies with erosional contacts (Fig. 2). Normally graded peloidal packstone to grainstone laminae to thin beds with planar erosive base, and thin bed of dark micritic flat- to irregular-shaped, granule to pebble conglomerate with uneven erosive base infrequently intercalate the La facies (Figs. 2 and 4f). Intraclasts contain some ghosts of filamentous microbes and rare peloids.

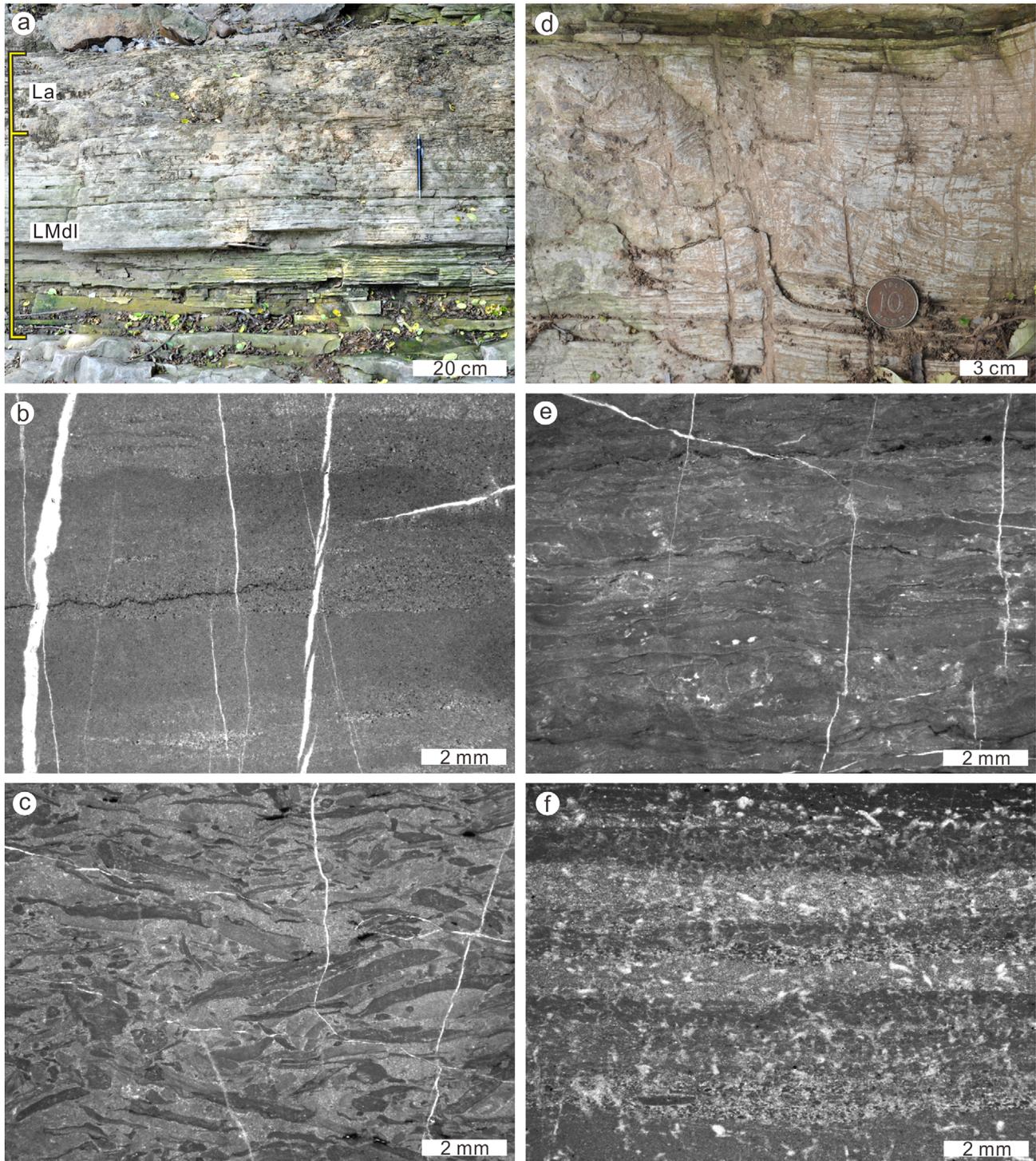


Fig. 4. (a) Photograph of laminated dolomitic lime mudstone (LMdl facies) gradationally overlain by wavy, wrinkled algal laminite (La facies). (b) Photomicrograph of laminated dolomitic lime mudstone composed of sets of graded, silty, lighter gray micritic lamina and homogeneous dark gray micritic lamina. (c) Photomicrograph of thin bed of flat to irregular granule to pebble conglomerate interbedded within the LMdl facies. (d) Photograph of algal laminite with tepee-like disturbed strata. (e) Photomicrograph of algal laminite (La facies), with dark gray micritic laminae thicker than light gray dolomitic laminae. (f) Photomicrograph of graded peloidal packstone to grainstone laminae interbedded in the La facies.

