Distribution of Chancelloriids in a Middle Cambrian Carbonate Platform Deposit, Taebaek Group, Korea

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Abstract: The onset of the Cambrian witnessed the diversification of “small shelly fossils (SSF)”, which affected carbonate depositional system. One of the problematic SSF, chancelloriids, are common components of the early to middle Cambrian carbonate and shale, and their contributions toward Cambrian carbonates are not yet fully understood. This study assesses distribution patterns of chancelloriid sclerites in the Cambrian Series 3 Daegi Formation based on microfacies analysis and discusses their sedimentologic implications. In the lower part of the formation, partially articulated chancelloriid sclerites occur mainly in bioclastic packstone and grainstone facies, with isolated sclerite rays in nodular packstone to grainstone facies. In the middle part of the formation, chancelloriid fragments occur only sporadically in bioclastic wackestone to packstone, bioclastic grainstone and oolitic packstone to grainstone facies, whereas boundstone facies are nearly devoid of their fragments. There are no chancelloriid fragments in the upper part of the formation, which consists of oolitic packstone to grainstone facies. Chancelloriids are interpreted to have primarily occupied platform margin shoal environments, shedding their sclerites to surrounding areas, and thus contributed as sediment producers. The distribution of Daegi chancelloriid sclerites is similar to other Cambrian examples, with the exception of common chancelloriids in Cambrian Series 2 reefs and their apparent near absence in the Daegi and other Cambrian Series 3 reefs. This disparity resulted from changes in the ecologic niche of chancelloriids after the end-Cambrian Series 2 reef crisis, coupled with an overall decline of chancelloriids in the middle Cambrian.

Key words: Cambrian Series 3, chancelloriid, shoal, carbonate platform, reef

1 Introduction

Diversity and biomass of skeletonized faunas increased rapidly at the onset of the Cambrian (Álvaro and Debrenne, 2010; Servais and Owen, 2010). The “small shelly fossils (SSF)”, which first appeared at the end of the Ediacaran, were short-lived taxa mostly preserved as millimeter-sized spicules, tubes, tests, conchs, shells, dermal sclerites, and ossicles (Bengtson, 2004). As one of these early skeletal organisms, chancelloriids emerged in the early Terreneuvian and lasted until the Furongian (Bengtson and Hou, 2001; Janussen et al., 2002). They have been previously regarded as poriferids (Rigby and Nitechi, 1975; Rigby, 1978), as well as suggested to be enigmatic non-poriferan metazoan Coeloscleritophora (Bengtson and Missarzhevsky, 1981; Beresi and Rigby, 1994; Mehl, 1996). Chancelloriids are composed of a sack-shaped body with a tapered lower end, which is covered by rows of spiny sclerites composed of multiple lateral rays with or without a central ray (Bengtson and Hou, 2001; Kloss et al., 2009) and commonly preserved as scattered sclerites and rays (Butterfield and Nicholas, 1996; Elicki, 2006).

Chancelloriids, mostly as sclerites, occur worldwide in lower to middle Cambrian carbonates and shales, associated with echinoderms, sponge spicules, brachiopods, and hyoliths (Álvaro and Vennin, 1997; Clausen and Álvaro, 2006; Wotte, 2009; Moore et al., 2014). They are also common in microbial–archaeocyath reefs of the Cambrian Series 2 (Mehl, 1996; Rowland and Shapiro, 2002). In Korea, silicified sclerites of

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Archiasterella and Allomia were reported from limestones of the Mungyong Group (Lee, 1987; Lee et al., 1993; Lee, 2006) and shale-dominant Myobong and carbonate-dominant Daegi formations of the Taebaek Group (Lee et al., 1992), and Chancelloria from the sandstone-dominant Sambangsan Formation of the Yeongwol Group (Lee et al., 1991). Despite numerous reports depicting them as a component of open marine shallow subtidal deposits (Beresi, 2003; James and Gravestock, 1990; Álvaro and Yennin, 1997; Álvaro and Clausen, 2006; Elicki, 2006; Wotte, 2009), their contributions toward the Cambrian carbonate depositional system are yet to be fully characterized. This study aims to assess distributions of chancelloriid sclerites in the Cambrian Series 3 carbonate platform deposit of Korea, and discusses their implications toward the evolution of Cambrian carbonate facies.

