

Depositional processes and sequence stratigraphy of the Jigunsan Formation (Middle Ordovician), Taebaeksan Basin, mid-east Korea: implications for basin geometry and sequence development

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ABSTRACT: This study focuses on the depositional processes of the Middle Ordovician Jigunsan Formation of the Taebaeksan Basin, mid-east Korea, an extensive fine-grained deposit (greenish to dark gray mudstone and interbedded limestone), in view of the recent plate reconstruction of the Sino-Korean Block. The Jigunsan Formation and the bounding formations are represented by eleven sedimentary facies that are organized into six successive facies associations (FAs). The facies successions reflect an overall development of a carbonate platform that was inundated during an initial phase of transgression (lower part of FA1) forming deep subtidal to basinal environments which were influenced by dilute turbidity currents and occasional storm-induced density currents (FAs 2, 3, and 4). During a stillstand in sea level, shallow platform sediments (FAs 5 and 6) prograded over the deep subtidal to basinal area. The initial flooding surface of the platform is the top of a supratidal deposit that is underlain by a peloidal grainstone (Gp) bed. The surface is interpreted as a sequence boundary/transgressive surface. The maximum flooding zone (MFZ) occurs in the upper part of facies association 2, which is characterized by a mudstone interval. The conodont and trilobite biostratigraphy suggests that the Jigunsan Formation represents a third-order (0.5–3 My) rise in sea level. The deposit formed in the early Darriwilian in the eastern end of a large-scale (ca. 1000 km long and 50 km wide) eastward-deepening embayment, an eastward extending arm of the North China Platform across the Pyeongnam Basin, North Korea. The early Middle Ordovician sequence boundary in the Taebaeksan Basin was formed by eustatic sea-level fall. During the subsequent transgression, the eastern arm was largely inundated and under a tidal regime. In the deepening eastern end of the arm (Taebaeksan Basin), however, deposition was largely influenced by the input of siliciclastic sediment and the expansion of oxygen-restricted deep water due to the proximity to the hinterland and the semi-enclosed basin configuration, respectively.

Key words: mixed carbonate-siliciclastic platform, sequence stratigraphy, Middle Ordovician, North China Platform, Taebaeksan Basin, Jigunsan Formation

1. INTRODUCTION

The Jigunsan Formation (Middle Ordovician) in the Taebaeksan Basin consists of greenish to dark gray mudstone and interbedded limestone. It is relatively thin (30–60 m in thickness), but can be traced for tens of kilometers across

the entire study area (Fig. 1). It is a mixed siliciclastic-carbonate unit that is under- and overlain by carbonate successions (Table 1). The underlying supratidal and peritidal succession (upper part of the Makgol Formation) consists of succession of stromatolites, desiccation cracks, fenestrae, and evaporite mineral casts, indicating a shallowing-upward trend (Paik, 1987), whereas the overlying succession (Duwibong Formation) is composed of lime mudstone, oolite, peloidal grainstone, and skeletal pack-grainstone that are interpreted as shallow subtidal and lagoonal facies (Lee, 1988; Hyeong and Lee, 2001). The characteristics of the Jigunsan Formation imply that processes related to a transgression had an important role on the deposition. Based on cursory descriptions of outcrop sections, including the most fossiliferous interval, the mudstone of the Jigunsan Formation was interpreted as deposition in either low-energy offshore (Kobayashi, 1966) or restricted and stagnant lagoonal environments (Choi et al., 2001).

The present study provides a detailed description of sedimentary facies in the Jigunsan and the bounding formations. Sedimentological descriptions of all available outcrop sections reveal the existence of abundant small-scale bioturbation and sharp-based thin laminae which are suggestive of dysaerobic conditions and active sedimentary processes, respectively (e.g. Wignall and Hallam, 1996; Wignall and Twitchet, 1999; Schieber, 2003). The new findings are characteristic of transgressive deposits in a sequence stratigraphic perspective. According to the recent reconstruction of the North China Block in the Korean peninsula, the Taebaeksan Basin is an eastern arm of the North China Platform through the Pyeongnam Basin in North Korea (Paek et al., 1996; Chough et al., 2000; Chough, 2006). A detailed sedimentological study of the Jigunsan Formation provides an understanding of the extent of basin-wide response of sea-level change in the entire North China Platform and new information on basin geometry and depositional processes.

2. GEOLOGIC SETTING

The Joseon Supergroup, a thick sequence of Cambrian-Ordovician carbonate and siliciclastic deposits, occurs in

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the Taebaeksan Basin, in the mideastern part of the Korean peninsula (Fig. 1A, B). The basin is bounded on the north and northwest by Precambrian granitic gneiss (Gyeonggi Massif) and Jurassic granites. It is bounded on the southwest by metamorphic and metasedimentary rocks (Okcheon Group; Fig. 1A, B). The sequence rests unconformably on Precambrian metasedimentary rocks (Yulli Group) and granitic gneiss (Yeongnam Massif) in the south and southeast and is unconformably overlain by Permo-Carboniferous siliciclastic strata (Pyeongang Supergroup). The Joseon Supergroup formed in a tectonically stable intracratonic basin and was predominantly deposited in a shallow marine setting (Kwon et al., 2006). It consists predominantly of carbonate with lesser amounts of sandstone and shale (Chough et al., 2000). The supergroup is divided into five lithologic units: Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups (Table 1; Fig. 1B). The Taebaek and Yeongwol groups yield diverse and abundant invertebrate fossils, whereas the other groups are poorly fossiliferous. The Taebaek Group is subdivided into two subgroups: the Jikdong Subgroup (Cam-

brian) and the Sangdong Subgroup (Ordovician) (Table 1; Choi, 1998). The Jikdong Subgroup comprises the Myeonsan/Jangsan, Myobong, Daegi, Sesong, and Hwajeol formations, whereas the conformably overlying Sangdong Subgroup includes a basal coarse siliciclastic unit (Dongjeom Formation) and overlying carbonate and shale units (Dumugol, Makgol, Jigunsan, and Duwibong formations) (Tables 1 and 2). In this study, we focus on the Jigunsan Formation and the adjacent strata (upper part of the Makgol Formation and the lower part of the Duwibong Formation).

In the upper part of the Sangdong Subgroup, the Makgol Formation (250–400 m thick) consists mainly of micritic limestone, grainstone, laminated lime mudstone, bioturbated wackestone, limestone breccia, limestone conglomerate, and dolostone (Table 2; Paik, 1985, 1986, 1987; Ryu et al., 1997; Woo, 1999). The upper part of this unit is characterized by strata with stromatolites, desiccation cracks, fenestrae, and evaporite mineral casts (Paik, 1987; Woo, 1999). Although fossils are sparse, trilobites (Kobayashi, 1966; Choi, 1998) and conodonts (Lee and Lee, 1990) are of Mid-

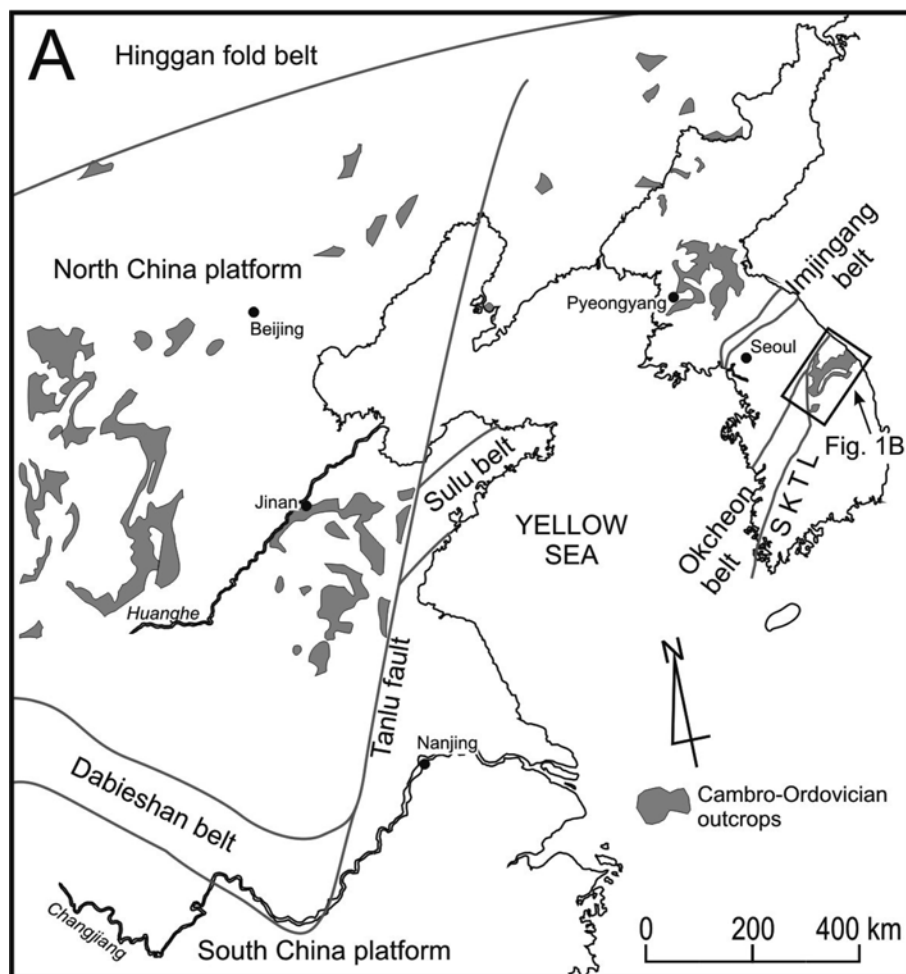


Fig. 1. (A) Distribution of Cambrian-Ordovician sedimentary rocks and outline of major orogenic belts and cratonic blocks of the north-eastern Asian margin. Modified from Ma et al. (1996) and Chough et al. (2000). TB=Taebaeksan Basin, SKTL=South Korean Tectonic Line.

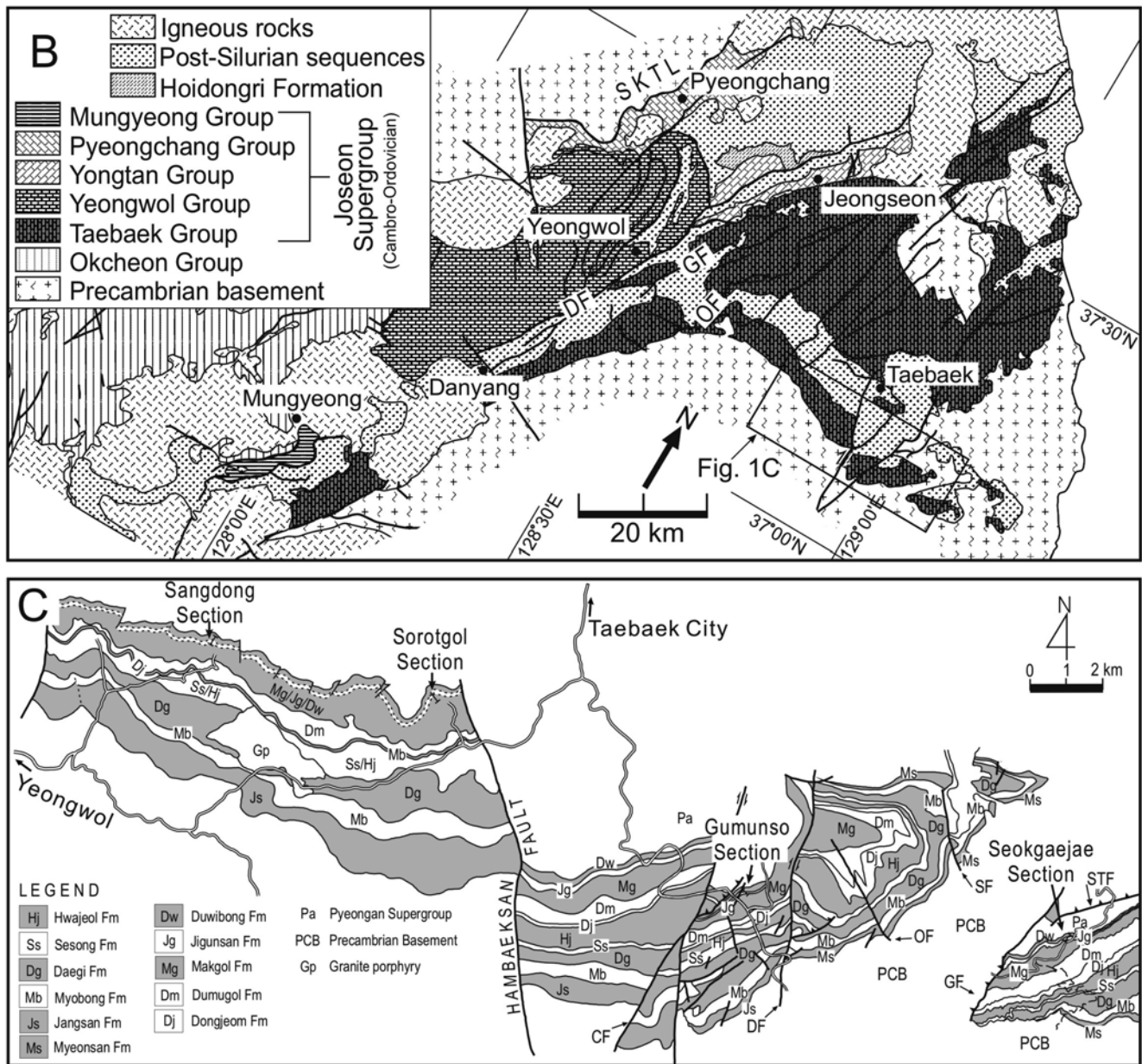


Fig. 1. (continued) (B) Geologic map of the Taebaeksan Basin (after Choi, 1998). DF=Deokpori fault, GF=Gogsuwon fault, OF=Okdong fault. (C) Geologic map of Sangdong-Samcheok area, showing the distribution of the Taebaek Group and the location of the measured sections. CF=Cheolam fault, DF=Dongjeom fault, OF=Ohongol fault, SF=Seonwol fault, STF=Sambang thrust fault, GF=Gwanghwari fault. Modified from GICTR (1962) and Chough et al. (2000).

dle Ordovician (late Arenig to Darriwilian) age. The overlying Jigunsan Formation (30–60 m thick) consists mainly of dark gray to black mudstone, laminated calcisiltite, limestone conglomerate, and interbedded limestones (Table 2). The dark gray mudstone in the lower part of the formation yields abundant Middle Ordovician fossils, including trilobites, graptolites, brachiopods, gastropods, cephalopods, ostracods, and fossils of uncertain affinity (Kobayashi, 1934). A single biozone of trilobite (*Dolerobasilicus* zone) indicating Llanvirnian (Darriwilian) age was established from the

most prolific part of the Jigunsan Formation (Table 3; Choi et al., 2001). Previous studies of conodonts suggest that deposition occurred during the *Eoplacognathus suecicus*–*Eoplacognathus jigunsanensis* zone of Llanvirnian (Darriwilian) age and can be correlated with the Upper Majiagou Formation of North China (Table 3; Lee and Lee, 1990). The Duwibong Formation (about 50 m thick), the uppermost unit of the Taebaek Group, consists of dark gray oolitic grainstone, bioclastic wackestone to grainstone, and oncoidal wackestone to packstone (Table 2). Trilobites, brachiopods,

Table 1. Stratigraphic nomenclature of the Cambro-Ordovician Joseon Supergroup in the Taebaeksan Basin (after Choi, 1998).

