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Depositional systems of the Lower Ordovician Mungok Formation in Yeongwol, Korea: implications for the carbonate ramp facies development

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ABSTRACT: Detailed study on the Lower Ordovician Mungok Formation in the mideastern part of the Korean peninsula has led to recognition of seven lithofacies which can be grouped into seven facies associations (FAs): FA1 (*lagoon*), FA2 (*shoal*), FA3 (*shoreface*), FA4 (*inner to mid-ramp*), FA5 (*inner to outer ramp*), FA6 (*mid- to outer ramp*), and FA7 (*outer ramp*). Spatio-temporal organization of the FAs represents homoclinal ramp environments with fringing ooid-peloid shoals. Correlation and lateral thickness variation of the FAs suggest that deep part of the basin might have been located toward the northern part of the study area. The relative sea-level curve inferred from the facies analysis suggests that the Mungok Formation evolved through three depositional stages in accordance with 3rd-order sea-level change. The organization of the facies succession indicates that the inner ramp facies associations (FA1 to 3) of the Mungok Formation are characterized by non-cyclic facies succession whereas the mid- and outer ramp facies associations (FA 4 to 7) have distinct cyclicity except non-cyclic FA 7. The difference in the facies successions between the inner ramp and the mid- to outer ramp area may result from the various depositional regime across a ramp. A non-cyclic facies successions of inner ramp facies (e.g., packstone to grainstone and lime mudstone) are suggestive of mosaic-type distribution that is controlled mostly by wave, storms, tides, currents, and local geomorphology. In contrast, cyclic facies successions (e.g., pebbly limestone conglomerate, limestone-shale alternation, and calcareous shale) represent a simple belt-type distribution of mid- to outer ramp facies that seems to reflect shifts of facies belt caused by sea-level changes. The partitioning of inner and mid- to outer ramp facies is appropriate for understanding the facies development of the Mungok Formation and similar ramp successions with distinct inner and mid- to outer ramp facies.

Key words: carbonate ramps, facies distribution, Lower Ordovician, Taebaeksan Basin, Mungok Formation

1. INTRODUCTION

Since the introduction of the carbonate ramp as a distinct type of a carbonate platform (Ahr, 1973), the ramp facies model has been well established to comprise tripartite facies belts reflecting varying degrees of wave influence on the gently sloping seafloor (Read, 1982; 1985). The three facies belts are inner, mid-, and outer ramps, the boundaries of which are defined by fair-weather wave base (FWWB) and storm wave base (SWB). The FWWB and SWB are key horizons for the subdivision in that wave regime and the resultant facies in a ramp setting change significantly across the boundaries. This wave-predominance concept was repeatedly introduced in the text books (e.g., Tucker and Wright, 1990; Reading, 1996; James and Dalrymple, 2010) and research papers (e.g., Jones and Desrochers, 1992; Somerville and Strogen, 1992; Handford and Loucks, 1993; Pomar, 2001).

In the inner ramp, sedimentation is controlled by a very complex interplay of wave, current, tide, biogenic processes, and pattern of siliciclastic input, rather than a single dominant process of wave (Burchette and Wright, 1992). Thus, the carbonate ramp facies models (Read, 1985) have been grouped according to characteristics of the inner ramp facies, the diversity of which have been reported from the modern ramps, e.g., Arabian Gulf (Purser, 1973; Kirkham and Twombley, 1994; Bosence and Wilson, 2003; Purkis and Riegl, 2005) and northwestern Australia (Read, 1985; James et al., 2005). Detailed facies analyses on superb exposures of ancient successions have also reported the lateral and stratigraphic heterogeneity of the shallow inner ramp facies which represent the interplay of several depositional processes (e.g., Brigaud et al., 2009; Bádenas et al., 2010; Amour et al., 2012). By contrast, facies and resultant stratigraphy below the FWWB are rather simple, with storm deposits decreasing gradually toward the basin. As such, Burchette and Wright (1992) described the mid- and outer ramp as a zone with "frequent storm reworking" and a zone with "infrequent storm reworking", respectively. Notwithstanding such a simple facies control, mid- and outer ramps can produce a variety of facies if topographic relief develops due to either offshore bioherms, truncation hollows (Phelps et al., 2008), or large-scale bedforms that migrated from the shallower part of the ramp (Puga-Bernabéu et al., 2009).

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The Lower Ordovician Mungok Formation is a ca. 200 m thick mixed siliciclastic-carbonate succession of the Yeongwol Group deposited in the Taebaeksan Basin, Korea (Choi and Chough, 2005). The depositional setting of the formation has been variously interpreted as a carbonate platform with ooid shoals (Paik et al., 1991), subtidal ramp (Choi and Lee, 2001), and carbonate shelf (Kim and Choi, 2002). These diverse interpretations resulted from scanty primary sedimentary structures of the formation and limited areal coverage of the exposed outcrops relative to the scale of whole platform. In order to delineate the depositional setting of the Mungok Formation, we carried out systematic facies analysis based on detailed description, mapping, and correlation of strata exposed to the west of the previously studied areas. The facies analysis of the Mungok Formation also stresses the facies contrast of inner ramp and mid- to outer ramp. Based on the result of the Mungok Formation, the spatio-temporal difference in development of ramp facies due to the complex interplay of various depositional processes on a ramp was discussed.

2. GEOLOGICAL SETTING

The Joseon Supergroup of the Taebaeksan Basin is represented by lower Paleozoic sedimentary rocks interpreted to have formed in mixed siliciclastic-carbonate marine environments that are located in the mid-eastern part of the Korean peninsula (Fig. 1) (Chough et al., 2000). The succession is composed dominantly of carbonate rocks with lesser amounts of sandstone and shale. The Cambro-Ordovician Joseon Supergroup rests unconformably on the Precambrian granitic gneiss and metasedimentary rocks, and is, in turn, overlain unconformably by upper Paleozoic siliciclastics (Lee and Chough, 2006). The Joseon Supergroup has been divided into the Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups, each with a unique lithologic succession and geographic distribution (Choi, 1998; Choi and Chough, 2005). The Yeongwol and Taebaek groups yield relatively diverse and abundant invertebrate fossils such as trilobites, brachiopods, graptolites, gastropods and so on, whereas other three groups are poorly fossiliferous (Kobayashi, 1966; Choi et al., 2004). The Taebaek Group has been extensively studied in terms of litho-, bio-, and sequence stratigraphy (e.g., Choi et al., 2004; Kwon et al., 2006; Kang and Choi, 2007; Lee and Choi, 2007; Sohn and Choi, 2007; Park and Choi, 2011), the Yeongwol Group mainly in terms of paleontology (e.g., Sohn and Choi, 2002; Hong et al., 2003; Choi et al., 2004). Sedimentological research of the Yeongwol Group has been limited due to the complex tectonic structures, obliterated primary structures, and scanty number of outcrops.

The Yeongwol Group is exposed in the western part of the Taebaeksan Basin and is subdivided into the Sambangsan, Machari, Wagok, Mungok, and Yeongheung formations (Figs. 1 and 2), in ascending order, which spans the Cambrian Series 3 (middle Cambrian) to the late Ordovician in age (Fig. 3)

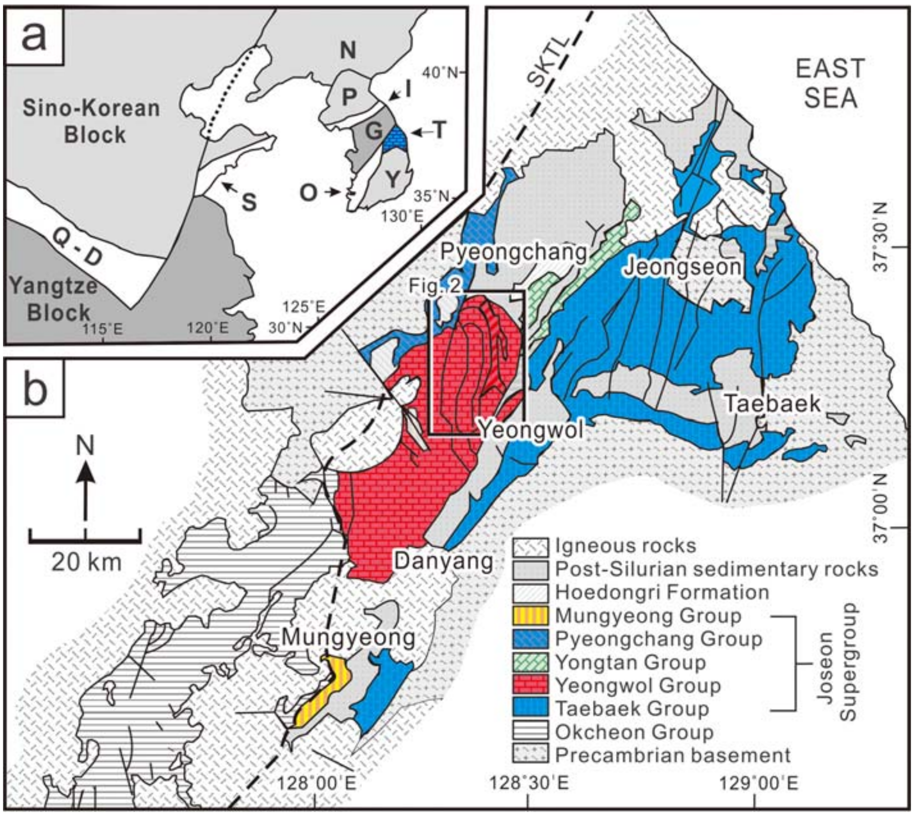

Fig. 1. (a) Tectonic division of the Korean peninsula and adjacent northeast Asia, showing the location of the Taebaeksan Basin. (I, Imjingang Belt; G, Gyeonggi Massif; N, Nangrim Massif; O, Okcheon Belt; P, Pyeongnam Basin; Q-D, Qinling-Dabie Belt; S, Sulu Belt; T, Taebaeksan Basin; Y, Yeongnam Massif). (b) Simplified geologic map of the Taebaeksan Basin (T in Fig. 1a), showing distribution of the Joseon Supergroup (SKTL, South Korean Tectonic Line) (Choi and Chough, 2005).

(Yoshimura, 1940; Kobayashi, 1966; Choi, 1998). It is composed predominantly of carbonate sediments except for the Sambangsan Formation which consists exclusively of siliciclastic sediments. The present occurrence of the Yeongwol Group is characterized by an imbricated stack of westward dipping thrust sheets and associated small-scale folds, forming an N-S to NW-SE trending belt-like distribution of strata (Fig. 2). It is bounded to the east by the Gakdong thrust, to the north by the Sangri thrust, and to the northwest by the Chonggok-Yongbongjong thrust; its southwestern boundary is not clearly defined (Kobayashi et al., 1942; Kobayashi, 1966; Choi, 1998). The thrusts are suggested to have formed during the Triassic Indosinian Orogeny (Songnim Orogeny) (Cluzel et al., 1990, 1991; Cluzel, 1992) or Jurassic Daebo Orogeny (Koh, 1995). The former event resulted in the collision of North and South China blocks and the latter in the emplacement of granites in the middle part of Korea peninsula (Chough et al., 2000).