2 Geological Setting and Methods

Extensive Cambro-Ordovician mixed carbonate-siliciclastic successions developed on the Sino-Korean (North China) Craton, which has been considered as a peri-Gondwanan terrain near to the paleoequator (Meng et al., 1997; McKenzie et al., 2011). The Taebaeksan Basin is located at the eastern margin of the craton, and early Paleozoic deposits of the basin constitute the Joscen Supergroup (Fig. 1). The supergroup is subdivided into the Taebaek, Yeongwol, Mungyong, Yongtan, and Pyeongchang groups (Chough et al., 2000; Chough, 2013). The Daegi Formation is the lowest carbonate-dominated unit of the Taebaek Group, which is part of regressive package of a transgressive-regressive wedge composed of underlying sandstone-dominant Jangsan/Myeomsan and shale-dominant Myobong formations (Kwon et al., 2006). The Daegi Formation is about 150–250 m thick and comprises massive to thin-bedded limestones with intercalated shale in the lower part, which is interpreted to be mid- to inner-ramp shallow subtidal deposits (Choi et al., 2004; Kwon et al., 2006; Sim and Lee, 2006). Trilobite biozones of Creipephalus, Amphoton and Jaulongshania from the lower, middle and uppermost Daegi Formation (Kang and Choi, 2007; Park et al., 2008) indicate a upper Stage 5 to middle Guzhangan age (Geyer and Shergold, 2000; Peng et al., 2012) (Fig. 2). The study area is located in the vicinity of Seokgajeae, about 17 km southeast of Taebaek (Fig. 1). The 180 m-thick Daegi outcrop was measured at 1:50 scale and more than 800 samples were collected with average vertical spacing of 21 cm. The formation in the study area is informally divided into the lower (0–42 m), middle (42–140 m) and uppermost (140–178 m) parts based on lithologic characteristics such as alternation of shale and coarse-grained limestones, intercalation of bioclastic limestones and reefs and dominance of oolitic limestones, respectively (Fig. 2). 1079 thin sections were prepared for microfacies study based on sedimentary textures, grain types and their relative proportions. The lower part of formation was primarily investigated by 141 standard (2.7 × 4.9 cm) thin sections, and the rest of the formation was logged using 938 large-format (5.2 × 7.6 cm) thin sections.

Fig. 1. Tectonic elements of eastern Asia, distribution of lithologic units in the Taebaeksan Basin and simplified geological map of the study area.

Studied section is marked by a white arrow. Modified after Chough et al. (2000).
Fig. 2. Simplified measured section of the Daegi Formation at Seokgaejae.
The formation is informally divided into lower part consisting of shales and coarse-grained packstone and grainstone (0–42 m), middle part dominated by wackestone to packstone and reefs (42–140 m) and upper part containing oolitic packstone to grainstone (140–178 m). Right side of the log records the number of chancelloriid sclerite fragments in each thin section. Note the large concentration of sclerite fragments in the lower part of the formation. S = shale; M = mudstone; W = wackestone; P = packstone; G = grainstone; B = boundstone at the end of the figure caption.
3 Results

Chancelloriid sclerites are found from 2 to 134 m of the formation. Most of the fragments occur in the 42 m-thick lower part of the formation (Figs. 2 and 3), where 31% of thin sections contain at least one or more sclerites (Table 1a). These sclerite fragments are 0.2 to 3 mm in size and occur as circular, ellipsoidal, teardrop- to spiny-shaped rays depending on degree of articulation and direction of cut. In addition, partially articulated sclerites with two or more rays connected to each other at their base, or symmetric arrangement of two teardrop-shaped rays in a row are also found. Nearly articulated, star-shaped sclerites are rare (Fig. 4a). Sclerite walls are replaced by sparry cements or micritized, with the inner space either filled with spar cements or micrite (Fig. 4a-b). Although most of the sclerite fragments cannot be identified, at least two genera of Chancelloria with characteristic central disks and Alloimia or Archiasterella, which lack central disks, are tentatively recognized from the Daegi Formation. Systematic study of these chancellorids is required to fully comprehend environmental distribution of the sclerites at genus level. These unidentified articulated rays and partial sclerite fragments selectively occur in some facies of the formation, as described below.

