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Space-time-dissociated differential sedimentation and its relationship with the rate of relative sea-level change: the Lower Ordovician Mungok Formation, Korea

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ABSTRACT

Hierarchically controlled sequence stratigraphic analysis shows that the Lower Ordovician mixed carbonate-siliciclastic Mungok Formation, Korea consists of three depositional sequences: T1, T2, and T3. Sequence boundaries are generally marked by abrupt transition from coarse-grained shallow-water carbonates to fine-grained deeper-water carbonates mixed with fine-grained siliciclastics, and show indication of subaerial exposure such as karstification. Within this sequence stratigraphic framework, facies characteristics indicate that the Mungok sequences were mostly deposited in subtidal ramp environments. High-frequency cycles consist of upward-shallowing facies successions. Cycles of shallow-water and basinal deposits are not represented well, probably due to cycle amalgamation. Cycle stacking patterns do not show a consistent thickness change that reflects a large-scale sea-level change due to unfilled accommodation space.

The Mungok sequences show that many factors including relative sea-level change and topography are involved in controlling sequence development on carbonate ramps. The depositional setting evolved from the high-energy ramps in the sequences T1 and T2 into the low-energy ramp in the sequence T3. Topography is interpreted to have been responsible for the different energy regimes of the carbonate ramps in the Mungok sequences. The high ramp gradient in the sequences T1 and T2 seems to be caused by space-time-dissociated differential sedimentation resulting in spatially narrow distribution of sediment filling, which in turn may be related to high rate of relative sea-level change. In contrast, low ramp gradient was maintained in the sequence T3 during slow changes of relative sea level resulting in broad distribution of sediment filling.

INTRODUCTION

Depositional systems respond to a complex interplay of various factors such as changes in accommodation, siliciclastic supply, and environmental conditions including climate (Hallock and Schlager, 1986; Sarg, 1988; Handford and Loucks, 1993). Among them, accommodation change and sediment supply have been considered the major controls on sequence development (e.g., Schlager, 1993). In tectonically stable regions with linear subsidence rate such as passive margins and intracratonic basins, the signal of long-term sea-level changes with millions of years′ duration is prominently recorded in carbonate ramp successions. Most carbonate ramps in the geological record are in high-energy settings dominated by wave and storm processes similar to siliciclastic shelves, in which high-energy, wave-agitated shoreface in the inner ramp grades to low-energy, terrigenous mud-dominated outer ramp facies via tempestite-rich middle ramp facies (Read, 1985; Osleger, 1991; Burchette and Wright, 1992). Low-energy ramps are scarce and relatively poorly known with exception of few studies (Fairchild and Hetherington, 1989; Choi and Simo, 1998; Choi *et al.*, 1999). They are characterized by lack of high-energy shoals composed of coarse-grained sediments so that tempestite-rich middle ramp facies grades landward into low-energy environments dominated by fine-grained sediments. The facies relationships typical to both energy settings of carbonate ramps are represented well in the Lower Ordovician Mungok Formation, Korea, in which the signal of long-term sea-level changes is also easily discernible (Choi, 1992; Choi *et al.*, 1993). In this paper, controlling factors on the energy regimes in carbonate ramp settings and its relationship with patterns of sequence development and rate of relative sea-level change are investigated. This work is accomplished by characterizing the facies of the Mungok Formation in a hierarchically ordered sequence stratigraphic framework and by interpreting the environmental evolution of the depositional system in relation to relative sea-level change.

GEOLOGIC SETTING

The Cambro-Ordovician strata in South Korea, the Joseon Supergroup, are exposed in the central eastern part of the Korean Peninsula, and consist predominantly of carbonate rocks with minor siliciclastic rocks. The Joseon Supergroup in the study area (Fig. 1) is divided into five lithostratigraphic units; the Sambangsan, Machari, Wagok, Mungok and Yeongheung formations with decreasing age (Fig. 2; Yoshimura, 1940). In the study area, these stratigraphic units are repeatedly distributed in several north-south trending thrust blocks dipping west (Fig. 1). The Mungok corresponds to the Early Ordovician (Tremadoc), and consists of a succession of carbonate rocks and minor marl to shale with a thickness of 120-200 m. It overlies conformably the Upper Cambrian Wagok Formation, and is overlain conformably by the Middle Ordovician Yeongheung Formation. The Wagok Formation consists predominantly of massive to poorly bedded dolostone with a thickness ranging from 200 m to 500 m. It is interpreted to have been deposited in shallow subtidal environments (Koo, 1992). The Yeongheung Formation consists predominantly of thin- to thick-bedded pure carbonates with a thickness up to 400 m. The Yeongheung Formation is interpreted to have been deposited in peritidal environments (Yoo and Lee, 1997). The depositional environments of the Mungok Formation has been interpreted as a tidal flat setting (Paik *et al.*, 1991; Chung *et al.*, 1993). In parallel with this interpretation Woo *et al.* (1990) reported the diagenesis of the Mungok Formation as having been under shallow marine, meteoric, and burial conditions. Moon and Martin (1994) also concluded based on trace fossil studies that the sediments were deposited in an intertidal setting. A different view on the depositional environments was addressed by Choi *et al.* (1993) and by Lee and Paik (1997). They interpreted that the Mungok Formation was deposited in subtidal environments on a low-gradient ramp, indicative of an open marine setting. Presence of open marine trilobite taxon also supports this interpretation (Park *et al.*, 1994; Kim, 1999).