The Mungok Formation is a ca. 200 m thick mixed carbonate-clastic succession. It has been studied in recent years in terms of depositional environments, diagenesis (dolomitization), chemostratigraphy, ichnology, and paleontology (Chung et al., 1993; Moon and Martin, 1994; Park et al., 1994; Lee and Lee, 1999; Kim and Choi, 2000; Choi and Lee, 2001;

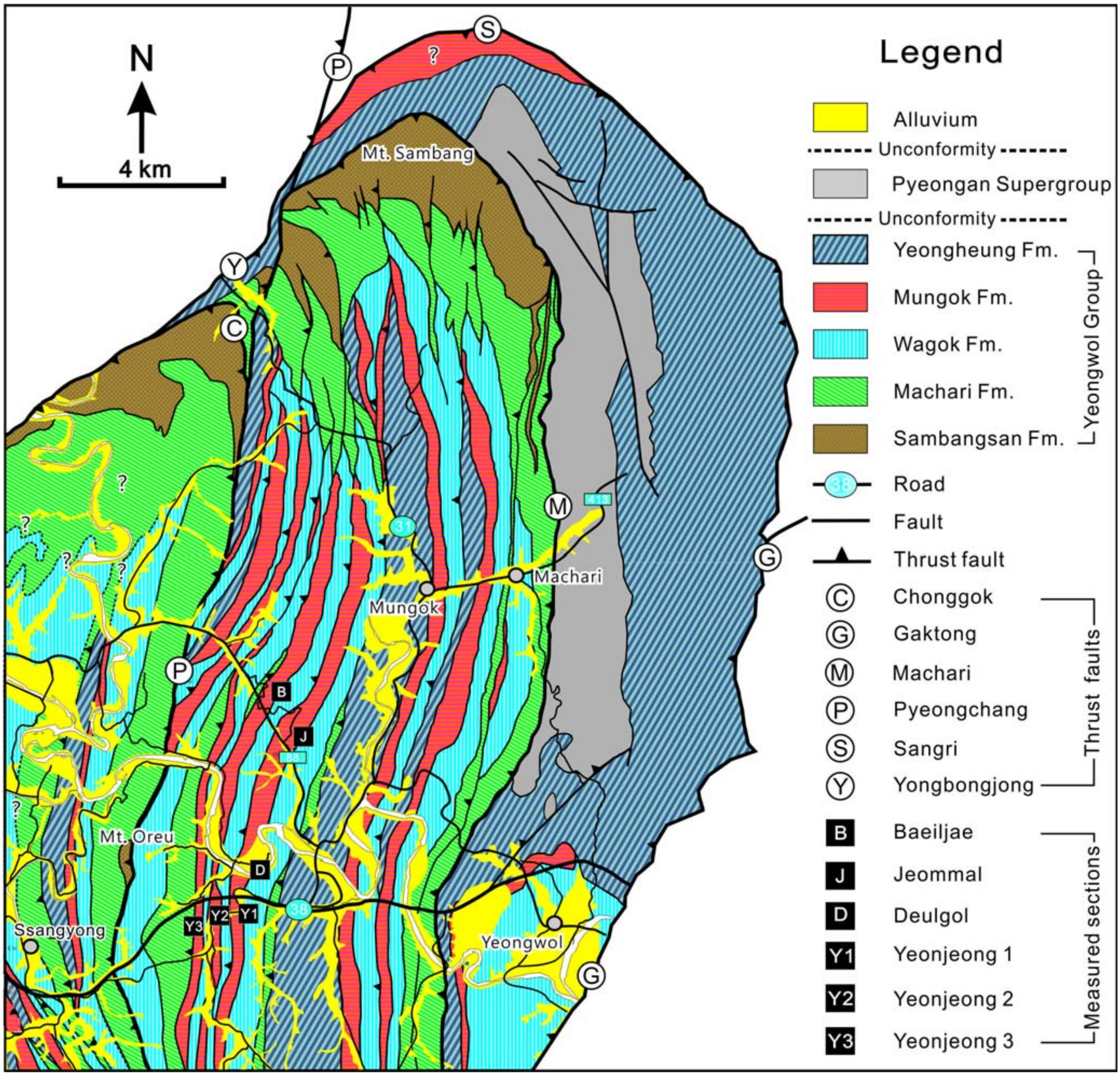

Fig. 2. Geologic map of the Yeongwol Group (modified from Lee (1995)).

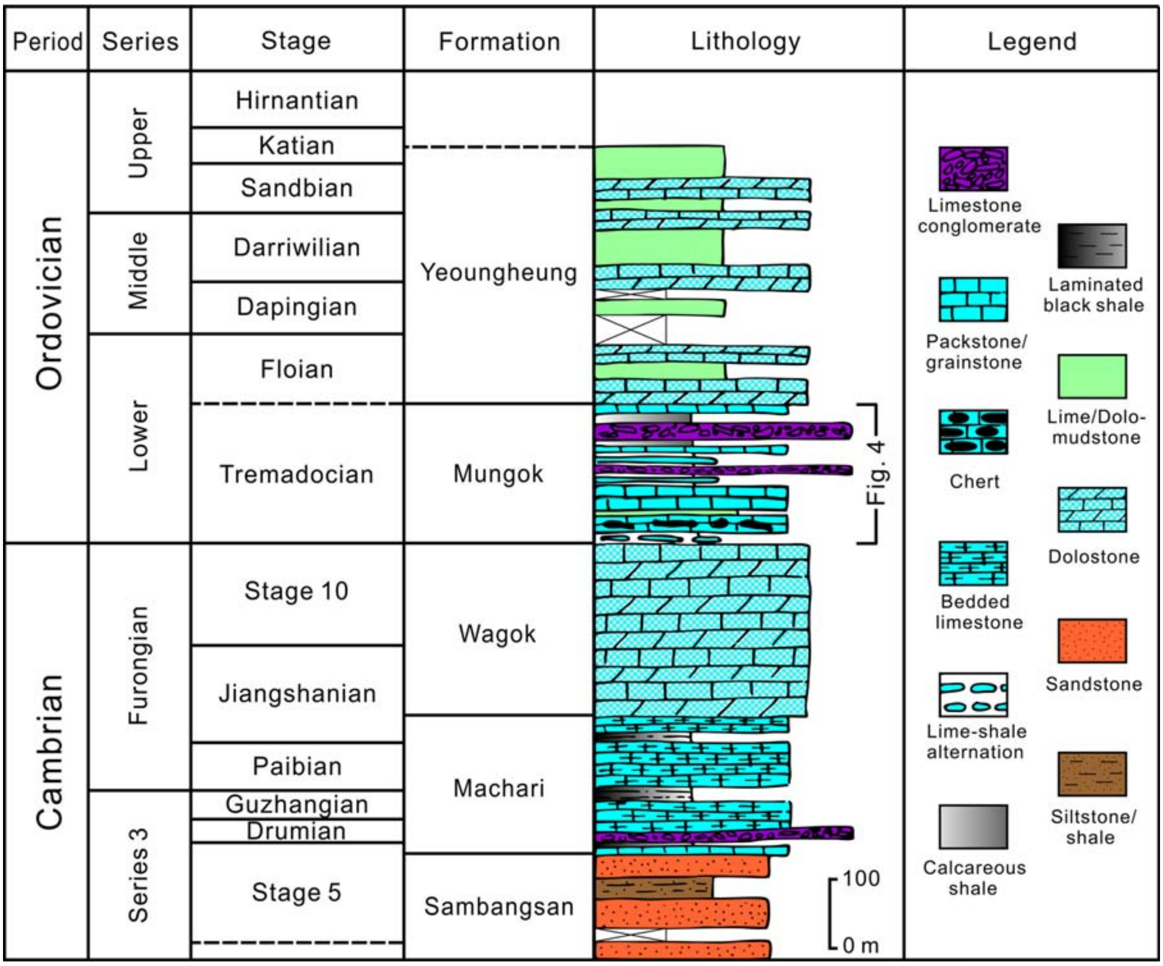

Fig. 3. Stratigraphic division and lithostratigraphic summary of the lower Paleozoic Yeongwol Group (modified from Lee (1995), Choi (1998), and Yoo and Lee (1998)).

Cho, 2007; Hong et al., 2011). Three trilobite biozones have been established within the formation: the *Yosimuraspis vulgaris*, *Kainella euryrachis*, and *Shumardia pellizzarii* zones in ascending order (Kim and Choi, 2000; Choi and Chough, 2005). The Cambro-Ordovician boundary is considered to lie at the base of the *Yosimuraspis vulgaris* Zone which is situated at the basal part of the Mungok Formation (see Choi et al., 2003). Because the Cambrian-Ordovician boundary lies within the basal part of the formation and the uppermost biozone of the Tremadoc occurs in the upper part of the formation, it is estimated that the entire Mungok Formation was deposited in ca. 10 million years (the duration of the Tremadoc) (Kim and Choi, 2000). The Mungok Formation has been divided into four lithologic members (Figs. 4 and 5): the Karam, Baeiljae, Jeommal, and Tumok members in ascending order (Kim and Choi, 2000). The four members are successively exposed only in the Baeiljae and Yeonjeong 2 sections (Fig. 6). The Karam member (45–65 m thick) is composed mainly of limestone-shale alternation, lime mudstone, and packstone to grainstone. The Baeiljae member (ca. 30 m thick) is comprised exclusively of packstone to grainstone. The Jeommal member (ca. 40 m thick) is characterized by intercalation of limestone-shale alternation and pebbly limestone conglomerate beds, and the Tumok member (ca. 65 m thick) consists of limestone-shale alternation, packstone to grainstone, pebbly limestone conglomerate, and calcareous shale facies.

3. METHODS AND FIELD APPROACH

The Mungok Formation was measured in six sections in the western part of the Yeongwol area: the Jeommal, Baeiljae, Deulgol, Yeonjeong 1 (Fig. 5), Yeonjeong 2, and Yeonjeong 3 sections. These measured sections are located in three different thrust sheets: the eastern (Jeommal, Deulgol, and Yeonjeong 1 sections), the middle (Baeiljae and Yeonjeong 2 sections), and the western thrust sheets (Yeonjeong 3 section) (Fig. 2). All studied outcrops occur along road cuts in the western part of the Yeongwol area. Thickness of the outcrops ranges from 43 m to 176 m, with a lateral extent of exposure about 1–5 m. Most sections are measured on 1:50

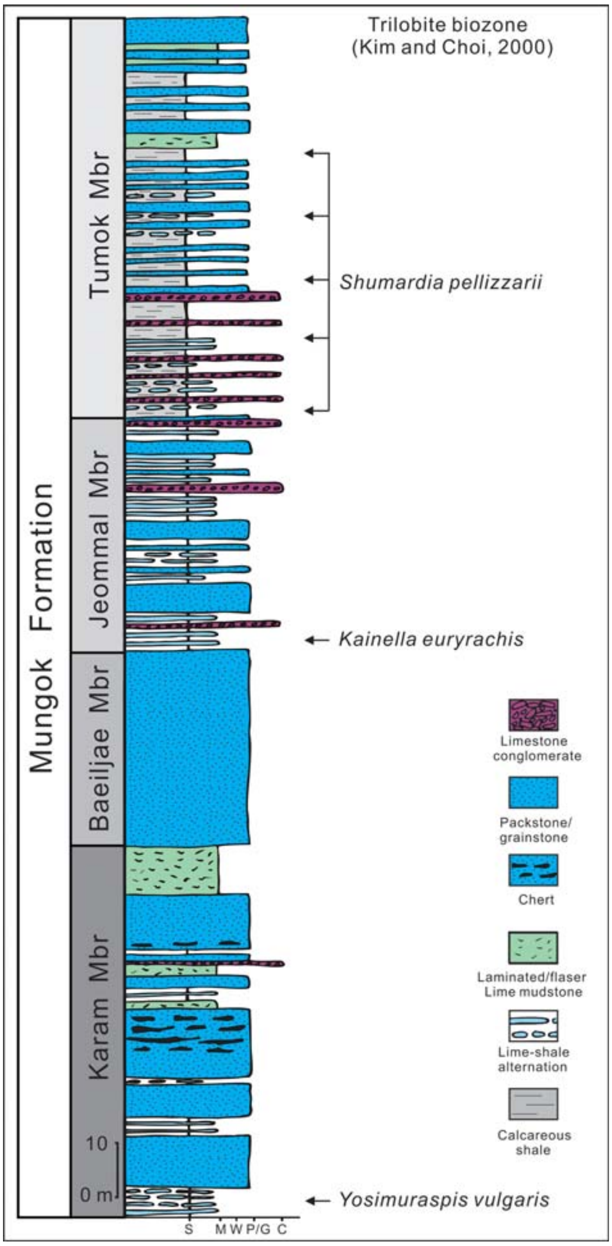

Fig. 4. Composite columnar description of the Mungok Formation in Yeongwol area. S: shale, M: lime mudstone, W: wackestone, P: packstone, G: grainstone, C: limestone conglomerate, Mbr: member.

scale with the exception of the Yeonjeong 1 section which was measured at 1:20 scale (Fig. 7) because some primary sedimentary structures were clearly recognizable in the field. A total of 621-m succession was recorded in columnar sections accompanied by photographs, line drawings, and sketches of the outcrops. Although the Yeongwol Group lost some of its primary sedimentary structure and texture during intermediate metamorphism and structural deformation, detailed petrographic observation from slabs and thin section for further information on sedimentary structures as well as allochem and matrix types were carried out in order to overcome this limitation.