3.1 Shale (Sh)

Centimeter- to meter-scale beds of greenish-gray shale up to 7 m in thickness constitute about half of the lower 42 m of the Daegi Formation (Table 1a). The facies is composed of millimeter- to submillimeter-scale alternations of silt and clay laminae and often encompasses centimeter-scale nodular limestone and thin limestone interbeds (Figs. 3 and 5a). Siltstone laminae are commonly associated with uneven to flat erosive bases that grade upward to clay. Siltstone laminae occasionally form cross-laminations and are commonly warped around limestone nodules by differential compaction (Fig. 5b). Small, sub-vertical to sub-horizontal burrows 1–7 mm in diameter that are filled with siltstone sporadically disrupt the laminations. Disarticulated trilobites, eocrinoids and brachiopods are rare, and chancelloriid sclerites are not found in this facies (Table 1a, c).

The shale facies represents deposition in slightly deeper subtidal environments below the fair-weather wave base (Markello and Read, 1981; Calvet and Tucker, 1988; Oslegar and Montañez, 1996; Kwon et al., 2006; Sim and Lec, 2006). Absence of dark-colored laminated shale and presence of common burrows indicate deposition under aerobic conditions (Tucker and Wright, 1990). Graded siltstone laminae with erosive bases are interpreted to reflect the influence of intermittent storms (Rees, 1986; Oslegar and Montañez, 1996).

3.2 Nodular packstone to grainstone (P/Gn)

This facies occurs within a 6 to 37 m interval of the formation as centimeter-scale, discontinuous and irregular-shaped nodules, lenses and thin beds encased by shale. These nodular limestone interbeds progressively thicken upward, gradationally and/or abruptly overlain by oolitic packstone to grainstone, bioclastic packstone or bioclastic grainstone facies (Fig. 3). Fragments of chancelloriid sclerites (Fig. 5c), trilobites, eocrinoids, quartz silt and peloids often constitute normally graded parallel laminations. A total of 5 (19%) samples of the facies contain chancelloriid fragments, and only a few (n = 11, 14%) of them are partially articulated sclerites (Table 1a, c).

Packstone to grainstone nodules with graded bioclasts and their occurrence within shale facies is possibly indicative of storm-transported calcareous sediments (Markello and Read, 1981; Calvet and Tucker, 1988). This facies might have been deposited as remnants of a short-lived influx of calcareous sediments from carbonate platform margin environments (Markello and Read, 1981; Moshier, 1986; Calvet and Tucker, 1988; Alvaro et al., 2000).

3.3 Oolitic packstone to grainstone (P/Go)

Amalgamated lenses and medium to very thick beds 0.1 to 3 m in thickness primarily composed of ooids with fibrous cements occur in the lowermost, uppermost, and intermittently in the middle part of the Daegi Formation (Fig. 2). This facies commonly overlies shale facies and is sharply overlain by bioclastic grainstone facies, intercalated with bioclastic grainstone facies in the lower part of the formation, and associated with Girvanella crust-Epiphyton boundstone to grainstone facies in the middle part of the formation. Well-rounded and sorted ooids up to 1 mm in diameter with tangential cortices surround nuclei of disarticulated eocrinoids, trilobites, and, occasionally, peloids (Fig. 5d). The ooids are often preserved as oomolds filled with calcite cement or micritized ooids. Well rounded, ellipsoidal to sub-spherical oocoids up to several centimeters in diameter with asymmetric, laminated micritic cortices and calcimicrobe Girvanella occur in the lowermost Daegi Formation (Figs. 3, 5e). Fragments of eocrinoid, trilobite, brachiopod, and intraclasts often serve as the nuclei of these coated grains. Other grains include trilobites, eocrinoids, chancelloriid fragments, intraclasts, calcimicrobe Renalis (and probable Angusticellularia), sponge spicules, as well as grapestones of aggregated ooids bounded by dark micrites. Only a few (n = 19) chancelloriid fragments occur in the facies from the lower
Fig. 3. Columnar section with abundance of carbonate grain types of the lower Daegi Formation. Fragments of chancellorid sclerites are one of the major grain types occurring in packstone to grainstone of the lower part of formation. S = shale; M = mudstone; W = wackestone; P = packstone; G = grainstone; B = boundstone at the end of the figure caption.
and middle part of the formation (Table 1a–c).

This oolitic packstone to grainstone facies is interpreted as open marine, near fair-weather wave base shallow subtidal shoal deposits (Tucker and Wright, 1990). Presence of marine cements and intraclasts may indicate submarine lithification and intermittent reworking by storms (Markello and Read, 1981). Vertical gradation from shaly, nodular packstone to grainstone facies to oolitic packstone to grainstone facies indicates deposition near the carbonate platform margin (Youngs, 1978; Markello and Read, 1981; Srinivasan and Walker, 1993; Álvaro et al., 2006; Sim and Lee, 2006).