Wrinkled and wavy laminations without distinct physical sedimentary structures such as erosional surfaces or normal grading are indicative of microbially influenced biogenic

lamination (Demico and Hardie, 1994). Organic-rich laminae containing poorly preserved calcified filamentous microbial remains and light dolo-micritic laminae are interpreted to

form via a combined process of grain trapping and rapid calcification by microbes (Riding, 2000). Both microbial laminites and laterally linked hemispheroidal stromatolites mostly occur in intertidal to supratidal conditions throughout the Phanerozoic (Pratt, 2010). Muddy fabrics of the laminae in this facies differ from common sand-mud couplets of subtidal isolated (SH-type) stromatolites commonly surrounded by grainstone, where frequent scour prevented mat growth or development of laterally linked stromatolites (Demicco and Hardie, 1994; Pratt, 2010). Associated tepees and disrupted crusts with evaporite pseudomorphs are indicative of upper intertidal to supratidal environments under arid conditions (Pratt and James, 1986; Demicco and Hardie, 1994; Pratt, 2002, 2010). Infrequently intercalated thin packstone to grainstone and conglomerate are interpreted as high-energy current deposits of probable storm origin (Aigner, 1985; Liang et al., 1993; Demicco and Hardie, 1994).

3.2.5. Oolitic packstone to grainstone (P/Go)

This facies occurs in one interval (Fig. 2), underlain by LMdl and sharply overlain by LM/W facies. It is mainly composed of ooids and subordinate peloids and small micritic intraclasts. Spherical to oval ooids 0.2 to 0.5 mm in diameter formed by thin radial cortices surrounding peloidal nuclei. Nucleus to cortices ratio ranges from 1:1 to 1:5. Some ooids are completely dissolved and present as moldic pores filled with calcite spar. Skeletal grains are very rare.

Small radial ooids commonly form in relatively quiet and restricted (high salinity) conditions (Flügel, 2004). Abundant peloidal nuclei, peloids and small micritic intraclasts suggest that this facies might have formed adjacent to the P/G facies, whereas the lack of skeletal grains and bioturbations indicates restricted water conditions. The rare occurrence of this facies and the lack of ooids in other facies indicate ephemeral development of restricted oolitic sand flats (e.g., Pratt et al., 2012).