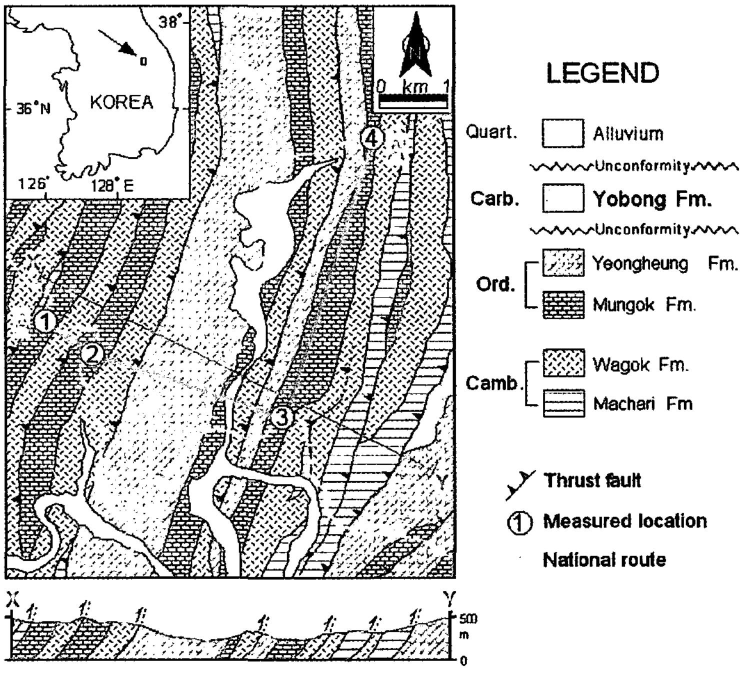

Fig. 1. Geologic map of the study area. Four sections are measured from three different thrust blocks and correlated along the line AA′ in Figure 3.

