Sequence Stratigraphy of the Yeongweol Group (Cambrian-Ordovician), Taebaeksan Basin, Korea: Paleogeographic Implications

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전기고생대 태백산분지 영월층군의 순차층서 연구를 통한 고지리적 추론

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전기 고생대 태백산분지 영월층군은 탄산염-규산쇄설성 퇴적암 복합체로서 하부로부터 삼방산층, 마차리층, 와곡층, 문곡층, 영흥층으로 이루어져 있다. 영월층군에 대한 순차층서학적 분석에 따르면 중기 캄브리아기에 일어난 범람에 의해 최하부의 규산쇄설성 사질 퇴적암이 우세한 삼방산층이 퇴적되었다. 이어지는 후중기 캄브리아기 ~ 전후기 캄브리아기에 지속적으로 발생한 빠른 해수면 상승으로 마차리층 하부에는 세일, 입자암, 각력암층을 협재한 사면 혹은 심부 램프 시퀀스가 형성되었다. 후기 캄브리아기 동안 지속된 해수면 상승은 실질적인 퇴적가능공간을 창출하였고, 조하대 환경에 탄산염 퇴적물 공장이 만들어졌으며, 탄산염 대지에는 마차리층을 구성하는 탄산염암이 우세한 조하대 시퀀스가 형성되었다. 마차리층 상부의 와곡층은 후후기 캄브리아기의 완만한 해수면 상승국면에서 만들어진 탄산염 램프 시퀀스로 해석되며, 퇴적 당시에는 리본 탄산염암과 탄산염 역암을 포함하는 이회암으로 구성되었던 것으로 보인다. 와곡층은 퇴적 직후에 일차적으로 캄브리아기와 오르도비스기 사이의 해수면 하강국면에서 불안전 백운암화 과정을 거치고, 후에 심부 매몰 속성환경에서 광범위한 백운암화 작용을 받은 것으로 해석된다. 전기 오르도비스기에도 세계적인 해수면 상승과 해침은 지속되었으며, 영월층군의 조하대 램프 퇴적환경은 그대로 유지되어 탄산염 역암층을 협재하는 석회이암과 이회암이 교호하는 전형적인 램프 시퀀스인 문곡층이 형성되었다. 문곡층은 중기 오르도비스기에 퇴적된 것으로 알려진 영흥층에 덮여 있다. 영흥층은 주로 윤회층리를 보이는 조석대지 탄산염암으로 이루어져 있으며, 문곡층의 최상부에서 조하대 퇴적환경이 영흥층의 조석대지 퇴적환경으로 변화한다. 세계적 1차 규모 순차 경계면인 소크(Sauk)와 티피카누(Tippecanoe) 시퀀스의 경계는 영흥층 중부에서 관찰되는 최소퇴적가능공간 부근에서 인지된다. 중기 오르도비스기 초기의 세계적 해수면 하강과 이어지는 해수면의 급격한 상승은 영흥층의 전반적인 상향 천해화 윤회층의 전진퇴적체를 형성하였다. 영월층군이 퇴적된 영월 탄산염 대지의 상대적 해수면 변동곡선을 복원해 보면 같은 태백산 분지의 태백층군이 퇴적된 태백 탄산염 대지의 해수면 변동 곡선과 유사함을 확인할 수 있다. 이것은 두 개의 탄산염 대지가 유사한 조구조적 운동 역사를 갖는다는 것을 의미하며, 이러한 유사성은 영월층군이 형성된 영월 탄산염 대지가 비록 태백층군이 퇴적된 태백 탄산염 대지와 상이한 퇴적시스템을 갖기는 하지만 상대적으로 가까운 지역에 속해 있었음을 암시한다. 퇴적층서 분석결과에 따르면 영월 탄산염 대지는 태백 탄산염 대지에 비해 상대적으로 열린 천해 환경이었을 것으로 추측된다. 고생대 후기와 중생대 전기에 걸쳐 발생한 북중국지괴와 남중국지괴의 충돌 시기에 영월 탄산염 대지와 태백 탄산염 대지가 복잡한 이동과정을 거쳐 현재의 태백산 분지에 모이게 된 것으로 해석된다.

주요어 : 고지리, 영월층군, 태백층군, 태백산분지, 순차층서

The Yeongweol Group is a Lower Paleozoic mixed carbonate-siliciclastic sequence in the Taebaeksan Basin of Korea, and consists of five lithologic formations: Sambangsan, Machari, Wagok, Mungok, and Yeongheung in ascending order. Sequence stratigraphic interpretation of the group indicates that initial flooding in the Yeongweol area of the Taebaeksan Basin resulted in basal siliciclastic-dominated sequences of the Sambangsan Formation during the Middle Cambrian. The accelerated sea-level rise in the late Middle to early Late Cambrian generated a mixed carbonate-siliciclastic slope or deep ramp sequence of shale, grainstone and breccia intercalations, representing the lower part of the Machari Formation. The