3.4 Bioclastic grainstone (Gb)

This facies comprises about 25% of the lower part of the formation in thickness and occurs as 0.1 to 2.2 m-thick lenticular to bedded units, commonly with planar erosive basal surfaces. In the lower part of the formation, it is commonly intercalated with bioclastic packstone, oolitic packstone to grainstone, and shale facies. The facies also rarely occurs in the middle part of the formation (Table 1), associated with bioclastic wackestone to packstone, boundstone and oolitic packstone to grainstone facies. Trilobites, eocrinoids, peloids and rare brachiopod fragments occur throughout the formation. These bioclasts are commonly surrounded by fibrous cements, and syntaxial overgrowths are also common around eocrinoid fragments. Chancelloriid sclerite fragments primarily occur as one of the dominant calcareous grains in the lower part of the formation of this facies (Fig. 3), where 53% (n = 25) of thin sections of the facies contain an average of 23 chancelloriid sclerite fragments and rays (Table 1a). Among these, 73% (n = 423) of chancelloriid fragments are isolated rays, and the rest (27%, n = 160) are partially articulated and radially aligned rays without central rays, possibly of Alloonia or Archiasterella affinity (Fig. 5f; Table 1a). In contrast, chancelloriid sclerites and rays only occur as minor constituents (six fragments per thin section) from 11% of thin sections of the facies in the middle part of the Daegi Formation (Table 1b).

The bioclastic grainstone facies is interpreted as platform margin, high-energy bioclastic shoal deposits, developed in close proximity to ooid shoals (Markello and Read, 1981; Álvaro et al., 2000; Sim and Lee, 2006). Common erosive surfaces and intercalation of lenses and thin beds across adjacent facies might reflect intermittent influence of storm-induced currents (Pfeil and Read, 1980; Álvaro et al., 2000).

Table 1 Abundance of chancelloriid sclerite fragments in the Daegi Formation

(a) Lower part (0-42 m interval) of the formation, logged with standard thin sections.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Cumulative thickness (m)</th>
<th>Total thin sections</th>
<th>Thin sections with chancelloriid fragments</th>
<th>Isolated chancelloriid sclerite rays</th>
<th>Partially articulated sclerites</th>
<th>Total chancelloriid fragments</th>
<th>Average chancelloriid fragments per thin section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gb</td>
<td>8.7</td>
<td>47</td>
<td>25 (53.2%)</td>
<td>423</td>
<td>160 (27.4%)</td>
<td>583</td>
<td>23</td>
</tr>
<tr>
<td>P/Go</td>
<td>4.0</td>
<td>21</td>
<td>5 (23.8%)</td>
<td>10</td>
<td>5 (33.3%)</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Pb</td>
<td>5.0</td>
<td>19</td>
<td>13 (68.4%)</td>
<td>132</td>
<td>71 (35.0%)</td>
<td>203</td>
<td>16</td>
</tr>
<tr>
<td>P/Gn</td>
<td>2.5</td>
<td>26</td>
<td>5 (19.2%)</td>
<td>68</td>
<td>11 (13.9%)</td>
<td>79</td>
<td>16</td>
</tr>
<tr>
<td>Sh</td>
<td>20.7</td>
<td>47</td>
<td>0 (0.0%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>40.9</td>
<td>141</td>
<td>50 (31.3%)</td>
<td>633</td>
<td>247 (28.1%)</td>
<td>880</td>
<td>18</td>
</tr>
</tbody>
</table>

(b) Middle upper part (42-178 m interval) of the formation, logged with large-format thin sections.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Cumulative thickness (m)</th>
<th>Total thin sections</th>
<th>Thin sections with chancelloriid fragments</th>
<th>Isolated chancelloriid sclerite rays</th>
<th>Partially articulated sclerites</th>
<th>Total chancelloriid fragments</th>
<th>Average chancelloriid fragments per thin section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bd</td>
<td>42.2</td>
<td>638</td>
<td>1 (0.2%)</td>
<td>0</td>
<td>1 (100.0%)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>W/Pb</td>
<td>39.0</td>
<td>198</td>
<td>10 (5.1%)</td>
<td>13</td>
<td>19 (59.4%)</td>
<td>32</td>
<td>3</td>
</tr>
<tr>
<td>Gb</td>
<td>10.5</td>
<td>56</td>
<td>6 (10.7%)</td>
<td>21</td>
<td>12 (36.4%)</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td>P/Go</td>
<td>4.7</td>
<td>46</td>
<td>1 (2.2%)</td>
<td>2</td>
<td>2 (50.0%)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>96.4</td>
<td>958</td>
<td>18 (1.9%)</td>
<td>36</td>
<td>34 (48.6%)</td>
<td>70</td>
<td>4</td>
</tr>
</tbody>
</table>