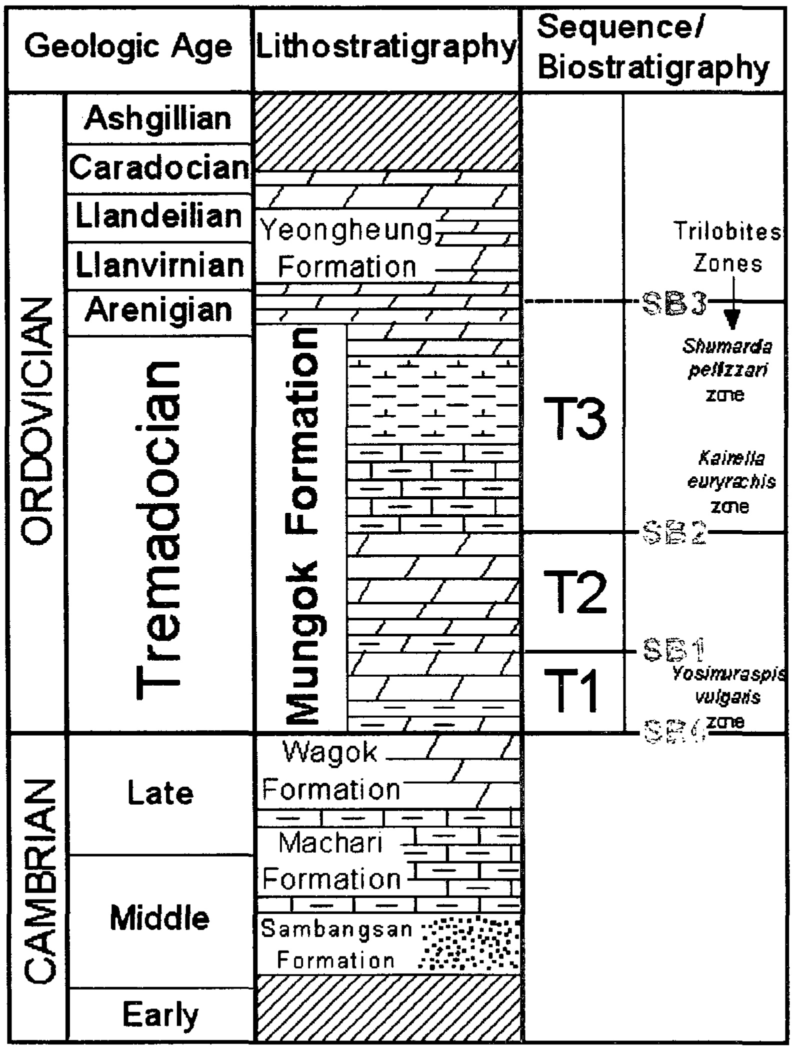

Fig. 2. Stratigraphy of the Cambro-Ordovician strata in the central eastern part (Yeongweol area) of the Korean Peninsula. Biostratigraphic data are from Kim (1999).

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Five lithofacies are defined in the Mungok Formation based on detailed sedimentologic logging of sedimentary structures, textures, and lithologic composition (Table 1). The thick-bedded grainstone, flaser rock, ribbon rock, and marl to shale lithofacies are interpreted to have been deposited from shallow, wave-agitated, high energy inner ramp to low energy outer ramp to basin environments with increasing water depth on a low gradient ramp. The one exception is the thin-bedded grainstone lithofacies, which is interpreted to have been deposited in middle to outer ramp environments during intensive storm events.

Table 1. Lithofacies summary of the Lower Ordovician Mungok Formation.

Lithofacies	Sedimentary Structure/Bedding	Texture/Grains/Lithologic Composition	Interpretation
Thick-bedded grainstone	Thick-bedded to massive; occasionally parallel-laminated	Well sorted; peloidal, bioclastic grainstone with subordinate intraclasts and ooids	Inner ramp
Thin-bedded grainstone	Thin- to medium-bedded with sharp erosive base, normally to poorly graded	Poorly sorted; mostly clast-supported intraclasts of variable lithologies in peloidal, bioclastic matrices	Proximal to distal storm deposits
Flaser rock	Medium- to thick-bedded; flasered with clay seams	Relatively pure micrite; less than 20% insoluble residues by weight	Upper middle ramp
Ribbon rock	Millimeter- to centimeter-scale alternation of pure carbonate and marl; planner- to nodular-bedded	Carbonate consists of micrite with subordinate peloidal wackestone to packstone when laminated; 20-20% insoluble residues by weight	Lower middle ramp
Marl to shale	Massive; grades upward into ribbon rock facies	More than 30% insoluble residues by weight	Outer ramp to basin

Lithofacies analysis shows that the Mungok Formation was deposited in an open marine ramp setting with no slope break. Presence of open marine fauna including brachiopods, trilobites, and crinoids also supports this interpretation. Figure 3 shows the correlation between four measured sections and the vertical and lateral variations of the lithofacies. Stratigraphically, the Mungok Formation is subdivided into three lithologic parts (Fig. 3). Depositional facies are recognized from the lithofacies tracts in each lithologic part. The lower part is dominated by shallow-water inner ramp facies consisting of the thick-bedded grainstone lithofacies. The middle part is dominated by middle ramp facies consisting predominantly of ribbon rock lithofacies, which gradually passes up into outer ramp to basinal facies represented primarily by marl to shale lithofacies. The upper part is dominated by middle ramp facies overlain by inner ramp facies consisting of flaser rock and intermittent thick-bedded grainstone lithofacies, which grades upward into tidal flat facies of the overlying Yeongheung Formation. Three-dimensional analysis of the lithofacies distribution indicates that the depositional dip trends approximately east-west direction, which is based mainly on relative proportion between the thickness of shallow-water vs. deep-water lithofacies within a sequence stratigraphic framework. This direction is consistent with that of the overlying Yeongheung Formation (Yoo and Lee, 1997).