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continued rise of sea level in the Late Cambrian made substantial accommodation space and activated subtidal carbonate factory, forming carbonate-dominated subtidal platform sequence in the middle and upper parts of the Machari Formation. The overlying Wagok Formation might originally be a ramp carbonate sequence of subtidal ribbon carbonates and marls with conglomerates, deposited during the normal rise of relative sea level in the late Late Cambrian. The formation was affected by unstable dolomitization shortly after the deposition during the relative sea-level fall in the latest Cambrian or earliest Ordovician. Subsequently, it was extensively dolomitized under the deep burial diagenetic condition. During the Early Ordovician (Tremadocian), global transgression (viz. Sauk) was continued, and subtidal ramp deposition was sustained in the Yeongweol platform, forming the Mungok Formation. The formation is overlain by the peritidal carbonates of the Yeongheung Formation, and is stacked by cyclic sedimentation during the Early to Middle Ordovician (Arenigian to Caradocian). The lithologic change from subtidal ramp to peritidal facies is preserved at the uppermost part of the Mungok Formation. The transition between Sauk and Tippecanoe sequences is recognized within the middle part of the Yeongheung Formation as a minimum accommodation zone. The global eustatic fall in the earliest Middle Ordovician and the ensuing rise of relative sea level during the Darrwillian to Caradocian produced broadly-prograding peritidal carbonates of shallowing-upward cyclic successions within the Yeongheung Formation. The reconstructed relative sea-level curve of the Yeongweol platform is very similar to that of the Taebaek platform. This reveals that the Yeongweol platform experienced same tectonic movements with the Taebaek platform, and consequently that both platform sequences might be located in a body or somewhere separately in the margin of the North China platform. The significant differences in lithologic and stratigraphic successions imply that the Yeongweol platform was much far from the Taebaek platform and not associated with the Taebaek platform as a single depositional system. The Yeongweol platform was probably located in relatively open shallow marine environments, whereas the Taebaek platform was a part of the restricted embayments. During the late Paleozoic to early Mesozoic amalgamations of the Korean massifs, the Yeongweol platform was probably pushed against the Taebaek platform by the complex movement, forming fragmented platform sequences of the Taebaeksan Basin.

Key words : paleogeography, Yeongweol group, Taebaek group, Taebaeksan Basin, sequence stratigraphy

1. Introduction

The paleogeographic reconstruction of tectonic segments in the Korean Peninsula have been a significant issue during the past two decades (Ree *et al.*, 1996; Chwae and Choi, 1999; Chough *et al.*, 2000; Kim *et al.*, 2001; Metcalfe, 2006; Oh, 2006; Zhai *et al.*, 2007). A considerable amount of petrographic, geochemical and geochronologic data have been accumulated, provided the basis for various models on paleogeography and tectonic history (e.g., Chwae and Choi, 1999; Lee and Kim, 2001; Zhai *et al.*, 2003; Kim, 2005; Choi and Kim, 2006; Metcalfe, 2006; Oh, 2006; Oh *et al.*, 2006; Zhai *et al.*, 2007; Kwon *et al.*, 2009). Recent stratigraphic and paleontologic studies, particularly from the Paleozoic Taebaeksan Basin, also contributed to unveiling paleogeography and paleo-depositional environments of pre-collision sedimentary basins (Chough *et al.*, 2000; Choi and Chough, 2005; Choi and Kim, 2006; Kwon *et al.*, 2006; Zhang *et al.*, 2008; Woo *et al.*, 2008).

The Yeongweol and Taebaek groups are principal lithologic units in the Lower Paleozoic Taebaeksan Basin (Fig. 1). They are typical Cambrian-Ordovician

platform sequences composed of mixed carbonates and siliciclastics (Kobayashi, 1966; Cheong, 1969; Choi, 1998; Chough *et al.*, 2000; Choi *et al.*, 2004; Choi and Chough, 2005). The Taebaek Group is considered to represent a part of the North China platform (Chough *et al.*, 2000; Kwon *et al.*, 2003; Choi and Chough, 2005; Kwon *et al.*, 2006), and are lithologically similar to the Lower Paleozoic sedimentary rocks in the North China platform (Meyerhoff *et al.*, 1991; Meng *et al.*, 1997; Choi, 1998; Choi *et al.*, 2004). Recent sequence stratigraphic analyses also indicate that the Taebaek Group is well correlated with the mixed carbonate-siliciclastic successions of North China platform (Ryu *et al.*, 2005; Kwon *et al.*, 2006).

The Yeongweol Group is located in the western part of the Taebaeksan Basin, immediately west of the Taebaek Group (Fig. 2; Chough *et al.*, 2000). In spite of the geographic proximity, it is lithologically distinct from the Taebaek Group, leading to considerable debate on the paleogeographic position of the Yeongweol platform during the Lower Paleozoic (e.g., Cluzel *et al.*, 1991; Yin and Nie, 1993; Chough *et al.*, 2000; Choi *et al.*, 2001; Ryu *et al.*, 2005; Choi and Kim, 2006). Cluzel *et al.*

Fig. 1. Spatial distribution of the Cambrian-Ordovician sedimentary rocks in the Northeast Asia (after Y.K. Kwon *et al.*, 2006).

Fig. 2. Geologic map of the Taebaeksan Basin. (A) five lithologic groups of the Taebaeksan Basin, (B) geologic map of the Yeongweol group composed of the five lithologic formations (after Y.K. Kwon *et al.*, 2006 and D.K. Choi, 1998).