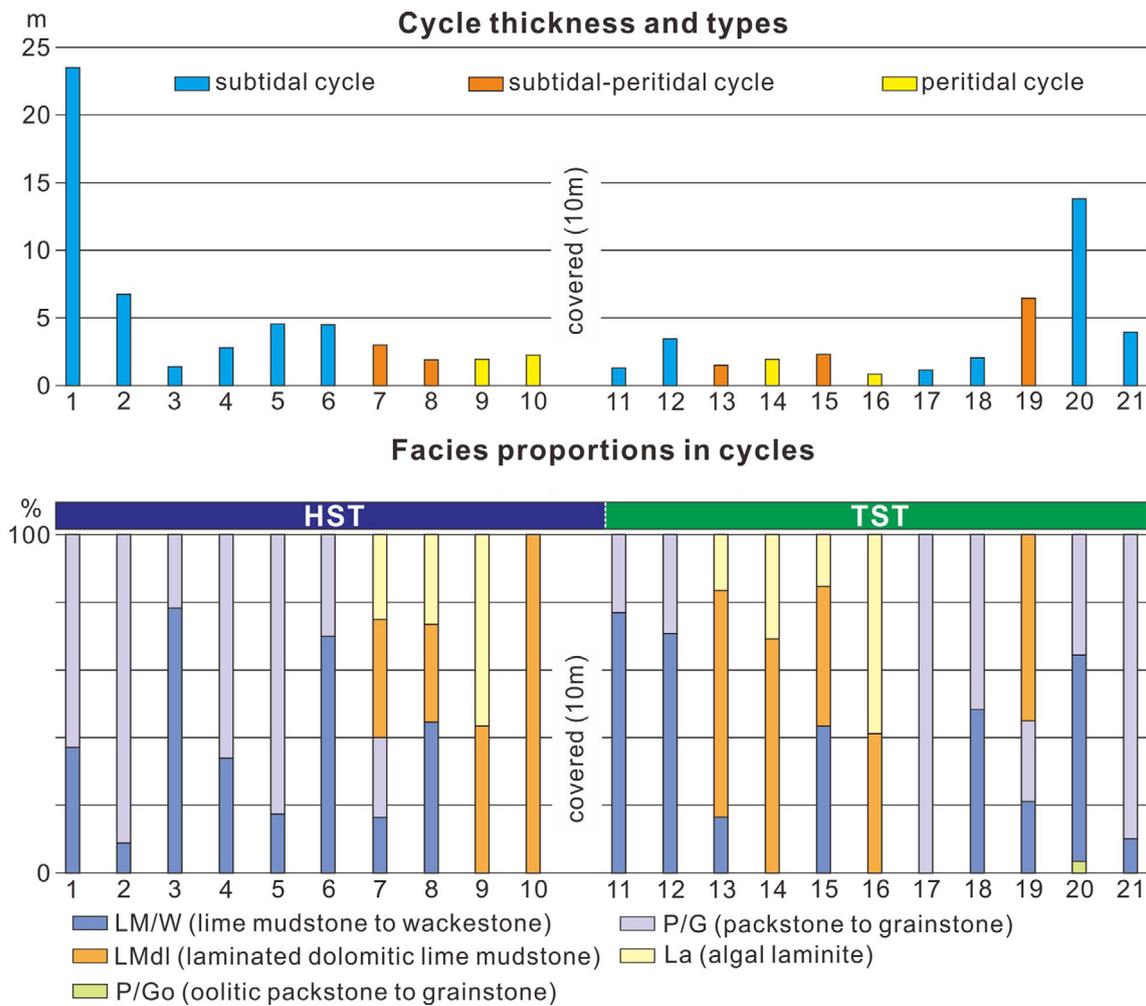


Fig. 5. Diagrams showing changes in thickness, types, and proportion of depositional facies in each cycle. Cycles 1 to 10 represent highstand systems tract (HST) with general shallowing upward trend, whereas cycles 11 to 21 indicate transgressive systems tract (TST) with increase in cycle thickness (see text for detail). Number of the cycles is indicated in Figure 2.

3.3. Shallowing-upward Cycles and Depositional Model

A total of 21 shallowing-upward cycles are identified based on vertical succession of facies (Fig. 2). These are subdivided into three types: subtidal cycles (LM/W to P/G facies; $n = 12/21$), subtidal to peritidal cycles (LM/W, P/G, LMdl and La facies in ascending order; $n = 5/21$), and peritidal cycles (LMdl to La facies; $n = 4/21$) (Figs. 2 and 5). The subtidal cycles range from 1.5 to 23.5 m in thickness, and occur at the lower half of the section and certain intervals of middle to upper part of the section. On the other hand, the peritidal cycles are less than 1–2 m thick, and mainly occur on top of the subtidal to peritidal cycles (Fig. 2). Subtidal to peritidal cycles range from 2 to 6.5 m in thickness, and occur between subtidal and peritidal cycles. The stacking of cycles shows a systematic shallowing upward pattern throughout the lower half of the section from subtidal to peritidal cycles with decrease in cycle thickness and proportions of LM/W and P/G facies to LMdl and La facies, indicating diminishing rate of accommodation space creation (Fig. 5). Turnaround of depositional style occurs at 62.5 m horizon from the base of the measured section, with systematic upward thickening of cycles, indicative of upward increase in rate of accommodation space creation (Figs. 2 and 5).

Subtidal facies (LM/W and P/G) are dominated by peloids and small micritic intraclasts, containing diverse fossil assemblages and intensive bioturbation, frequently intercalated by thin storm deposits. Such characteristics suggest deposition in open marine environment with normal salinity and well-oxygenated bottom conditions. On the other hand, peritidal facies (LMdl and La facies) are characterized by thinly laminated mudstone

without fossil and bioturbation, occurrence of gypsum pseudomorphs, tepee structures, and desiccation cracks. These collectively indicate low-energy inter- to supratidal environments with high salinity conditions caused by arid climate. Overall, the studied interval of the Yeongheung Formation is interpreted as product of progradation and retrogradation of carbonate ramp with intermittent storms, which could be partly comparable to modern sabkha of Arabian Gulf (Fig. 6; Choi and Woo, 1993; Yoo and Lee, 1997; Alsharhan and Kendall, 2003; Jones, 2010; Pratt, 2010).

3.4. Occurrence of Stromatoporoids

In the Yeongheung Formation, two genera of labechiid stromatoporoids, *Labechia* and *Labechiella*, are found in 16 horizons (S1–16) of the Namgyo section (Fig. 2) (Jeon et al., 2017). Skeletons of each stromatoporoid range from a few cm to less than 20 cm in height and less than 30 cm in width. Their external shapes are commonly low domical (Figs. 7a and b) with laminar, high domical, and irregular massive forms (Figs. 7c–e). In some horizons (S5, S10 and S16), the stromatoporoids are attached to each other, forming small patch reefs (Hong et al., 2017) up to 80 cm wide and 45 cm high. Stromatoporoids and stromatoporoid patch reefs only occur in the P/G facies (Fig. 2). They are distributed within the subtidal cycle-dominated intervals, and do not occur when the cycles are intercalated with peritidal cycles (Fig. 2). Most stromatoporoids overlie peloidal to small intraclastic packstone to grainstone (Figs. 7b, e, and f). It is interpreted that these stromatoporoids attached and developed on grainy substrates of moderate to high-energy conditions in normal marine subtidal environments (Fig. 6).

