Lithofacies and Stable Carbon Isotope Stratigraphy of the Cambrian Sesong Formation in the Taebaeksan Basin, Korea

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Abstract: The Sesong Formation, mixed carbonate-siliciclastic deposits of late Middle Cambrian (Series 3) to Furongian in age, in the Taebaeksan Basin shows the Steptoean Positive Carbon Isotope Excursion (SPICE) with the δ¹³C values ranging from 1.14 to 2.81‰ in the approximately 15-m-thick stratigraphic interval. The SPICE in the Sesong Formation occurs in the lower part of the Paibian Stage which contains trilobite biozones of the Fenghuangella laevis Zone, Prochuangia mansuyi Zone and the lower part of the Chuangia Zone. The Sesong Formation is composed of six lithofacies including laminated mudstone, nodular shale, laminated sandstone, massive sandstone, limestone conglomerate, and limestone-shale couplet facies. The Sesong Formation is known to have been deposited in the outer shelf below storm wave base. The SPICE occurs in the stratigraphic interval associated with highstand systems tract, correlative conformity and transgressive systems tract of the Sesong Formation. The peak carbon isotope value in the SPICE may coincide with the correlative conformity formed by relative sea-level fall. The occurrence of the SPICE in the Sesong Formation suggests that the SPICE can be used as a tool of global correlation for the successions of mixed carbonate-siliciclastics which lack fossils.

Keywords: Sesong Formation, SPICE, stable carbon isotope stratigraphy, mixed carbonate-siliciclastics, Taebaeksan Basin

요약: 태백산 분지에 분포하는 단산염 및 규절의 섬유 흔적으로 구성된 세송층(late Middle Cambrian to Furongian)은 δ¹³C값이 1.14에서 2.81‰가 갖는 SPICE(Steptoean positive carbon excursion)를 15 m 두께의 충층구간에서 보여준다. SPICE는 Fenghuangella laevis대, Prochuangia mansuyi대 그리고 Chuangia대로 구성된 삼업층 생물대에서 산출되며 이는 Paibian Stage의 하부에 해당한다. 세송층은 엽추리 이알, 단단염 세일, 엽추리 사암, 구질사암, 석회암, 석회암-세일 쌍을 포함한 6개의 압장으로 구성된다. 세송층은 폭풍파도기적인 아래의 외대류층에서 퇴적된 것으로 알려져 있다. 시기적으로 Paibian Stage에 속하는 SPICE는 세송층에서 고수위 퇴적계 다발, 대비 정합면과 해침

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Introduction

The $\delta^{13}C$ value of DIC (dissolved inorganic carbon) of the ocean has been varied over geologic time due to partitioning of carbon between organic carbon and carbonate carbon reservoirs in the lithosphere (Kump and Arthur, 1999; Veizer et al., 1999; Saltzman and Thomas, 2012). Variation of the $\delta^{13}C$ values of DIC of the ocean is caused by changes in the size and rate of the exchange fluxes between the Earth's surface carbon reservoirs and the lithosphere (Saltzman and Thomas, 2012). As the light carbon incorporates into marine photosynthetic biota, active production of organic matter by photosynthesis in the ocean removes $^{12}C$ preferentially over $^{13}C$ from the ocean. If there is more removal of carbon from the ocean by organic matter and subsequent burial of organic matter in the ocean floor, the $\delta^{13}C$ value of DIC of the ocean increases, whereas if there is more oxidation of organic matter compared to deposition, the $\delta^{13}C$ value of DIC of the ocean decreases.