(c) Distribution of chancelloriid fragments in the Daegi Formation by facies.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Cumulative thickness (m)</th>
<th>Total thin sections</th>
<th>Thin sections with chancelloriid fragments</th>
<th>Isolated chancelloriid sclerite rays</th>
<th>Partially articulated sclerites</th>
<th>Total chancelloriid fragments</th>
<th>Average chancelloriid fragments per thin section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bd</td>
<td>42.2</td>
<td>638</td>
<td>1 (0.2%)</td>
<td>0</td>
<td>1 (100.0%)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>W/Pb</td>
<td>39.0</td>
<td>198</td>
<td>10 (5.1%)</td>
<td>13</td>
<td>19 (59.4%)</td>
<td>32</td>
<td>3</td>
</tr>
<tr>
<td>Gb</td>
<td>19.2</td>
<td>103</td>
<td>31 (30.1%)</td>
<td>444</td>
<td>172 (27.9%)</td>
<td>616</td>
<td>20</td>
</tr>
<tr>
<td>P/Go</td>
<td>8.7</td>
<td>67</td>
<td>6 (9.0%)</td>
<td>12</td>
<td>7 (36.8%)</td>
<td>19</td>
<td>3</td>
</tr>
<tr>
<td>Pb</td>
<td>5.0</td>
<td>19</td>
<td>13 (68.4%)</td>
<td>132</td>
<td>71 (35.0%)</td>
<td>203</td>
<td>16</td>
</tr>
<tr>
<td>P/Gn</td>
<td>2.5</td>
<td>26</td>
<td>5 (19.2%)</td>
<td>68</td>
<td>11 (13.9%)</td>
<td>79</td>
<td>16</td>
</tr>
<tr>
<td>Sh</td>
<td>20.7</td>
<td>47</td>
<td>0 (0.0%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>137.3</td>
<td>1098</td>
<td>66 (6.0%)</td>
<td>656</td>
<td>281 (29.0%)</td>
<td>917</td>
<td>16</td>
</tr>
</tbody>
</table>

Bd = boundstone, W/Pb = bioclastic wackestone to grainstone; Gb = bioclastic grainstone; P/Go = oolitic packstone to grainstone; Pb = bioclastic packstone; P/Gn = nodular packstone to grainstone; Sh = shale.
3.5 Bioclastic packstone (Pb)

Thick-bedded units of this facies with dissolution seams occur primarily in the lower part of the formation, either gradationally intercalated with shale facies or sharply bounded with lenticular, thin- to thick-bedded bioclastic grainstone facies. It is composed mainly of cancelloroid sclerites and disarticulated eocrinoid ossicles, with subordinate trilobites, peoloids, ooids, brachiopods, oncoinds, hyoliths, and quartz silts (Fig. 3). Numerous cancelloroid sclerites and rays are present in 68% (n = 13) of samples of the facies (Table 1a, c), where 35% of sclerites (n = 71) are partially articulated. Radially arranged lateral rays with central rays, possibly assignable to genus Chancelloria, are rarely present (Figs. 4a, 5g; Table 1a, c). Common intercalation with bioclastic grainstone facies and gradual transition to shale facies indicate that this facies was deposited in slightly lower energy subtidal environments peripheral to and seaward of the bioclastic shoals (Oslegar and Montañez, 1996; Saltzman, 1999; Nowrouzi et al., 2015).