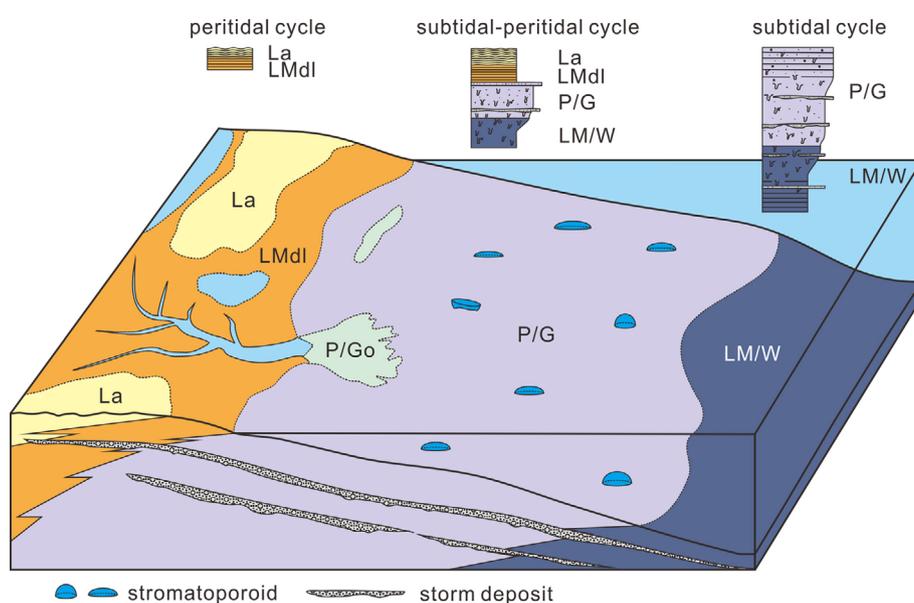


Fig. 6. Idealized depositional model and depositional cycles of the Yeongheung Formation.