Positive stable carbon isotope excursion in the Upper Cambrian successions known as the SPICE, an increase in $\delta^{13}C$ values of marine carbonate above their background value of $-1$ to $+1$‰ VPDB (Vienna PeeDee Belemnite) to a maximum of $+4$ to $+5$‰ shift (Fig. 1) has been documented in sections of many parts of the world including North America (Saltzman et al., 1998; Saltzman et al., 2000; Saltzman et al., 2004; Glumac and Mucci, 2007; Elrick et al., 2011), China (Zhu et al., 2004; Peng et al., 2004), Australia (Lindsay et al., 2005), Argentina (Sial et al., 2008; Sial et al., 2013), Kazakhstan (Saltzman et al., 2000), Siberia (Kouchinsky et al., 2008), Scandinavia (Ahlberg et al., 2009), France (Alvaro et al., 2008); and Korea (Chung et al., 2011). The SPICE has a duration of 2 to 4 Myr (Gill et al., 2011) and occurs within the Paibian Stage of the Furongian Series of the Cambrian, ranging in age of 497 to 494 Ma (Peng et al., 2012). The SPICE may be caused by the high rate of primary production and the high burial rate of organic matter with probable association of the high rate of input of terrigenous sediments (Saltzman et al., 2004). The increase in burial of organic carbon on the

Fig. 1. The SPICE (Steptoean Positive Carbon Isotope Excursion) in Laurentia, an increase in $\delta^{13}C$ values of marine carbonate above their background value of $-1$ to $+1$‰ VPDB to a maximum of $+4$ to $+5$‰; the peak of $\delta^{13}C$ values coincides with sequence boundary (Glumac, 2011).
The SPICE occurs in the stratigraphic interval marked by an influx of quartz sand into carbonate platform during regression in association with development of the Sauk II-III sequence boundary in Laurentia (Saltzman et al., 2004; Glumac, 2011). In the North China Platform the SPICE is also found in the stratigraphic interval associated with relative sea-level fall identified by erosion surface and missing trilobite biozone (the Prochuangia Zone of early Paibian age) (Chen et al., 2011; Lee et al., 2015). In spite of numerous studies of SPICE in other continents of the world, there has been no research on SPICE in the Cambrian section of the Taebaeksan Basin which is thought to be part of the North China Platform (Kwon et al., 2006). The purpose of study is to document the stable carbon isotope stratigraphy as well as the SPICE in the Sesong Formation in association with trilobite biostratigraphy and sequence stratigraphy.

**Geologic Setting**

The Sesong Formation belongs to the Taebaek Group of the Joseon Supergroup in the Taebaeksan Basin (Fig. 2). The Sesong Formation overlies the Daegi Formation and underlies the Hwajeol Formation, and is known to be Late Cambrian Epoch 3 to early Furongian in age (Sohn and Choi, 2005). The Sesong Formation was reported to be dominated by mudstone and shale, with subordinate intercalation of laminated, massive, and crudely stratified sandstone, and limestone conglomerate (Kwon et al., 2006). The lower part of the Sesong Formation consists mainly of nodular shale with frequent intercalations of limestone conglomerate; the middle part fine to medium-grained sandstone with a couple of limestone conglomerate beds; the upper

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**Fig. 2.** Location and geologic maps. Index map (A) showing the location of and geology of the Taebaeksan Basin with the location of Taebaek area in rectangle (B). Jikdong and Sagundari sections are shown in road map of the Taebaek area (C).
part siltstone and fine-grained sandstone with occasional intercalation of limestone conglomerate beds (Park et al., 2012). The lower boundary of the Sesong Formation is characterized by an abrupt facies change from limestone to shale. The upper boundary of the Sesong Formation shows a facies change from fine-grained sandstone in the uppermost part of the Sesong Formation to limestone-shale couplets of the lowermost part of the Hwajeol Formation (Park et al., 2012).

Methods

Stratigraphic sections were measured at the Jikdong and Sagundari sections in the Taebaeksan Basin (Fig. 2). Forty rock samples were obtained from 40 horizons with 0.4 to 3 m interval, and thin sections were prepared for microscopic observation. The cut surface of mounted chip for making thin section was micro-drilled to obtain powder sample of 2 to 3 mg for the analyses of stable carbon and oxygen. The micro-drilling spot in rock chip was determined by microscopic observation to identify petrographic characteristics of the micro-drilled spot and to obtain the least altered sample such as micrite as much as possible. The analysis of stable carbon and oxygen was conducted at the Korea Basic Science Institute. The powder sample was reacted with phosphoric acid to convert the CO$_2$ gas which was analyzed by the Optima isotope-ratio mass spectrometer with dual inlet system. The precision of $\delta^{13}$C measurement was 0.03‰ and $\delta^{18}$O was 0.05‰.