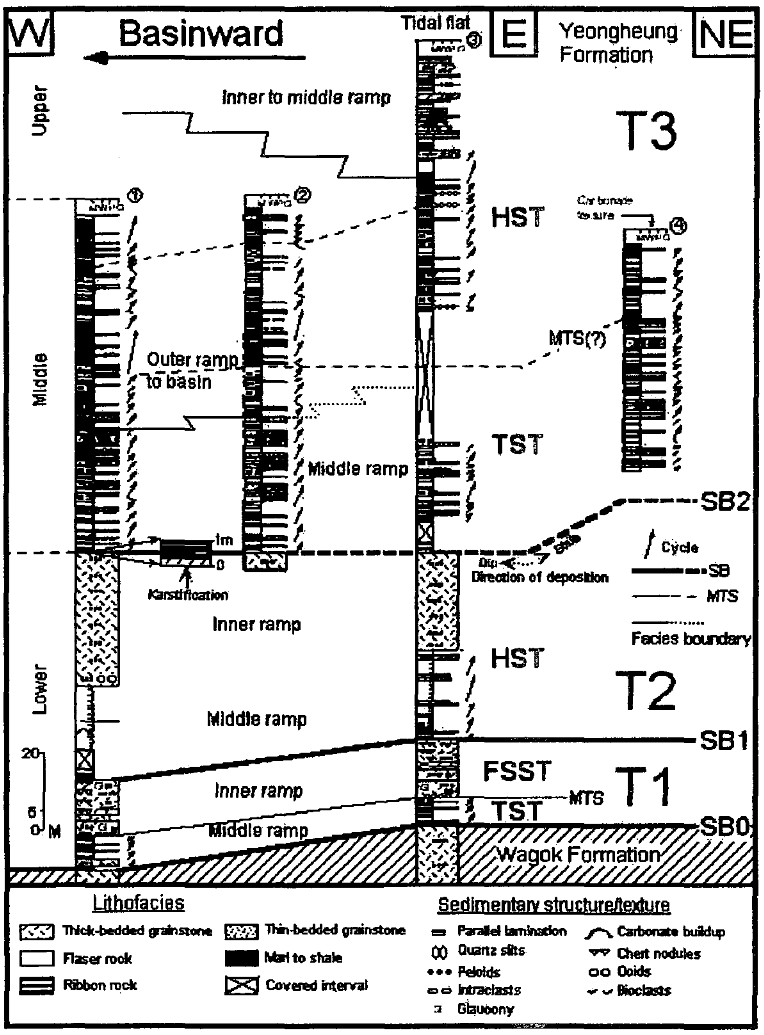

Fig. 3. Stratigraphic cross section along the correlation line AA′ in Figure 1. Datum is the sequence boundary SB2. Abbreviations: TST=transgressive systems tract, HST=highstand systems tract, FSST=falling stage systems tract, SB=sequence boundary; MTS= maximum transgressive surface.

SEQUENCE STRATIGRAPHY

The Mungok Sequences

Three depositional sequences are defined in the Mungok Formation (Figs. 2 and 3). The sequence framework is based upon overall facies stacking patterns as well as the recognition of sequence boundaries, i.e., subaerial unconformities and correlative conformities formed during relative sea-level fall. Depositional sequences in the Mungok Formation are relatively conformable successions bounded by these surfaces across which facies changes occur abruptly from coarse-grained shallow-water carbonates to fine-grained deeper-water carbonates mixed with siliciclastics.

Sequence T1 is bounded below by the sequence boundary SB0 on top of the Wagok Formation and above by the sequence boundary SB1. The SB0 is the lowermost sequence boundary formed on the massive dolostones of the Wagok Formation. An abrupt facies change is recognized across the SB0 from shallow-water carbonates composed of peloidal grainstones (Wagok Formation) below to deeper-water carbonates composed of ribbon rocks and marls above. The SB0 is also characterized by petrographic features such as subhorizontally developed irregular fissures of non-tectonic origin and millimeter-scale vesicular to vuggy pores interpreted to be dissolution vugs. The vesicular and vuggy pores are partly or completely filled with limpid dolomite and gradually decrease in abundance downward. Occasional fine-grained quartz sands are observed above SB0. All these features are indicative of subaerial exposure of SB0. Main lithofacies of the sequence T1 are thick-bedded grainstone, ribbon rock and marl to shale. The ribbon rock and marl to shale lithofacies dominate the lower half of the sequence T1, whereas the thick-bedded grainstone lithofacies comprise the upper half exclusively (Fig. 3). Stratigraphically, the sequence T1 shows an overall deepening upward trend in the lower half and a shallowing upward trend in the upper half. The boundary between the lower and upper halves of the sequence T1 is a sharp erosional surface truncating underlying beds with 10-20 cm-scale relief and the lowermost bed above this surface often contains intraclasts of underlying lithology. Glaucony grains are common in the overlying thick peloidal grainstones, and especially rich in several horizons of a-few-meter-thick interval above the boundary (Lee and Paik, 1997). The glaucony-bearing horizons appear in the field as 1-5 cm-thick rust-stained beds due to oxidation.