(1991) and Yin and Nie (1993) correlated the Yeongweol Group with the South China block. They also suggested that the Yeongweol and Taebaek groups were juxtaposed by a right-lateral transcurrent movement during the Permian-Triassic collision at the same time with the collision of the North China and South China blocks. On the other hand, Choi *et al.* (2001) and Choi and Kim (2006) suggested, on the basis of trilobite occurrence data, that the Yeongweol platform was involved in the North China platform.

This study aims to establish sequence stratigraphy of the Yeongweol Group and to examine the stratigraphic similarity between the Yeongweol and Taebaek groups. The sequence stratigraphic interpretation explains depositional scenario and vertical stacking patterns of the 2nd-order sequences and sedimentary response of mixed carbonate-siliciclastic systems to the sea-level fluctuations during the Early Paleozoic. The suggested depositional history of the group will help understanding of sedimentary systems of the Yeongweol Group and provide a significant foundation for the paleogeographic reconstruction of the Joseon Supergroup.

2. Geologic Setting

The Taebaeksan Basin is located in the mid-eastern part of the Korean Peninsula (Fig. 1). The basin consists of the Joseon Supergroup (Cambrian-Ordovician) and the unconformably overlying Pyeongan Supergroup (Carboniferous-Permian) (Fig. 2). The Joseon Supergroup comprises the mixed carbonate-siliciclastic sequences of sandstones, shales, and carbonates (Kobayashi, 1966; Woo and Park, 1989; Choi *et al.*, 2004; Choi and Chough, 2005). This supergroup can be divided into five lithologically-different regional stratigraphic units: the Taebaek, Yeongweol, Yongtan, Mungyeong, and Pyeongchang groups (Fig. 2; Choi, 1998). Among these, the Yeongweol Group occupies the western part of the Taebaeksan Basin, bounded to the east with the Taebaek Group along the Gakdong thrust (Fig. 2). It consists of five lithologic members: Sambangsan, Machari, Wagok, Mungok, and Yeongheung formations in ascending order (Table 1; Kobayash, 1966; Choi, 1998; Choi and Chough, 2005). The basal Sambangsan Formation is a siliciclastic sequence composed of shale, siltstone

and (locally gravelly) sandstone deposited mainly during the Middle Cambrian. The overlying Machari Formation is a mixed carbonate-siliciclastic sequence with limestone breccias and dolostone beds formed in the early Late Cambrian. The late Late Cambrian Wagok Formation is a white-gray dolostone sequence. During the Early Ordovician, the Mungok Formation was formed in the ramp-type subtidal carbonate platform, and is overlain by the Yeongheung Formation which mainly consists of peritidal carbonates.

3. Lithostratigraphy

For sequence stratigraphic interpretation, this study describes and identifies a total of 23 sedimentary facies, which are grouped into 11 facies association (Table 2 and Fig. 3).

3.1. Sambangsan Formation

The Sambangsan Formation is the basal lithostratigraphic unit of the Yeongweol Group, composed of siltstone, shale and sandstone (Fig. 3 and 4A), ranging in thickness from about 400 m to over 700 m (Choi and Chough, 2005). Based on trilobite assemblages, the formation is considered to be the Middle Cambrian in age (Choi *et al.*, 1999).

The Sambangsan Formation is divided into two facies associations; the lower outer shelf (OS) and the upper inner shelf (IS) (Table 2 and Fig. 3). The lower OS facies association is dominated by purple and green siltstone and shale with some intercalations of limestone beds (Choi, 1998). The dominance of fine-grained sediments suggests that this facies association was deposited in an outer shelf environment.

The upper IS facies association consists predominantly of greenish gray, light brown, massive to thick-bedded, fine-grained micaceous sandstone, interbedded with siltstone, shale and limestone (Choi, 1998). Frequent intercalations of fine-grained sandstone beds of storm origin in the facies association represent an upward-shallowing transition from the underlying OS facies association.

3.2. Machari Formation

The Machari Formation overlies conformably the Sambangsan Formation and comprises shale, limestone breccia, argillaceous to dolomitic limestone and limestone pebble conglomerate. The thickness

Table 1. Lithostratigraphic summary of the Yeongweol Group

Age (Ma)	Formation (Thickness: meter)		Lithology	Biozone
445	Ashgillian			
460	Caradocian		Massive packstone/grainstone Bioturbated wackestone to grainstone Oncoid/ooid grainstone Limestone-shale couplet Homogeneous mudstone Laminated lime-mudstone	
468	Darwillian	Yeongheung (400)	Massive or laminated grainstone Limestone pebble conglomerate Massive dolostone(breccia) Stromatolitic limestone	Kaysersapis
478	Arenigian		Finely-laminated dolomitic limestone Bioturbated wackestone to grainstone Calcareous shale	
	Tremadocian	Mungok (140-210)	Limestone-shale couplet Bioturbated or flaser-bedded limestone Massive grainstone Limestone pebble conglomerate Massive sandstone Laminated or cross-stratified sandstone Calcareous shale	Shumardia pellizzarii Kainella euryraxis Yosimuraspis vulgaris
488		Wagok (200-250)	Massive grainstone Calcareous shale Limestone-shale couplet	Fatocephalus hunjiangensis
	Late	Machari (200)	Bioturbated or flaser-bedded limestone Massive grainstone Limestone pebble conglomerate Homogeneous or laminated mudstone Massive or laminated sandstone	Pseudoyuepingia asaphoides Agnostotes orientalis Eochuangia hana Eugonocare longifrons Hancrania brevilimbata Proceratopyge tenuis Glyptagnostus reticulatus Glyptagnostus stolidotus Lejopyge armata Tonkinella
501				
	Middle	Sanbansan (400-700)	Limestone pebble conglomerate Anastomosing wackestone to grainstone Massive grainstone Oncoid/ooid grainstone Homogeneous or laminated mudstone	Megagraulos semicircularis Metagraulos sampensis
513				