Geologic Age		Distribution											
		Yeongwol (Yongwol)		Taebaek-Samcheok (Taebaek-Samchok)			Jeongseon (Chongson)		Pyeongchang (Pyongchang)	Mungyeong (Mungyong)			
Ord.	Ashgill												
	Caradoc	Yeongwol (Yongwol) Group	Yeongheung (Yonghung) Fm	Taebaek Group	Sangdong Subgroup	Duwibong (Tuwibong) Fm	Yongtan Group	Haengmae Fm	Pyeongchang (Pyongchang) Group	Mungyeong (Mungyong) Group	carbonate strata		
	Llanvirn												
	Arenig					Jigunsan (Chigunsan) Fm		Jeongseon (Chongson) Fm					
						Makgol (Makkol) Fm							
Tremadoc	Mungok Fm					Dumugol (Tumugol) Fm							
Camb.	Late		Taebaek Group	Jikdong (Chiktong) Subgroup	Hwajeol (Hwajol) Fm								
		Machari Fm			Sesong Fm								
	Middle	Sambang-san Fm			Daegi (Taegi) Fm								
					Myobong Fm								
	Early											Jangsan (Changsan) Fm	

This table uses a new system for transcribing formation names from the Korean alphabet. The old system (1983–2000) is in parentheses.

Table 2. Lithostratigraphic summary of the Taebaek Group.

Geologic Age	Lithostratigraphic Unit	Lithofacies	Thickness
Ordovician	Duwibong Fm.	Light gray, massive limestone with shale	50 m
	Jigunsan Fm.	Dark gray mudstone with limestone	30–60 m
	Makgol Fm	Laminated limestone, dolostone, bioturbated limestone, breccia, and stromatolite	250–400 m
	Dumugol Fm.	Marlstone, limestone-shale couplet, and intraformational conglomerate	100–200 m
	Dongjeom Fm.	Gray to pinkish quartzite and dark gray sandstone	10–50 m
Cambrian	Hwajeol Fm.	Intraformational conglomerate and limestone-shale couplet	200–260 m
	Sesong Fm.	Gray to red marl or slate with sandstone and limestone	10–30 m
	Daegi Fm.	Light to dark gray, massive limestone with breccia, oolitic limestone, and dolostone	150–300 m
	Myobong Fm.	Dark gray or greenish gray argillaceous siltstone to shale with sandstone	100–250 m
	Jangsan Fm.	White or pinkish white quartzite and conglomerate	5–200 m
	(Myeonsan Fm.)	(Conglomerate and dark gray to black sandstone)	(60–90 m)

cephalopods, gastropods, bivalves, and ostracods indicate that deposition occurred during the Late Ordovician (Caradoc; Kobayashi, 1966). Lee and Lee (1990), however, recognized two Llanvirnian (Darriwilian) conodont zones (Table 3).

The strata of the Taebaek Group are well correlated for long distances, although the strata in the western part of the basin are offset by a series of large-scale strike-slip and thrust faults (Fig. 1B). Chough et al. (2000) suggest that these thrusts represent accretion of the Gyeonggi Massif

(and the Okcheon Basin) to the Yeongnam Massif (and the Taebaeksan Basin). These faults mark a major tectonic boundary between the Sino-Korean Block and the South China Block, named the South Korean Tectonic Line (SKTL). During the accretion, a series of north-trending thrusts developed in the western part of the Taebaeksan Basin, whereas in the eastern part a series of north-trending dextral strike-slip movements occurred. The Jigunsan Formation can be traced in the eastern part of the basin, but not

Table 3. The conodont zones and correlation (after Lee and Lee (1990) for conodont and Choi et al. (2001) for trilobite biozones).

Global Series	Global Stages	British Series	Europe		North America	North China		Korea (Taebaek Group)				
			Conodont biozone			Lithologic Units	Conodont biozone	Lithologic Units	Conodont biozone	Trilobite biozone		
Middle Ordovician	Darrivillian (Volkhovian)	Llandellio	<i>Pygodus inseridus</i>			unnamed zone						
			<i>Pygodus serra</i>	<i>E. Lindstroemi</i>				<i>Aurilobodus serratus</i>	<i>Aurilobodus serratus</i>			
				<i>E. robustus</i>								
				<i>E. reclinator</i>	5		6				<i>Plectodina onychodonta</i>	<i>P. onychodonta</i>
				<i>E. foliaceus</i>								
		Llanvirn	<i>Eoplacognathus suecicus</i>			Upper Majiagou Fm.	<i>E.suecicus</i> - <i>Acontiodus</i> (?) <i>linxiensis</i>	<i>Jigunsan Fm.</i>	<i>E. suecicus</i> - <i>E. jigunsanensis</i>	<i>Dolerobasilicus</i>		
			<i>Ambalognathus variabilis</i>				unnamed zone					
		Arenig	<i>Microzarkodina parva</i>		4	Lower Majiagou Fm.		<i>Upper part of the Makgol Fm.</i>	unnamed zone			
			<i>Paroistodus originalis</i>				<i>Tangshanodus tangshanensis</i>			<i>Aurilobodus leptosomatus</i>	generally barren interval	
			<i>Prioniodus navis</i>	3								
			<i>Prioniodus triangularis</i>				<i>Aurilobodus leptosomatus</i> - <i>Loxodus dissectus</i>					
			<i>Oepikodus evae</i>	2								

across the north-trending Gakdong and Deokpori thrusts (Fig. 1B).

Palaeogeographic studies based on the affinities of trilobites (Choi et al., 2001) and conodonts (Jeong and Lee, 2000, 2004) and the coeval occurrence of green marine claystone (Kim and Lee, 2000) are suggestive of a close affinity between the Taebaeksan Basin and the North China Platform, both of which were in low latitudes during the Cambrian and Ordovician. According to the recent plate reconstruction of the Sino-Korean Block (Chough et al., 2006), the Taebaeksan Basin formed in an eastward extending arm of the North China Platform across the Pyeongnam Basin, North Korea (Fig. 2).

3. FACIES ANALYSIS

Four sections (Sangdong, Sorotgol, Gumunso, and Seokgaejae; Fig. 1C) were measured in detail. Eleven sedimen-

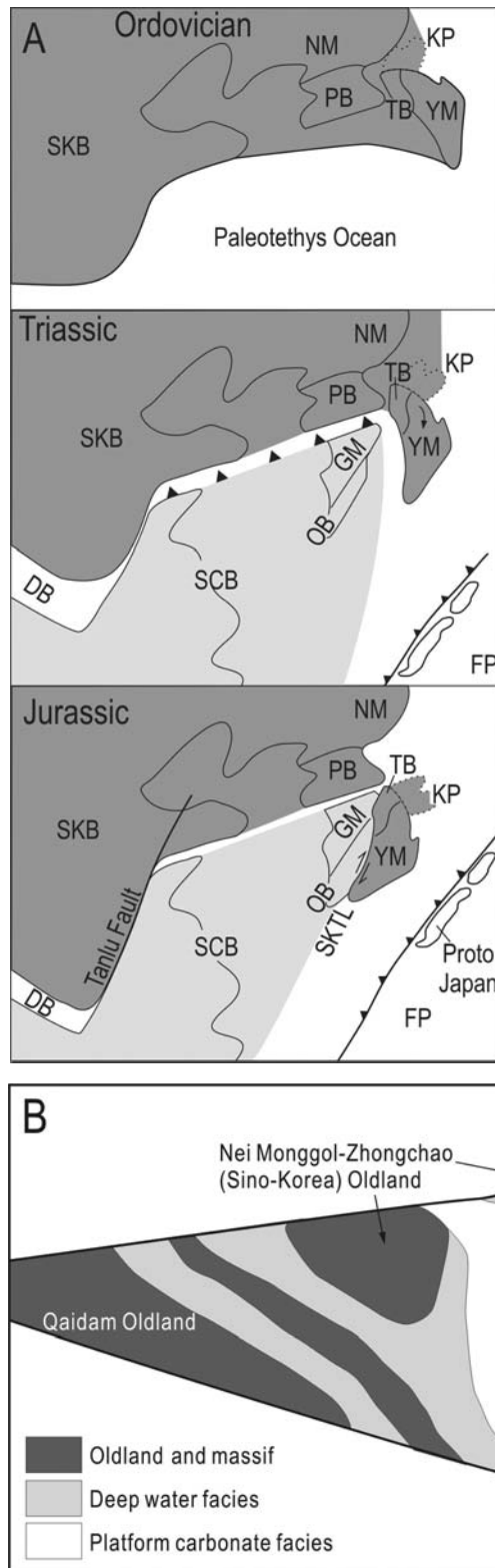
tary facies are recognized based on grain size, sedimentary structures, color, and constituents of carbonate grains (Table 4; Fig. 3). These facies are grouped into 6 facies associations (FAs) representing depositional environments or depositional cycles (Table 5). The facies associations are numbered, from 1 to 6 in ascending order. Figure 3 is a columnar section of the Seokgaejae section and its representative facies associations. In the four measured sections, the facies associations are generally well correlated with one another (Fig. 4).

3.1. Facies Association 1 (FA1): Shallow Subtidal to Supratidal (peritidal) Platform

Facies association 1 (Table 5) consists mainly of tabular beds of thickly laminated lime mudstone (LMT; Fig. 5B), bioturbated wackestone (Wb; Fig. 5C), and finely laminated lime mudstone (LML; Fig. 5D). These facies occur as meter-

Table 4. Description and interpretation of sedimentary facies.

Facies	Description	Interpretation
Dark gray mudstone (<i>facies Md</i>)	Parallel lamination in some horizons; horizontally elongated micro-burrows; organic-rich (0.75–6% TOC); iron sulfide (pyrite) rich; silt- to very fine sand-sized quartz grains in part; illite and chlorite clay mineral assemblage; common pyritic calcareous nodules; abundant fossils (trilobites, brachiopods, gastropods, cephalopods, graptolites and ostracods) in some horizons.	Deep basinal sediment deposited by hemipelagic suspension settling and distal storm current in oxygen restricted condition (O'Brien, 1996; Schieber, 2003)
Greenish gray siltstone (<i>facies Mg</i>)	Severely bioturbated; partly calcareous; consists of silt-sized quartz grains (0.025–0.05 mm in diameter), opaque minerals (or organic matter) and small skeletal grains; a few peloids or mudchips; abundant calcareous nodules; sedimentary structures such as parallel lamination in some nodules.	Suspension settling deposit disturbed by bioturbation in well oxygenated deep to shallow subtidal condition
Thickly laminated lime mudstone (<i>facies LMi</i>)	Crude alternation of lime mudstone and dolomitic argillaceous (or organic-rich) laminae; less than 5 mm in thickness and indistinct boundaries; few peloids and intraclasts (0.25–2.5 mm in diameter) in lime mudstone; pyrites commonly associated with stylolitic structures.	Suspension settling sediment low energy condition such as lagoon or deep subtidal; with variation of argillaceous contents
Finely laminated lime mudstone (<i>facies LMI</i>)	Mainly consist of lime mudstone laminae which slightly vary in color and occasionally parted by thin argillaceous (organic-rich) laminae; each lamina less than 1 mm in thickness and parallel to subparallel each other; slightly wavy and undulatory lamination; thin argillaceous laminae commonly associated with micro-stylolite parallel to bedding plane; about 40% of total volume dolomitized	Intertidal to supratidal cryptalgal laminite (Hardie, 1977; Shinn, 1983)
Bioturbated wackestone (<i>facies Wb</i>)	Lime mud matrix, a few skeletal grains, peloids and dolomite crystals; slightly bioturbated (ichnofacies index-2 or index-3); burrows commonly filled with dolomites and argillaceous materials; crudely laminated; peloids and various shapes of small lime mudstone clasts in some layers.	Shallow subtidal deposit slightly disturbed by bioturbation (Paik, 1987; Overstreet et al., 2003)
Massive pack-grainstone (<i>facies P-Gm</i>)	Massive mixture of brachiopods, cephalopods, gastropods and trilobites; lime mud matrix and/or sparry calcite cement in porespace; various lime mud contents ranging from packstone to grainstone; partly intercalating laminated layers.	Deposition in moderately agitating shallow subtidal (Glumac and Walker, 2000)
Peloidal grainstone (<i>facies Gp</i>)	Light gray to gray in color; various peloids (0.1–10 mm in diameter) and dolomite crystals; well rounded circular, subcircular and ellipsoidal peloids; usually massive except stylolite and microstylolite swarms parallel to bedding plane; slightly dolomitized; texture selective dolomitization; few fine sand-sized quartz grains.	Winnowed deposit in high energy shoreface (Overstreet et al., 2003)
Oolitic grainstone (<i>facies Go</i>)	Medium sand-sized ooids (~ 0.4 mm in average diameter) and lesser amounts of peloids and skeletal grains; moderately sorted and rounded, subrounded to ellipsoidal ooids; many ooids with nuclei of skeletal grains of various shape; radial and concentric internal laminae; a few aggregated ooids.	High-energy subtidal shoal (Tucker and Wright, 1990)
Massive grainstone (<i>facies Gm</i>)	Predominant sand-sized skeletal grains without lime mud matrix; skeletal grains composed of fragments of echinoderms lesser amounts of brachiopods, trilobites and peloids; thin to medium (1–30 cm) bedded facies unit; laterally continuous with small variation of thickness change; sharp lower and upper boundary; occasional occurrence of normal grading and parallel or wavy lamination.	High-energy shallow subtidal deposit such as bioclastic sand sheets; accumulated during full-to waning-storm conditions (Jones and Desrochers, 1992; Lavoie and Asselin, 1998)
Laminated calcisiltite (<i>facies CZI</i>)	Parallel, ripple cross-laminated or low-angle (10–15°) cross laminated (hummocky or swaley) laminae; lamination of alternating calcareous and shaly materials; calcareous lamina consist of silt-sized particles; darker argillaceous lamina consist of unclear finer grains; distinct, sharp and erosional bases of each unit; faint, gradational and occasionally wavy upper boundaries; horizontal, oblique and v-shaped burrows; each unit from several millimeters to 15 cm in thickness.	Unidirectional current on low angle platform, with oscillatory movement of water induced by storm (Aigner, 1985; Myrow and Southard, 1996)
Limestone conglomerate (<i>facies LC</i>)	Matrix supported; grainstone clasts and grainstone matrix; clasts of peloidal and skeletal grainstone; round subcircular and ellipsoidal clasts (about 1–2 cm in diameter); matrix mostly consist of skeletal, peloidal grains and ooids; sharp erosional base and sharp or diffuse upper boundary; variable in thickness from a few centimeters to deci-meter; continuous.	Storm lags in a subtidal setting Or deposit derived from locally developed gentle slope (Markello and Read, 1981; Seguret et al., 2001)



scale cycles (Fig. 5A) composed of a basal well-rounded intraclastic peloidal grainstone (Gp; Fig. 5E), overlain by thickly laminated lime mudstone and/or bioturbated wackestone in ascending order and capped by finely laminated lime mudstone (Fig. 5A). Laminae of the thickly laminated lime mudstone are alternations of lime mudstone and argillaceous dolomitic lime mudstone. The boundaries of the laminae are diffusive (Fig. 5B). Original bedding of the bioturbated wackestone is moderately disrupted by small vertical and inclined burrows (Fig. 5C). Finely laminated lime mudstone is characterized by very thin (less than 1 mm) horizontal laminae of different color (Fig. 5D). About 40% of the total volume of the facies is dolomitized. All facies units are tabular and laterally continuous at outcrop scale, ranging in thickness from 0.5 to 2.5 m. This facies association occurs in the upper part of the Makgol Formation (Fig. 4).