3.6 Bioclastic wackestone to packstone (W/Pb)

This facies occurs as massive decimeter- to meter-scale beds up to 4 m in thickness, intercalated with boundstone, thin- to thick-bedded bioclastic grainstone, and rarely with oolitic packstone to grainstone facies. The facies comprises up to 40% of the middle and upper part of the formation (Table 1b), and is mostly composed of trilobite fragments and peloids, with less common eocrinoids and brachiopods (Fig. 5h). Sponge spicules, Epiphyton and Girvanella crusts are rare. Only 5% (n = 10) of thin sections of the facies in the middle part of the formation contains cancelloroid fragments (Table 1b, c). The occurrence of fragmented cancelloroid sclerites decreases abruptly from the base of the Amphoton Zone in the middle part of the formation (Fig. 2).

This facies is interpreted as low-energy subtidal deposits, possibly favored by soft-bottom deposit-feeding trilobites (Glumac and Walker, 1997; Lefebvre and Fatka, 2003; Sim and Lee, 2006). Occasional intercalation of bioclastic grainstone and oolitic packstone to grainstone facies indicates proximities from platform margin shoals.

3.7 Boundstone (Bd)

Numerous Epiphyton-siliceous sponge patch reefs of several cm to 3.3 m in thickness occur throughout the middle part of the formation, intercalated with bedded bioclastic wackestone to packstone and bioclastic grainstone facies. The Epiphyton-siliceous sponge boundstone is mainly composed of centimeter-scale mesoclots of Epiphyton bushes and millimeter- to centimeter-scale irregular-shaped spicule networks of unidentified spiculate sponges (Hong et al., 2012). Interspaces of Epiphyton bushes and spicule networks are mostly filled with micrites. Some shelter and growth framework space built by reef constituents are filled with micritic internal sediments, calcite cements and rare Epiphyton attaching to the ceilings of cavities (Hong et al., 2012). In addition, subordinate centimeter- to meter-scale, lenticular to massive Girvanella crust-Epiphyton boundstone to grainstone are also sporadically distributed in a 39 to 134 m interval of the formation. This subfacies is mostly surrounded by either Epiphyton-siliceous sponge boundstone or bioclastic wackestone to packstone facies. Some meter-scale bodies of Girvanella crust-Epiphyton boundstone overlie bioclastic wackestone to packstone facies, and are overlain by oolitic packstone to grainstone facies. These boundstones consist of centimeter-scale, subvertical to sub-horizontally aligned arcuate Girvanella crusts locally encrusted by Epiphyton and grainstone

Fig. 4. Fragments of cancelloroid sclerites with variable degree of articulation and shapes.
(a), Basal surface of nearly articulated, star-shaped cancelloroid sclerites with central disk enclosed by spiny lateral rays, indicating its probable affinity to genus Chancelloria; (b), Partially articulated cancelloroid sclerites (white arrows) and circular- and spiny-shaped, isolated sclerite rays (black arrows). Refer to sample locations in Fig. 3.
Fig. 5. Facies of the Daegi Formation.
(a), Photograph of lower part of the formation comprising bioclastic grainstone (Gb), bioclastic packstone (Pb) and nodular packstone to grainstone (P-Gn)-shale (Sh) interbeds; (b), Photomicrograph of nodular packstone to grainstone and shale facies with convoluted laminae (line) above the nodule; (c), Enlargement of white rectangle in Fig. 5b, showing grainstone with isolated rays (black arrows) and partial articulation of chancelloriid sclerites (white arrow); (d), Photomicrograph of oolitic packstone to grainstone facies with well-sorted ooids and minor ooid grapestone (black arrow); (e), Photomicrograph of well-rounded oncooids with asymmetric laminae (black arrow) and ooids in oolitic packstone to grainstone facies; (f), Photomicrograph of bioclastic grainstone facies composed of many isolated chancelloriid sclerite rays (black arrows) and partially articulated (white arrows) to whole sclerites (white rectangle), together with subordinate coconoids and ooids. Walls of the chancelloriid sclerite rays are mostly micritized. Nearly articulated chancelloriid sclerite consists of four lateral rays without central disk suggesting its affinity to genus Alonnia or Archiasterella (white rectangle and sketch); (g), Photomicrograph of bioclastic packstone facies dominated by fragments of chancelloriid sclerites (white arrows); (h), Photomicrograph of bioclastic wackestone to packstone facies with fragments of trilobites (black arrows) and subordinate coconoids (white arrow; E). Refer to sample locations in Figs. 2 and 5.
composed of fragmented *Girvanella* crusts and abraded *Epiphyton* thalli. It is noteworthy that chancelloriid fragments are virtually absent in this facies, with only one out of 638 thin sections of the facies containing a single partially articulated chancelloriid sclerite.