Results

Lithofacies

The lithofacies of the Sesong Formation at the Jikdong and Sagundari sections are laminated mudstone, nodular shale, laminated sandstone, normally-graded sandstone, massive sandstone, limestone conglomerate, and limestone-shale couplet (Table 1).

Laminated mudstone (Ml): This facies consists of alternating laminae of argillaceous mud and calcareous mud (Fig. 3A). Most laminae are very thinly to thinly laminated but some are thickly laminated (Fig. 3B). Argillaceous mud consists mainly of clay minerals with minor amount of quartz silts (Fig. 3C). Calcareous mud is consisted of micrite to sparry calcite with quartz silts and allochems (Fig. 3C). Less than 10% of allochems are observed. Calcareous mud laminae show sharp lower boundary and gradational upper boundary. This facies is medium gray to dark gray with good lateral continuity. The thickness of facies is 10 to 105 cm with an average thickness of 44 cm.

Fine-grained sediments and good lateral continuity suggest deposition in deep water environment presumably below storm wave base. The occurrence of mm-scale laminations suggests suspension settling (Elliott et al., 2015). Alternations of siliciclastic mud and calcareous mud suggest that calcareous mud might have been transported from shallow depths as diluted turbidity currents into sea floor below storm wave base where siliciclastic muds settle as pelagic settling.

Nodular shale (Fn): This facies consists of horizontally laminated to massive dark gray to gray argillaceous mudstone containing discontinuous calcareous nodular layer (Fig. 3D). Argillaceous mudstone of mm thick laminae consists of clay minerals with some quartz silts. Calcareous nodules are 1 to 15 cm long and 0.3 to 4 cm thick (Fig. 3E). Nodule content is 10 to 40%. Argillaceous laminae consist of clay minerals and they are alternating with limestone consisted of microsparry to sparry calcite or quartz silt laminae. Calcareous nodules consist of microsparry calcite to sparry calcite (Fig. 3F). This facies is 13 to 420 cm thick and about 50 cm thick in average. This facies occurs mainly in the lower part of the Sesong Formation and shows good lateral continuity.

Occurrence of horizontally laminated to massive dark gray to gray argillaceous mudstone containing calcareous nodules suggests deposition by suspension settling below storm wave base. Calcareous nodules are thought to be formed by early marine cementation (Flugel, 2004; Banerjee et al., 2006).
Laminated sandstone (Sl): This facies consists of alternating horizontal laminae of very fine- to medium-grained sandstone of 3 to 5 mm in thickness and in outcrop lamination is not clear on the weathered surface (Fig. 3G), but mm-scale laminae are observed well in rock slab (Fig. 3H). Sandstone laminae consist of subangular to subrounded quartz grains with relatively good sorting (Fig. 3I). The thickness of facies is 10 to 600 cm with 250 cm thick in average. Most of the sandstone in the Sagundari section consists of very fine-grained sandstone with calcite cement. Sandstone in the Sagundari section is grayish purple in color. Alternation of slight difference in size of quartz grains makes laminae in the Sagundari section (Fig. 3I). This facies shows relatively good lateral continuity.

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**Table 1. Lithofacies of the Sesong Formation**