This facies association is interpreted as deposits of peritidal cycles, with a facies succession ranging from subtidal to supratidal environments (e.g. Tucker and Wright, 1990; Pratt et al., 1992; Holland and Patzkowsky, 1998). The peloidal grainstone unit consists of irregular clasts of lime mudstone (Fig. 5E) and represents lag deposits under high-energy conditions of high-order relative sea-level rise (e.g. Overstreet et al., 2003), whereas the thickly laminated lime mudstone represents suspension settling or *in situ* accumulation of degraded debris from calcareous algae in low-energy conditions. The abundance of horizontal and slightly inclined burrows in bioturbated wackestone is suggestive of shallow subtidal environments (Rhoads, 1967; Paik, 1987; Woo, 1999). The finely laminated lime mudstone is suggestive of cryptalgal mats in the upper intertidal or supratidal envi-

Fig. 2. (A) Tectonic reconstruction of the Sino-Korean Block (SKB) and South China Block (SCB): the Ordovician pre-deformational stage and post-deformational stages in the Triassic and Jurassic. The North China Platform and the sedimentary basins in Korea were adjacent in the Ordovician. NM=Nangrim Massif, PB=Pyeongnam Basin, TB=Taebaeksan Basin, KP=Korea Plateau, YM=Yeongnam Massif, GM=Gyeonggi Massif, OB=Okcheon Belt, FP=Farallon Plate. Modified from Chough et al. (2000). (B) Paleogeographic reconstruction of the Sino-Korean Block and distribution of oldlands, massifs and the Middle Ordovician deposits (modified from Mey-erhoff et al., 1991). Broken lines indicate inferred extent of the Taebaeksan Basin (TB) and the Pyeongnam Basin (PB).

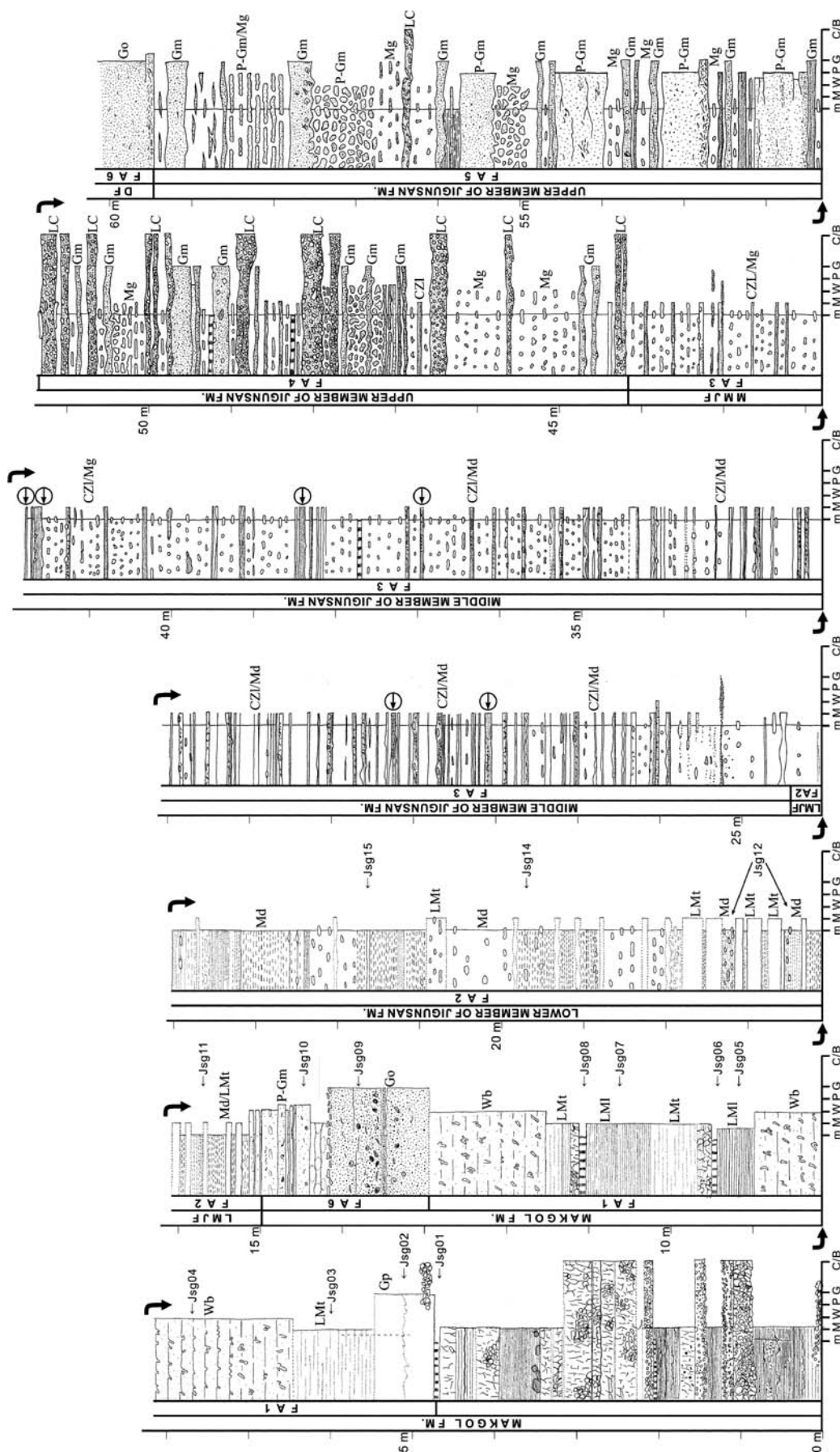


Fig. 3. Representative columnar description of the upper part of the Makgol and Jigunsan formations in the Seokgaegae section. LMJF: lower member of Jigunsan Formation, MMJF: middle member of Jigunsan Formation, DF: Duwibong Formation, m: mudstone, M: lime mudstone, W: wackestone, P: packstone, G: grainstone, C/B: limestone conglomerate/breccia. Arrows in circle indicate direction of paleocurrents. For facies codes, see Table 3.

Table 5. Constituent facies and interpretation of the facies associations.

Facies association	Constituent facies	Depositional environment
FA 1	Peloidal grainstone	Shallow subtidal to supratidal (peritidal) platform (Tucker and Wright, 1990; Pratt et al., 1991)
	Thickly laminated lime mudstone	
	Bioturbated wackestone	
	Finely laminated lime mudstone	
FA 2	Dark gray mudstone	Oxygen-restricted deep subtidal to basinal environments (Einsele and Ricken, 1991; De Boer, 1991)
	Thickly laminated lime mudstone	
	Pyritic calcareous nodules	
FA 3	Dark gray mudstone	Storm-influenced deep subtidal platform (outer ramp) (Aigner, 1985; Molina et al., 1997)
	Greenish gray siltstone	
	Laminated calcisiltite	
FA 4	Greenish gray siltstone	Storm-influenced deep to shallow subtidal platform and slope (mid ramp) (Aigner, 1985; Evans et al., 1995)
	Massive grainstone	
	Limestone conglomerate	
FA 5	Greenish gray siltstone	Shallow subtidal platform (Glumac and Walker, 2000)
	Massive pack-grainstone	
FA 6	Oolitic grainstone	Shallow subtidal shoal (Elric and Read, 1991; Hyeong and Lee, 2001)
	Massive pack-grainstone	

ronments. The peritidal shallowing-upward cycles result from rapid sedimentation and consequent progradation of the tidal flat (Pratt et al., 1992).

3.2. Facies Association 2 (FA2): Oxygen-restricted Deep Subtidal to Basinal Environments

Facies association 2 (Table 5) is characterized by alternations of thickly laminated lime mudstone (LMt) and siliciclastics (dark gray siliciclastic mudstone, Md) with layered pyritic-calcareous nodules (Fig. 6). This facies association occurs in the lower part of the Jigunsan Formation and makes up one unit about 10 m in thickness. Several dark gray mudstone horizons in the lower part of the facies association unit contain a high content of organic matter (0.75–6% total organic carbon). The facies boundaries are commonly indistinct and gradational. Facies association 2 shows an upward trend of increasing dark-gray mudstone. In the lower part of the unit, the alternating lime mudstone and dark gray mudstone beds are decimeters thick. In the upper part, a few thin and nodular lime mudstone beds are interbedded with thick dark gray mudstone (Fig. 4). Small-scale (less than 3 mm in diameter) burrows are common in both facies (Fig. 6B). The contact with the underlying unit (FA6) is indistinct and transitional. In the Sangdong and Sorotgol sections, facies association 2 includes a few layers of laminated calcisiltite. This facies association yields open marine fauna such as cephalopods and graptolites.

The alternation of dark gray mudstone and lime mudstone is interpreted to represent deep subtidal cycles of deep platform to basinal environments (De Boer, 1991; Einsele and Ricken, 1991). The homogeneous or faintly laminated

dark gray mudstone represents hemipelagic suspension settling (O'Brien, 1996). Abundant pyrite grains in the dark gray mudstone and relatively high content of organic matter suggest oxygen-depleted depositional conditions. The lack of macro-bioturbation also implies that oxygen levels were relatively low, but the common occurrence of micro-bioturbation is suggestive of low oxygen level, i.e. dysoxic conditions (Wignall and Hallam, 1996). Lime mudstone was deposited by suspension settling in low-energy conditions such as deep subtidal environments. An alternation of these facies probably formed by changes in water depth or oceanographic conditions such as water temperature or salinity causing fluctuation of carbonate production (De Boer, 1991; Einsele and Ricken, 1991) as well as changes in runoff induced by long-term climatic changes. The indistinct boundaries and the gradual changes between the constituent facies are suggestive of a gradual shift in these conditions.

3.3. Facies Association 3 (FA3): Storm-influenced Deep Subtidal Platform (outer ramp)

Facies association 3 (Table 5) consists of thin-bedded laminated calcisiltite (CZl; Fig. 7B), dark gray mudstone (Fig. 6B), and greenish gray siltstone (Mg; Fig. 7C). The lower boundaries of the laminated calcisiltite beds are very sharp and slightly erosional (Fig. 7B). Each bed is tabular and continuous. A few beds contain current ripple lamination and both small-scale hummocky and swaley cross-laminations (Figs. 8 and 9). The upper boundaries of the laminated calcisiltite beds are gradational and commonly disturbed by various burrows (Figs. 7B and 9). The mudstone beds, which alternate with the laminated calcisiltite

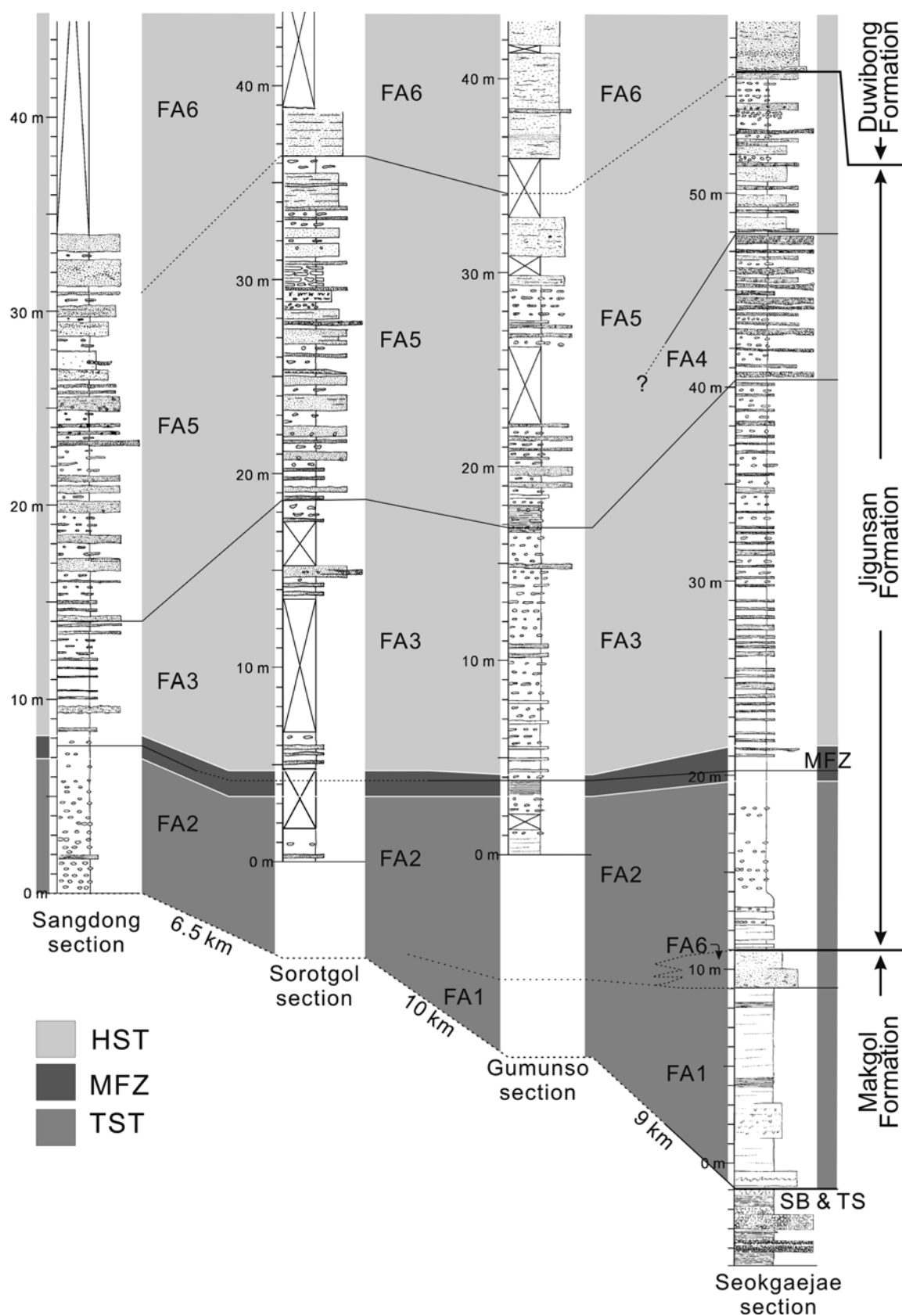


Fig. 4. Correlation of facies associations (FAs), bounding surfaces and systems tracts in the Jigunsan Formation. SB=sequence boundary, TS=transgressive surface, MFZ=maximum flooding zone, TST=transgressive systems tract, HST=highstand systems tract. For location of the sections, see Figure 1C.