4. FACIES ANALYSIS

4.1. Description and Interpretation of Facies and Facies Association

The Mungok Formation consists of seven sedimentary facies, classified mainly on lithology, grain size, composition (ratio of limestone and shale), and sedimentary structures. The classification scheme of Dunham (1962) and common descriptive facies names were used for the facies definitions. The seven sedimentary facies are pebbly limestone conglomerate (Cp), packstone to grainstone (P/G), laminated lime mudstone (LMl), flaser-bedded lime mudstone (LMf), planar limestone-shale alternation (Lp-S), nodular limestone-shale alternation (Ln-S), and calcareous shale (Sc) (Table 1) (Figs. 8, 9, and 10).

They can be classified into seven facies associations (FAs) that are indicative of constituent and dominant facies: FA 1 (LMf-dominated), FA 2 (P/G-dominated), FA 3 (P/G with argillaceous material), FA 4 (non-Sc-base to P/G-top cycle), FA 5 (Sc-base to P/G-top cycle), FA 6 (Sc-base to non-P/G top cycle), and FA 7 (shale-dominated) (Table 2). They were divided into non-cyclic versus cyclic facies groups. The non-cyclic facies groups can be classified into two types on the basis of dominant facies: limestone-dominated (FA 1 to 3) and shale-dominated (FA 7) types. The cyclic facies group is characterized by a regular repetition of the constituent facies forming a coarsening upward unit, accompanied by systematic changes in the grain size, lime mud content, and skeletal

Fig. 5. Panoramic view of the Yeonjeong 1 section showing the meter-scale coarsening-upward cycles in the upper part of the Mungok Formation. Note a thrust fault boundary between the upper part of the Mungok Formation and the overlying Wagok Formation. The outcrop is a ca. 10 m in height. See Figure 2 for location.

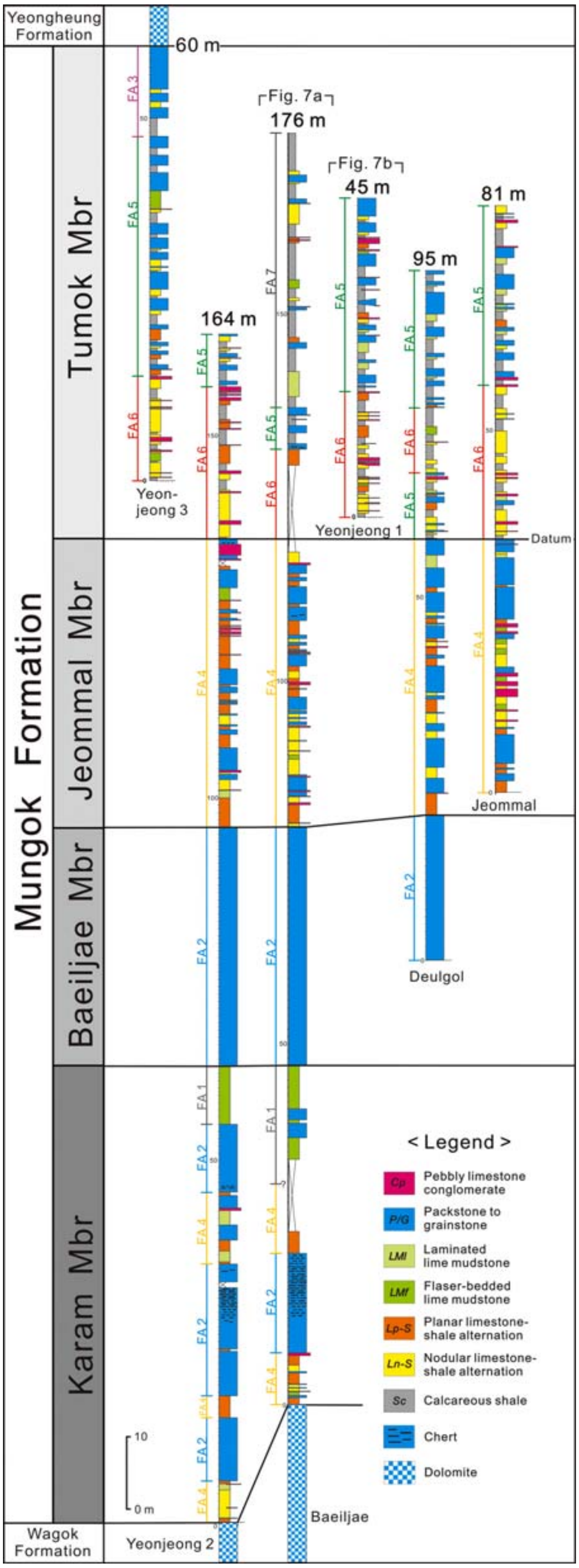

Fig. 6. Columnar description of the Mungok Formation from all measured sections. Datum is the contact between Jeommal and Tumok members, which is characterized by the first occurrence of calcareous shale (inferred at locality Yeonjeong 1 and Yeonjeong 3 sections where the contact is not exposed). See Table 2 for facies association codes.

composition. The cyclic facies group can be divided into FA 4, FA 5, and FA 6 (Table 3). The seven facies associations represent subenvironments of ramp: *lagoon* (FA 1), *shoal* (FA 2), *shoreface* (FA 3), *inner to mid-ramp* (FA 4), *inner to outer ramp* (FA 5), *mid- to outer ramp* (FA 6), and *outer ramp* (FA 7) environments (Fig. 11).

4.1.1. Facies association 1 (FA 1): Lagoon

***Description*:** Facies association 1 consists mainly of LMf and a minor amount of P/G (Fig. 11). The succession of LMf facies at the Yeonjeong 2 section is 8 m in thickness while the succession of LMf facies at the Baeiljae section is more than 10 m in thickness. The beds of LMf facies show gray lime mudstone with flaser shape argillaceous layer. The intercalated P/G beds are tabular and continuous, and 1.5–2 m in thickness. Although primary structures in the P/G facies are not clearly recognizable due to pervasive dolomitization, ghosts of peloids, bioclasts, and ooids can be recognized. Bioturbations occur in the lime mudstone layers of LMf facies. This association occurs in the uppermost part of the Karam member at the Baeiljae and Yeonjeong 2 sections. FA 1 is underlain and overlain by FA 2 (thick-bedded P/G).

***Interpretation*:** The dominance of fine-grained carbonate sediment is suggestive of deposition under low-energy conditions. Bioturbation and lack of argillaceous materials indicate shallow subtidal conditions (e.g., Srinivasan and Walker, 1993). The low-energy condition might have been formed by protection from wave and currents by basinward barriers of carbonate shoal. Intercalated P/G facies that contains ooid ghost and bioclastic allochems is probably suggestive of resedimentation under relatively high-energy conditions. It might have been formed by spill-over current of sweeping sediment from the seaward barrier (Elrick and Snider, 2002) or by winnowing during exceptionally strong storm conditions. Dominant LMf facies with intercalated P/G facies and close association with shoal deposit (FA 2) are suggestive of the deposition in a lagoonal setting (Read, 1985; Jones and Desrochers, 1992).

4.1.2. Facies association 2 (FA 2): Shoal

***Description*:** Facies association 2 comprises thick succession (more than 10 m thick) of massive or crudely bedded P/G with intercalated chert layers (Fig. 11). The P/G consists of ghosts of peloids, bioclasts, and ooids. In the Karam member, the succession of P/G facies is 12–17 m and show lateral thickness changes (about 1–2 m), however, the 30-m-thick P/G facies in the Baeiljae member shows no lateral change in thickness within the section and between the Baeiljae and Yeonjeong 2 sections. Pervasive dolomitization and stylolites prevent clear recognition of primary sedimentary structures.

***Interpretation*:** The occurrence of thick succession of P/G without intercalated fine-grained sediments are indicative of fair-weather winnowing of sediment under high-energy con-

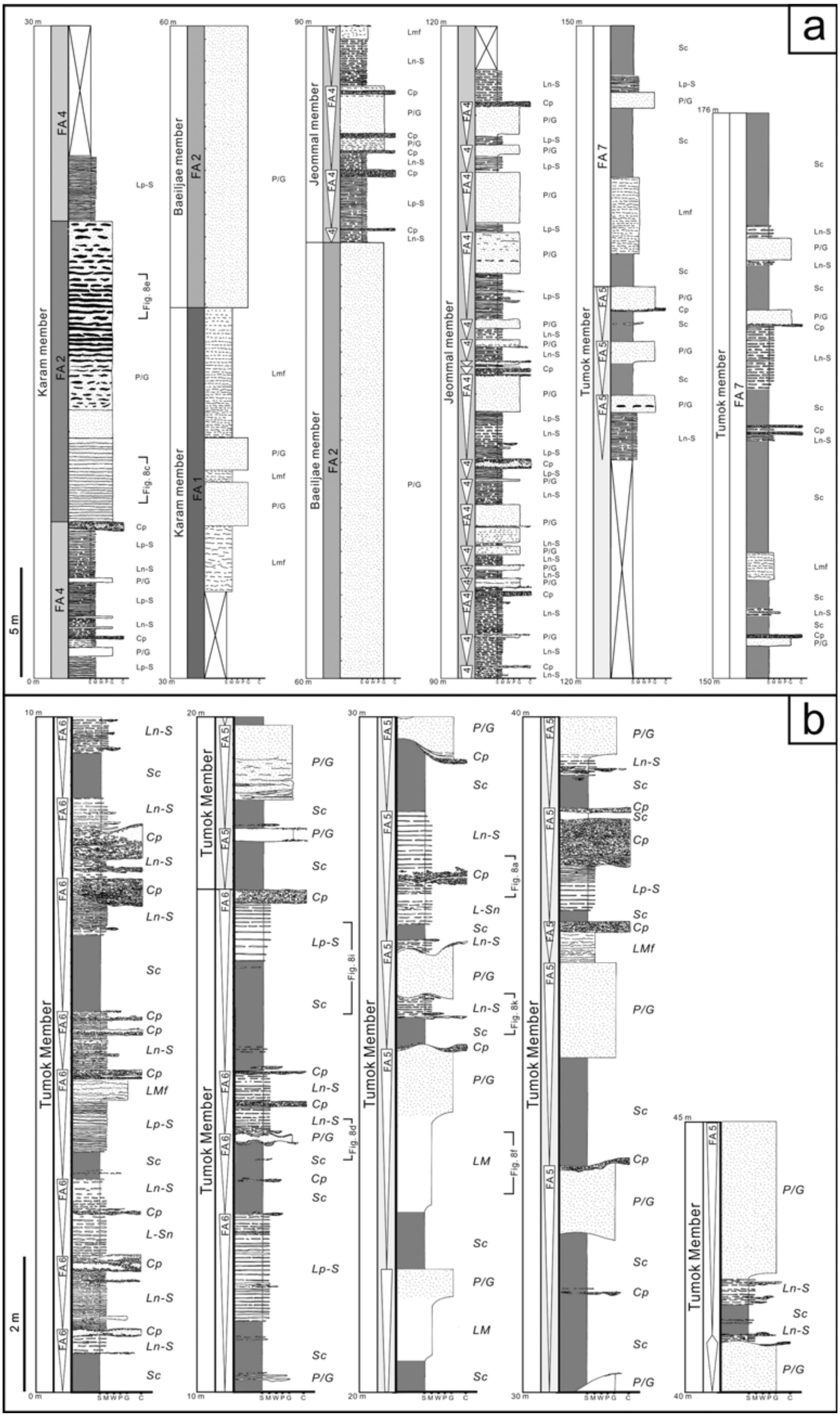

Fig. 7. Detailed columnar description of the (a) Baeilje section and (b)Yeonjeong 1 section. For facies and facies association codes, see Tables 1 and 2. For section location, see Figure 2. S: shale, M: lime mudstone, W: wackestone, P: packstone, G: grainstone, C: limestone conglomerate.