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>Laminated mudstone (Ml)</td>
<td>Alternations of very thin to thick laminae of argillaceous mud and calcareous mud or argillaceous laminae of mud and silt; dark gray argillaceous laminae and gray calcareous laminae; sharp lower boundary of lime mudstone laminae; good lateral continuity; medium gray to dark gray; 10 to 105 cm thick with 44 cm in average</td>
<td>Deposition by suspension settling or turbidity currents (Elliott et al., 2015)</td>
</tr>
<tr>
<td>Nodular shale (Fn)</td>
<td>Calcareous nodules in mudstone; nodules of 1 to 15 cm long and 0.3 to 4 cm thick; 10 to 40 % of calcite nodule contents in argillaceous mudstone; nodules consisted of fine to coarsely crystalline sparly calcite with some allochems; good lateral continuity; dark to light gray; 13 to 420 cm thick with 50 cm thick in average</td>
<td>Deposition by suspension settling or turbidity currents and marine cementation (Flügel, 2004; Banerjee et al., 2006)</td>
</tr>
<tr>
<td>Laminated sandstone (Sl)</td>
<td>Alternation of very fine-grained sandstone with medium-grained sandstone of 3 to 5 mm thick laminae; sandstone layer consisted of subangular to sub-rounded quartz grains with relatively good sorting; intercalation of mudstone laminae; medium to dark gray or grayish purple; good lateral continuity; 10 to 600 cm thick with 250 cm thick in average</td>
<td>Deposition of strong current with intermittent introduction of mud by storm activity (Nichols, 2009)</td>
</tr>
<tr>
<td>Massive sandstone (Sm)</td>
<td>Very fine- to medium-grained sandstone to calcareous sandstone; angular to sub-rounded quartz grains with moderate sorting; quartz grains with some bioclasts and pebble size intraclasts; quartz sands and allochems in microsparry to sparry calcite matrix; occasional sharp lower boundary; a few to 50 cm thick; gray</td>
<td>Rapid suspension settling (Kwon et al., 2006)</td>
</tr>
<tr>
<td>Limestone conglomerate (Cl)</td>
<td>Limestone conglomerate consisted of rounded to subrounded 1 to 10 cm long pebbles; 30 to 50% pebble contents; spherical or ellipsoidal; limestone clasts consisted of laminated wackestone to grainstone intraclasts; sharp erosional base; subparallel to parallel to bedding surface; pinky gray to light gray; sometimes channel-fill shaped; relatively good horizontal extension.</td>
<td>Storm deposition or autoconglomeration (Chen et al., 2009)</td>
</tr>
<tr>
<td>Limestone-shale couplet (L-S)</td>
<td>Alternating layers of thickly laminated (7 to 8 mm) to thinly bedded (2 to 3 cm) light gray lime mudstone and gray shale; allochems of bioclasts and peloids in limestone layer; gradational contact between limestone and shale layer and sharp contact between shale layer and limestone layer; 8 to 164 cm thick with 40 cm thick in average; good lateral continuity</td>
<td>Suspension settling of argillaceous lime mudstone with periodic introduction of lime mud by turbidity currents (Elrick et al., 1991)</td>
</tr>
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</table>

Massive sandstone (Sm): This facies forms almost
Fig. 3. Lithofacies of the Sesong Formation including photos of outcrop, rock slab, and photomicrographs. All photomicrographs are in cross-polarized light. Scales in rock slabs are in cm. Laminated mudstone (A to C); outcrop (A), rock slab consisted of very thinly to thinly laminated argillaceous and calcareous mudstone (B) and thin section photomicrograph showing alternation of clay to fine silt (lower two thirds) and coarse silt (upper one third) (C). Nodular shale (D to F); outcrop (D), rock slab showing discontinuous calcareous nodules of 1 to 15 cm long and 0.3 to 4 cm thick (E) and thin section photomicrograph characterized by sparry calcite (lower two thirds) and argillaceous clay to silt (upper one third) (F). Laminated sandstone (G to I); outcrop (G), rock slab showing alternation of millimeter-scale laminae (H) and thin section photomicrograph showing subtle alternation of very fine sands in the lower half and fine sands in the upper half (I). Massive sandstone (J to L); outcrop (J), rock slab showing alternation of massive sands with calcareous allochems (upper one third) and massive sand beds (lower two thirds) (K) and thin section photomicrograph showing sand grains with sparry calcite (L). Limestone conglomerate (M to O); outcrop (layer just below hammer and layer covered by upper three fourths of hammer) (M), rock slab (N) and thin section photomicrograph characterized by three micrite intraclasts with sparry calcite (presumably recrystallized matrix) in the center (O). Limestone-shale couplet (P to R); outcrop (P), rock slab alternating limestone layer (light) and argillaceous layer (dark) (Q) and thin section photomicrograph alternating argillaceous clay (lower half) and sparry calcite (upper half) with gradation in limestone layer (R).
homogeneous outcrop comprised of very fine- to medium-grained sandstone (Fig. 3J). Sometimes very thinly to thinly laminated beds are observed (Fig. 3K). Most of this facies is calcareous sandstone. Quartz grains are subangular to subrounded with moderate sorting (Fig. 3L). Quartz grains and some bioclasts occur in microsparry to sparry calcite matrix. It contains discontinuous thin laminae of carbonate bioclasts and pebble-size intraclasts. Very fine- to medium-grained sandstone beds are alternating with bioclastic wackestone. This facies is gray in color and a few cm to 50 cm thick and alternates with laminated sandstone facies. This facies occurs in the upper part of the stratigraphic interval exposed in the Jikdong section.