of the formation was estimated less than 200 m (Fig. 3; Lee, 1995). It is conformably overlain by massive dolostone of the Wagok Formation.

The Machari Formation is divided into three facies associations: the lower basin (BA), the middle basin to outer shelf (BA/OS) and the upper outer to inner shelf (OS/IS) facies associations (Table 2 and Fig. 3). The lower BA facies association consists of dark gray dolomitic limestone and

shale with intercalations of limestone breccias and argillaceous limestone beds. Recently Hong *et al.* (2003) recognized the *Lejopyge armata* Zone from the dolomitic limestone beds. The limestone breccia in this facies association were interpreted as slope apron deposits (Chung and Land, 1997), although the evidence for mass flow movement is not convincing. In this study, this facies association is considered to have been deposited in a basin to

Table 2. Brief summary of facies associations in the Yeongweol Group

Formation	Facies Associations	Composite Facies	Sedimentary Environment
Yeongheung	SS/PT	Lime-mudstone Oolitic grainstone Peloidal grainstone to packstone Stromatolitic limestone Limestone pebble conglomerate	Shallow Subtidal or Peritidal
	PT	Massive dolostone Oolitic grainstone Peloidal grainstone to packstone Lime-mudstone Cryptalgal laminate	Peritidal
Mungok	OS/IS	Ribbon carbonate Limestone pebble conglomerate Lime-grainstone Limestone-shale couplet	Outer Shelf or Inner Shelf
	SS/PT	Crudely-bedded dolostone Limestone-shale couplet Ribbon carbonate	Shallow Subtidal or Peritidal
	IS/SS	Ribbon carbonate Limestone pebble conglomerate Limestone grainstone Chert Limestone-shale couplet	Inner Shelf or Shallow Subtidal
Wagok	SS/PT	Massive dolostone Calcareous shale Limestone-shale couplet	Shallow Subtidal or Peritidal
Machari	OS/IS	Thinly-bedded dolomitic limestone Black shale Limestone pebble conglomerate	Outer Shelf or Inner Shelf
	BA/OS	Laminated shale Dolomitic limestone	Basin or Outer Shelf
	BA	Dolomitic limestone Shale Limestone breccias Argillaceous limestone	Basin
Sanbangsan	IS	Fine-grained sandstone Siltstone Shale limestone	Inner Shelf
	OS	Siltstone Shale limestone	Outer Shelf

slope setting, based on the predominance of fine-grained sediments, the occurrence of probable slope apron deposits, and no evidence for shallow water deposition.

The middle basin to outer shelf (BA/OS) facies is dominated by laminated dark gray to black shale and thin-bedded dolomitic limestone (Fig. 4B-C). This facies association has been known to be highly fossiliferous (Choi and Chough, 2005). The laminated black shale and abundance of cosmopolitan

trilobite taxa in this facies association are suggestive of deposition in a dysaerobic deep-water environment (Chough *et al.*, 2000). In this study, the depositional environment of this facies association is interpreted to have been shallower than that of the underlying BA facies association (basin to outer shelf setting), based on frequent intercalations of dolomitic limestone layers.

The upper outer shelf to inner shelf (OS/IS) facies association is characterized by alternations

Fig. 3. Brief columnar description of the Yeongweol Group and vertical successions of the composite facies associations.

of thinly-bedded dolomitic limestone and black shale layers (Table 2, Fig. 3 and 4D). The alternations become progressively obscure toward the uppermost part of the formation which grades into massive dolostone of the Wagok Formation (Choi and Chough, 2005). Limestone pebble conglomerates are occasionally intercalated within this facies association. The depositional environment of this association is thought to have been similar to that of the underlying BA/OS facies association. However, some intercalated limestone pebble conglomerates

of storm origin (Sepkoski, 1982; Kim and Lee, 1996), suggest that this association was deposited in an inner shelf setting near the storm wave base.