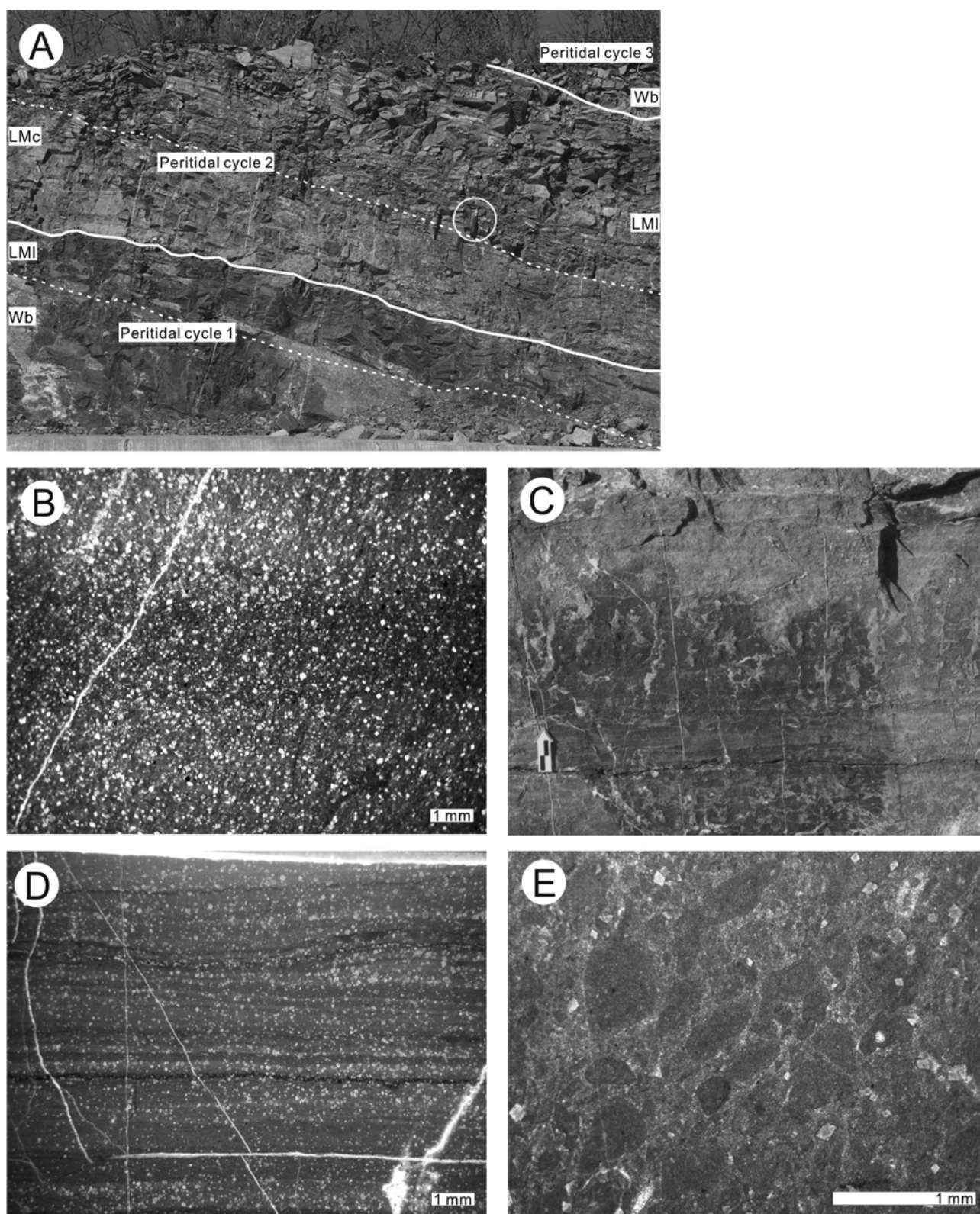


Fig. 5. Photographs and photomicrographs of facies association 1 and constituent facies. (A) Close-up of peritidal cycle 2 showing shallowing-upward facies succession. Hammer for scale is 27 cm long. (B) Photomicrograph of thickly laminated dolomitic lime mudstone (*LMI*). Crude dark lamina is composed of argillaceous materials. Dolomite crystals are pervasive in both dark and light laminae. (C) Outcrop photograph of bioturbated wackestone (*Wb*). Scale is in cm. (D) Photomicrograph of finely laminated lime mudstone (*LMI*). Laminae consist of alternation of light and dark laminae. (E) Photomicrograph of peloidal grainstone (*Gp*). Peloidal grainstone comprises various peloids and dolomite crystals.

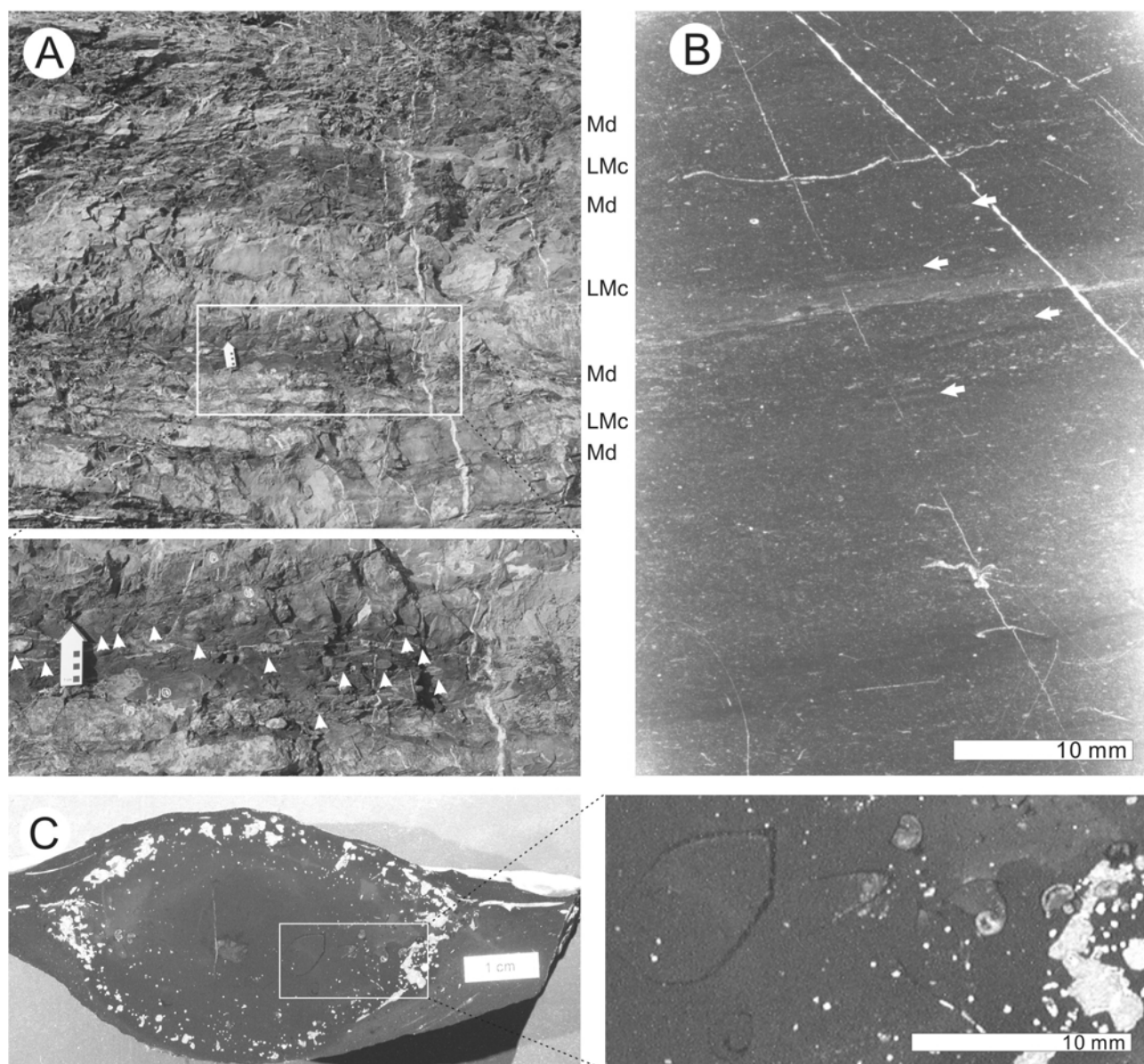


Fig. 6. Photographs and photomicrographs of facies association 2 and constituent facies. (A) Outcrop photograph of facies association 2 in the Seokgaejae Section showing alternation of lime mudstone (*LMt*) and dark gray mudstone (*Md*). Note that both the upper and lower boundaries of the units are gradual. The lower part is enlarged view of boxed area showing organic rich (~6% total organic carbon) dark gray mudstone with pyritic calcareous nodules (arrows). Scale is in cm. (B) Photomicrograph of dark gray mudstone (*Md*) showing horizontal lamination and micro-bioturbations (arrows). (C) Pyritic calcareous nodule. Note pyrite crystals and fossil fragments replaced by pyrite in the outer rim. Enlarged area shows details of the outer rim and small shells in the nodule.

beds, show coarsening-upward trend from dark gray mudstone to greenish gray siltstone. Along with the changes in grain size and color, the intensity of bioturbation in the mudstone significantly increases in the upper part of the facies associations. This unit ranges in thickness from 10 to 23 m in the Sokgaejae, Sangdong, and Sorotgol sections (Fig. 4). In the Sangdong and Sorotgol sections, it includes a few massive grainstone beds (Fig. 4).

The rare occurrence of small-scale hummocky and swaley cross-laminae in the laminated calcisiltite is suggestive

of storm activity (Kreisa, 1981; Handford, 1986; Monaco, 1992; Molina et al., 1997). The parallel and cross-laminated calcisiltite beds are interpreted as deposits of dilute density currents induced by storms (Aigner, 1985; Myrow and Southard, 1996; Myrow et al., 2002). Paleocurrent data from current ripple laminae in the calcisiltite indicate westward flows (Fig. 3). The siliciclastic mudstone facies represent background deposition of suspension settling in deep platform to basinal environments. The facies change of the background sediment from dark gray mudstone to greenish

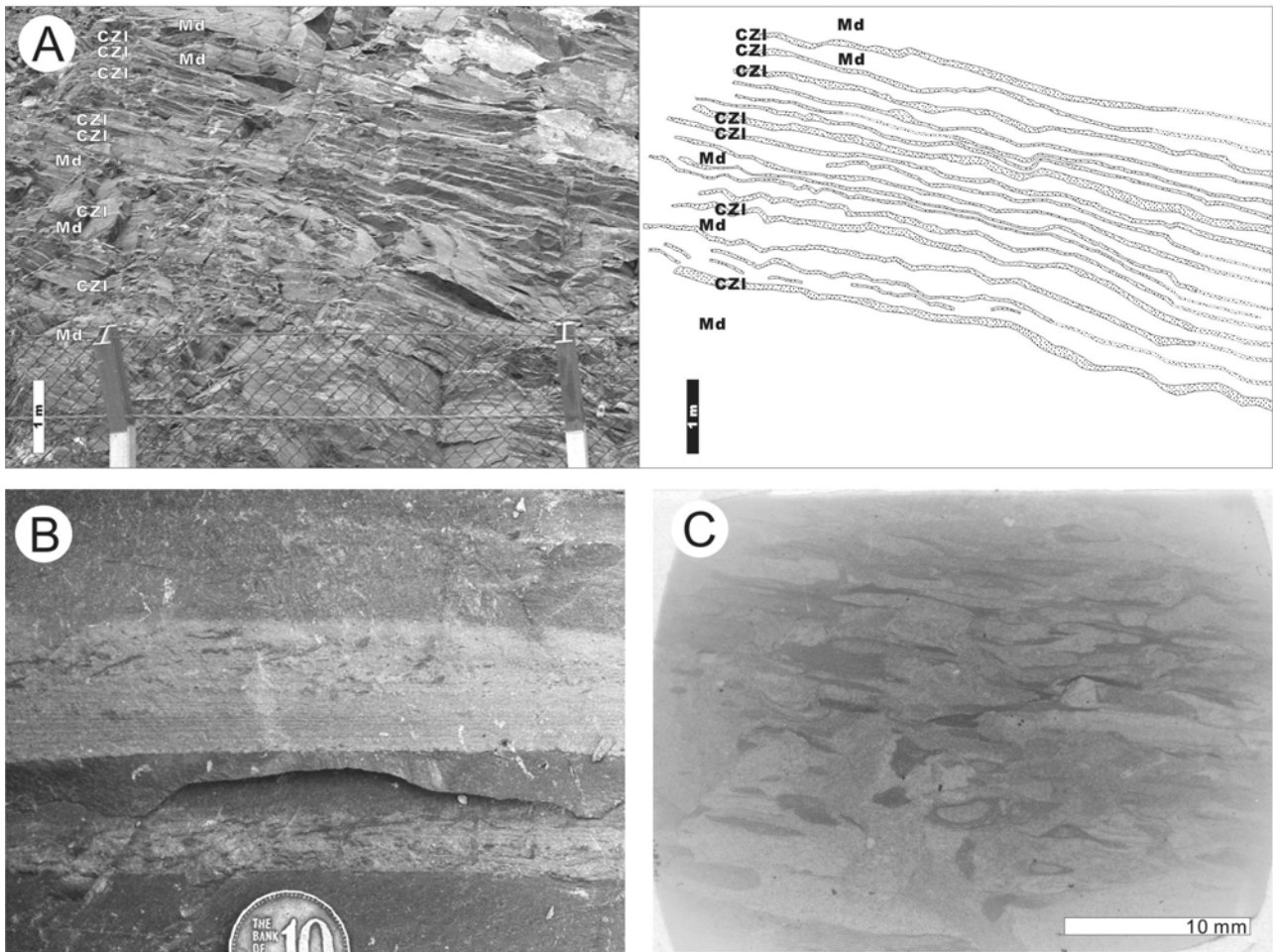


Fig. 7. Photographs and photomicrographs of facies association 3 and constituent facies. (A) Outcrop photograph and line drawing of facies association 3 showing frequent alternation of dark gray mudstone (*Md*) and laminated calcisiltites (*CZI*) in the Seokgaejae section. (B) Outcrop photograph of laminated calcisiltite (*CZI*) with sharp base, parallel lamination and burrows in the upper part. Coin for scale is 2.3 cm in diameter. (C) Polished hand sample of strongly bioturbated greenish gray siltstone (*Mg*).

gray siltstone is suggestive of an increase in oxygen levels. The upward decrease in water depth and the consequent more frequent input of storm induced density currents probably record change from an oxygen-restricted to well-oxygenated conditions.