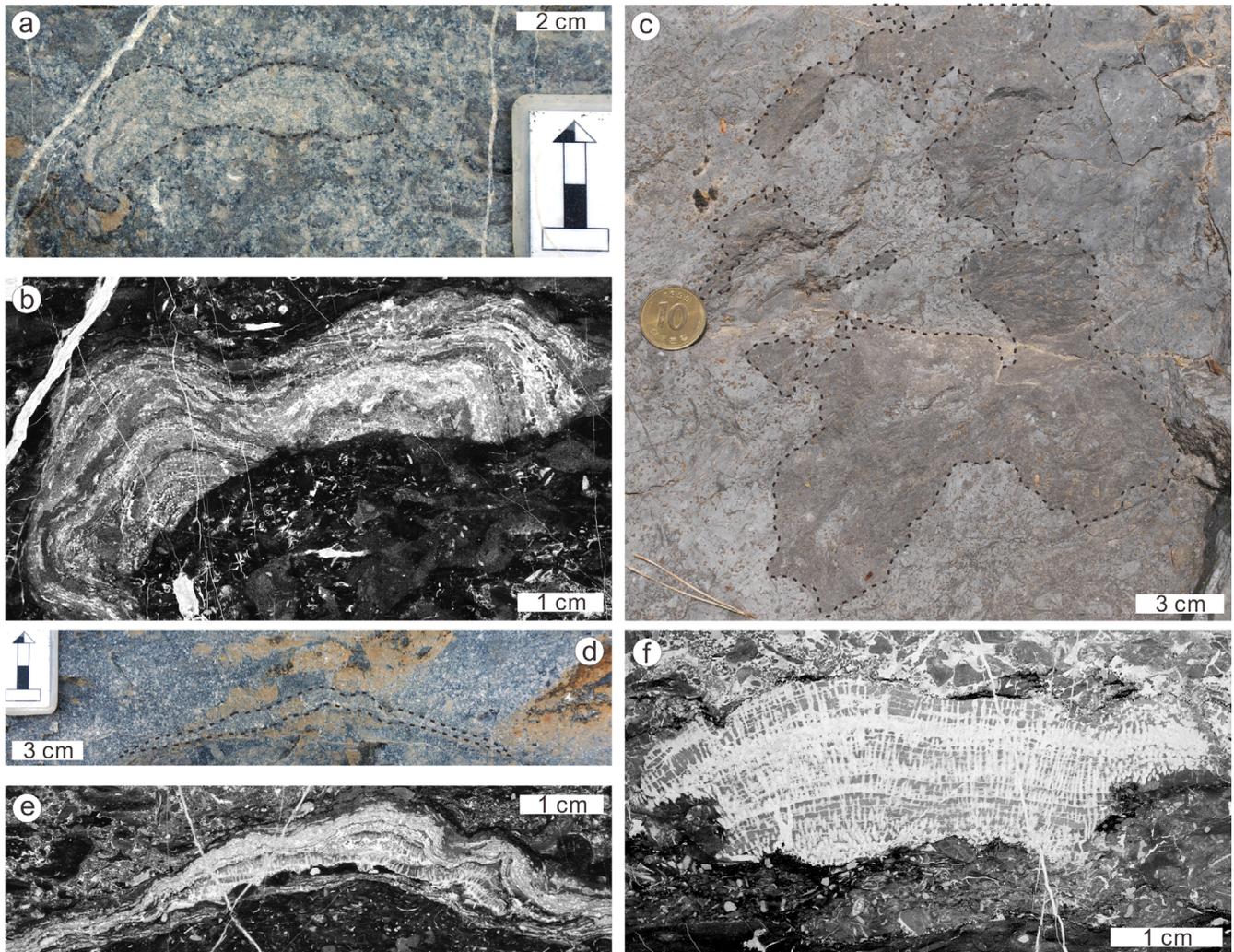


Fig. 7. (a) Photograph of low domical labechiid (dotted line) with a convex-up base (S3). (b) Photomicrograph of low domical stromatoporoid (Fig. 7a) surrounded by packstone. (c) Photograph of irregular labechiids (dotted line) within P/G facies (S10). (d) Photograph of laminar labechiid stromatoporoid (dotted line) with a convex-up base (S12). (e) Photomicrograph of laminar stromatoporoid (Fig. 7d) surrounded by packstone. (f) Photomicrograph of tabular stromatoporoid surrounded by packstone to grainstone (S8).

They would have flourished when thick succession of subtidal cycles developed, and diminished together with shallowing of the platform.

4. DISCUSSION: IMPORTANCE OF SUBSTRATE ON STROMATOPOROID DEVELOPMENT

Middle Ordovician stromatoporoids primarily occupied shallow warm water largely represented by two sub-environments: laminar, domical, and bulbous type stromatoporoids primarily formed in higher energy condition, whereas columnar and cylindrical branching stromatoporoids mainly in low energy setting (Webby, 2004). The early stromatoporoids in the Middle Ordovician appears to have developed on shallow grainy substrates. The late Early to early Middle Ordovician laminar to massive pulchrilaminids *Pulchrilamina* and *Zondarella*

formed reefs of South China, Laurentia, and Precordillera (Toomey and Ham, 1967; Keller and Flügel, 1996; Adachi et al., 2012). The reefs are typically underlain and surrounded by packstone to grainstone (Adachi et al., 2012) or grainstone (Toomey and Ham, 1967; Keller and Flügel, 1996), indicating a preferential development in higher energy grainy substrate conditions. The late Middle Ordovician labechiids have mostly been described as benthic encruster or reef builders of shallow, moderate to high-energy conditions. Early labechiid *Pseudostyloclytion lamottense* (Rosenellidae) of the Day Point and lower Crown Point formations, northeastern USA, initiated as laminar form and often grew to high domical shape embedded in packstone to grainstone (Kapp, 1974; Kapp and Stearn, 1975). Similarly, reef mounds of the Crown Point Formation consist of framework composed of laminar *Pachystylostroma* (Stylostromatidae) and *Labechia* (Labechiidae)

surrounded by grainy calcarenite (Kapp, 1974; Kapp and Stearn, 1975). The laminar encrusting *Cystostroma* (Rosenellidae) of the Duwibong Formation in the Korean Peninsula also formed bulbous to rounded frameworks, initiated on packstone to grainstone substrate (Oh et al., 2015).

During the Late Ordovician, however, stromatoporoids appeared to have expanded toward the lower energy muddy substrates, while retaining their dominance on high energy grainy substrates. Accordingly, laminar to domical labechiids (e.g., *Labechia*, *Labechiella* and *Stratodictyon*) developed in reefs surrounded by packstone to grainstone (Webby et al., 1997; Nestor, 1999; Batten Hender and Dix, 2006). Other laminar to domical rosenellids (e.g., *Rosenella*, *Cystostroma*, *Pseudostylodictyon*) and stylostromatids (e.g., *Pachystylostroma*, *Stylostroma*) occur in wackestone to grainstone substrates and reefs surrounded by wackestone to packstone (Kano and Fujishiro, 1997; Webby et al., 1997; Nestor, 1999; Nestor et al., 2010). Columnar to branching form labechiids (e.g., aulaceratid) mainly occurred in low-energy substrates (e.g., Kano and Fujishiro, 1997; Webby et al., 1997; Webby, 2004). Laminar to domical form *Stromatocerium* of family Stromatoceriidae (labechiid), which first appeared in the Late Ordovician (Sandbian) (Nestor and Webby, 2013), formed in argillaceous wackestone to packstone (Nestor, 1999), or lime mudstone to wackestone (Walker, 1972).