3.3. Wagok Formation

The Wagok Formation is characterized by a monotonous sequence of massive dolostone (Fig. 3 and 4E), and is poorly fossiliferous (Choi, 1998; Choi and Chough, 2005). Due to severe dolomitization, it is difficult to recognize original grain components and sedimentary structures/textures

Fig. 4. Photographs of common sedimentary facies (scale bar in (A) is in cm; pen for scale in (B), (C), (D), (I), (K) and (L) is 15 cm long; coin for scale in (E), (F), (G), (H) and (J) is 2.4 cm in diameter). A: Fine-grained sandstone, Sambangsan Formation; B: laminated shale with dolomitic limestone interbeds, Machari Formation; C: Thickly-bedded dolomitic limestone and black shale, Machari Formation; D: Thinly-bedded dolomitic limestone and black shale, Machari Formation; E: Massive dolostone, Wagok Formation; F: Marl, Mungok Formation; G: Limestone conglomerates, Mungok Formation; H: Ribbn Rock, Mungok Formation; I: Dolostone, Mungok Formation; J: Chert, Mungok Formation; K and L: Desiccation crack, Yeongheung Formation.

prior to the dolomitization. However, some relics of original components such as ooids, peloids, bioclasts and intraclasts can be occasionally observed where the dolomitization is not pervasive. The relics suggest that the dolostone may be originated from alternating facies of limestone and marl beds, limestone conglomerate, and bioclastic/peloidal grainstone. The formation has been known to range from 200 to 250 m in thickness (Park *et al.*, 1994). Choi and Chough (2005) envisaged a shallow depositional environment above the wave base such as carbonate shoals where persistent grain mobility can be maintained by water turbulence or tidal activity. A shallow subtidal (SS) or pertidal (PT) facies association represents the Wagok Formation (Table 2).

3.4. Mungok Formation

The Mungok Formation consists of shale, marl, limestone conglomerate, and alternation of thin-bedded limestone and shale (Fig. 4F-I). It has been divided into four lithologic members: basal, lower,

middle and upper members in ascending order (Fig. 3; Kim and Choi, 2000). The basal member is composed mainly of ribbon carbonates and limestone conglomerates with intercalations of grainstone and chert layers. The lower member is characterized by a monotonous sequence of crudely-bedded dolostone. The middle member comprises ribbon carbonates and limestone conglomerates. The predominant facies of the upper member is marl to shale and ribbon carbonates with limestone conglomerate and grainstone interbeds. The total thickness has been known to range from 140 m to 210 m (Fig. 3; Choi and Chough, 2005). The formation has been interpreted to represent a shallow subtidal environment comprising lagoonal/restricted marine, shoal, inner shelf, and outer shelf facies (Kim and Choi, 2002). The Mungok Formation consists of IS/SS, SS/PT and OS/IS facies associations (Table 2).

3.5. Yeongheung Formation

The Yeongheung Formation has been known to

consist mainly of massive to thick-bedded dolostone in the lower part and of limestone-dominated sequence in the upper part (Fig. 3; Lee, 1987). Yoo *et al.* (1994) described the composite facies of this formation (Table 1), suggesting that the formation shows vertical stacking of shallowing-upward successions. However, the base and top of the formation are not well defined and the lithologic successions vary from section to section (Yoo *et al.*, 1994; Choi and Chough, 2005). The formation was estimated to be about 400 m in thickness, interpreted as shallow subtidal and peritidal successions (Fig. 3; Yosimura, 1940; Choi and Woo, 1993; Yoo *et al.*, 1994). The Yeongheung Formation is composed of PT and SS/PT facies associations (Table 2).

4. Bio- and Chrono-stratigraphy

A total of 17 biozones have been recognized within the Yeongweol Group, based on trilobite assemblages (Table 3; Choi and Chough, 2005).

Additionally, stromatolite, graptolite, and conodont biozones are also employed for the biostratigraphy and chronostratigraphic correlations.

The lowermost Sambangsang Formation includes *Metagraulos sampoensis* and *Megagraulos semicircularis* zones (Choi *et al.*, 1999). The trilobite biozones indicate a deposition of the middle Middle Cambrian. The upper part of the Myobong Formation and lower part of Daegi Formation of the Taebaek Group are considered to have been formed during this period. The overlying Machari Formation consists of ten biozones. The lower three biozones (*Tonkinella*, *Lejopyge armata*, and *Glyptagnostus stolidotus* zones) correspond to the late Middle Cambrian. The upper seven biozones (*Glyptagnostus reticulatus*, *Proceratopyge tenuis*, *Hancrania brevilimbata*, *Eugonocare longifrons*, *Eochuangia hana*, *Agnostotes orientalis*, and *Pseudoyuepingia asaphoides* zones) indicate an age of the Furongian (Late Cambrian). In the Wagok Formation, only one biozone, *Fatocephalus hunjiangensis* Zone, was recognized, suggesting an age

Table 3. Biostratigraphic summary of the Yeongweol and Taebaek groups (modified after Duck K. Choi and Sung Kwun Chough, 2005)