Table 1. Lithologic summary and interpretation of facies in the Mungok Formation

<table>
<tr><th colspan="2">Facies</th><th>Description</th><th>Interpretation</th></tr>
<tr><td colspan="2">Pebbly limestone conglomerate (Cp)</td><td>Flat-laying or disorganized (Figs. 8a, b, and 9c); well-rounded flat tabular, spherical, discoidal, or oval in shape clasts; poorly sorted; clast-supported; mono/oligomictic clast composed of either dark gray lime mudstone (Fig. 10a), peloidal packstone to grainstone (Fig. 10b), bioclastic wackestone to packstone (Figs. 10b and c), or reworked conglomerates (Fig. 10c); clast long axis ranges from 0.5 to 8 cm; slightly sutured clast contacts (Figs. 10b and d); matrices of bioclastic fragments and micrite with slight dolomitization (Figs. 10c, d, and e); beds of tabular continuous or centimeter-scale gutter casts; sharp or occasionally gradual base, either flat or irregular (Figs. 8a and b); capped by calcareous shale with a sharp flat boundary (Figs. 8a, b, and 9a); variable in thickness from 5 cm to 2 m</td><td>Subtidal pebbly conglomerates made by reworking (tabular geometry) and transported (gutter cast) of early-cemented (semiconsolidated) sediments by storm events (Sepkoski, 1982; Sepkoski et al., 1991; Demicco and Hardie, 1994; Kwon et al., 2002; Chen et al., 2009)</td></tr>
<tr><td colspan="2">Packstone to grainstone (P/G)</td><td>Light gray to gray in color; crudely bedded to massive (Fig. 8c); boudinage structure (Fig. 8d); rare faint parallel laminae (Fig. 9b); intercalated silt- to clay-sized argillaceous material; anastomosing structures and well developed stylolites (Fig. 9c); dolomitized peloids, bioclasts, and ooids (Figs. 10f, g, and h); matrices of dolomitized sparite and some part micrite; medium- to coarse-crystalline idiotopic mosaic (euhedral) dolomites, occasional nodular (Fig. 8e), layered, massive and/or laminated chert (Fig. 9b)</td><td>Fair-weather winnowed sediment under high-energy conditions (Ahr, 1973; Tucker, 1985; Wright, 1986; Betzler et al., 2007)</td></tr>
<tr><td rowspan="2">Lime mudstone (LM)</td><td>Crudely laminated lime mudstone (LMl)</td><td>Light gray to gray in color; alternation of gray micrite laminae and dark gray thin argillaceous laminae, crude parallel lamination, less than 5 mm in thickness of each lamina (Figs. 8f and 9d); numerous fine-crystalline dolomite rhombs; common pyrites with about 2 cm in maximum diameter</td><td>Suspension settling and/or some tractional current in low energy conditions of lagoon or subtidal environment (Steinfauff and Walker, 1995; Becker and Bechstadt, 2006)</td></tr>
<tr><td>Flaser-bedded lime mudstone (LMf)</td><td>Flaser-bedded with argillaceous layer (Fig. 8g); argillaceous layer 0.2 to a few centimeters in thickness (Fig. 9e); limestone layer consisting of lime mudstone; microstylolite swarms with scattered fine-crystalline dolomite rhombs; bioturbation; gradationally associated with Ln-S</td><td>Lagoon or subtidal sediments with some argillaceous component in low-energy condition (Wanless, 1979; Markello and Read, 1981; Shinn and Robin, 1983)</td></tr>
<tr><td rowspan="2">Limestone-shale alternation (L-S)</td><td>Planar limestone-shale alternation (Lp-S)</td><td>Rhythmic centimeter-scale alternation of light gray lime mudstone and dark gray shale layers (Figs. 8h and 9f); limestone layers 0.5 to a few centimeters in thickness and argillaceous layers 0.2 to a few centimeter in thickness; dark gray shale layer with dolomite crystals; weak bioturbation</td><td>Alternating suspension settling of carbonate and siliciclastic mud in low-energy condition (Markello and Read, 1981; Sherman et al., 2001)</td></tr>
<tr><td>Nodular limestone-shale alternation (Ln-S)</td><td>Irregular centimeter-scale alternation of gray to bluish gray nodular limestone and dark gray shale beds (Figs. 8i and 9g); limestone nodules of 0.5 to a few centimeters thick limestone nodules and thicker argillaceous layers; discoidal and ellipsoidal shapes of nodules; nodule composed of lime-micrite and lesser amount of fossil fragments; small gutter cast; bioturbation, small-scale (1 to 3 mm in diameter) vertical to horizontal burrows (Fig. 9g)</td><td>Alternating suspension settling of carbonate and siliciclastic mud in low-energy condition relatively deeper than Lp-S facies (Markello and Read, 1981; Chen et al., 2011)</td></tr>
<tr><td colspan="2">Calcareous shale (Sc)</td><td>Brownish gray to reddish gray in color; laminated and fissile calcareous shale with interlayered grainstone layers (Figs. 8k, l, and 9h); silt- to fine sand-sized quartz; centimeter-scale gutter casts (Fig. 8l); fossil fragments; good lateral continuity and highly variable in thickness, ranging from 5 cm to 2 m</td><td>Suspension settling in low-energy condition below storm wave base (O'Brien, 1996; Allison and Wright, 2005)</td></tr>
</table>

ditions (Ahr, 1973; Tucker, 1985; Wright, 1986; Betzler et al., 2007). Thick beds of P/G feature ooids, peloids, and skeletal fragments which may have originated from shoals (Tucker and Wright, 1990). The thicker succession of the FA of the Karam member at the Yeonjeong 2 section is suggestive of high carbonate productivity than that at the Baeiljae section or earlier onset and prolonged finally deposition of carbonate sand in the Yeonjeong 2 area. In the Baeiljae member, the continuous P/G beds are indicative of broad shoals.

4.1.3. Facies association 3 (FA 3): Shoreface

***Description*:** Facies association 3 consists mainly of thick beds of P/G and minor intercalated thin beds (less than 1 m thick) of L-S. Although the L-S is intercalated within the P/G, the overall FA is characterized by massive monotonous succession without cyclic appearance. About 10-m-thick FA

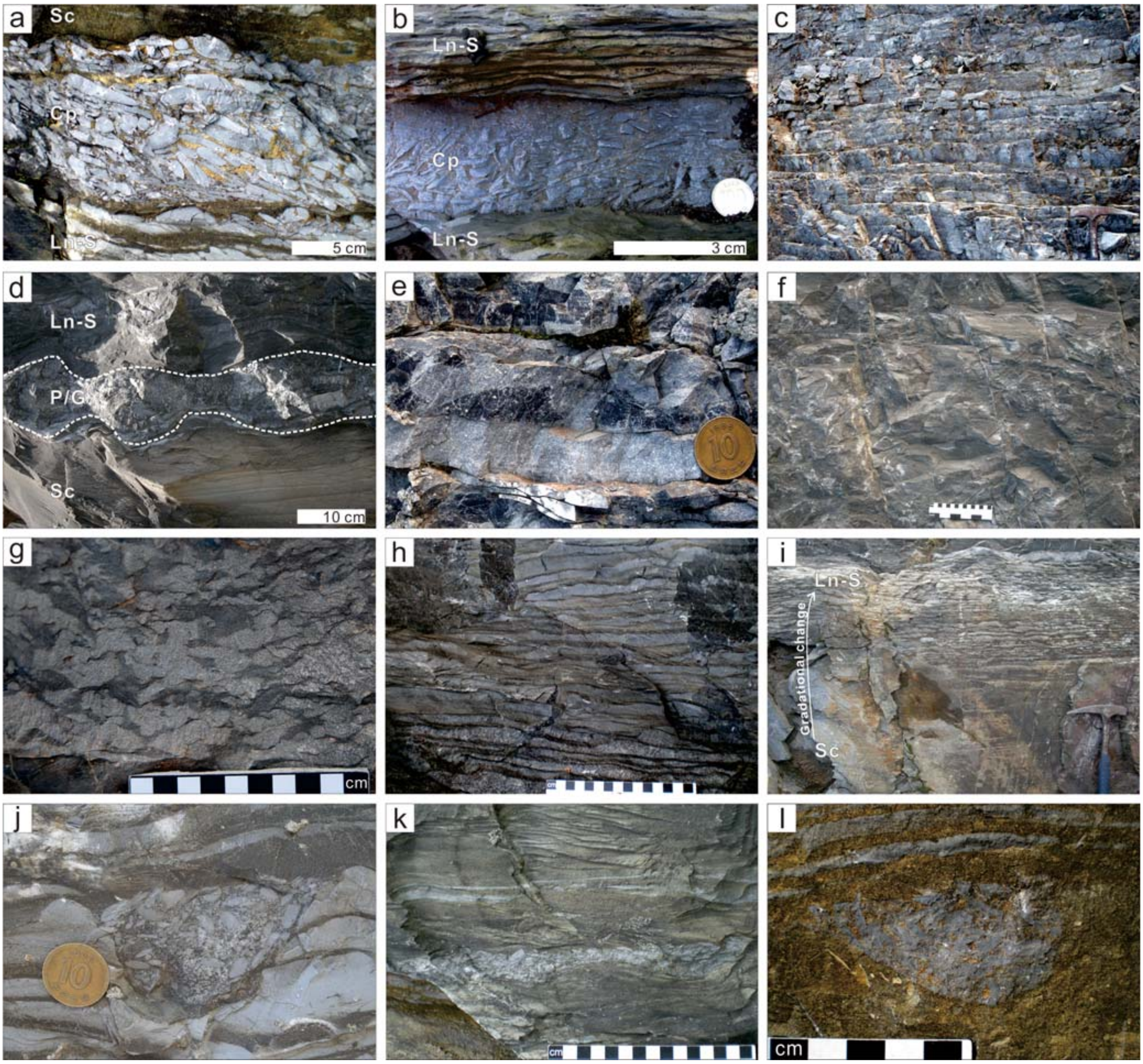

Fig. 8. Representative outcrop photographs of sedimentary facies of the Mungok Formation. (a) Pebbly limestone conglomerate with inclined clasts and gradational lower boundary. (b) Pebbly limestone conglomerate showing disorganized clasts associated with limestone-shale alternation. Coin is 2.4 cm in diameter. (c) Light gray thin-bedded packstone to grainstone. Hammer is 32.5 cm long. (d) Boudinage structure of packstone to grainstone which is structural deformation. (e) Nodular chert within packstone to grainstone. Coin is 2.2 cm in diameter. (f) Crudely laminated gray lime mudstone. Scale bar is 15 cm long. (g) Bioturbated flaser-bedded lime mudstone. (h) Planar limestone-shale alternation is characterized by centimeter-scale alternation of lime mudstone and shale layers. (i) Nodular limestone-shale alternation shows irregular centimeter-scale alternation and gradational change of calcareous shale to nodular limestone-shale alternation. Hammer is 32.5 cm long. (j) A gutter cast in nodular limestone-shale alternation which is filled by small intraclasts. (k) Calcareous shale with occasionally intercalated grainstone layer. (l) A gutter cast in calcareous shale which is filled with small intraclasts.