Sequence T2 is bounded below by SB1 and above by SB2. The SB1 is a sharp undulatory surface separating massive peloidal, bioclastic grainstones below from the overlying marls and ribbon rocks (Fig. 3). SB1 is also characterized by sub-millimeter-thick iron-mineral coating on its surface and vuggy to vesicular pores below it, which indicates possible subaerial exposure. Main lithofacies of the sequence T2 are thick-bedded grainstone and flaser rock with minor ribbon rock and marl to shale (Fig. 3). The sequence T2 shows a gradual transition from marl to shale lithofacies at the base to the thick-bedded grainstone lithofacies at the top. Gradual upward increase in coarse-grained lithofacies with accompanying increase in the carbonate/siliciclastic ratio indicates depositional shallowing.

Sequence T3 is bounded below by SB2 and above by SB3. The SB2 is a very sharp discontinuity surface with decimeter-scale relief and is interpreted to have been formed by karstification during subaerial exposure (Fig. 3). The SB2 forms on massive peloidal grainstones and the cavities below the karstified surface with overhangs are filled with fine-grained sediments infiltrated from above. The SB2 is also characterized by petrographic features such as a millimeter-thick iron-mineral coating on the surface and centimeter-scale irregular vuggy pores filled with limpid dolomites below the surface. SB3 is stratigraphically positioned at the top of peritidal carbonate succession in the basal portion of the Yeongheung Formation (Yoo and Lee, 1997) into which shallow subtidal succession in the uppermost portion of the Mungok Formation gradationally changes. Main lithofacies of the sequence T3 are marl to shale, ribbon rock, and thin-bedded grainstone with minor flaser rock and thick-bedded grainstone. The sequence T3 consists of a deepening upward succession in the lower part followed by a shallowing upward succession in the upper part. The lower part shows an overall transition from ribbon rock and flaser rock lithofacies-dominated base to marl to shale lithofacies-dominated top. The upper part shows a reverse transition from the marl to shale lithofacies at the base grading upward into the flaser rock and thick-bedded grainstone lithofacies and finally into mud-cracked dolomites in the basal portion of the Yeongheung Formation.

Cycles

Lithofacies in the Mungok Formation are stacked in repetitive patterns that define cycles. Cycle boundaries are at the turn-around from base-level-fall to base-level-rise (e.g., Kerans and Tinker, 1997). An ideal cycle consists of a succession of the basal marl to shale lithofacies grading upward into ribbon rock, flaser rock, and the thick-bedded grainstone lithofacies top, part of which comprise actual cycles. The thin-bedded grainstone lithofacies episodically intercalates in any part of a cycle but most closely associated with the ribbon rock lithofacies.

Cycles are represented well in middle to outer ramp successions in which ribbon rock is the predominant lithofacies with marl to shale at the base and flaser rock lithofacies at the top. However, they are not represented well in the inner ramp or basinal successions in which several cycles comprise one homogeneous succession (e.g., cycle amalgamation; Goldhammer *et al.*, 1990).

Cycle Sets

Cycle sets are defined as bundles of cycles that show a consistent trend in a cycle stacking pattern. The consistent trend is represented as either progradational, aggradational, or retrogradational (e.g., Kerans and Tinker, 1997). Cycle stacking patterns in the Mungok sequences, however, do not show a consistent thickness change that reflects a large-scale sea-level change (Fig. 3). The lack of consistent cycle thickness change is interpreted to have resulted from the unfilled accommodation space, which is common in subtidal deposits (e.g., Gianniny and Simo, 1996). In the Mungok Formation, frequent storms may have also played a significant role in controlling the upward limit of sediment accumulation (e.g., Osleger, 1991). The consistent trend in a cycle stacking pattern is commonly recognized by gradual changes in predominant lithofacies in stacked cycles. Based on the consistent trend and stratigraphic position within a sequence, each cycle set is expressed as systems tract in relation to relative sea-level change (Fig. 4).