Patch reefs constructed by intergrowths of *Epiphyton* and siliceous sponges intercalating with bioclastic wackestone to packstone or bioclastic grainstone facies are interpreted to have formed in shallow subtidal platform margin to interior conditions (Fig. 6). Thromboids and *Epiphyton* are considered to have functioned as frame-builder, encruster and cryptic dweller when creating aggregated microbial masses, covering the surfaces of siliceous sponges and inhabiting cryptic spaces, respectively (Riding and Toomey, 1972; James, 1981; James and Gravestock, 1990). Framework-building *Girvanella* crusts with *Epiphyton* encrustations formed reefs in environments similar to *Epiphyton*-siliceous sponge reefs (Gandin et al., 2007).

3.8 Interpretation

The Daegi Formation is a shallow subtidal carbonate-
odominant deposit, devoid of typical peritidal features such as algal laminations, silt and mud drapes and desiccation cracks. Stratigraphic changes in facies package and relative proportion of each facies are interpreted to reflect deposition at a transitional zone between carbonate platform margin to off-platform for the lower part of the formation, subsequent shift to deposition on a carbonate platform (middle part of the formation), and back to platform margin oolitic shoal conditions for the upper part (Kwon et al., 2006; Sim and Lee, 2006) (Fig. 2; Table 1a, b). The Daegi chancelloriid sclerites widely occur from off-platform to platform interior environments and are most commonly found from platform margin shoal deposits (Fig. 6). In the lower part of the formation, the occurrence of chancelloriid sclerites and rays as well as partially articulated sclerites are primarily from the bioclastic grainstone and bioclastic packstone facies, which are interpreted as platform margin bioclastic shoals and their peripheral lower energy deposits, respectively, whereas the rest of the facies only contain a few fragments (Fig. 6; Table 1a). This suggests chancelloriiids mainly inhabited areas near platform margin bioclastic shoals and

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![Fig. 6. Schematic reconstruction of depositional environments of the Daegi Formation and occurrence of chancelloriid fragments. In the lower part of the formation, fragmented chancelloriid sclerites mainly occur in bioclastic shoals and its peripheries, and decrease away from the shoals. In the middle part of the formation, chancelloriid sclerite fragments only rarely occur in bioclastic wackestone to packstone facies.](image-url)
shed their sclerites to nearby environments, where they became an important constituent of the carbonate sediments. Some of these sclerites might have been transported into slightly deeper, off-platform environments, possibly by occasional storms (e.g., Álvaro and Vennin, 1997; Álvaro and Clausen, 2006), and preserved in nodular bioclastic packstone to grainstone facies. In addition to environmental controls on the distribution of chancelloriid sclerites, a sharp decrease of chancelloriid sclerites within bioclastic grainstone facies in the middle part of the Daegi Formation may reflect a temporal change in biomass of chancelloriid during the Drumian Stage (Fig. 6; Table 1). In addition, although chancelloriid sclerites are sporadically distributed in bioclastic wackestone to packstone facies of the middle part of the formation, they are conspicuously absent in boundstone facies, which are interbedded with bioclastic wackestone to packstone and bioclastic grainstone facies (Table 1b, c). This finding appears to reflect mutually exclusive relationships between the Daegi reef constituents and chancelloriid.