3 only occurs in the uppermost part of the Mungok Formation at the Yeonjeong 3 section (Fig. 11). The FA 3 is overlain by blue-gray irregular laminated dolo-mudstone of the Yeongheung Formation. Degree of dolomitization in this FA becomes higher toward the contact with the overlying Yeongheung Formation.

Interpretation: The P/G-dominated facies association was formed in shallow-water near fair-weather wave base (e.g., shoreface). Intercalated L-S is indicative of rare transgressions of the lower shoreface environments over the shoreface (Lee and Chough, 2011). The lack of discernible cyclic facies is probably indicative of aggradation-dominant stacking of strata

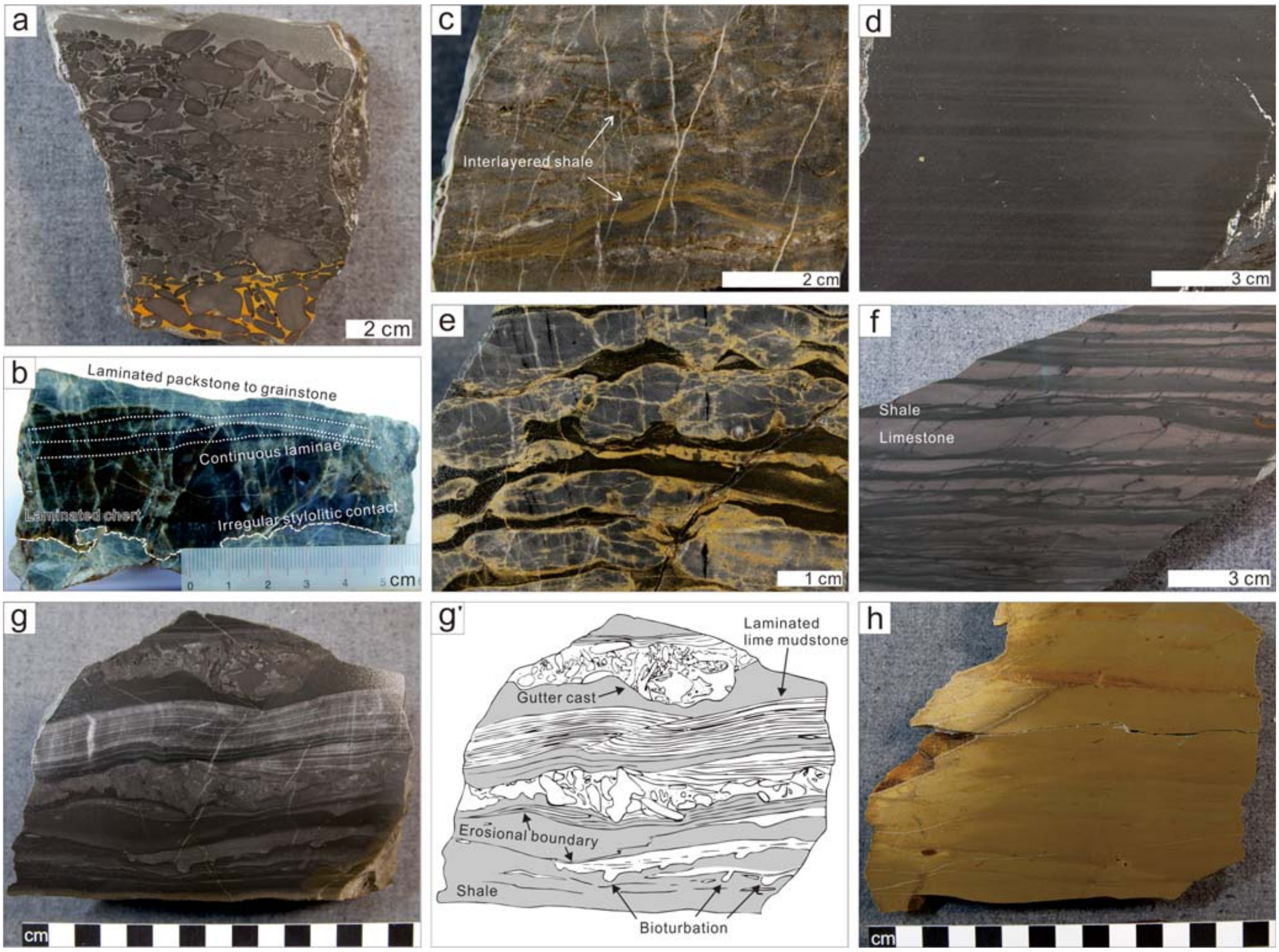

Fig. 9. Representative slab photographs of sedimentary facies of the Mungok Formation. (a) Pebbly limestone conglomerate has well rounded clasts. (b) Laminated chert layer. The laminae have good lateral continuity and cross the irregular boundary between packstone to grainstone. (c) Packstone to grainstone containing irregular-shaped shale interlayers. (d) Slab of crudely laminated lime mudstone with planar-parallel laminations. (e) Flaser-bedded lime mudstone consists of dark gray argillaceous part and gray lime mudstone part. (f) Centimeter-scale alternation of lime mudstone and shale layers of planar limestone-shale alternation facies. (g) Nodular limestone-shale alternation includes various structures such as gutter casts, erosional structures, laminated limestone layers, and bioturbations. (g') Line drawing of (g). (h) Crudely laminated calcareous shale.

which implies a high sedimentation rate on the ramp. The relationship with the underlying and overlying FAs indicates a gradual transition from outer ramp (FA 5) to inner ramp (FA 3) and to tidal-flat environments (Yeongheung Formation) without an intervening lagoonal environment (FA 1) between high-energy shoal and tidal flat facies. This also indicates the shoreface environments.

4.1.4. Facies association 4 (FA 4): Inner to mid-ramp

Description: Facies association 4 consists mainly of L-S and P/G, and minor amount of Cp and LM which is represented by meter-scale coarsening-upward cycles. It begins with a lower L-S, or LM, followed by P/G, and occasionally overlain by Cp (Table 3) (Fig. 11). The mean thickness of FA 4 cycles is 2.1 m. There is typically an increase in grain size up through a cycle. Cp facies, however, does not form the coarsest cap of the cycle but occurs within the cycles. Facies association 4 alternates with FA 2 in the lower part of the Mungok Formation. In the Karam member, the FA 4 sharply overlies light gray massive dolostone of the Wagok Formation. The upper boundaries of each cycle are relatively sharp, whereas the vertical facies changes within a cycle are gradational. FA 4 in the Karam member is overlain by FA 2, while that of the Jeommal member is overlain by FA 6 of the lower part of Tummok member.

Interpretation: Similar meter-scale coarsening-upward cycles are reported from peritidal and shallow subtidal environments (Paik, 1987; Woo, 1999; Hamon and Merzeraud, 2008). The predominance of subtidal facies and lack of inter-, supratidal facies caps, and shale are suggestive of a shallow subtidal

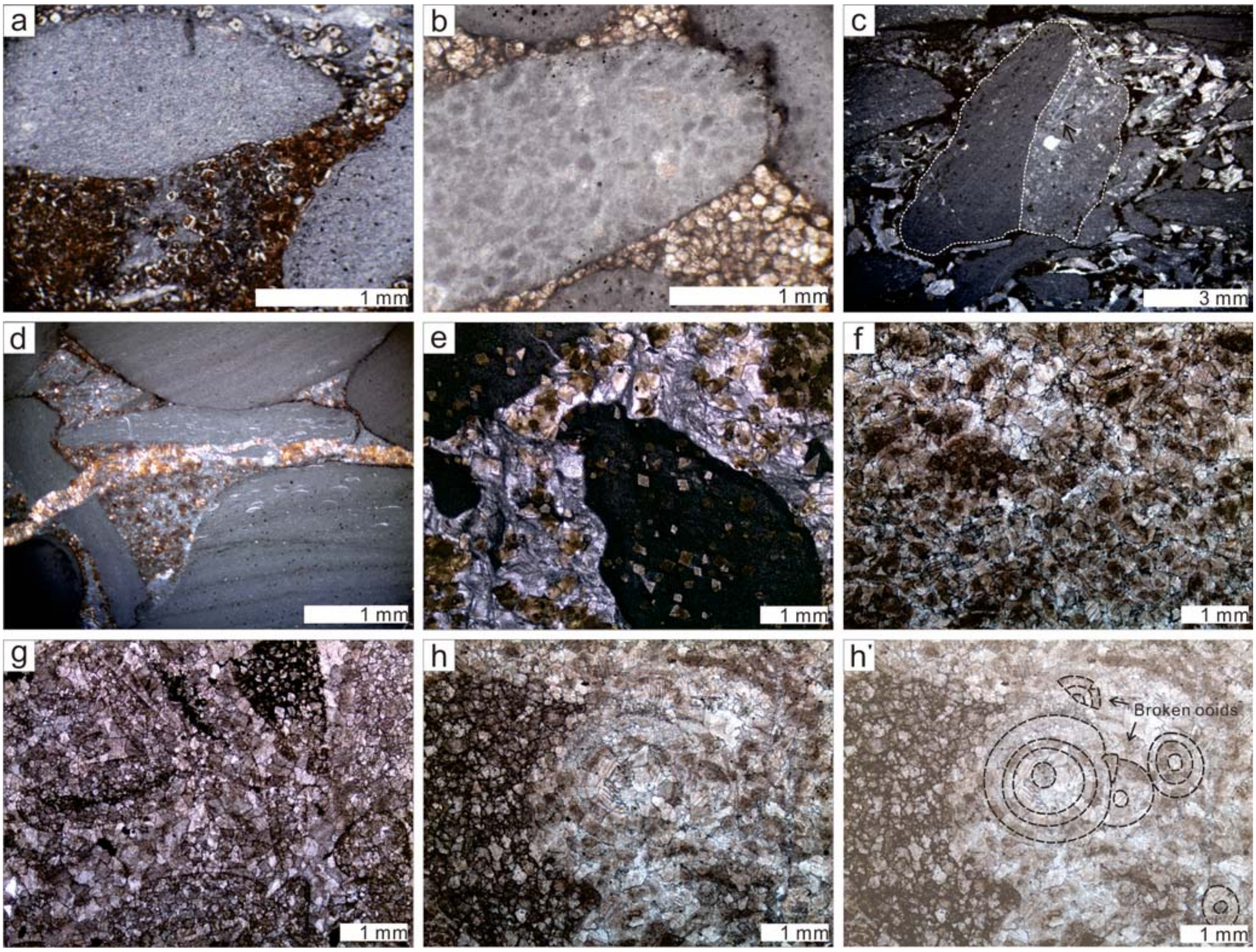

Fig. 10. Photomicrographs of sedimentary facies of the Mungok Formation. (a–e) various clasts and matrices of pebbly limestone conglomerate. (a) Micritic clasts and recrystallized dolomitic matrix in pebbly limestone conglomerate. (b) Peloidal clasts are sutured each other in their contact. (c) Reworked clast showing a hook-shaped trilobite fragment (arrow) and various bioclastic fragments. (d) Ostracod shells orientated parallel to long axis of clasts. (e) Scattered crystalline dolomite rhombs in clasts and matrices. (f–h) various remnant structures of packstone to grainstone which is overall recrystallized; (f) Packstone to grainstone showing ghosts of numerous peloidal grains. (g) Packstone to grainstone with ghosts of bioclasts. (h) Packstone to grainstone with faint concentric laminae which might be former ooid. Some ooids appear to be broken. (h') Line drawing of (h).