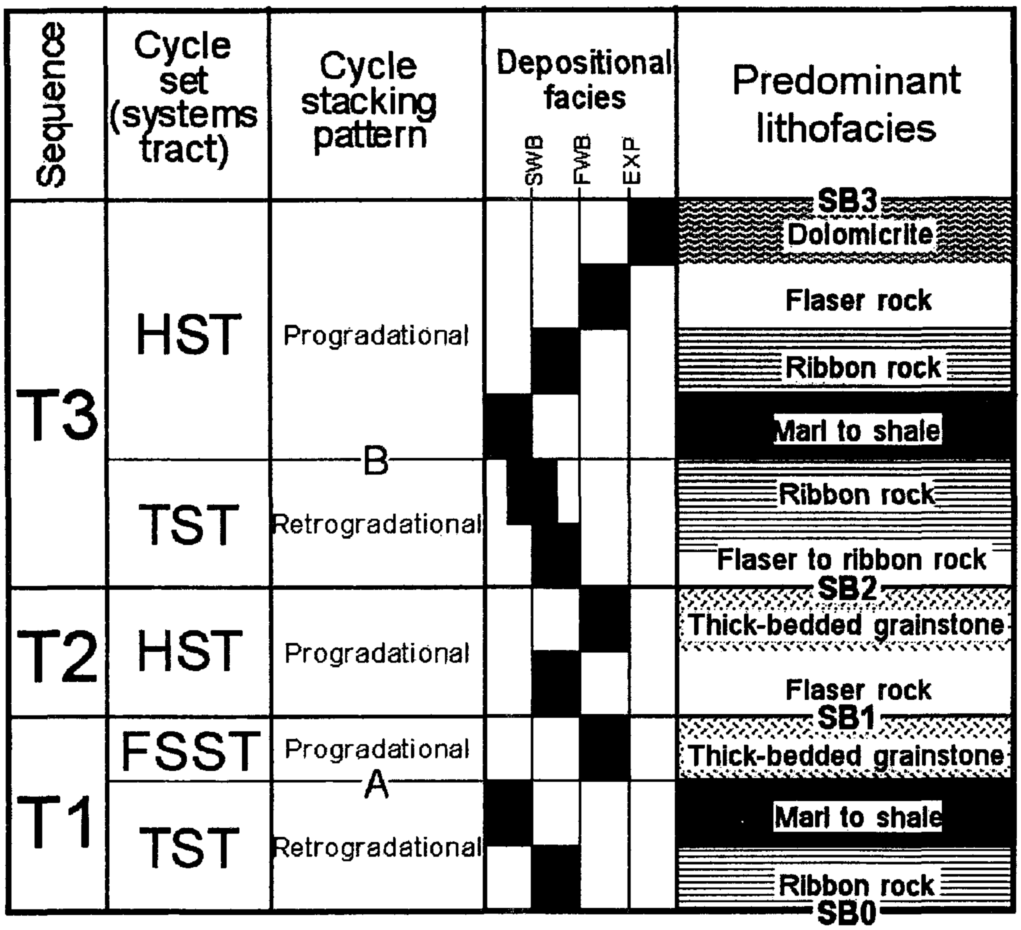

Fig. 4. Sequence summary of the Mungok Formation. Sequences are subdivided into systems tracts in relation to relative sea-level change. Depositional facies with main lithofacies are represented in each sequence by black boxes. A: maximum transgressive surface modified by the regressive surface of erosion, B: maximum transgressive surface positioned at the base of deepest-water facies at the most landward section. SWB: storm wave base,FWB: fair-weather wave base, Exp: exposure

The sequence T1 consists of two systems tracts. The retrogradational cycle set comprising the lower half of the sequence T1 is interpreted as a TST since it shows an overall upward-deepening trend overlying a sequence boundary (SB0). The progradational cycle set in the upper half of the sequence T1 is interpreted as a FSST since it shows an overall upward-shallowing trend and abrupt basinward facies shift at its base. The boundary between the retrogradational and progradational cycle sets is interpreted as representing the MTS modified by subsequent erosion (e.g., regressive surface of erosion; Plint, 1988). The glauconies in the peloidal grainstone beds above the MTS are interpreted as having been reworked from the condensed section formed after long exposure on the sea floor under very low sedimentation rate (Lee and Paik, 1997). The progradational cycle set in the sequence T2 is interpreted as a HST based on a gradual upward-shallowing trend and the presence of subaerial exposure surface (SB2) on its top. The retrogradational cycle set and the overlying progradational cycle set in sequence T3 are interpreted as TST and HST, respectively. The maximum transgressive surface does not occur as a single horizon in the sequence T3, but is recognized as a transitional zone.

DISCUSSION

Based on the hierarchically controlled sequence stratigraphic analysis, reconstructed are two types of cross section that are extrapolated beyond the study area (Fig. 5). The depositional history is interpreted as follows. After development of the SB0 (Fig. 5a, t0), the sea level gradually increased depositing the TST of the sequence T1. A prolonged non-deposition continued in the study area resulting in formation of a condensed section (Fig. 5a, t1) and subsequent deposition of prograding HST of the sequence T1 was confined to the east. A rapid relative sea-level fall brought in deposition of the FSST composed of shallow-water carbonates directly on top of the deeper water carbonates in the study area (Fig. 5b) and the SB1 was formed on top of it (Fig. 5a, t2). A possible LST was deposited to the west of study area. Subsequent rapid relative sea-level rise moved the shoreline to the east while in the study area non-deposition continued (Fig. 5a, t3). As sedimentation rate exceeded relative sea-level rise, the HST of the sequence T2 gradually prograded from east. A prolonged subaerial exposure resulted in karstification of the exposed platform including the study area forming the SB2 (Fig. 5a, t4). During subsequent relative sea-level rise, the TST of the sequence T3 was deposited gradually onlapping onto the SB2 until sedimentation rate started to exceed the relative sea-level rise in the shoreline (Fig. 5a, t5). Deposition of the HST of the sequence T3 followed over broad area of the Mungok platform.