The late Middle Ordovician labechiids in the Yeongheung Formation mark the very beginning of 90 My domination of shallow carbonate environments by stromatoporoids. The laminar to domical labechiids on packstone to grainstone substrates with diverse marine invertebrates are interpreted to have inhabited shallow subtidal, normal marine environments (Fig. 6). It is speculated that laminar skeletal form and encrusting habit of the early labechiid stromatoporoids were advantageous for adaptation on grainy substrates of shallow, higher energy environments. Taken together with the examples of the Chazy Group of eastern North America, these early labechiids initially developed on grainy substrates of moderate- to high-energy shallow marine environments, which conforms to the previous notion that the Middle Ordovician stromatoporoids primarily formed in warm, shallow, well-circulated conditions suggested by Webby (2004). Absence of hardground and hardground-encrusting stromatoporoids in the Yeongheung Formation suggests that hard substrate was not necessary for the development of early stromatoporoids.

5. CONCLUSIONS

1. The Yeongheung Formation in the Namgyo section comprises five depositional facies: lime mudstone to wackestone (LM/W), peloidal, intraclastic, and bioclastic packstone to

grainstone (P/G), laminated dolomitic lime mudstone (LMdl), algal laminite (La), and oolitic packstone to grainstone (P/Go), representing deposition in shallow carbonate ramp under arid climate.

2. Three types of shallowing upward depositional cycles, which are subtidal, subtidal-peritidal, and peritidal cycles, are identified. Their overall thickening and thinning trend indicates progradation followed by retrogradation of the ramp.

3. Laminar to domical labechiid stromatoporoids (*Labechia* and *Labechiella*) occur in 16 horizons of the Yeongheung Formation, exclusively within the P/G facies. It is interpreted that the early stromatoporoids including the Yeongheung examples developed on grainy substrates of moderate- to high-energy environments, conforming to patterns of incipient settlement of early sessile metazoans.

ACKNOWLEDGMENTS

We thank two anonymous reviewers for detailed and constructive comments that significantly improved the manuscript. We are grateful to Sung Kwun Chough (Seoul National University) for helpful comments on early version of the manuscript. We also thank H.-J. Cho and J. Jeon of Andong National University for their assistance in the field and thin section preparation. This study was supported by Korea University Grant to J. Hong and grants by National Research Foundation of Korea to JHL (2016R1C1B1012104), SJC (2015R1A2A2A01007063) and DJL (2013R1A2A2A01067612).

REFERENCES

- Adachi, N., Liu, J., and Ezaki, Y., 2012, Early Ordovician stromatoporoid *Pulchrilamina spinosa* from South China: Geobiological significance and implications for the early development of skeletal-dominated reefs. *Paleontological Research*, 16, 59–69.
- Aigner, T., 1985, Storm depositional systems: dynamic stratigraphy in Modern and ancient shallow-marine sequences. *Lecture Notes in Earth Sciences* 3, Springer-Verlag, Berlin, 174 p.
- Alsharhan, A.S. and Kendall, C.G.St.C., 2003, Holocene coastal carbonates and evaporites of the southern Arabian Gulf and their ancient analogues. *Earth-Science Reviews*, 61, 191–243.
- Batten Hender, K.L. and Dix, G.R., 2006, Facies, geometry and geological significance of Late Ordovician (early Caradocian) coral bioherms: Lourdes Formation, western Newfoundland. *Sedimentology*, 53, 1361–1379.
- Brookfield, M.E. and Brett, C.E., 1988, Paleoenvironments of the Middle Ordovician (Upper Caradocian) Trenton limestones of southern Ontario, Canada: Storm sedimentation on a shoal-basin shelf model. *Sedimentary Geology*, 57, 75–105.
- Burchette, T.P. and Wright, V.P., 1992, Carbonate ramp depositional systems. *Sedimentary Geology*, 79, 3–57.
- Choi, D.K., 1998, The Yongwol Group (Cambrian-Ordovician) rede-