This facies is interpreted to have been deposited by rapid suspension settling (Kwon et al., 2006). Mixed siliciclastic sand grains and carbonate mud with allochems are thought to have been transported from shallow depths to outer shelf via turbidity currents.

Limestone conglomerate (Cl): This facies is composed of two types. The first type is composed of subrounded to rounded 1 to 10 cm long pebbles of spherical, oval, or tabular shape and the pebble content is 30 to 50% (Fig. 3M and N). Limestone clasts consist of lime mudstone or laminated wackestone to grainstone with sparry calcite (Fig. 3O). This type is pinky gray to light gray with irregular arrangement and relatively good lateral continuity. They are subparallel to parallel to the bedding surface. Some of lime conglomerate facies of this type show channel-fill feature. The second type is composed of 0.5 to 1 cm thick and several mm to several cm long intraclasts. It shows 40 to 60% clast contents and subparallel to the bedding surface. Lime conglomerates are mostly light gray with abrupt lateral change into lime mudstone and show partly edgewise arrangement with poor lateral continuity.

Occurrence of limestone pebbles of the first type with a good lateral continuity suggests deposition by storm activities. Limestone pebbles may have originated from erosion or reworking of cemented shallow carbonate sea floor and then were transported into outer shelf below storm wave base as turbidity currents (Myrow et al., 2004). Edgewise arrangement of intraclasts with poor lateral continuity of the second type was suggested to be formed by postdepositional autoconglomeration (Chen et al., 2009).

Limestone-shale couplet facies (L-S): This facies consists of alternating layers of thickly laminated (7 to 8 mm thick) to thinly bedded (2 to 3 cm thick) light gray limestone and dark gray shale (Fig. 3P & Q). Sometimes this facies shows sharp boundary between shale and limestone layers with upward gradation in limestone layer (Fig. 3R). Limestone layer consists of micrite to sparry calcite with some allochems of bioclast, intraclast and peloids. Dark gray layer consists of clay minerals. This facies is 8 to 164 cm in thickness with an average thickness of 40 cm. It shows good lateral continuity.

Alternation of shale and limestone layer suggests that lime mud was introduced as event deposits such as distal storm deposits or turbidity currents into outer shelf where siliciclastic mud was settling as background sedimentation (Elrick et al., 1991; Sim and Lee, 2006). Carbonates are thought to have been introduced intermittently.

Stable carbon isotopes

The Sesong Formation in the Jikdong and Sagundari sections shows stable carbon isotope value of $-1.66$ to $-2.81\%$ and stable oxygen isotope value of $-28.73$ to $-11.60\%$ (Table 2). The SPICE occurs about 21 m above the lower boundary of the Sesong Formation in the stratigraphic interval of approximately 15 m thick, which is mostly composed of laminated mudstone, nodular shale, massive to laminated very fine- to fine-grained sandstone with intercalation of limestone conglomerate beds. The $\delta^{13}C$ values of SPICE interval range 1.14 to 2.81\%.
Sequence stratigraphy and SPICE

Based on the dominant occurrence of mudstone and shale with intercalation of limestone pebble and sandstone beds, the depositional setting of the Sesong Formation is interpreted to be the outer shelf (Kwon et al., 2006). The Sesong Formation shows different lithology in stratigraphic position; the lower part consists mainly of nodular and laminated shale with frequent intercalation of limestone pebble, the middle part the fine- to medium-grained sandstone and the upper part very fine to fine-grained sandstone (Fig. 4). Occurrence of mixed carbonate-siliciclastics may be associated with the deposition in the carbonate platform margin where siliciclastics were introduced (Chen et al., 2006).
2012). No occurrence of shallow water features developed above storm wave base or fair weather wave base such as scour marks and ripple laminations suggests that the depositional environment of the Sesong Formation was below storm wave base.