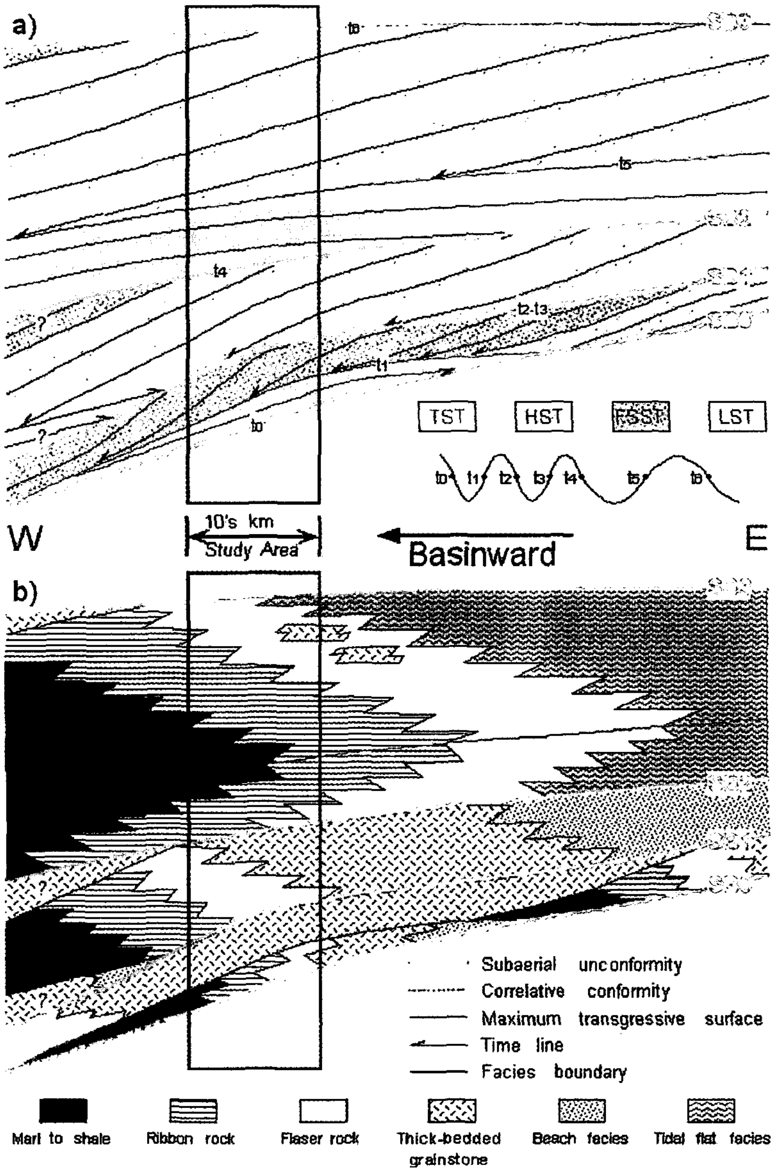

Fig. 5. Schematic inferred cross sections that are extrapolated beyond the study area. A. Systems tract cross section representing depositional history. B. Facies cross section based on interpreted depositional history. C. Sea-level curve with different steepness between sequences T1, T2 and T3.

Sequences in the Mungok Formation consists predominantly of subtidal sediments except the uppermost portion of the sequence T3, where peritidal deposits caps the regressive succession (HST). Compared with the sequences T1 and T2, the sequence T3 is characterized by scarcity of shallow-water high-energy facies, presence of tidal-flat deposits as the capping facies below the exposure surface (SB3), and a complete overall transgressive - regressive (T-R) cyclicity with a gradual shift in facies across the MTS (Figs. 3, 5b). In contrast, sequences T1 and T2 are characterized by thick accumulation of high-energy facies and incomplete T-R cyclicity or abrupt T-R cycle change. In addition, tidal-flat deposits such as dolomicrite are absent in the sequences T1 and T2, and subaerial exposure surfaces (SB1 and SB2) are directly developed on tops of the subtidal high-energy facies. Distribution of systems tracts in the sequences T1 and T2 are relatively narrow and spatially differentiated, and facies shifts are abrupt across systems tract boundaries as well as across sequence boundaries (Fig. 5).