Table 2. Classification of facies associations

Facies associations	FA 1	FA 2	FA 3	FA 4	FA 5	FA 6	FA 7
Constituent facies[a]	**LMf**, P/G	**P/G**	**P/G**, Sc, L-S	**L-S**, **P/G**, Cp, LM (cyclic)	**P/G**, **Sc**, LM, L-S, Cp (cyclic)	**Sc**, **L-S**, **Cp** (cyclic)	**Sc**, LM, L-S, P/G, Cp
Environments	Inner ramp			Inner to mid-ramp	Inner to outer ramp	Mid- to outer ramp	Outer ramp
	Lagoon	Shoal	Shoreface				

[a]Dominant facies of the facies association is indicated by bold.

origin for this facies association. The repeated occurrence of large amounts of P/G facies suggests that FA 4 formed in relatively shallow environments (e.g., inner to mid-ramp) (cf. Burchette and Wright, 1992; Kwon et al., 2006). Cp beds formed by reworking of semi-consolidated carbonate sediments during intermittent high-energy conditions (e.g., storms). The cyclic successions of L-S and P/G facies reflect a repeated shallowing of the depositional environment.

4.1.5. Facies association 5 (FA 5): Inner to outer ramp

Description: Facies association 5 consists mainly of P/G and Sc, and minor amount of LM, L-S, and Cp. These facies

Table 3. Depositional cycle types and percentage in the FA 4, FA 5, and FA 6

Facies associations	Cycle types	Percentage
FA 4	L-S → P/G	54%
	L-S → (LM) → Cp	31%
	L-S → (LM) → P/G → Cp	15%
FA 5	Sc → P/G → Cp	44%
	Sc → LM → P/G	29%
	Sc → L-S → P/G	27%
FA 6	Sc → L-S → Cp	38%
	L-S → Cp	33%
	Sc → Cp	19%
	Sc → L-S	10%

occurs as meter-scale cyclic succession of Sc at the base, followed by L-S or LM, and the uppermost P/G facies (Table 3) (Figs. 6 and 11). The mean thickness of individual cycles is 2.5 m. Within a cycle, grain size increases toward the top of the cycle and relative amount of argillaceous material gradually decreases upwards. The upper and lower boundaries are relatively sharp whereas the facies boundaries within a cycle are gradational. Lenticular or channel shaped Cp beds occasionally intercalate within Sc, and tabular and continuous beds of Cp rarely cap a cycle. This FA occurs in the middle Tumok member of the upper Mungok Formation and grades into the FA 3 in the Yeonjeong 3 section.

Interpretation**:** The cyclic facies successions with a Sc-base and P/G-top suggest a shallowing of subtidal environments (Tucker and Wright, 1990). The Sc in the lower part of the cycle was deposited in low-energy conditions, deeper than fair-weather wave base, and P/G was deposited in high-energy conditions around normal wave base. Sharp cycle boundaries are generated during stages of rapid flooding of the carbonate ramp whereas gradational boundaries are formed during stages of gradational decrease in water depth. Cp beds consisting of reworked carbonate sediments might have been formed by storms. Large volumes of Sc suggest that FA 5 was formed in intermediate to deep subtidal environments (e.g., mid- to outer ramp) (Palma et al., 2007).

4.1.6. Facies association 6 (FA 6): Mid- to outer ramp

Description**:** Facies association 6 is composed of Sc, L-S, and Cp. Meter-scale coarsening-upward cycles of FA 6 begin with Sc and are successively overlain by L-S and/or Cp (Table 3) (Figs. 6 and 11). The Cp beds include tabular continuous beds and small channel-shape beds. The mean thickness of individual cycles is 1.7 m. There are systematic increases in grain size and decreases in the relative amount of argillaceous material (shale) toward the top of a cycle. The upper boundaries of individual cycles are relatively sharp, whereas the facies boundaries within a cycle are gradational. FA 6 occurs in the Tumok member in the upper Mungok Formation and is underlain by FA 4 with a sharp boundary and is capped by FA 5.

Interpretation**:** Dominance of Sc and LS in the FA is interpreted as the deposits of mid- to outer ramp environments (e.g., Kwon and Chough, 2005). Vertical successions of Sc and L-S are indicative of coarsening-upward cycles in low-gradient outer ramp settings (Kim and Lee, 1998; Kwon and Chough, 2005). Tabular continuous Cp beds composed of reworked carbonate sediments might have been formed by storms, whereas Cp filling small channels (gutter cast) composed of coarse-grained carbonate sediments from shallower areas might indicate sporadic input by storm-induced basinward currents (Lee and Kim, 1992).

4.1.7. Facies association 7 (FA 7): Outer ramp

Description**:** Facies association 7 is mainly composed of thick beds of laminated calcareous shale (Sc) with intercalated LM, L-S, P/G, and Cp (Fig. 11). This FA is dominated by Sc which constitutes more than 60% of the total measured thickness of the facies association. Occasional grainstone layers with centimeter-scale gutter casts are present. This FA only occurs in the Tumok member of the upper Mungok Formation at the Baeiljae section.

Interpretation**:** Facies association 7 represents a low-energy, deeper-water environments (e.g., outer ramp) (Markello and Read, 1981; Glumac and Walker, 2000; Elrick and Snider, 2002). Shale was most likely deposited by suspension settling of argillaceous material (cf. Dalrymple et al., 1985), whereas the grainstone layers with gutter casts were formed by occasional input of carbonate sediments from shallower area by relatively high-energy currents (e.g., storm-induced outflow).

4.2. Correlation and Depositional History

Two representative sections in the northern and southern parts of the study area, the Baeiljae (northern part) and Yeonjeong 2 (southern part) sections, are about 5 km away from each other within the same thrust sheet. They are correlated by lithology in order to demonstrate the facies change in the study area (Fig. 12). The Yeonjeong 3, located ca. 600 m west of the Yeonjeong 2 section, but occurring in another thrust sheet, is used as a supplementary section for the upper Mungok Formation in the southern area. The datum for the correlation between the measured sections is drawn at the first occurrence of the calcareous shale facies and, in turn, is defined as the boundary between the Jeommal and Tumok members.

In both sections, the Karam member overlies the dolomite bed of the Wagok Formation and is characterized by alternation of FA 4 and 2 with the gradation into FA 1 toward top. The Karam member in the Yeonjeong 2 section is about 16 m thicker than that in the Baeiljae section. The repeated alternation of FA 4 and 2 are suggestive of the transition of depositional environments from mid-ramp to inner ramp (lagoon)

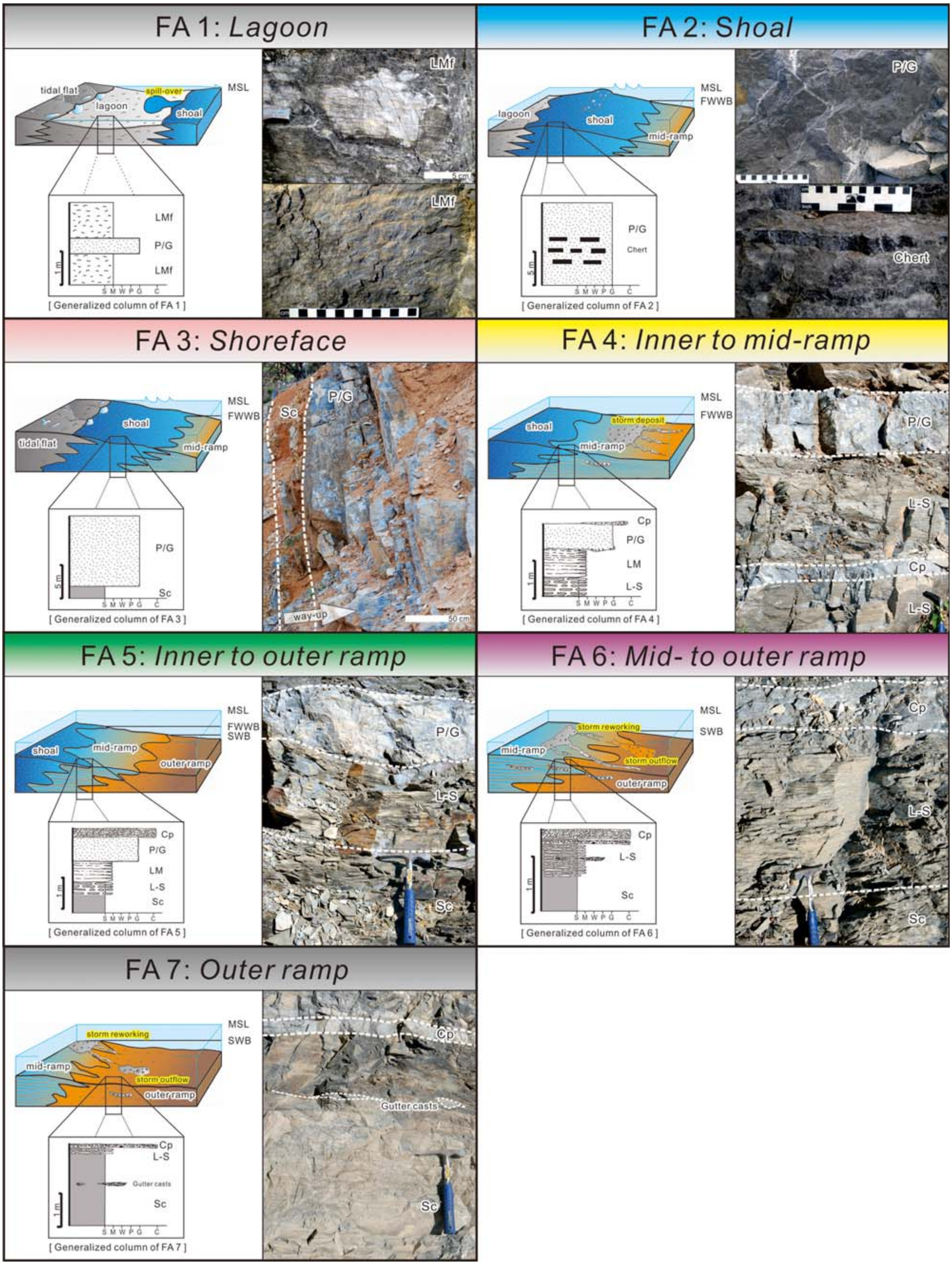

Fig. 11. Summary of facies associations of the Mungok Formation with their depositional environments, generalized columns, and outcrop photographs.