3.4. Facies Association 4 (FA4): Storm-influenced Shallow Subtidal Platform (mid ramp)

Facies association 4 (Table 5) consists of greenish gray siltstone (Fig. 7C) and interbeds of centimeter- to decimeter-thick massive and normally graded pack-grainstone (P-Gm; Figs. 10B and 11B), massive grainstone (Gm; Fig. 10C), and limestone conglomerate (LC; Fig. 10E). These facies make up coarsening-upward cycles with a siltstone base and a grainstone and/or limestone conglomerate top (Fig. 3 and 10A). Tabular, well-bedded, and continuous cycle units are characterized by limestone conglomerate layers (Figs. 4 and 10A). The limestone conglomerate is matrix-supported

and consists of grainstone (or calcisiltite) clasts in a grainstone matrix (Fig. 10E). Clasts are composed of partly laminated argillaceous peloidal/skeletal grainstone of skeletal grains such as crinoids and ostracods as well as quartz grains (Fig. 10F). Although rounded subspherical and ellipsoidal clasts (about 1–2 cm in diameter) are most common, very irregular-shaped clasts with rugged outlines also occur (Fig. 10E, F). Tabular clasts are generally flat-lying. The matrix consists of larger skeletal (gastropods, trilobites, crinoids, cephalopods, and bryozoans) and peloidal grains which show texture similar to that of the massive grainstone facies (Fig. 10C). Massive grainstone commonly contains ooids (Fig. 10D) and the beds are in cases graded with parallel-lamination in the upper part (Fig. 11B). The facies transition from greenish gray siltstone to limestone conglomerate and/or massive grainstone is abrupt with a sharp boundary, whereas the reverse is gradational. Facies association 4 is about 8 m thick and occurs only in the Seokgaejae section (Fig. 4).

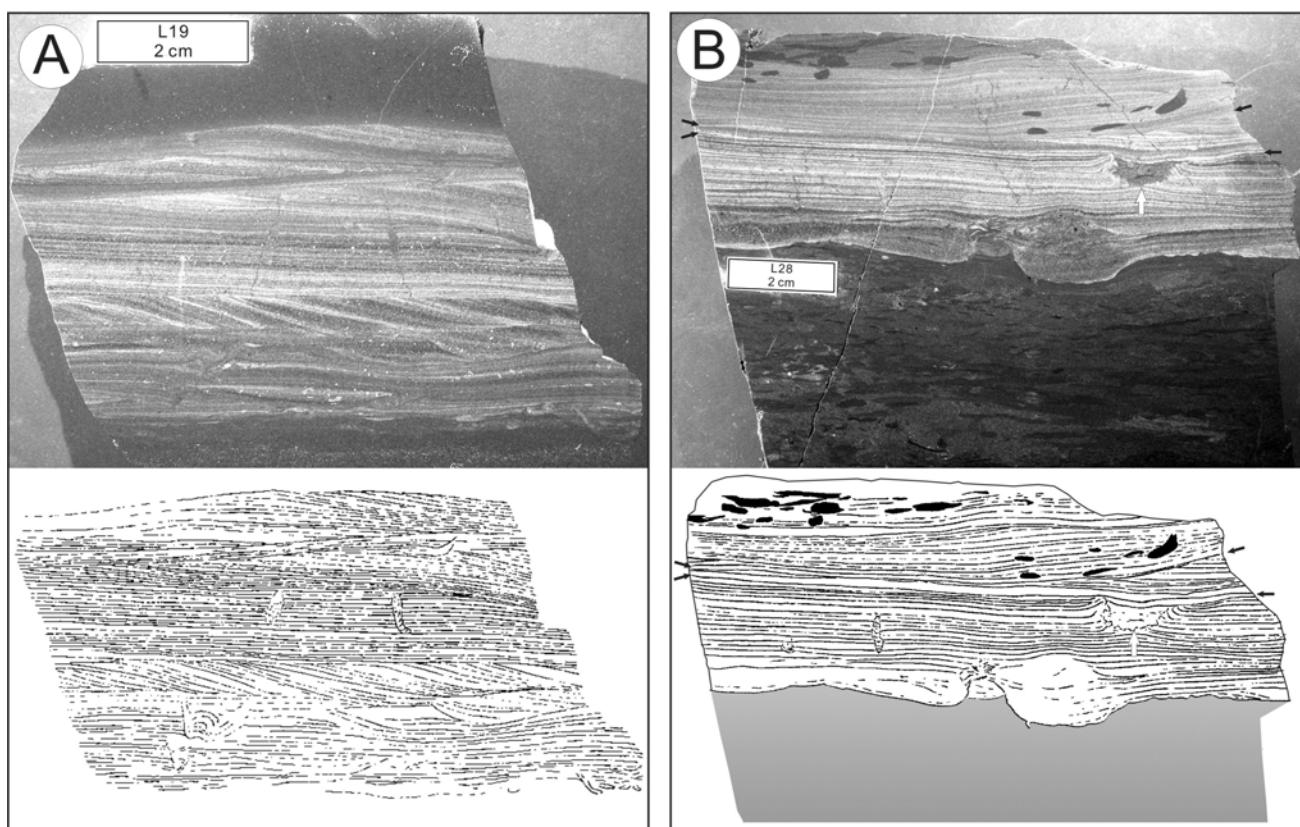


Fig. 8. (A) Slab photograph (upper) and line drawing (lower) of laminated calcisiltite (bed no. L19) showing various types of lamination including parallel lamination, ripple lamination and internal truncation. (B) Slab photograph (upper) and line drawing (lower) of laminated calcisiltite (bed no. 28) showing erosional surfaces (black arrows). The lower boundary is partly deformed by formation of calcareous nodules (center of the figure). Note various types of burrows; horizontal elongated burrows of dark gray mudstone and greenish gray siltstone beneath the laminated calcisiltite; elliptical and subhorizontal burrows in the upper part of laminated calcisiltite; and relatively large shallow vertical burrows disturbing the erosional surface (white arrow).

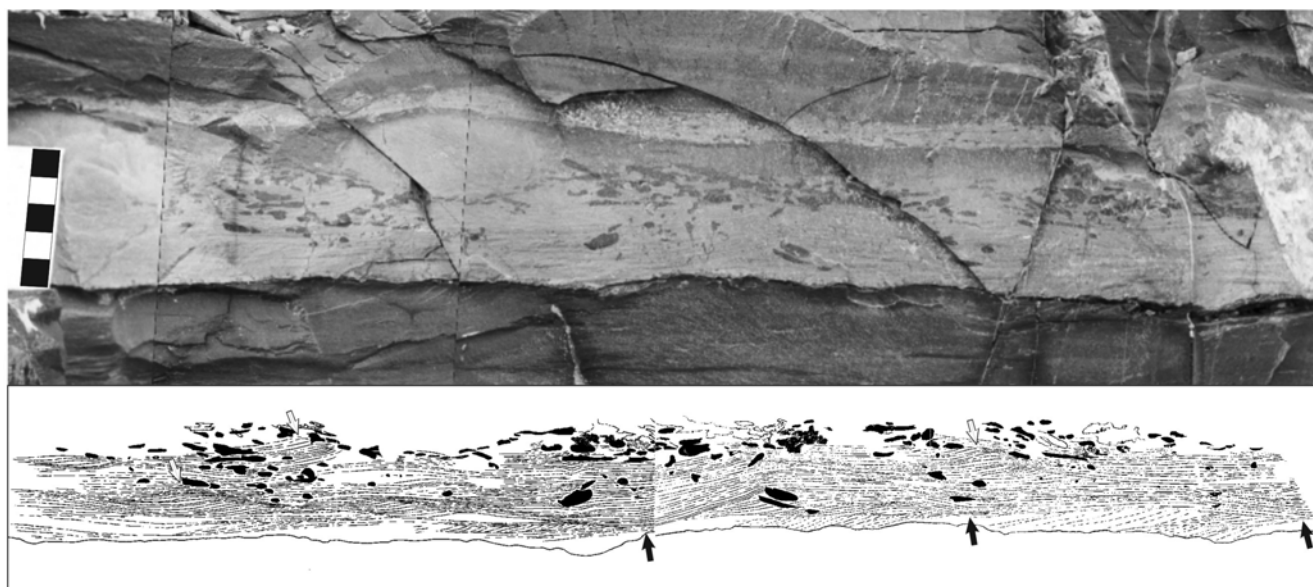


Fig. 9. Outcrop photograph (upper) and line drawing (lower) of laminated calcisiltite (bed no. 7) showing swaley cross-laminae (arrows) and ripple drift (open arrows). Burrows are abundant in the upper part of the bed. Scale is in cm.

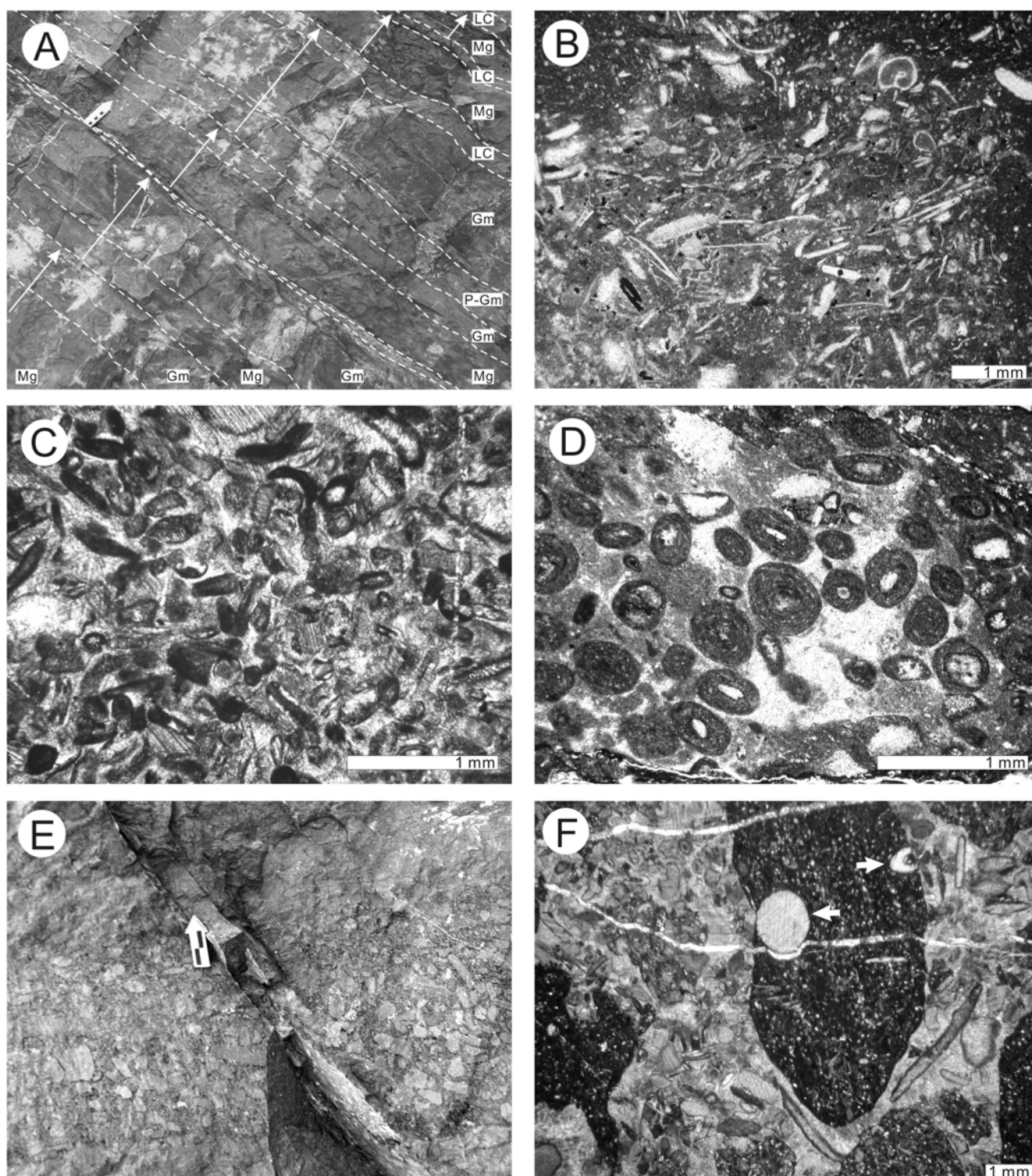


Fig. 10. Photographs and photomicrographs of facies association 4 and constituent facies. (A) Outcrop photograph annotated to show facies codes of facies association 4 in the Seokgaejae Section. Each facies unit is tabular and laterally continuous. Arrows indicate shallowing-upward cycles. Scale is in cm. (B) Photomicrograph of massive pack-grainstone (*P-Gm*). Skeletal grains embedded in lime mudstone matrix. (C) Photomicrograph of massive grainstone (*Gm*) including recrystallized and micritized grains. (D) Photomicrograph of ooid grains in massive grainstone. (E) Outcrop photograph of limestone conglomerate (*LC*). Note sharp lower boundary and matrix-supported texture. Scale is in cm. (F) Photomicrograph of limestone conglomerate. Round or irregular clasts consist of silt-sized grains with some larger skeleton fragments (arrows). Larger skeletal grains form matrix which shows texture that is similar to massive pack-grainstone.