	Age	Taebaek Group		Yeongweol Group	
		Formation	Biozone	Formation	Biozone
Ordovician	Ashgillain				
	Caradocian	Diwibong		Yeongheung	Kayseraspis
		Jigunsan	Dolerobasilicus		
	Darriwilian	Makgol			
	Arenigian	Dumugol	Kayseraspis Protopliomerops Asaphells	Mungok	Shumardia pellizzarii Kainella euryrachis
Cambrian	Tremadocian	Dongjeom	Pseudokainella		Yosimuraspis vulgaris
	Furongian	Hwajeol	Eoorthis Dictyites	Wagok	Fatocephalus hunjiangensis
			Kaolishania	Machari	Pseudoyuepingia asaphoides Agnostotes orientalis Eochuangia hana Eugonocare longifrons Hancrania brevilimbata
			Chunagia		Proceratopyge tenuis Glyptagnostus reticulatus Glyptagnostus stolidotus
			Prochuangia		Lejopyge armata Tonkinella
			Drepanura Stephanocare		
	Middle	Sesong	Olenoides Solenoparia Megagraulos	Sambangsang	Megagraulos semicircularis Metagraulos sampoensis
		Daegi	Bailiella Mapania Elrathia Redlichia		
		Myobong			
	Early	Jangsang/Myeonsan			

of the latest Cambrian.

The Mungok Formation contains three biozones (*Yoshimuraspis vulgaris*, *Kainella euryraxis*, and *Shumaridia pellizzarii* zones), corresponding to the Tremadocian of the Early Ordovician. In the lower Yeongheung Formation, only one biozone, *Kayseraspis* Zone, was recognized, indicating an age of the Arenigian (Choi and Chough, 2005). However, Cho and Kim (2007) based on graptolite occurrence, suggested that the lowermost part of the Yeongheung Formation corresponds to an age of the latest Tremadocian. The occurrence of a stromatoporoid, *Labechia regularis* in the middle part of the Yeongheung Formation is indicative of the Llanvirnian (Middle Ordovician). The conodont biozones of the formation also indicate the time span from Arenigian to Caradocian (Lee, 1987).

5. Sequence Stratigraphy

In the Taebaek platform, the Sauk transgression inundated topographic lows of the Precambrian basement of granitic gneiss and meta-sedimentary rocks during late Early and early Middle Cambrian (Kwon *et al.*, 2006). During the early Sauk transgression, most of the Taebaek region was submerged, whereas the Yeongweol platform was most likely exposed until early Middle Cambrian (Fig. 5A).

In the middle Middle Cambrian, initial flooding in the Yeongweol platform formed siltstone and shale sequences in the lower part of the Sambangsan Formation (Fig. 3). A gradual decrease of sea-level rise resulted in progradation of nearshore sand-prone facies, which generated sandstone-dominated sequence in the upper part of the Sambangsan Formation (Fig. 5B). Until the middle Middle Cambrian, the carbonate factory in subtidal zones of the Yeongweol platform has not been activated. The Sambangsan Formation is the lowermost second-order sequence (supersequence-1).

During the late Middle Cambrian, tectonic tilting of the North China platform resulted in the drowning of the platform. Formation of a drowning unconformity between the Daegi and Sesong formations in the Taebaek platform has been correlated with that result (Kwon *et al.*, 2006). The drowning probably also occurred in the Yeongweol platform, which caused deepening, resulting in a

deep carbonate ramp or slope deposition of the Machari Formation (Fig. 5C). The continued rise of sea level during the Late Cambrian formed a typical ramp sequence, such as the Hwajeol Formation of the Taebaek Group and the upper Machari and Wagok formations of the Yeongweol Group. They are composed of ribbon limestone, shale, and limestone conglomerate (Fig. 5D). The ramp sequences are characterized by cyclic sedimentation of subtidal shallowing upward successions, showing the superposition of third-order transgressive-regressive sequences (Fig. 3).

In the latest Cambrian and earliest Ordovician, a thick sandstone succession (the Dongjeom Formation) formed in the Taebaek platform. It probably resulted from an abrupt fall of relative sea level and large supply of coarse-grained siliciclastics (Kwon *et al.*, 2006). The fall of relative sea level was most likely caused by diastrophism in the northeastern part of the North China platform (Meyerhoff *et al.*, 1991). The local uplift and the subsequent base-level fall might also have influenced the Yeongweol platform in the latest Cambrian and earliest Ordovician (Fig. 5E). The shallowing by base-level fall probably exposed the Yeongweol platform or submerged the platform at a very shallow level (Fig. 5E). The shallowing can be evidenced by type-I dolomitization which occurred penecontemporaneously, or shortly after deposition of the Wagok Formation, perhaps in an oxidizing environment (Woo and Moore, 1996). During its subsequent burial, the unstable dolomite was entirely recrystallized by deep burial dolomitization. The transgressive-regressive successions from the Machari to Wagok formations constitute the supersequence-2 in the Yeongweol Group.

The resumed sea-level rise during the late Sauk transgression in the Early Ordovician (Tremadocian to Arenigian) formed typical subtidal ramp-type transgressive-regressive successions and successive highstand peritidal cyclic successions (Fig. 3 and 5F). In the Yeongweol platform, the subtidal sequence of the Mungok Formation is correlated with the Dumugol Formation (Tremadocian) in the Taebaek region, whereas the peritidal sequence in the lower part of the Yeongheung Formation can be correlated with the Makgol Formation (Arenigian) in the Taebaek area (Table 3).

A gradual rise of eustatic sea level during the

Fig. 5. Sedimentary evolution of the Yeongweol platform sequences.