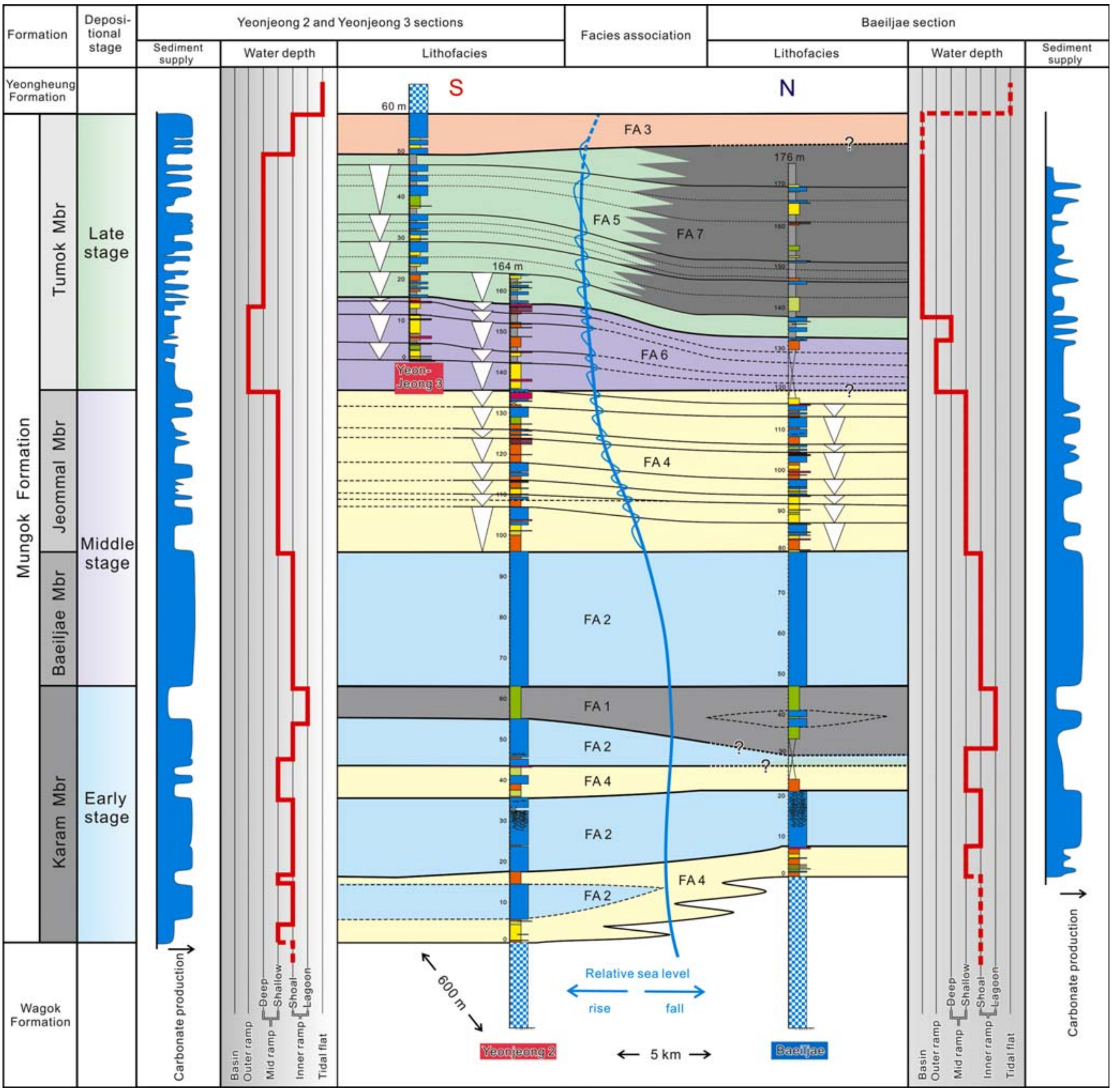

Fig. 12. Correlation of facies associations (FAs) and relative sea-level curve of the Mungok Formation. Only representative sections in south (Yeonjeong 2 and Yeonjeong 3 sections) and northern (Baeiljae section) part of the studied area are presented.

and *vice versa*. Thicker Karam member in the Yeonjeong 2 section might be ascribed to higher productivity of carbonate sediments or larger accommodation in the southern part. The overlying Baeiljae member at the Yeonjeong 2 and Baeiljae sections solely consist of a thick (up to 30 m) FA 2 bed which indicates inner ramp shoal environments. Close association of the widespread lagoonal facies (FA 1) and the extensive shoal facies (FA 2) are suggestive of a large-scale barrier and associated lagoonal system landward of the shoal. The Jeommal member at the Yeonjeong 2 and Baeiljae sections consists of the FA 4 which is well correlated by their overall thickness and cyclic patterns and interpreted to represent inner to mid-ramp environments. The lower part of Tumok member consists of FA 6 in Yeonjeong 2 and Yeonjeong 3 sections, respectively. In the Baeiljae section, the lowermost part of Tumok member is mostly covered and obscured. The middle part of Tumok member in the Baeiljae section consists of FA 7 (outer ramp environments) whereas that in Yeonjeong 2 and Yeonjeong 3 sections is comprised of FA 5 (inner to outer ramp environments). Thickening upward trend of the cycles in the lower and middle part of Tumok member can be explained by a progressive increase in accommodation space and prolonged progradation of shallow carbonate facies. The uppermost part of the Tumok member at the Yeonjeong 3 section is characterized by dominant P/G with intercalated L-S (FA 3) representing inner ramp (shoreface) environments. Degree of dolomitization increases toward the contact with the overlying Yeongheung Formation, which begins with the blue gray irregular laminated dolo-mudstone containing evaporite mineral. The boundary between the formations marks a transition of depositional environments from inner ramp (shoreface) of the uppermost Mungok Formation to tidal-flat environments of the lowermost part of the Yeongheung Formation.

Collectively, the Karam and Baeiljae members, which consist of limestone dominated facies associations of FA 1, FA 2, and FA 4, represent relatively shallow environments. The Jeommal and Tumok members are characterized by facies associations of FA 3, FA 4, FA 5, FA 6, and FA 7, containing significant amount of fine-grained argillaceous sediments (Sc, L-S), which form the base of meter-scale coarsening-upward cycles. The difference in dominant facies indicates relatively deeper environments for the Jeommal and Tumok members than for the Karam and Baeiljae members. The Jeommal and Tumok members are frequently influenced by storm processes, as evinced by a variety of storm deposits, such as Cp facies and gutter casts.

The spatial distribution and temporal changes of the facies associations suggest that the N-S directional depositional gradient of the platform was not significant during the deposition of the lower three members. But in the uppermost Tumok member, thickening of FA 5 toward south and increase of the shale-rich facies in the northern part suggest that a depositional gradient was developed during the deposition of Tumok member. These imply that the deeper part of the basin might have been located at the northern part of the study area rather than the southern part.

The overall depositional setting of the Mungok Formation is interpreted to be a homoclinal ramp because there is no evidence of a slope break and associated mass flow deposits. Thick beds of ooid-peloid packstone to grainstone representing carbonate shoals are the highest-energy facies of the formation. The lateral thickness change of P/G facies in the Karam member indicates irregular and variable topographic relief on the seafloor. Thick beds (more than 30 m thick), of which the thickness persists throughout the study area in the Baeiljae member, are indicative of broad, extensive shoals. In the Jeommal member, a variety of storm deposits such as Cp facies and gutter casts are frequently intercalated within meter-scale coarsening-upward cycles. Sc-base coarsening-upward cycles in the Tumok member are indicative of relatively deeper setting than the Jeommal member. Such a gradational facies change implies a monotonous low angle slope (ramp), frequently affected by storm events. The absence of supra- to intertidal facies (e.g., stromatolites, fenestrae, and mud cracks) could be circumstantial evidence for an extensive subtidal environments developed over the study area during the deposition of the Mungok Formation. To sum up, the succession of the Mungok Formation have been formed on a homoclinal ramp with fringing ooid-peloid shoals.

5. DISCUSSION

5.1. Relative Sea-level Changes

The Early Ordovician relative sea-level curve of Yeongwol area is reconstructed by the water-depth and the rate of sediment supply inferred from facies analysis. According to the sea-level curve, the Mungok Formation evolved through three depositional stages: the early, middle, and late stages (Fig. 12). The early stage is represented by shallow marine conditions while the middle stage shows the features related to the sea-level rise. The late stage is represented by highstand shallow to deep marine settings. The platform of the early stage, represented by the Karam member, was affected by gentle and low amplitude sea-level fluctuations. The Baeiljae and Jeommal members represent the middle stage. The facies in the lower part of the middle stage suggest that the initial gradual sea-level rise was followed by a rapid rise with small-scale fluctuations. The Tumok member formed during the late stage. The rate of the sea-level rise in the boundary between the Jeommal and Tumok members decelerated and shallow facies association was developed.

This sea-level change seems to have a scale of ca. 10 m.y. based on trilobite biostratigraphy, which can be regarded as a 3rd-order cycle sensu Einsele et al. (1991). The cyclic facies succession in the Jeommal and Tumok members records small-scale fluctuations superimposed on the lower-order sea-level trend. The higher-order sea-level fluctuations might have been superimposed on the sea-level curve of the Karam and Baeiljae members, too. The complex facies patches, however, hamper recording and the recognition of the sea-level change in the stratigraphic record.

5.2. Ramp Facies Distribution

Most carbonate ramp depositional models assume relatively simple geometry of a homoclinal ramp in which the facies belts simply move up and down along the ramp in response to relative sea-level change (Ahr, 1973; Tucker, 1993). In a smaller scale, however, there is a more complex interplay between autogenic processes and geomorphology of the ramp. In fact, modern inner ramps are characterized by complex mosaic-type facies distributions, which are resulted from the complex interplay between the various dynamic processes such as storms, tides, currents, and waves (Table 4). Modern inner ramp facies of the Trucial Coast of the Arabian Gulf displays many local shoals instead of a simple geometry; barrier-tidal delta complexes occur along the inner ramp, which are mainly controlled

Table 4. Summarized characteristics of the modern and ancient carbonate ramp system