The Daegi Formation which underlies the Sesong Formation is composed of carbonates deposited in the carbonate ramp (Sim and Lee, 2006). The Sesong Formation may have begun to deposit in the outer shelf with transgression as transgressive systems tract first. Abrupt change in facies at the boundary between the Daegi and Sesong Formations is interpreted to be
A rapid rise of sea-level which might have resulted in the development of a transgressive systems tract forms the lower part of the Sesong Formation. Highstand of sea level may have been followed by a sea-level lowstand which developed a correlative conformity above which the occurrence of very fine- to fine-grained sand increases (Fig. 5). There might have been a fast sea-level fall between the development of highstand systems tract and the development of correlative conformity, and the fast sea-level fall resulted in absence of falling stage and lowstand systems tracts. Instead, the sea-level fall resulted in the development of a correlative conformity and coincides with initiation of influx of quartz sands (Figs. 4 & 5). Very fine quartz sands begin to appear near the suggested correlative conformity. Above the suggested correlative conformity laminated shale facies is changed into massive sandstone facies, which means, with a drop of sea-level, deposition of mud changed to deposition of sand (Figs. 4 & 5).

Development of the SPICE in association with major sequence boundary has been reported in Laurentia and other continents (Saltzman et al., 2004; Glumac, 2004).
In the Sesong Formation the correlative conformity approximately coincides with upper limit of the *Prochuangia mansuyia* Zone (Fig. 5). Lee et al. (2015) reported relative sea-level fall in the early Paibian Stage in Shandong Province, China in the Sino-Korean Block (North China platform) based on a subaerial unconformity with erosional surface of limestone bed overlain by a glauconite-rich bioclastic grainstone (transgressive lag deposit) and shale-dominated deposit, which resulted in the absence of the *Prochuangia Zone* (early Paibian Stage), suggesting that this unconformity between the Cambrian Series 3 and Furongian in the North China Platform (Surface 2) coincides with the SPICE-occurring interval. In contrast, the occurrence of the *Prochuangia Zone* in the Sesong Formation suggests a continuous deposition of siliciclastics at the margin of North China platform (Chen et al., 2012; Lee et al., 2015). The lowstand of sea level is followed by deposit of a transgressive systems tract with rise of sea level (Fig. 5). With the relative sea-level rise very fine- to medium-grained sandstone was deposited with infrequent introduction of limestone intraclasts as event deposits such as distal storm deposits or turbidity currents. Subsequent transgression was resulted in the deposition of the very fine-grained sandstone in the upper part of the Sesong Formation and was followed by the deposition of highstand systems tract. A marine flooding surface marks the boundary between the Sesong Formation and the overlying Hwajeol Formation (Chen et al., 2012).