Cambrian (Sauk transgression) was maintained until the Early Ordovician (e.g., Vail *et al.*, 1977). During the earliest Middle Ordovician (early Darrwillian), global eustatic fall occurred and generated the globally-recognized bounding surfaces of 1st order megasequences (Sauk and Tippecanoe boundary) (Sloss, 1963). In the Taebaek platform, the megasequence boundary is preserved at the uppermost part of the Makgol Formation (Kwon *et al.*, 2006). In the Yeongweol platform, some evidences of subaerial exposure such as supratidal laminites, evaporite mineral casts, desiccation cracks and tepee structures have been recorded at the lower (or middle) part of the Yeongheung Formation (Figs. 3 and 4K-L; Yoo *et al.*, 1994). These evidences support a broad and significant sea-level fall after deposition of the lower Yeongheung Formation (Fig. 5G). The transgressive-regressive successions from the Mungok Formation to the lower part of the Yeongheung Formation can be interpreted as Supersequence-3, bounded by the Sauk-Tippecanoe sequences. Over the wide exposure surface of the underlying peritidal carbonate successions, a resumed transgression occurred in the Middle Ordovician (Fig. 5H). The Tippecanoe transgression formed the siliciclastic-dominated transgressive sequence of the Jigunsan Formation and the overlying carbonate-dominated regressive sequence of the Duwibong Formation in the Taebaek platform (Kwon *et al.*, 2006). In contrast, the Darrwillian and Caradocian Yeongweol sequence is composed of simple stackings of shallowing-upward successions consisting of shallow subtidal and peritidal carbonates (Fig. 5H). In the cyclic successions, more than five third-order sequences have been recognized, superimposing second-order sea level fluctuations (Yoo *et al.*, 1994; Yoo and Lee, 1997). The cyclic successions in the middle and upper parts of the Yeongheung Formation comprise the uppermost supersequence-4 in the Yeongweol Group.

In the Yeongweol platform, the successive stacking of carbonate-dominated sequences was maintained, passing through first-order megasequence boundary. The omission of deep platform sequence formed during the early transgression (such as Jigunsan Formation in the Taebaek platform) was probably due to the much more active carbonate factory and too far away sources for supply of

siliciclastic sediments.

6. Discussion

Among the five formations of the Yeongweol Group, the lower three correspond to the Cambrian sequences, whereas the upper two correspond to the Ordovician sequences. In the Taebaek platform, the Sauk transgression was initiated in the late Early Cambrian, whereas it started in the middle Middle Cambrian in the Yeongweol platform (Fig. 6). The delayed initiation of transgression implies that the basement of the Yeongweol platform might be topographically higher than that of the Taebaek platform. During the Sauk transgression from the Middle Cambrian to Early Ordovician, three supersequences were formed in the Yeongweol platform.

Supersequence-1 (Sambangsan Formation) consists of siliciclastic-dominated units formed during the initial flooding of the platform (Fig. 6). Tectonic tilting and drowning of the North China platform probably occurred in the late Middle Cambrian and might be related to the generation of a type-3 sequence boundary and the drowning of the Yeongweol platform. On the drowning surfaces, the supersequence-2 (Machari and Wagok formations) was formed in the late Middle and Late Cambrian (Fig. 6). Around the Cambrian and Ordovician boundary, local diastrophism occurred in the northeastern part of the North China platform, resulting in uplifting, base-level fall, and basin rejuvenation. The base-level fall generated the supersequence-3 (Dongjeom, Dumugol and Makgol formations) in the Taebaek Group, whereas in the Yeongweol platform, it also formed the supersequence-3 composed of the Mungok Formation and the lower part of the Yeongheung Formation during the Early Ordovician (Fig. 6).

After the relative sea-level drop in the earliest Middle Ordovician between the Sauk and Tippecanoe transgression, the supersequence-4 (upper part of the Yeongheung Formation) was formed in the Yeongweol platform (Fig. 6). The supersequence comprises shallowing-upward subtidal and peritidal cyclic successions. In the Yeongweol platform, the continuous stacking of carbonate-dominated successions was maintained, passing through first-order megasequence boundary. The absence of

Fig. 6. Sequence stratigraphic interpretation of the Yeongweol Group.

deep platform sequence formed during the early transgression (such as Jigunsan Formation in the Taebaek region) in the Yeongheung Formation can be attributed to a very strong catch up of carbonate factory in the Yeongweol platform which was located far from siliciclastic sources inhibiting the input of such material to the platform.

The paleogeographic relation between the North China platform and Taebaeksan Basin has been a primary concern of geologists working (e.g., Chough *et al.*, 2000; Chough and Choi, 2005; Kwon *et al.*, 2006). According to Kwon *et al.* (2006) and Woo *et al.* (2008), the Taebaeksan Basin was located in the northeastern margin of the North China platform. The North China platform sequences have been known to be deposited in a broad and open shallow-marine platform with limited clastic or river-sediment inputs, whereas the Taebaeksan platform sequences were probably formed in a restricted embayment with substantial clastic input (Fig. 7; Kwon *et al.*, 2006).