		Modern carbonate ramps					Ancient carbonate ramps					
Location		Trucial Coast, southern Arabian-Persian Gulf	Yucatan Peninsula	Northeastern Brazil	West Florida, USA	Shark Bay, Western Australia	West-central Portugal	Italy and Malta	North-eastern Spain	Northern Sinai	Central Appalachian, Upper Knox Group	Middle-eastern Korea
Reference		Kirkham and Twombley, 1994	Bosence and Wilson, 2003	Testa and Bosence, 1998	Mullins et al., 1988	Read, 1985 James et al., 2005	Azerêdo, 1998	Pedley, 1998	Bdenas et al., 2010	Bachmann and Kuss, 1998	Pope and Read, 1997	This study
Age		Holocene to present	Tertiary to present	Present	Cretaceous to present	Recent	Middle Jurassic	Middle Tertiary	Lower Cretaceous	Middle Cretaceous	Lower Ordovician	Lower Ordovician
Morphology		Homoclinal ramp	Distally steepened ramp	Distally steepened ramp	Distally steepened ramp	Homoclinal ramp	Homoclinal ramp	Distally steepened ramp	Homoclinal ramp	Homoclinal ramp	Homoclinal ramp?	Homoclinal ramp
Width		200 km	ca. 200 km	200–250 m	200 km	>500 km	100–150 km	ca. 500 km	ca. 400 km	ca. 500 km	>800 km	>200 km?
Length		>300 km	>600 km	>500 km	>800 km	200 km	250–300 km	ca. 500 km	ca. 400 km	ca. 400 km	ca. 400 km	>200 km?
Facies distribution	Inner ramp facies	Oolitic barriers and beaches, lagoon, sabkha	Molluscan, intraclastic sands	Calcareous algal sand with large-scale dunes, coral patch reefs	Molluscan, Quartz sands	Oolitic barriers and shoals sea-grass banks, intraclast, stromatolite	Sand sheets, detached shoal, lagoon (narrow)	Peritidal, lagoon, grainstone, barrier	Bioclast, ooid	Oolitic shoal, bioclast shoal, rudist biostromes	Ooid shoals, Thrombolite, fenestrae	P/G, LMf, L-S
	Mid-ramp facies	Muddy mid-ramp	Relict coral, ooid, peloid lithoclast sands	Planktonic foram sands with increasing mud content with depth	coralline algal and ooid limestones, planktonic foram sands	Skeletal sand	Wackestone	Shallow subtidal patch reef	Bioturbated	Nodular limestone	Packstone, buildups lime wackestone/ mudstone	L-S, Cp, LMl
	Outer ramp facies	Muddy outer ramp	Planktonic foram ooze > 60–200 m	Planktonic foram ooze > 100–150 m	Planktonic foram ooze > 600 m	Muddy sand, plankticforam	Mudstone	Foraminifera, wackestone, marls	Marls and limestones	Mudstone	Nodular shaly skeletal wackestone, bedded black limestone/ shale	Sc, Cp
Climate		Arid tropical	Humid tropical	Seasonal arid to humid equatorial	Humid subtropical	Semi-arid	Tropical	Tropical	Arid	Tropical	Semi-arid	Humid tropical
Tectonic setting		Foreland basin	Passive margin	Continental margin	Passive margin	Passive margin	Continental margin	Passive continental margin	Foreland basin	Passive continental margin	Uplift and erosion, Taconic orogenesis	Continental margin (Lee, 2003)
Dominant controlling factors for facies development		Wave and tide	Storm, strong marine currents, (low tidal energy)	Wind-dominated, marine currents	Wind (leeward with winter storms), marine currents	Wind-dominated?	Tide	Storm and wind	Wave	Complex	Sea-level fluctuations	Storm and wave

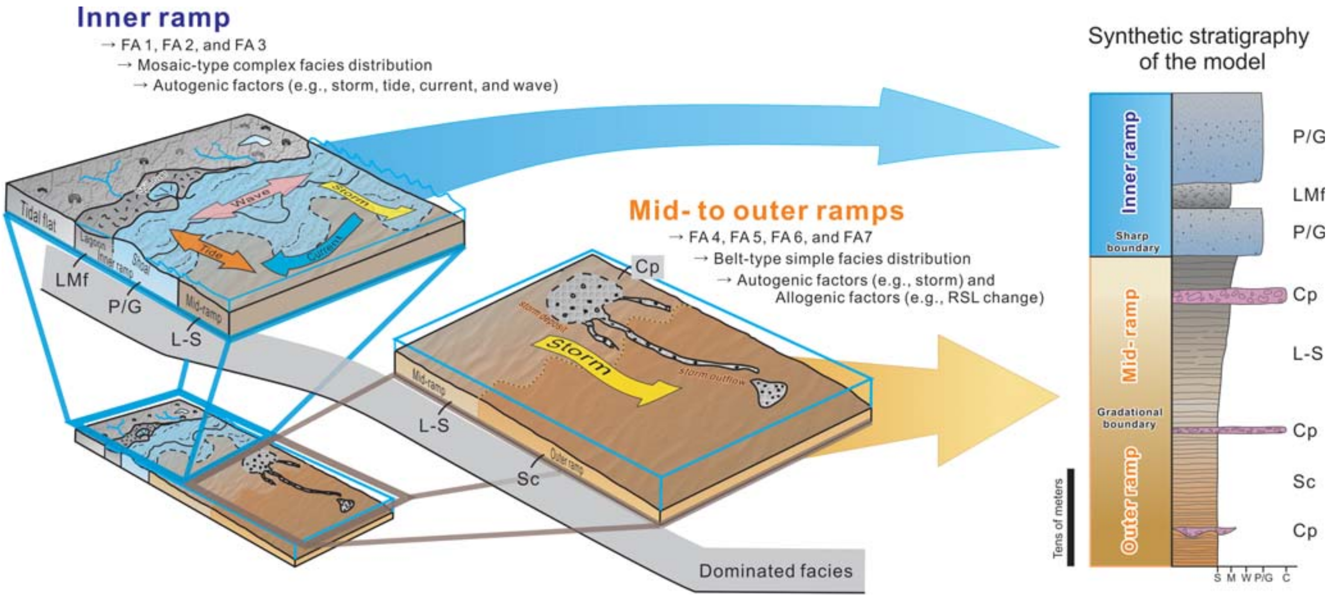

Fig. 13. Schematic diagram of carbonate ramp facies model and the synthetic stratigraphy of the Mungok Formation. The inner ramp has complex mosaic-type facies distribution, controlled by storms, tides, currents, and waves. The mid- to outer ramps have simple belt-type facies distribution under storm effect. Idealized synthetic stratigraphic column represents the case of normal regressive sequence. The boundary between inner ramp facies and mid-ramp facies is sharp, but that between mid- and outer ramp facies is gradational.

by waves and tides. Sediment distribution is controlled by seasonal winds that generate several-meters-high waves and wave bases to the depths of 30 m (Ahr, 1973; Burchette and Wright, 1992; Kirkham and Twombley, 1994; Bosence and Wilson, 2003). The Yucatan coast of Mexico is an example of a ramp with an inner stranded plain zone of beach ridges. It is an inner ramp under a regime of storms and strong marine currents which could quickly modify the sedimentation patterns (Ward and Halley, 1985; Bosence and Wilson, 2003). Winds and marine currents are also main controlling factors of the geometries in the inner ramp, where shoreline and shelf margin parallel currents are driven by a combination of oceanic, tidal, and wave processes (e.g., Northeast Brazil, West Florida, and Shark Bay) (Mullins et al., 1988; Read, 1985; Testa and Bosence, 1998; James et al., 2005). Some ancient carbonate ramp successions have also displayed development of small-scale (ca. hundred-m-scale) geomorphic features such as local shoals and barriers in shallow area, resulting in an irregular topography and facies distribution (Table 4). For example, the architecture and geometry of lagoon and sand bodies within an inner ramp of west-central Portugal in the Middle Jurassic period were interpreted to be controlled by tide processes (Azerêdo, 1998). Storms were also an important factor for sediment redistribution on the ancient inner ramp (Bádenas and Aurell, 2001), generating different coarse-grained deposits including dunes, storm lobes, bars, and tempestites on a Mesozoic ramp in Spain (Bádenas and Aurell, 2001). In the Lower Jurassic of northeast Spain, facies heterogeneities and variable stratigraphic trends of wave-influenced facies were controlled mainly by a laterally migrating mosaic of facies over an irregular topography (Bádenas et al., 2010). Observations of the modern and ancient examples suggest that the shallow ramps are chiefly affected by four controlling factors: storms, tides, currents, and waves. These factors in combination control the formation and lateral migration of a mosaic of facies over an irregular topography.

In contrast, the mid- to outer ramps of modern and ancient ramps have relatively simple belt-type facies distribution (Ahr, 1973, 1998; Read, 1985; Burchette and Wright, 1992; Kirkham and Twombley, 1994; Pope and Read, 1997; James et al., 2005; Bádenas et al., 2010). Mid-ramp facies usually consist of coarsening-upward cycles and comprise storm-related deposits such as tempestites, hummocky cross-stratification, and swaley cross-stratification (e.g., Johnson and Baldwin, 1996; Faulkner, 1988). Outer ramp facies mainly consist of fine-grained sediments (shale or lime mud) with thin distal tempestite layers and gutter casts formed by occasional inputs of carbonate sediments by storm-induced outflow. The mid- and outer ramp facies belts have variable width, and the boundary of mid- and outer ramps is gradually transitional depending on storm activity (Burchette and Wright, 1992).

The inner ramp has a complex mosaic-type facies distribution, which would represent various geomorphic features such as lagoons, dunes, tidal channels, and tidal deltas. These geomorphic features are resulted from the complex interaction of storm, tide, current, and wave processes, which would lead to dune migration, tidal channel shifting and substrate reworking. The resulting facies succession is most likely non-cyclic because it is very difficult for all the other controlling factors to have tuned recurrent frequency. The non-cyclic inner ramp facies of the Mungok Formation is represented by poor correlatability, lateral thickness changes, and frequent alternation of FA 1, and 2 in the Karam and Baeiljae members. They are similarly ascribed to the overprint of the controlling factors over the wave and storm related sedimentary features.

The complexity of facies distribution disappears quickly in the mid- and outer ramps. The mid- to outer ramps succession is represented by FA 4, FA 5, FA 6, and FA 7 of the Mungok Formation in the Jeommal and Tumok members. Individual facies appears to be thinner and more frequently alternating than those of the inner ramp. Systematic facies succession and good lateral correlatability of the cycles are indicative of a belt-type facies distribution. Main controlling factors of the facies development are the allogenic control by relative sea-level change and the autogenic control by storm-induced currents and waves. Storm processes are represented by Cp facies and gutter casts which, inherently, are autogenic features independent of allogenic processes. These facies, however, do not form significant geomorphic features which may affect the subsequent facies development (Fig. 13).

If the sedimentary facies development of the inner ramp is controlled by interplay of various dynamic and biogenic factors, the boundary between inner and mid- ramps does not have to depend on a fair-weather wave base. Instead, the boundary would represent the deepest reach of major controlling factors of the inner ramp sedimentation, which varies depending on depositional settings of ramps. Furthermore, recent year-round monitoring on the magnitude of waves in the Caribbean, the Gulf of Mexico, and the western Atlantic areas suggests that at least in some settings, the population of the wave-size is not bimodal as traditionary suggested (Peters and Loss, 2012), but shows a unimodal distribution with the mean wave length around 100 m. If this is the case, conventional shoreline-offshore and ramp subdivision system based on the notion with two distinct wave bases needs to be reconsidered. The boundary of mid- and outer ramps is rather dynamic and mobile boundary, which may shift by changes in the magnitude of storm activity. The boundary in the stratigraphic record, therefore, is not easy to pin-point. Difficulty in the distinction between storm-reworked deposits and deposits by storm-induced outflow hamper defining the boundary between the mid- ramp and the outer ramp.

6. CONCLUSIONS

Detailed study of the facies distribution and succession of the Mungok Formation (Lower Ordovician) in the Yeongwol area reveals that there are seven facies associations representing carbonate ramp environments. A facies division into the 'inner ramp' and 'mid- to outer ramp' is suggested to explain the facies development of the Mungok Formation. The inner ramp has complex mosaic-type facies distribution, which was affected by storms, tides, currents, and waves processes. The complex interaction of these autogenic factors could lead to development of various geomorphic features and then result in the formation of non-cyclic sedimentary successions of laterally variable facies and thickness. This is exemplified by poorly correlated FAs in the Karam and Baeiljae members of the Mungok Formation. In contrast, the mid- to outer ramp has simple belt-type facies distribution, and the resulting facies succession displays cyclic association of storm-influenced facies and deeper background settling sediments. These cyclic successions compose a lower-order fluctuation caused by allogenic controls of sea-level changes. On the other hand, the facies partitioning is marked by a sharp boundary between the Baeiljae and Jeommal members, which may reflect the boundary of different major depositional agents on a ramp profile. The facies distribution and succession of the Mungok Formation and similar sedimentary records can be better explained by distinct partitioning of facies on a carbonate ramp.

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