**Comparison of SPICE**

The positive excursion in $\delta^{13}C$ curve in the Sesong Formation occurs at the stratigraphic interval of which $\delta^{13}C$ value is 1.14 to 2.81‰ (Fig. 5). The SPICE event occurs in the trilobite biozones including the *Fenghuangella laevis* Zone, *Prochuangia mansuyia* Zone and the lower part of the *Chuangia* Zone (Fig. 5). The SPICE event in the Sesong Formation at the Jikdong section begins above 21 m of the boundary between the Daegi and Sesong formations, and occurs in about 15 m thick stratigraphic interval (Fig. 5). The occurrence of SPICE in the Sesong Formation can be compared with those of Laurentia and China (Fig. 6). Coincidence of the SPICE with relative sea-level fall has been reported in Laurentia, North China and South China (Saltzman et al., 2004; Chen et al., 2011; Lee et al., 2015). In Laurentia the maximum positive excursion coincides with a maximum regression during which a craton-wide hiatus separating the Sauk II and Sauk III sequences occurred (Saltzman et al., 2004; Glumac, 2011). Chen et al. (2011) documented an abrupt positive excursion (SPICE) of $\delta^{13}C$ up to 3.46‰ across the erosion surface which forms the boundary between the Cambrian Series 3 and the Furongian in the North China Platform, and this abrupt increase of $\delta^{13}C$ value at the lower part of the SPICE is associated with missing of the *Prochuangia Zone* due to erosion. The maximum values of positive carbon isotope excursion varies depending on continents. The SPICE up to 2.23‰ of positive carbon isotope excursion is found at the *Chuangia Zone* and the lower part of *Changshania-Irvingella* Zone in the the Changshan Formation, Gushan, Shandong Province in the North China Block forming the beginning part of Furongian Series (Zhu et al., 2004). Compared to the SPICE interval in the North China Block, the SPICE interval in the South China Block shows distinctive peak of positive carbon isotope excursion up to 5.05‰ (Fig. 6) at the Wa’ergang and Paibi sections in Hunan Province of the South China Block (Saltzman et al., 2000; Zhu et al., 2004). Chen et al. (2011) documented that positive C isotope excursion up to 3.46‰ at the lower part of the Chaomidian Formation (early Furongian) at the Wanliangyu section in Shandong Province, which belongs to North China Platform (Fig. 6), showing that there was an erosion of the *Prochuangia Zone* at the boundary between *Neodrepanura* and *Chuangia* zones which resulted in an abrupt increase in $\delta^{13}C$ value across the erosion surface. Most of the maximum $\delta^{13}C$ values of the SPICE, 4 to 5‰ were reported in Laurentia (Saltzman et al, 2004), and South China (Saltzman et al, 2000; Zhu et al., 2004; Peng et al., 2004). In the Sesong Formation the upper boundary between the Paibian
The δ¹⁸O values of brachiopod were used as a proxy of seawater temperature as the brachiopod is less affected by freshwater diagenesis; relatively high δ¹⁸O values were observed at the onset of the SPICE and decreasing and lowest values during the main event, and an increase in values at the end of the event (Elrick et al., 2011). The increase in δ¹⁸O values at the onset of the SPICE was interpreted to be caused by the rise of sea level accompanied with upwelling of cool anoxic waters (high δ¹⁸O values in brachiopod) onto the shallow shelf. The expansion of anoxic water on the shallow depths resulted in increased burial of C_<sub>org</sub> and seawater δ¹³C values were increased (Elrick et al., 2011). The cooling event of seawater was followed by seawater warming which is associated with reduced thermohaline circulation rates contributed to decreased dissolved O₂ concentrations, which enhanced the preservation/burial of C_<sub>org</sub> causing the positive δ¹³C shift (Elrick et al., 2011). The δ¹⁸O curve of the SPICE interval in the Sesong Formation shows somewhat similar pattern to that of δ¹⁸O values of brachiopod skeletons of the SPICE in Laurentia (Elrick et al., 2011). However, as carbonates are sensitive to freshwater diagenesis, the δ¹⁸O values of limestone in the Sesong Formation may not reflect the δ¹⁸O value of the ocean. Although the δ¹⁸O values of the onset of the SPICE in the Sesong Formation show a maximum, and low values of δ¹⁸O values during the main event (Fig. 5), this pattern of variation of δ¹⁸O values in the SPICE in the Sesong Formation may not represent the Paibian oceanic δ¹⁸O values, but the they may represent the diagenetic effect.