- fined: a proposal for the stratigraphic nomenclature of the Choson Supergroup. *Geosciences Journal*, 2, 220–234.
- Choi, D.K. and Chough, S.K., 2005, The Cambrian-Ordovician stratigraphy of the Taebaeksan Basin, Korea: a review. *Geosciences Journal*, 9, 187–214.
- Choi, S.J. and Woo, K.S., 1993, Depositional environment of the Ordovician Yeongheung Formation near Machari area, Yeongweol, Kangweondo, Korea. *Journal of the Geological Society of Korea*, 29, 375–386.
- Chough, S.K., 2013, *Geology and sedimentology of the Korean Peninsula*. Elsevier, Amsterdam, 363 p.
- Copper, P., 2002, Silurian and Devonian reefs: 80 million years of global greenhouse between two ice ages. In: Kiessling, W., Flügel, E., and Golonka, J. (eds.), *Phanerozoic reef patterns*. SEPM Special Publication, 72, p. 181–238.
- Demicco, R.V., 1983, Wavy and lenticular-bedded carbonate ribbon rocks of the upper Cambrian Conococheague Limestone, Central Appalachians. *Journal of Sedimentary Petrology*, 53, 1121–1132.
- Demicco, R.V. and Hardie, L.A., 1994, Sedimentary structures and early diagenetic features of shallow marine carbonate deposits. *SEPM Atlas Series No. 1*, Tulsa, 265 p.
- Flügel, E., 2004, *Microfacies of carbonate rocks: analysis, interpretation and application*. Springer, Berlin, 976 p.
- Folk, R.L., 1987, Detection of organic matter in thin-sections of carbonate rocks using a white card. *Sedimentary Geology*, 54, 193–200.
- Hong, J., Choh, S.-J., Park, J., and Lee, D.-J., 2017, Construction of the earliest stromatoporoid framework: Labechiid reefs from the Middle Ordovician of Korea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 470, 54–62.
- Jeon, J., Park, J., Choh, S.-J., and Lee, D.-J., 2017, Early labechiid stromatoporoids of the Yeongheung Formation (Middle Ordovician), Yeongwol Group, mideastern Korean Peninsula: Part II. Systematic paleontology and paleogeographic implications. *Geosciences Journal*, 21, 331–340.
- Jones, B., 2010, Warm-water neritic carbonates. In: James, N.P. and Dalrymple, R.W. (eds.), *Facies models 4*. Geological Association of Canada, p. 341–369.
- Kano, A. and Fujishiro, N., 1997, Facies and paleoecology of the Late Ordovician (Caradoc-Ashgill) stromatoporoid bioherms of Tasmania, Australia. *Facies*, 37, 65–84.
- Kano, A., Lee, D.-J., Choi, D.K., and Yoo, C.-M., 1994, Ordovician (Llanvirnian) stromatoporoids from the Youngwol Area, southern Korea. *Transactions and Proceedings of the Palaeontological Society of Japan New Series*, 174, 449–457.
- Kapp, U.S., 1974, Mode of growth of middle Chazyan (Ordovician) stromatoporoids, Vermont. *Journal of Paleontology*, 48, 1235–1240.
- Kapp, U.S. and Stearn, C.W., 1975, Stromatoporoids of the Chazy Group (Middle Ordovician), Lake Champlain, Vermont and New York. *Journal of Paleontology*, 49, 163–186.
- Keller, M. and Flügel, E., 1996, Early Ordovician reefs from Argentina: stromatoporoid vs stromatolite origin. *Facies*, 34, 177–192.
- Kershaw, S., 1998, The applications of stromatoporoid palaeobiology in palaeoenvironmental analysis. *Palaeontology*, 41, 509–544.
- Kershaw, S. and Brunton, F.R., 1999, Palaeozoic stromatoporoid taphonomy: ecologic and environmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 149, 313–328.
- Kim, Y.-H., Rhee, C.W., Woo, J., and Park, T.-Y., 2014, Depositional systems of the Lower Ordovician Mungok Formation in Yeongwol, Korea: implications for the carbonate ramp facies development. *Geosciences Journal*, 18, 397–417.
- Kobayashi, T., 1966, Stratigraphy of the Chosen Group in Korea and South Manchuria and its relation to the Cambro-Ordovician formations of other areas, Section A, The Chosen Group of South Korea. *Journal of the Faculty Science, University of Tokyo, Section II*, 16, 1–84.
- Lee, D.-J. and Yu, C.M., 1993, Middle Ordovician stromatoporoids from the Yeongheung Formation and its biostratigraphic implications. *Journal of the Paleontological Society of Korea*, 9, 131–142. (in Korean with English abstract)
- Lee, H.-Y., 1979, A study on biostratigraphy and bioprovince of the Middle Ordovician conodonts from South Korea. *Journal of the Geological Society of Korea*, 15, 37–60.
- Leinfelder, R.R., Schlagintweit, F., Werner, W., Ebli, O., Nose, M., Schmid, D.U., and Hughes, G.W., 2005, Significance of stromatoporoids in Jurassic reefs and carbonate platforms – concepts and implications. *Facies*, 51, 287–325.
- Liang, C., Friedman, G.M., and Zheng, Z., 1993, Carbonate storm deposits (tempestites) of middle to upper Cambrian age in the Helan Mountains, northwest China. *Carbonates and Evaporites*, 8, 181–190.
- Matthew, A.J., Woods, A.J., and Oliver, C., 1991, Spots before the eyes: new comparison charts for visual percentage estimation in archaeological material. In: Middleton, A. and Freestone, I. (eds.), *Recent developments in ceramic petrology*. British Museum Occasional Paper 81, British Museum, London, p. 211–264.
- Nestor, H., 1999, Community structure and succession of Baltoscandian early Paleozoic stromatoporoids. *Proceedings of the Estonian Academy of Sciences*, 48, 123–138.
- Nestor, H. and Webby, B.D., 2013, Biogeography of the Ordovician and Silurian stromatoporoida. In: Harper, D.A.T. and Servais, T. (eds.), *Early Palaeozoic biogeography and palaeogeography*. Geological Society of London Memoir, 38, p. 67–79.
- Nestor, H., Copper, P., and Stock, C., 2010, Late Ordovician and Early Silurian stromatoporoid sponges from Anticosti Island, Eastern Canada: Crossing the O/S mass extinction boundary. *NRC Research Press, Ottawa*, 163 p.
- Oh, J.-R., Choh, S.-J., and Lee, D.-J., 2015, First report of *Cystostroma* (Stromatoporoida; Ordovician) from Sino-Korean Craton. *Geosciences Journal*, 19, 25–31.
- Park, J., Lee, J.-H., Hong, J., Choh, S.-J., Lee, D.-C., and Lee, D.-J., 2015, An Upper Ordovician sponge-bearing micritic limestone and implication for early Palaeozoic carbonate successions. *Sedimentary Geology*, 319, 124–133.
- Pratt, B.R., 2002, Tepees in peritidal carbonates: origin via earthquake-induced deformation, with example from the Middle Cambrian of western Canada. *Sedimentary Geology*, 153, 57–64.
- Pratt, B.R., 2010, Peritidal carbonates. In: James, N.P. and Dalrymple, R.W. (eds.), *Facies models 4*. Geological Association of Canada, p. 401–420.
- Pratt, B.R. and James, N.P., 1986, The St George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbon-