4 Discussion

Chancelloriids are commonly regarded as soft bottom dwellers (Dornbos et al., 2005; Kloss et al., 2009) of open marine, peri-platform or shelf-margin environments (Beresi, 2003). Chancelloria, Alloonia and Archiasterella are common constituents of Cambrian Series 2 to Series 3 open marine deposits of platform margin oolitic/bioclastic shoal complexes (Debenne et al., 1989; Álvaro and Clausen, 2006; Clausen and Álvaro, 2006), carbonate buildups (James and Gravestock, 1990; Kruse et al., 1995; Debenne et al., 2002), off-platform limestone interbeds or nodules in limestone-shale alternations (James and Gravestock, 1990; Álvaro and Vennin, 1997; Álvaro et al., 2000; Wotte, 2009), shale and calcisilites (Butterfield and Nicholas, 1996; Randell et al., 2005; Kloss et al., 2009), and carbonate olistoliths (Beresi, 2003; Wrona, 2004). The overall distribution of Daegi chancelloriid sclerites, from slightly deeper off-platform environments, platform-margin shoal complexes, to open marine shallow subtidal carbonate facies, is comparable to other Cambrian examples reported to date (Álvaro and Vennin, 1997; Álvaro et al., 2000; Beresi, 2003; Álvaro and Clausen, 2006). This reveals the contribution of chancelloriids as a sediment producer of platform margin shoal and nearby deposits. The current study demonstrates that chancelloriid sclerites and rays are widely dispersed in these environments as chancelloriids inhabited soft substrates peripheral to shoals, and provided partially articulated sclerites and rays to shoals and adjacent environments upon their death, which became increasingly fragmented as those are transported to off-platform, deeper subtidal conditions. The Daegi Formation also records a sharp decline of chancelloriids during the middle Cambrian Epoch 3, as well as their diminishing impact as a calcareous sediment producer. Cambrian Series 3 chancelloriid were mostly reported from lower Cambrian Series 3 successions in Laurentia, Precordillera and other regions of Gondwana (Butterfield and Nicholas, 1996; Álvaro and Vennin, 1997; Beresi, 2003; Wotte, 2009). Though it is not clear whether this recession happened synchronously or diachronously on regional to global scales, it is apparent that chancelloriids began their downturn during the Cambrian Epoch 3.

On the other hand, distributions of chancelloriid sclerites in the Daegi Formation do not follow other Cambrian examples in two aspects: their absence in shale and boundstone facies. The former is possibly attributable to the study method and sampling bias of the current study, which primarily relied on thin sections made perpendicular to bedding, as there are many examples of chancelloriid occurrences within shale (e.g., Butterfield and Nicholas, 1996; Randell et al., 2005; Kloss et al., 2009). The latter is considered to indicate temporal difference of chancelloriid occurrences between the Cambrian Series 2 and Series 3 reefs. Chancelloriid sclerites commonly occur in matrix and cavities of Cambrian Series 2 shallow marine archaeocyath-microbial reefs and mounds, where they participated as dwellers in reef communities (Riding and Zhuravlev, 1995; Pratt et al., 2001; Rowland and Shapiro, 2002). However, the Daegi microbial-siliceous sponge patch reefs (Hong et al., 2012), similar to microbial buildups that have developed on cratonic interiors to platform margins of Cambrian Series 3 (Glumac and Walker, 1997; Rowland and Shapiro, 2002), are virtually devoid of chancelloriid sclerites. It is possible that microbial-dominated Cambrian Series 3 reefs do not incorporate chancelloriids as a common component (Pratt et al., 2001). Possible scenarios are proposed for these discrepancies: 1. It might be related to local decline of chancelloriids, coincident with rapidly decreasing chancelloriid occurrences in the middle part of the Daegi Formation; 2. The collapse of archaeocyath-microbial reefs at the end of Cambrian Series 2 and ensuing shakeup of ecological niches, which might have driven off chancelloriids from being a common reef participant of the microbial-dominant Cambrian Series 3 reefs; 3. A combination of scenarios 1 and 2. The current study suggests that even though chancelloriids survived the end-Cambrian Series 2 extinction (Pratt et al., 2001), their ecologic niche in one of the earliest microbial-metazoan reefs of the Cambrian Series 3 apparently have
changed. Further studies are needed in order to resolve this discrepancy of chancelloriid occurrences and to elucidate their distributions in Cambrian carbonate facies.

5 Conclusions

Occurrences of chancelloriid sclerites from the Cambrian Series 3 Daegi Formation of the Joseon Supergroup, Korea located at eastern margin of Sino-Korean (North China) Block are reported. Chancelloriid sclerites occur mostly in the lower part of the formation deposited within high-energy platform margin shoal deposits. Many articulated chancelloriid sclerites commonly occur within bioclastic packstone and grainstone facies, whereas the sclerites are increasingly fragmented in nodular packstone to grainstone facies in the lower part of the formation. In the middle part of the formation, the chancelloriid sclerites and rays become sharply decreased in abundance and are virtually absent in boundstone facies. The Daegi chancellorii inhabited near platform margin shoals and shed their sclerites to adjacent environments. Their distribution is comparable with other Cambrian examples, although their near-absence in the Daegi and other Cambrian Series 3 reefs contradict unlike their common occurrence in Cambrian Series 2 archaeocyath-microbial reefs. This discrepancy possibly reflects a combination of local decline of the chancellorii and changes in ecothic niches subsequent to the end-Cambrian Series 2 extinction.

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