This facies association is interpreted as the deposit of a storm-influenced shallow subtidal environment such as open mid ramp (e.g. Holland, 1993; Pope and Read, 1997; Choi et al., 1999). The sporadic interlayers of grainstone or conglomerate interbedded with siltstone are suggestive of repetitive event sedimentation (Einsele et al., 1991). The limestone conglomerate and grainstone interbedded in greenish gray siltstone are indicative of episodic storm activity in a mid ramp below fair-weather wave base (Aigner, 1985). Normally graded grainstone beds are suggestive of deposition from waning flow conditions (e.g. Kresia, 1981; Monaco, 1992). The bioturbated siltstone is suggestive of deposition in well-oxygenated conditions.

3.5. Facies Association 5 (FA5): Shallow Subtidal Platform

Facies association 5 (Table 5) consists mainly of greenish gray siltstone (Fig. 7C), massive (or graded) skeletal pack-grainstone (Figs. 10B and 11B) and lesser amounts of lime mudstone (Fig. 4), locally stacked into shallowing-up cycles (Figs. 3 and 4). Siltstone and grainstone beds form the lower part of these cycles, whereas the thicker packstone and grainstone comprise the upper divisions of the cycles (Fig. 3). Beds of individual facies are tabular and continuous (Fig. 11A), although the thin gravelly skeletal layers at

the base of pack-grainstone beds are discontinuous and lenticular. The greenish gray siltstone is much coarser than the dark gray mudstone facies and contains significant amounts of calcareous materials. The pack-grainstone and massive grainstone beds are characterized by a skeletal base and a laminated top. These deposits are highly bioturbated by abundant centimeter-scale burrows. The single unit of this facies association ranges in thickness from 8 to 17 m and occurs in the upper part of the measured sections (Figs. 3 and 4).

This facies association is similar to facies association 4 except for the absence of limestone conglomerate beds, and is interpreted as a shallow subtidal platform deposit. Strong bioturbation in pack-grainstone and greenish gray siltstone, albeit remnants of primary sedimentary structures, represents high biological activities in well-oxygenated conditions. Mixed calcareous grains in the siltstone are suggestive of deposition in moderately agitated platform (e.g. Glumac and Walker, 2000). The siltstone beds represent deeper water facies, whereas the thicker pack-grainstone beds represent shallower water facies in the cycle. The massive or graded pack-grainstone and massive grainstone beds with laminated tops, which are interbedded with the greenish gray siltstone, are suggestive of waning flow conditions during a storm event (Aigner, 1985).

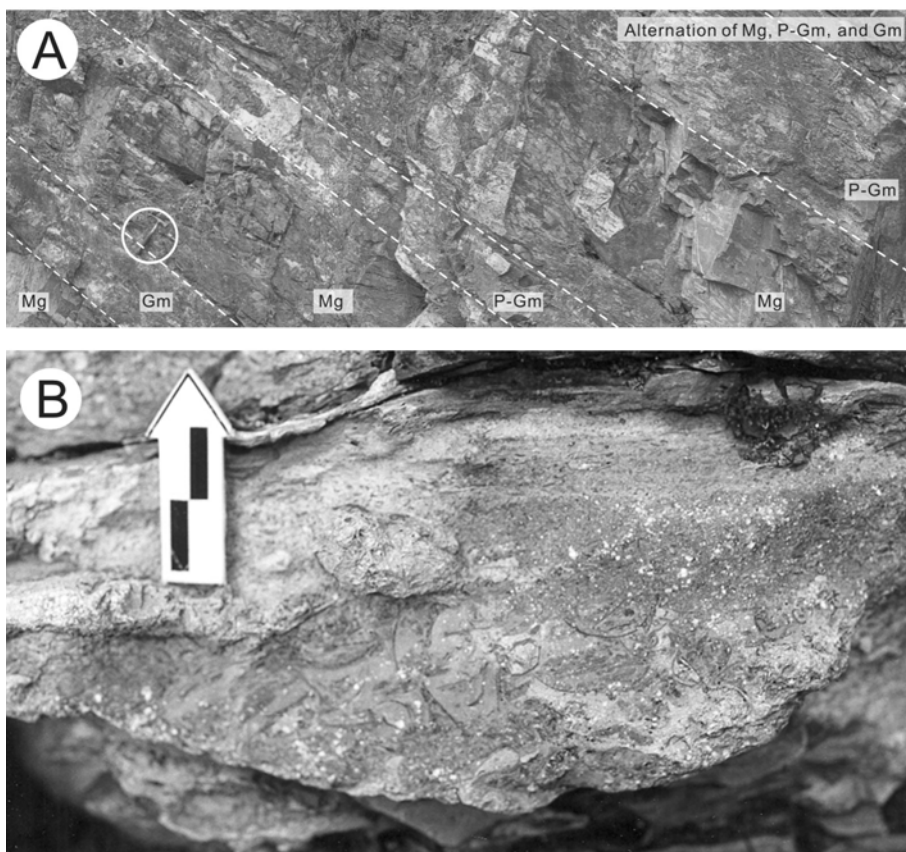


Fig. 11. (A) Outcrop photographs with facies codes of facies association 5 in the Sangdong section. Each facies unit is tabular and laterally continuous. Hammer for scale (circle) is 27 cm long. (B) Massive pack-grainstone (*P-Gm*) with normal grading from gravelly skeletal grains to laminated top. Scale is in cm.

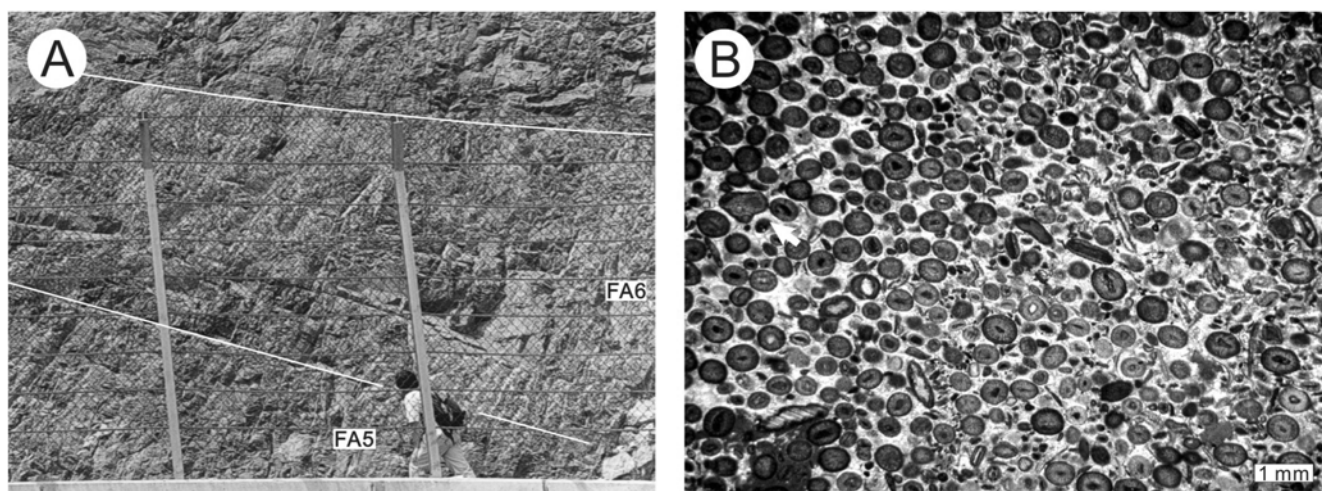


Fig. 12. Photograph and photomicrograph of facies association 6 and constituent facies. (A) Outcrop photograph of facies association 6, which predominantly consists of massive oolitic grainstone above the boundary between the Jigunsan and Duwibong formations in the Seokgaejae section. (B) Photomicrograph of oolitic grainstone (*Go*). Grains predominantly consist of ooids; skeletal grains and small peloids are minor constituents. A few ooids are aggregated (arrow).

3.6. Facies Association 6 (FA6): Shallow Subtidal Shoal

This facies association (Table 5) is composed of thick tabular beds of (massive) oolitic grainstone (*Go*; Fig. 12), massive or thick-bedded skeletal pack-grainstone, and grainstone (Fig. 4). The oolitic grainstone contains minor amounts of oncoids and fragments of crinoids and brachiopods (Fig. 12B). Ooids (0.4 mm in average diameter) are well-sorted and all other grains are well rounded. Large skeletal fragments of brachiopods and trilobites occur at the base of some oolitic grainstone beds. The massive pack-grainstone and grainstone consist predominantly of fragments of crinoids and lesser amounts of brachiopods, gastropods, trilobites, ostracods, peloids, and ooids; oncoids occur rarely in some beds. The intensity of bioturbation of these facies is variable. In the Seokgaejae section, this facies association occurs in the uppermost part of the Makgol Formation and the lowermost part of the Duwibong Formation. In other sections, however, only thin oolitic grainstone beds occur in the upper part of the Jigunsan Formation and the lowermost part of the Duwibong Formation (Fig. 4).

The open marine biota and variable degree of bioturbation are suggestive of deposition under normal open marine conditions. Oolitic grainstone represents high energy current- or wave-agitating shallow subtidal environments (Hine and Neumann, 1977). The textural maturity of the ooids and skeletal fragments in the oolitic grainstone is suggestive of deposition in high-energy shoals (Preto and Hinnov, 2003). Migration of oolitic sand shoals formed shallowing-upward facies succession, ranging from massive pack-grainstone to oolitic grainstone (e.g. Elrick and Read, 1991). Gravelly skeletal fragment layers are indicative of deposition during

high-energy conditions. Oncoids in lime mudstone are suggestive of relatively low-energy conditions possibly in back shoal environments (Hyeong and Lee, 2001).

4. DEPOSITIONAL ENVIRONMENTS

The cyclic succession of shallowing-upward units, ranging from subtidal to supratidal platform (FA1), probably resulted from progressive long-term rise in relative sea level with minor higher-frequency fluctuations (Fig. 13A). The occurrence of finely laminated, desiccation-cracked, and brecciated dolostone in the upper part of the Makgol Formation is suggestive of extensive supratidal environments and occasional subaerial exposure (Paik, 1987). The well-sorted and well-rounded quartz grains in the same interval are interpreted as wind-blown sand. Abundant cryptalgal laminite is suggestive of deposition in low energy conditions, protected from tidal and wave activities by seaward shoals (FA6 in the uppermost part of the Makgol Formation) or the tidal or wave energy was reduced on the shallow ramp (Choi et al., 1999).

The dominance of fine-grained siliciclastic units (FA2) is ascribed to rapid regional transgression, resulting from an increased rate of relative sea-level rise, which resulted in drowning of the carbonate factory or restricted production of carbonates to form a deep platform (Fig. 13B). Here, rare bioturbation, abundant pyrite, and pyritic calcareous nodules are suggestive of oxygen restricted (dysoxic) conditions (Wignall, 1994). Abundant micro-bioturbation and sharp erosional laminae suggest that the basin was neither fully anoxic nor stagnant (Schieber, 2003). Abundant organic matter (about 6% total organic carbon) suggests high surface productivity that might have been associated

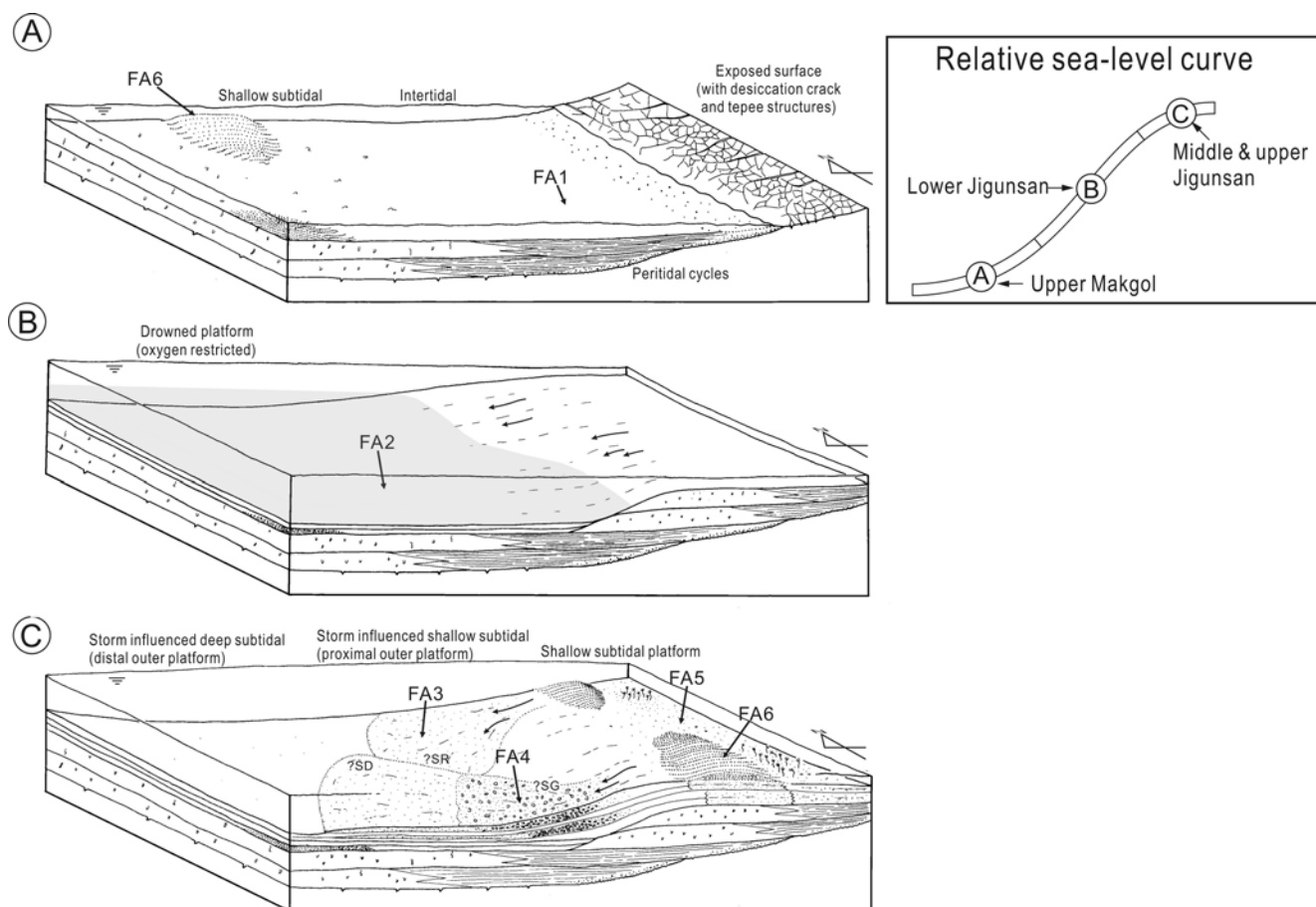


Fig. 13. Depositional environments of the upper Makgol and Jigunsan formations plotted in relation to relative sea level. (A) In the initial stage of the sea-level rise, peritidal environment develops. The peritidal sequences generally retrograde with several fluctuations. Oolitic and skeletal shoals form in shallow subtidal environments. (B) Drowning of the platform and the retreat of the carbonate factory. During transgressive episode, oxygen-restricted deep-water prevails. Local slope forms due to spatial differences in sedimentation rate and oceanic conditions. Offshore flows induced by storms result in dilute turbidity currents. (C) During slow rise or steady state in sea-level, productivity of platform top sediments is enhanced and subtidal shoals develop on the platform. Dilute turbidity currents and density currents induced by storms occur. SD=Sangdong section, SR=Sorotgol section, SG=Seokgaejae section.

with upwelling accompanied by sea-level rise.