- ate sedimentation in shallow epeiric seas. *Sedimentology*, 33, 313–343.
- Pratt, B.R., Raviolo, M.M., and Bordonaro, O.L., 2012, Carbonate platform dominated by peloidal sands: Lower Ordovician La Silla Formation of the eastern Precordillera, San Juan, Argentina. *Sedimentology*, 59, 843–866.
- Riding, R., 2000, Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. *Sedimentology*, 47, 179–214.
- Selden, P. A., 2015, *Treatise on Invertebrate Paleontology. Part E (Revised), Porifera, Vol. 4–5, Hypercalcified Porifera*. The University of Kansas Paleontological Institute, Lawrence, Kansas, 1223 p.
- Stearn, C.W., Webby, B.D., Nestor, H., and Stock, C.W., 1999, Revised classification and terminology of Palaeozoic stromatoporoids. *Acta Palaeontologica Polonica*, 44, 1–70.
- Toomey, D.F. and Ham, W. E., 1967, *Pulchrilamina*, a new mound-building organisms from Lower Ordovician rocks of west Texas and southern Oklahoma. *Journal of Paleontology*, 41, 981–987.
- Walker, K.R., 1972, Community ecology of the Middle Ordovician Black River Group of New York State. *Geological Society of America Bulletin*, 83, 2499–2524.
- Webby, B.D., 2002, Patterns of Ordovician reef development. In: Kiessling, W., Flügel, E., and Golonka, J. (eds.), *Phanerozoic reef patterns*. SEPM Special Publication, 72, p. 129–179.
- Webby, B.D., 2004, Stromatoporoids. In: Webby, B.D., Paris, F., Droser, M.L., and Percival, I.G. (eds.), *The great Ordovician biodiversification event*. Columbia University Press, New York, p. 112–118.
- Webby, B.D., Zhen, Y.Y., and Percival, I.G., 1997, Ordovician coral- and sponge-bearing associations: distribution and significance in volcanic island shelf to slope habitats, Eastern Australia. *Boletín de la Real Sociedad Española de Historia Natural, Sección Geológica*, 92, 163–175.
- Woo, K.S. and Choi, S.J., 1993, Diagenetic histories of the Yeongheung Formation near Machari area, Yeongweol, Kangweondo, Korea. *Journal of the Geological Society of Korea*, 29, 450–463.
- Yabe, H. and Sugiyama, T., 1930, On some Ordovician stromatoporoids from south Manchuria, North China and Choseon (Corea), with notes on two new European forms. *Tohoku University Science Report Series*, 2, 47–62.
- Yoo, C.M. and Lee, Y.I., 1997, Depositional cyclicity of the Middle Ordovician Yeongheung Formation, Korea. *Carbonate and Evaporites*, 12, 192–203.
- Yoo, C.M. and Lee, Y.I., 1998, Origin and modification of early dolomites in cyclic shallow platform carbonates, Yeongheung Formation (middle Ordovician), Korea. *Sedimentary Geology*, 118, 141–157.