The Taebaeksan sequences are divided into two large and three relatively smaller lithologic groups. The larger two are the western Yeongweol and eastern Taebaek groups (Fig. 1). On the basis of lithological similarity and paleontological affinity, the Taebaek Group is interpreted as a part of the North China platform (Choi, 1998; Chough *et al.*, 2000; Choi *et al.*, 2004; Kwon *et al.*, 2006). Although the trilobite assemblages suggest that the Yeongweol platform was included in the North China platform (Choi *et al.*, 2001), however, there have been considerable debates on the paleogeographic position of the Yeongweol platform based on the lithologic difference between the Yeongweol platform sequence and other North China platform sequences (Cluzel *et al.*, 1991; Yin and Nie, 1993).

The present work evaluates the sequence stratigraphic interpretation of the Yeongweol platform sequence (Fig. 6) and the paleogeographic correlation between the Yeongweol and Taebaek sequences (Fig. 7). The relative sea-level fluctuations in the Yeongweol platform are very similar to those of

Fig. 7. Sequence stratigraphic correlation between the Yeongweol and Taebaek groups (after Y.K. Kwon *et al.*, 2006).

the Taebaek platform (Fig. 7). The rapid sea-level rise in the late Middle Cambrian resulted in a drowning event in the Yeongweol platform, forming an abrupt deepening represented by the lower Machari Formation (Fig. 6).

The relative sea-level fall in the earliest Ordovician occurred in the Taebaek platform, which might be related to local diastrophism in the northeastern part of the North China platform, subsequent basin rejuvenation and clastic dumping in the shallow platform (Kwon *et al.*, 2006). In the Yeongweol platform, the sea-level drop was documented in the upper part of the Wagok Formation, evidenced by almost syndepositional dolomitization (Fig. 5). The major eustatic sea-level fall between the Sauk and Tippecanoe sequences occurred in the uppermost Makgol Formation of the Taebaek Group (Kwon *et al.*, 2006). In the Yeongweol platform, passing through first-order megasequence boundary, shallowing-upward peritidal cycles were stacked successively with some exposure surfaces (Fig. 3). The exposure has been interpreted as a result of a few third-order relative sea-level falls in the Middle Ordovician (Yoo and Lee, 1997). Among these, the lowermost one can be correlated with

first-order eustatic sea level drop between the Sauk and Tippecanoe transgressions (Fig. 8).

According to sequence stratigraphic interpretation, the reconstructed relative sea-level curve of the Yeongweol platform is very similar to that of the Taebaek platform. It suggests that the Yeongweol and Taebaek platform sequences simultaneously experienced the similar tectonic history in the northeastern North China platform during the Cambrian and Ordovician (Fig. 6; Kwon *et al.*, 2006). Based on the absence of coarse-grained clastic sequence and the successive stacking of peritidal platform carbonates in the Early to Middle Ordovician Yeongweol Group, we suggest that the Yeongweol platform was probably located in a relatively open shallow marine environment. Whereas the Taebaek platform was formed in a restricted embayment, possibly located in the northeastern margin of the North China platform (Fig. 9). The Yeongweol platform also had a strong catch up ability of carbonate factory, as it was located far from siliciclastic sources with little input of these components in the platform (Fig. 9). The Yeongweol platform was probably juxtaposed with the Taebaek platform, forming the Joseon

Fig. 8. Stratigraphic position of first order sequence boundary between the Sauk and Tippecanoe sequences within the Yeongheung Formation (modified after C.M. Yoo and Y.I. Lee., 1997).

Supergroup in Taebaeksan Basin through the complex movements associated with the late Paleozoic and early Mesozoic amalgamation between the North and South China blocks (Fig. 9).

7. Conclusions

The Yeongweol Group is a Lower Paleozoic mixed carbonate-siliciclastic sequence, and consists of five lithologic formations: Sambangsang, Machari, Wagok, Mungok, and Yeongheung formations in ascending order. The Cambrian-Ordovician Yeongweol Group consists of four second-order sequences (supersequence-1, -2, -3, and -4). Supersequence-1 consists of the Sambangsang Formation (middle Middle Cambrian), lithologically composed of siltstone, shale and sandstone, terminated by rapid deepening of the Yeongweol platform. The

overlying supersequence-2 comprises the Machari and Wagok formations (late Middle to Late Cambrian). The drop and ensuing rise of relative sea level during the latest Cambrian or earliest Ordovician would produce supersequence-3, representing the subtidal platform carbonates (Mungok Formation) and the overlying peritidal platform carbonates (lower part of the Yeongheung Formation). Passing through the Sauk and Tippecanoe boundary, supersequence-4 was formed in the Yeongweol platform during the Middle Ordovician. The reconstructed relative sea-level curve of the Yeongweol platform is very similar to that of the Taebaek platform, suggesting that the Yeongweol platform was located somewhere between the North and South China platforms, much closer to the North China platform. The lithologic and stratigraphic differences imply that the Yeongweol and Taebaek

Fig. 9. Paleogeography of the Yeongweol and Taebaek platforms in the North China Platform during the Cambrian and Ordovician.

platforms might not belong to a single depositional system within the North China platform. The Yeongweol platform was probably located in relatively open shallow marine environments, whereas the Taebaek platform was a part of the restricted embayments of the northeastern margin of the North China platform.

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