**Cause and implication of SPICE**

Anoxic ocean has been suggested for the cause of SPICE during the Late Cambrian (Gill et al., 2011; Saltzman and Thomas, 2012). The organic matter is preserved in the sediment of ocean floor in the anoxic condition of the ocean, and δ¹³C value of sea water is enhanced as the light ¹²C is preferentially incorporated into organic matter. The maximum value of δ¹³C value in the SPICE in the Sesong Formation is suggested to be caused by oceanic anoxia. In the Sesong Formation, the increase in the δ¹³C value which is associated with seawater warming and reduced thermohaline circulation rates contributed to decreased dissolved O₂ concentrations, which enhanced the preservation/burial of C_<sub>org</sub> causing the positive δ¹³C shift (Elrick et al., 2011). The δ¹³C curve of the SPICE interval in the Sesong Formation shows somewhat similar pattern to that of δ¹³C values of brachiopod skeletons of the SPICE in Laurentia (Elrick et al., 2011). However, as carbonates are sensitive to freshwater diagenesis, the δ¹³C values of limestone in the Sesong Formation may not reflect the δ¹³C value of the ocean. Although the δ¹³C values of the onset of the SPICE in the Sesong Formation show a maximum, and low values of δ¹³C values during the main event (Fig. 5), this pattern of variation of δ¹³C values in the SPICE in the Sesong Formation may not represent the Paibian oceanic δ¹³C values, but the they may represent the diagenetic effect.
which have been formed during the lowstand of sea level, is consistent with the increased input of terrigenous sediment to bury organic matter on the ocean floor. During lowstand of sea level influx of terrigenous sediments into sea may have been increased and resulted in increase in burial of organic matter. During the Late Cambrian the Taebaeksan Basin was in the eastern margin of the North China Platform where carbonate deposition was limited by input of siliciclastics (Chen et al., 2012). Near the boundary between the Cambrian Epoch 3 and the Furongian, the North China Platform (especially Shandong Province) was subaerially exposed forming an unconformity whereas in the Taebaeksan Basin a continuous sedimentation occurred forming a correlative conformity (Chen et al., 2012). Development of the SPICE in the mixed carbonate-siliciclastic deposits in the Sesong Formation suggests that positive excursion of C isotopes during the Late Cambrian was a global phenomenon including the platform interior as well as the platform margin where mixed carbonate-siliciclastics were deposited.

Conclusions

The Sesong Formation, mixed carbonate-siliciclastics of the Cambrian Epoch 3 to Furongian in age consists of six lithofacies of laminated mudstone, nodular shale, laminated sandstone, massive sandstone, limestone conglomerate, limestone-shale couplet facies. The depositional setting of the Sesong Formation was interpreted to be the outer shelf. The Sesong Formation began to form during sea-level rise on the upper boundary of the Daegi Formation which is interpreted as a drowning surface. The lower part of the Sesong Formation mainly composed of nodular and laminated shale with frequent intercalation of limestone conglomerate is interpreted to be transgressive systems tract. The SPICE, positive stable carbon isotope of which $\delta^{13}C$ value above +1‰, begins to occur in the stratigraphic interval composed of nodular and laminated shale with intercalation of limestone pebble as well as very fine- to fine-grained sandstone. The SPICE interval of the Sesong Formation covers the relative sea-level variation ranging from highstand at first, subsequent rapid fall, and then rise again. The SPICE occurs in stratigraphic interval of highstand systems first, followed by correlative conformity and transgressive systems tract. Maximum positive carbon isotope excursion in the SPICE is interpreted to correspond to maximum relative sea-level lowstand which is equivalent to correlative conformity. The cause of the SPICE in the Sesong Formation seems to be related to the anoxic condition of the Paibian as well as the sea-level lowstand which is related to the burial of organic matter on the ocean floor due to increased input of terrigenous sediments.

In terms of trilobite biostratigraphy the SPICE event occurs in the stratigraphic interval of about 15 m thick which contains the trilobite Fenghuangella laevis and Prochuangia mansuyi zones and the lower part of Chuangia Zone with the $\delta^{13}C$ values ranging from 1.14 to 2.81‰. The occurrence of the SPICE in the Sesong Formation suggests the anoxic condition during the Paibian was a global event. Well constrained age and good correlation of the SPICE suggest that the SPICE is a powerful tool for correlation of the stratigraphic successions which lack fossils.

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