In the following stage, the productivity of the carbonate systems was enhanced, suggesting a decrease in rate of sea-level rise, and as a consequence, the platform continued to prograde (Fig. 13C). Carbonate sediments in shallow subtidal environments were transported to the deep platform, forming alternation of laminated calcisiltite and hemipelagic mud (FA3). Erosional base, skeletal lags, small-scale hummocky and swaley cross-laminations are suggestive of storm-induced flows. Some paleoflow directions inferred from the cross laminations in the laminated calcisiltites (Fig. 3) indicate that sediments were transported to the west, i.e. to the south after plate reconstruction (Fig. 2). In the middle part of FA 3, dark gray mudstone is replaced by greenish gray siltstone that formed in well-oxygenated bottom water conditions.

The massive or graded pack-grainstone and grainstone interbedded with greenish gray siltstone (FA4) probably

represent proximal storm deposit. The occurrence of limestone conglomerate in FA4 also supports deposition during storm events (e.g. Séguret et al., 2001). The outer platform was characterized by discrete carbonate storm beds in fine-grained siliciclastic deposits and it progressively evolved into a shallow subtidal platform with migrating ooid shoals (FA6).

5. SEQUENCE STRATIGRAPHY

Based on the conodont and trilobite biostratigraphy (Table 3), the succession of sedimentary facies in the upper part of the Makgol Formation and the Jigunsan Formation records 3rd-order (0.5–3 My) sea-level changes during the Middle Ordovician. The strata record a sequence boundary and transgressive surface in the upper Makgol Formation (Fig. 13), and a transgressive systems tract (TST), maximum flooding zone (MFZ), and highstand systems tracts (HST) in the Jigunsan Formation. Each boundary and systems tract are

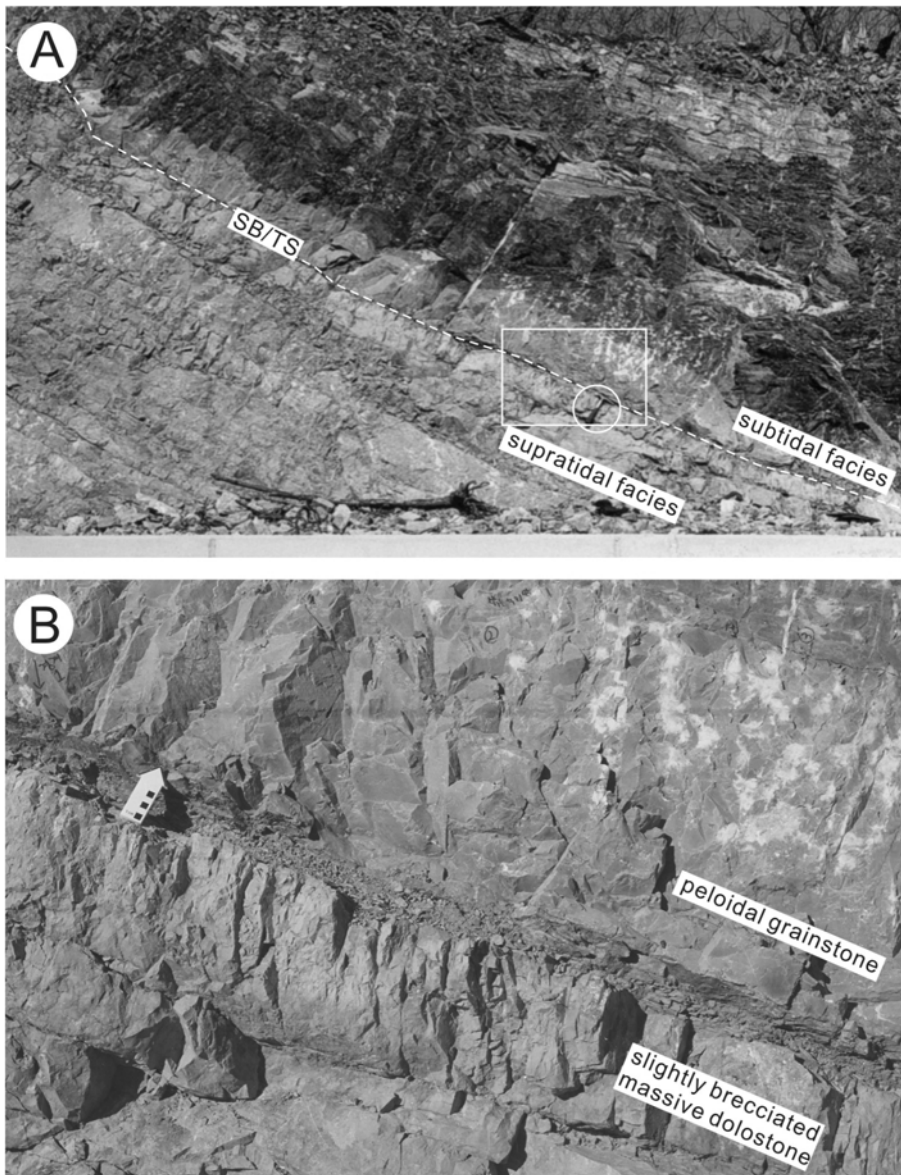


Fig. 14. Outcrop photograph showing sequence boundary/transgressive surface (SB/TS). (A) The sequence boundary is delineated by the boundary between the underlying supratidal facies and the overlying peritidal facies. Hammer for scale (circle) is 27 cm long. (B) Close-up of boxed area in Figure A showing the lithofacies across the sequence boundary. Scale bar is in cm.

correlated among outcrop sections that are several tens of kilometers apart (Fig. 4).

5.1. Sequence Boundary and Transgressive Surface

The upper part of the Makgol Formation shows several shallowing-upward peritidal cycles of subtidal bioturbated wacke-packstone, shoal grainstone, and supratidal laminite. The supratidal laminite contains teepee structures and intraclast breccia. The subsequent deeper facies such as thickly laminated lime mudstone and bioturbated wackestone, occur in the overlying units (Fig. 4). The boundary between the supratidal facies and the overlying subtidal facies is interpreted as a type 1 sequence boundary (Figs. 14 and 15A). The transgressive surface generally passes landward to the ravinement surface, which then merges with the sequence boundary (Cattaneo and Steel, 2003). Especially on low

gradient platforms, such as carbonate ramps, both the sequence boundary and the transgressive surface are usually coincident because the lowstand systems tracts are poorly preserved in the landward part of the platform (e.g. Holland and Patzkowsky, 1998). An abrupt facies change from the supratidal to subtidal facies across the sequence boundary in the Seokgaejae section (Fig. 3) is suggestive of transgressive surface. The overlying thin peloidal grainstone bed with very sharp base (Fig. 14) and small intraclasts of lime mudstone (Fig. 5E) most likely originated from reworking of the previous deposit. The peloidal grainstone bed is thus interpreted as a transgressive lag deposit formed when vigorous erosion occurred on the shoreface during transgression.

5.2. Transgressive Systems Tract

The transgressive systems tract (TST) in the Seokgaejae

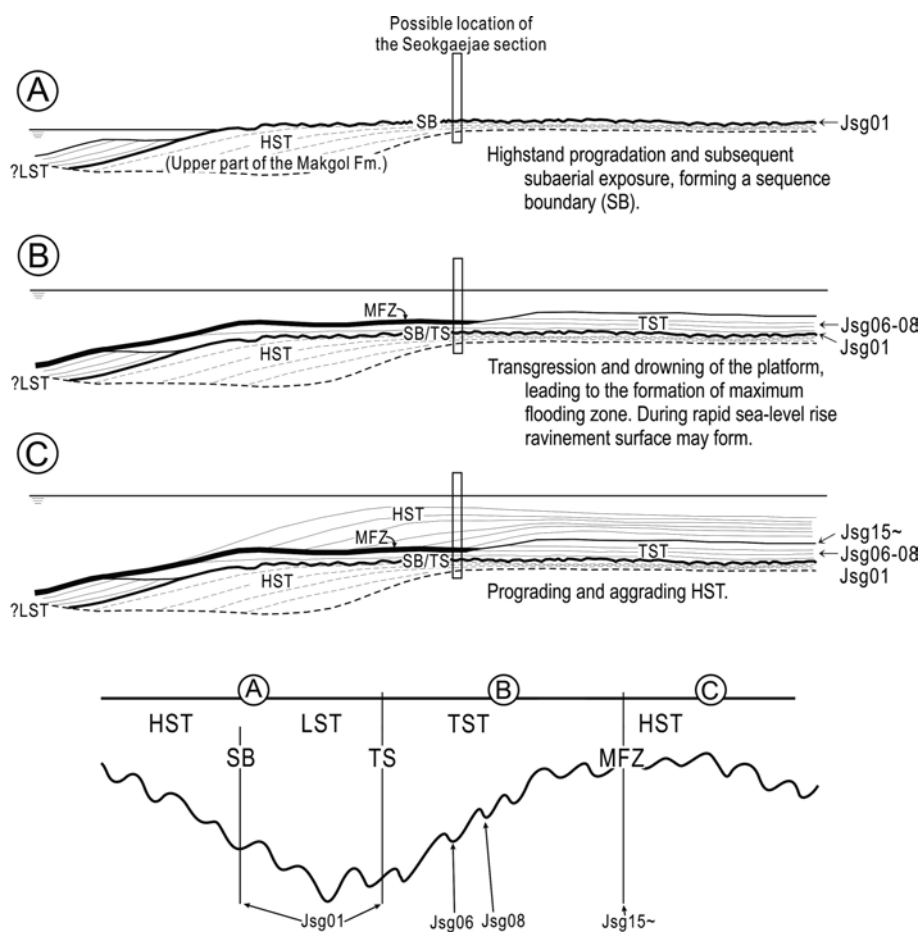


Fig. 15. A conceptual reconstruction of sequential development for the Makgol, Jigunsan, and Duwibong formations during sea-level changes (A–C). Jsg01–15 denote stratigraphic positions in Figure 3.

section is characterized by the fining-upward facies associations of peritidal cycles (FA1) and overlying deep subtidal and basinal facies (FA2; Figs. 4 and 15B). This is suggestive of upward deepening and retrograding of the platform which resulted from increase in accommodation space. The lower part of the transgressive systems tract consists of several meter-scale shallowing-upward cycles (FA1) which represent the high-order fluctuations superimposed on the long-term rise in sea-level. Localized oolitic grainstone (FA6) in this systems tract is suggestive of the existence of a restricted and starved shallow subtidal ooid sand shoal formed in the transgressive phase (e.g. Hine and Neumann, 1977). Enhanced productivity may have caused oxygen deficiency and development of stratified oxygen-poor deep water resulting in the formation of thickly laminated lime mudstone and organic-rich dark gray mudstone with pyritic calcareous nodules. Based on these trends, the TST is interpreted as an overall deepening-upward interval overlain by a maximum flooding zone.

5.3. Maximum Flooding Zone

The maximum flooding zone (MFZ; Figs. 4 and 15B) is recognized as an interval (about 2 m thick) between deep-

ening- and shallowing-upward successions (cf. Holland and Patzkowsky, 1998). The interval lacks carbonates and yields abundant fossils such as graptolites and trilobites. This interval is interpreted as a zone that marks sedimentation in the deepest water. The MFZ extends for about 40 km across the basin (Fig. 4).