The presence of high-energy, subtidal, coarse-grained facies vs. low-energy, peritidal, fine-grained facies may be a function of energy regime in the depositional setting in each sequence. The depositional systems of the sequences T1 and T2 are interpreted as having been in open-marine, high-energy ramp settings, whereas that of the sequence T3 were probably in a low- to moderate-energy setting. Osleger (1991) suggests that the presence of subtidal vs. peritidal carbonate cycles is related to platform morphology, which governs energy regime of the depositional setting. Open ramps are considered high-energy settings subject to fair-weather wave and storm processes, whereas rimmed shelves are low-energy settings protected from those high-energy processes so that fine-grained sediments could accumulate to form peritidal facies. However, there is no indication that the Mungok platform evolved from open ramps in the sequences T1 and T2 to a protected rimmed shelf in the sequence T3. The reconstructed depositional profile in the sequence T3 is a ramp without a slope break based on the gradational relationships between facies and the absence of reef structures and associated mass-flow deposits (Ahr, 1973, 1985; Read, 1985; Wright, 1986). Meter-scale mounds are the only carbonate buildup type in the Mungok Formation (Choi, 1992). The different energy regime in ramp settings may relate to topography such as ramp gradient (Franseen *et al.*, 1997; Choi and Simo, 1998, Choi *et al.*, 1999). The ramp gradients in the sequences T1 and T2 were fairly steep compared to that in the sequence T3 so that fair-weather wave energy concentrated on narrow belt of shallow-water ramps forming high-energy shoals composed of grainy sediments. In contrast, in the sequence T3 exited a low-energy ramp with very low gradient on which the wave energy was not strong enough to form shoals because the impinging oceanic waves lost most of their energy very gradually over wide areas before reaching the distant shore (e.g., Keulegan and Krumbein, 1949).

The different ramp gradient in the sequence T3 from those in the sequences T1 and T2 is interpreted to have resulted in part from filling of antecedent topography that existed in the sequences T1 and T2 and space-time dissociated differential sedimentation. As mentioned above, the systems tracts within the sequences T1 and T2 are relatively narrow in spatial distribution and shift abruptly along the depositional dip so that the facies within them are detached across the systems tract boundaries (Fig. 5b). This differential sedimentation might have helped maintain high ramp gradient along the fast-moving depositional locus until the basin topography was filled and the gradient was subdued in the sequence T3 in which depositional locus covers wide areas to keep the established low-gradient ramp. The differential sedimentation in turn may relate to the rate of relative sea-level change (steepness of sea-level curve, Fig. 5c). The rate of relative sea-level change in the sequences T1 and T2 is interpreted to have been relatively high, which is supported by the presence of abrupt basinward facies shift during falling stage of the sequence T1 and prolonged non-deposition during rising stages of the sequences T1 and T2 (Fig. 5b). Although this interpretation can not be verified from field evidence due to lack of exposure of the Mungok Formation outside the study area, it seems to be certain that many aspects such as predominant facies, topography, differential sedimentation affecting lateral and vertical continuity of facies, and the rate of relative sea-level change are closely interrelated. Computer simulation with differing input parameter (e.g., different sea-level curve and basin topography) may help verify the scenario presented in this study.

CONCLUSIONS

The Lower Ordovician mixed carbonate-siliciclastic sediments of the Mungok Formation are interpreted to have been deposited in open marine, subtidal environments. Three (T1, T2, and T3) depositional sequences are defined in these strata based on overall facies stacking patterns and recognition of sequence boundaries formed during relative sea-level fall. Sequence boundaries are marked by abrupt facies shifts from shallow-water carbonates to deeper-water carbonates mixed with fine-grained siliciclastics and show indication of exposure. Meter-scale asymmetric cycles are well represented in middle to outer ramp successions of the Mungok Formation, whereas cycles of shallow-water and basinal deposits are not represented well due to cycle amalgamation. Cycle stacking patterns do not show a consistent thickness change and it is interpreted to have resulted from the unfilled accommodation space.

The uppermost sequence, sequence T3, is different from the underlying sequences T1 and T2 in terms of many aspects such as predominant facies, spatial distribution of systems tract, completeness of overall T-R cyclicity, and lateral and vertical continuity of facies. The presence of subtidal (in sequences T1 and T2) vs. peritidal facies (in sequence T3) below subaerial exposure surfaces may depend on energy regime in the depositional setting, which in turn is governed by topography of carbonate ramp. The sequences T1 and T2 were deposited on a high-gradient ramp during fast changes of relative sea level, whereas the sequence T3 was deposited on a low-gradient ramp during slow changes of relative sea level. Topography can be affected by space-time-dissociated differential sedimentation, which may relate to the rate of relative sea-level change.

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