5.4. Highstand Systems Tract

The highstand systems tract (HST) shows an overall coarsening- and shallowing-upward trend (Figs. 4 and 15C). It is divided into the lower and upper HST based on the abundance of the carbonate sediment and the textural differences; the lower HST is characterized by a low to moderate proportion of carbonate strata whereas the upper HST is predominately carbonate sediment (Fig. 4). The lower half of the lower HST is characterized by progradational deep subtidal siliciclastic units (dark gray mudstone and greenish gray siltstone) with sporadic input of carbonate grains such as laminated calcisiltite or massive grainstone (FA3). Carbonate grains were derived from the platform with enhanced productivity, shedding excess carbonate grains. The upper half of the early HST is represented by alternating massive grainstone, limestone conglomerate, and greenish gray silt-

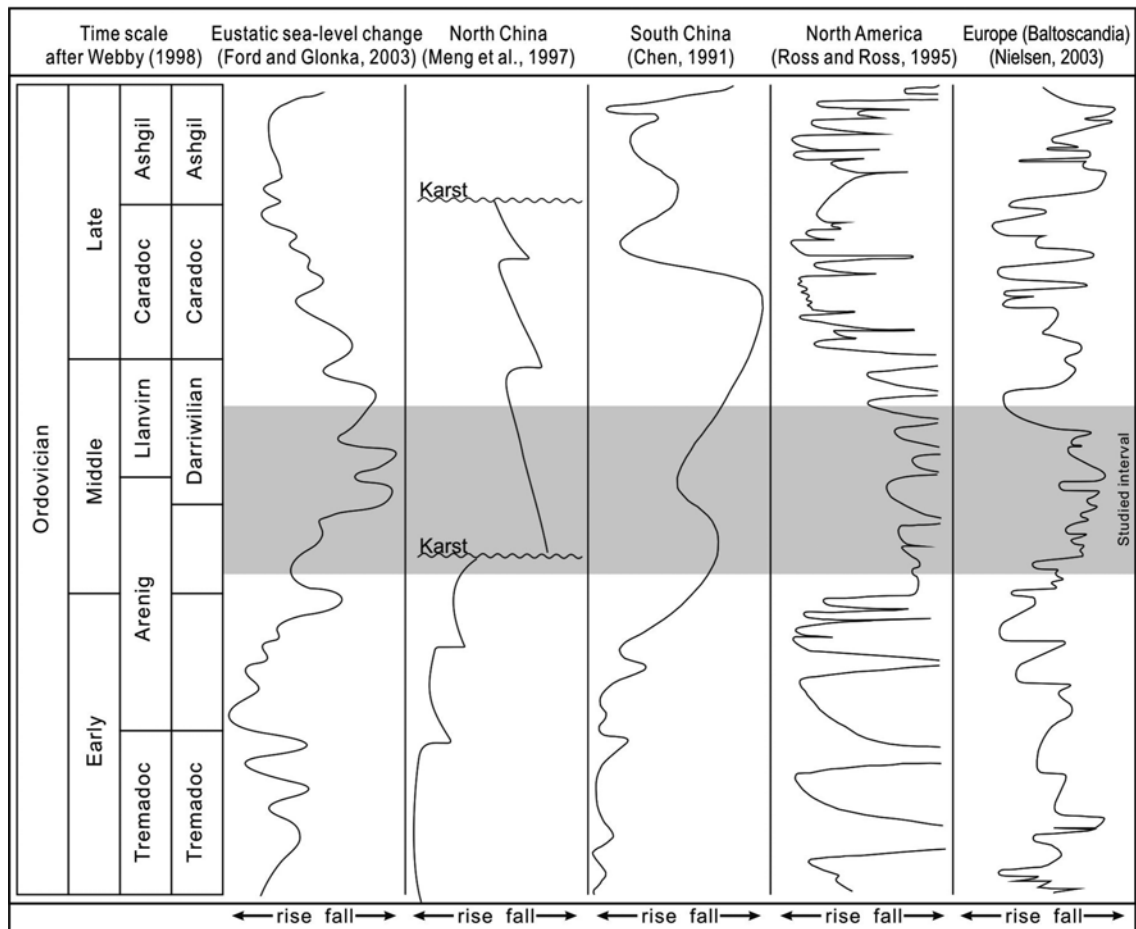


Fig. 16. The Ordovician eustatic and relative sea-level curves of North China, South China, North America, and Baltoscandia showing significant sea-level lowstand in the Middle Ordovician.

stone beds (FA4 and 5; Fig. 4). An increase in the ratio of carbonate to siliciclastic strata is suggestive of increased carbonate production that was in excess of creation of the accommodation space. The overlying thick carbonate succession of the lower part of the Duwibong Formation indicates culmination of late HST.

6. DISCUSSIONS

6.1. Eustatic Control on Sequence Development

In the early Middle Ordovician, sea level was generally lowered worldwide (Fig. 16). A sea-level curve from the Yangtze Platform in South China records a prolonged sea-level lowstand from the early Middle Ordovician to the early Late Ordovician (Chen, 1991). In North America, most Appalachian successions recorded a significant lowering in sea level in the early Middle Ordovician, as represented by large-scale karst and solution-related breccia (Mussman and Read, 1986; Ross and Ross, 1995). The sea-level curve inferred from the Baltoscandian sections also shows a significant lowstand in the early Middle Ordovi-

cian (Nielsen, 2003). The sea-level lowstand also occurs on the coastal onlap curve of Vail et al. (1977) in the Early to Middle Ordovician. The subsequent rise in sea level (the Llanvirnian transgression) is one of the most significant events of the Ordovician in the North American sequences (Hallam, 1992). It lasted for about 10 million years with superimposed shorter-term fluctuations of 0.1 to 1 million years (Cisne and Gildner, 1988).

In the Cambrian-Ordovician succession of the North China Platform, two megasequences are recognized (Meng et al., 1997). The lower megasequence boundary is the middle Arenigian age (early Middle Ordovician) and the upper sequence boundary (middle Upper Ordovician) marks the cessation of the Cambrian-Ordovician carbonate deposition. The latter represents a regional hiatus between the lower Paleozoic and upper Paleozoic in the North China Platform and the Taebaeksan Basin (Chough et al., 2000). These megasequence boundaries are characterized by the regional development of karst surface in the North China Platform (Meng et al., 1997). The sequence boundary described in this study can be correlated with the first megasequence boundary of the North China Platform. Both the worldwide

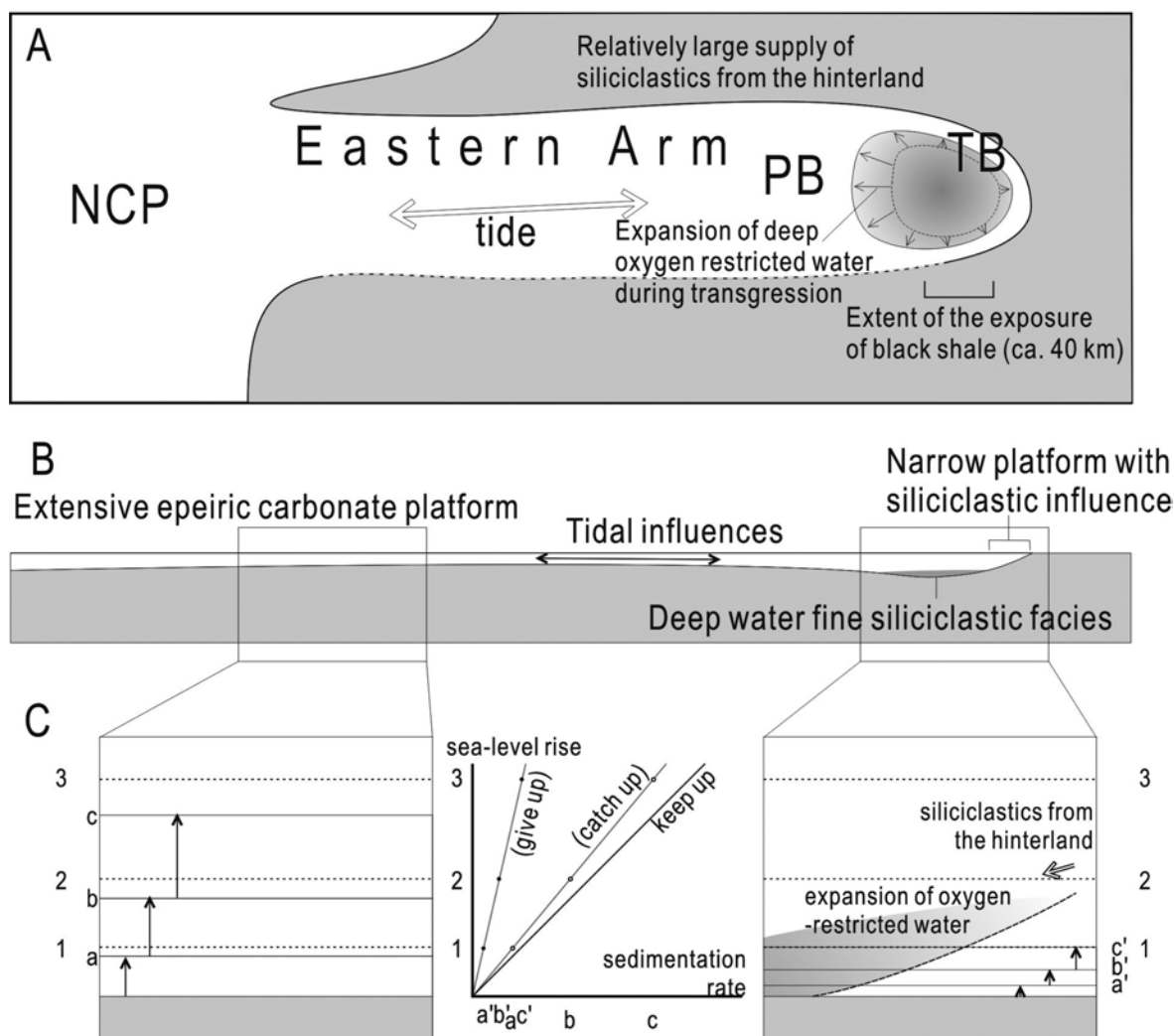


Fig. 17. Schematic configuration of the eastern arm (A) and cross section along the extending arm (B). (C) Depositional response to the Middle Ordovician transgression in the platform interior and eastern end of the embayment. Numbers (1, 2, and 3) with dashed lines indicate eustatic sea level at a certain time and show progressive acceleration of sea-level rise. Sedimentation rate in the North China Platform (a, b, and c) caught up the sea level whereas that in the Taebaeksan Basin did not keep up (a', b', and c'). NCP=North China Platform, PB=Pyongnam Basin, TB=Taebaeksan Basin.

records of the Middle Ordovician transgression and the concurrent depositional signatures in the Taebaeksan Basin are suggestive of eustatic control on sequence development. However, the sequence which formed during eustatic sea-level rise shows quite different depositional characteristics. In the North China Platform extensive carbonate deposition resumed (Meng et al., 1997), whereas in the Taebaeksan Basin carbonate production was minimal. The difference was likely due to the contrasting features in basin geometry and configuration.

6.2. Implications on Basin Geometry

The paleogeographic reconstruction of the North China Block, based on the recent tectonic reconstruction and the

distribution of sedimentary deposits suggests that it was an extensive major epeiric platform, whereas the Taebaeksan Basin was an embayment, an eastern arm of the platform in the Cambrian and Ordovician (Figs. 2B and 17A). This configuration probably led to the deposition of fine-grained sediment in the Taebaeksan Basin during transgression in the Middle Ordovician.

The early Middle Ordovician sequence boundary in the North China Platform was characterized by a large-scale karst surface, suggestive of prolonged subaerial exposure of the platform (Meng et al., 1997). The correlative sequence boundary in the Taebaeksan Basin occurs between the supratidal and overlying subtidal facies. The extent of subaerial exposure in the North China Platform was greater than that of the Taebaeksan Basin during the global low-

stand in sea level. The subsequent TST in the Taebaeksan Basin consists of transgressive lag deposit (lowermost part of FA1), peritidal carbonates (FA1), subtidal oolitic grainstone (FA6), and deep subtidal to basinal oxygen-restricted mudstone (FA2).

In the Yeongwol Group, the western part of the Taebaeksan Basin, the age-equivalent strata (Yeongheung Formation) consist of peritidal and shallow subtidal facies (Yoo, 1996). Further west, in the North China Platform, the equivalent sequence unit, the Majiagou Formation, is characterized by thick carbonate with dolomitized subunits suggestive of peritidal to shallow subtidal environments (Meng et al., 1997). This regional change in sedimentary facies associations suggests that the eastern arm of the North China Platform progressively deepened toward the east in the Llanvirnian (Darriwilian; Fig. 17B). The eastward deepening was probably caused by a difference in sedimentation rate between the North China Platform and the Taebaeksan Basin. In the Early to Middle Cambrian, no significant depth difference from the inherent basement physiography was recognized. During the Middle and Late Cambrian, however, there was active growth of carbonate buildups in the North China Platform, whereas in the Taebaeksan Basin the contribution of the carbonate buildups was subdued mainly due to siliciclastic input. The cumulative thickness variations resulted in the Ordovician difference in the elevation of the seafloor between the North China Platform and the Taebaeksan Basin.

6.3. Depositional Control of Basin Configuration

The physiographic difference between the North China Platform and the Taebaeksan Basin led to the contrasting conditions for depositional processes. The extensive North China Platform probably was unaffected by siliciclastic sediment input from the adjacent craton because of its distance from the siliciclastic source region. The Taebaeksan Basin in the eastern portion of the platform received relatively more siliciclastic input from the hinterland, and the carbonate production was thus significantly subdued. Furthermore, the Taebaeksan Basin had a semi-enclosed deep-subtidal to basinal portion with oxygen-restricted, deep water which were likely harmful to carbonate-secreting organisms on the shallow part of the basin during transgression (e.g. Wignall and Newton, 2001). The differences between the extensive epeiric platform and the smaller basin attached to the cratonic body resulted in the separate response to the sea-level rise. In the extensive epeiric platform, extensive carbonate sediments were produced *in situ* and deep water influence was restricted in the platform. In the epeiric North China Platform, the carbonate production kept up with or caught up to sea-level rise of the transgressive stage (Fig. 17C), and the platform formed the extensive and thick carbonate deposits during the Middle Ordovician transgression. In contrast, the relatively small platform (Taebaeksan Basin),

attached to the cratonic body and facing the deeper part of the basin, produced lesser amounts of carbonate sediments and thus could not keep up with the sea-level rise due to the siliciclastic input from the hinterland and the expansion of deep water (Fig. 17). This sedimentary system in a cratonic basin lacks a modern analogue (Wignall, 1991), especially during an event of sea-level rise. The Jigunsan Formation has characteristics of a transgressive deposit for a mixed carbonate-siliciclastic system with an oxygen-restricted subbasin (e.g. Wignall, 1991; Wignall and Newton, 2001).

7. CONCLUSIONS

The Jigunsan Formation consists of six facies associations, representing peritidal (FA1), storm influenced subtidal (FAs3 and 4), basinal (FA2), and shallow subtidal and shoal (FAs5 and 6) environments. Peritidal cycles (FA1) were accumulated in response to sea-level rise, followed by oxygen-restricted basinal conditions (FA2). The overlying units (FAs 3 and 4) of alternating laminated calcisiltite, grainstone, and mudstone represent storm-influenced subtidal environments. Subtidal environments (FA5) with migrating ooid shoals (FA6), represented by the overlying units, are suggestive of gradual shallowing of the platform.

The extensive fine-grained deposition of the Jigunsan Formation represents a transgressive phase of the third-order eustatic rise in sea level, overlying a peritidal to supratidal carbonate succession formed during a global lowstand. The Taebaeksan Basin, an eastern arm of the epeiric North China Platform, records semi-enclosed deep subtidal and basinal environments. Whereas the majority of the epeiric platform was under a tidal regime, the eastern arm was under relatively deep water with restricted production of carbonate sediment and large input of siliciclastic sediment.

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