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LATE MIDDLE CAMBRIAN (CAMBRIAN SERIES 3) TRILOBITE FAUNAS FROM THE LOWERMOST PART OF THE SESONG FORMATION, KOREA AND THEIR CORRELATION WITH NORTH CHINA

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ABSTRACT —The Sesong Formation is a member of the Taebaek Group, Korea, which extends from late Cambrian Series 3 to middle Furongian in age. Recent studies on the trilobites of the Sesong Formation have contributed significantly to the revision of the biostratigraphy. However, trilobites in the lower part of the formation, which may include the "*Stephanocare* Zone", have remained essentially overlooked since the establishment of the biozone, making it difficult to correlate with the equivalent biozones of North China. Here we report trilobite faunas from the lower part of the Sesong Formation in two different sections, the Seokgaejae and the Jikdong sections, which yield two species of *Jiulongshania* among other species. Species of *Jiulongshania* have been known to occur successively in North China, so are useful for detailed correlation. Specimens of *Stephanocare richthofeni* are fragmentary and rarely occur in association with *Jiulongshania regularis*, while *Jiulongshania* species occur throughout the studied intervals. Accordingly, it is reasonable to extend the previously established *Jiulongshania* Zone of the uppermost part of the underlying Daegi Formation into the lower part of the Sesong Formation. By doing so, the *Jiulongshania* Zone is correlated with the *Blackwelderia* Zone of North China with confidence. The lowermost part of the Sesong Formation in the Jikdong section yields a fauna including *J. regularis*, which implies that the boundary between the Daegi and Sesong formations is diachronous within the Taebaeksan Basin. The Daegi/Sesong formation boundary in Korea is comparable to the Zhangxia/Gushan boundary in North China in that it displays an abrupt change from a carbonate-dominant facies to a shale-dominant facies. The correlation employing the *Jiulongshania* species indicates that the facies shift occurred significantly earlier in Shandong, North China than in the Taebaeksan Basin, Korea.

INTRODUCTION

THE SESONG Formation is a member of the Taebaek Group, Korea and spans the upper part of the Cambrian Series 3 (middle Cambrian) to the middle Furongian (late Cambrian). Trilobites from the Sesong Formation were first reported by Kobayashi (1935, 1960) who established five biozones on the basis of a few poorly preserved specimens from the Sesong Formation as currently understood (see Park and Choi, 2011): i.e., the *Stephanocare*, *Neodrepanura*, *Prochuangia*, *Chuangia* and *Kaolishania* zones in ascending order. The biostratigraphic scheme of Kobayashi (1935, 1960) was employed in Korea without any amendment for decades (e.g., Choi and Chough, 2005). Recently, Park and Choi (2011) revised the biostratigraphy of the middle part of the Sesong Formation based on silicified trilobites, and established three new biozones between the *Neodrepanura* and *Chuangia* zones: i.e., the *Liostracina simesi*, *Fenghuangella laevis*, and *Prochuangia mansuyi* zones in ascending order. The base of the Furongian Series in the Taebaek Group was suggested to be at the base of the *Fenghuangella laevis* Zone. Recently, Park et al. (2012) reported the *Kaolishania* fauna from the uppermost part of the Sesong Formation. However, the biostratigraphy of the lower part of the Sesong Formation remains to be revised. Kobayashi (1935) established the "*Stephanocare* Zone" in the lower part of the formation, based on a few specimens of *Pseudagnostus douvillei* (Bergeron, 1899), *Eodiscus* (?) sp. and *Stephanocare richthofeni* Monke, 1903. Of these, *Eodiscus* (?) sp. was reported from a single poorly-preserved cranidium. Given the fact that the species of *Eodiscus* Hartt *in* Walcott, 1884 have not been reported from North China (see Zhang and Jell 1987), the identification of *Eodiscus* (?) sp. from the "*Stephanocare* Zone" is doubtful. As a result, the zonal concept of the "*Stephanocare* Zone" has remained poorly understood. Kobayashi (1966) correlated the "*Stephanocare* Zone" with the "*Damesella* Zone" of North China, and subsequent studies have compared it with the *Blackwelderia* Zone of North China (e.g., Choi and Chough 2005). However, without the occurrence data of other trilobites, reliable correlation of the "*Stephanocare* Zone" is elusive, because *Stephanocare richthofeni* is known to occur also in the overlying *Neodrepanura* Zone of North China as noted by Kobayashi (1935).

The species of *Jiulongshania* have been reported mainly from the Gushan (Kushan) Formation of Shandong Province, North China (Park et al., 2008b). In the Gushan Formation, five species of *Jiulongshania* occur successively (Park et al., 2008b). They are, in ascending order, *J. longa* Park et al. 2008b, *J. acalle* (Walcott, 1906), *J. rotundata* (Resser and Endo *in* Endo and Resser, 1937), *J. longispina* (Wittke and Zhu *in* Zhu and Wittke, 1989) and *J. regularis* (Walcott, 1906). Recently, Kang and Choi (2007) reported *Cyclolorenzella rotundata* (Resser and Endo *in* Endo and Resser, 1937) from the uppermost part of the Daegi Formation which underlies the Sesong Formation, and established the *Cyclolorenzella* Zone. *Cyclolorenzella rotundata* was transferred to *Jiulongshania rotundata* by Park et al. (2008b), and accordingly this biozone should be renamed the *Jiulongshania* Zone. In a preliminary report, Park et al. (2009) documented a poorly preserved *Jiulongshania regularis* (Walcott, 1906) from the lowermost part of the Sesong Formation at the Gadeoksan section, situated about 12 km north of Taebaek City.

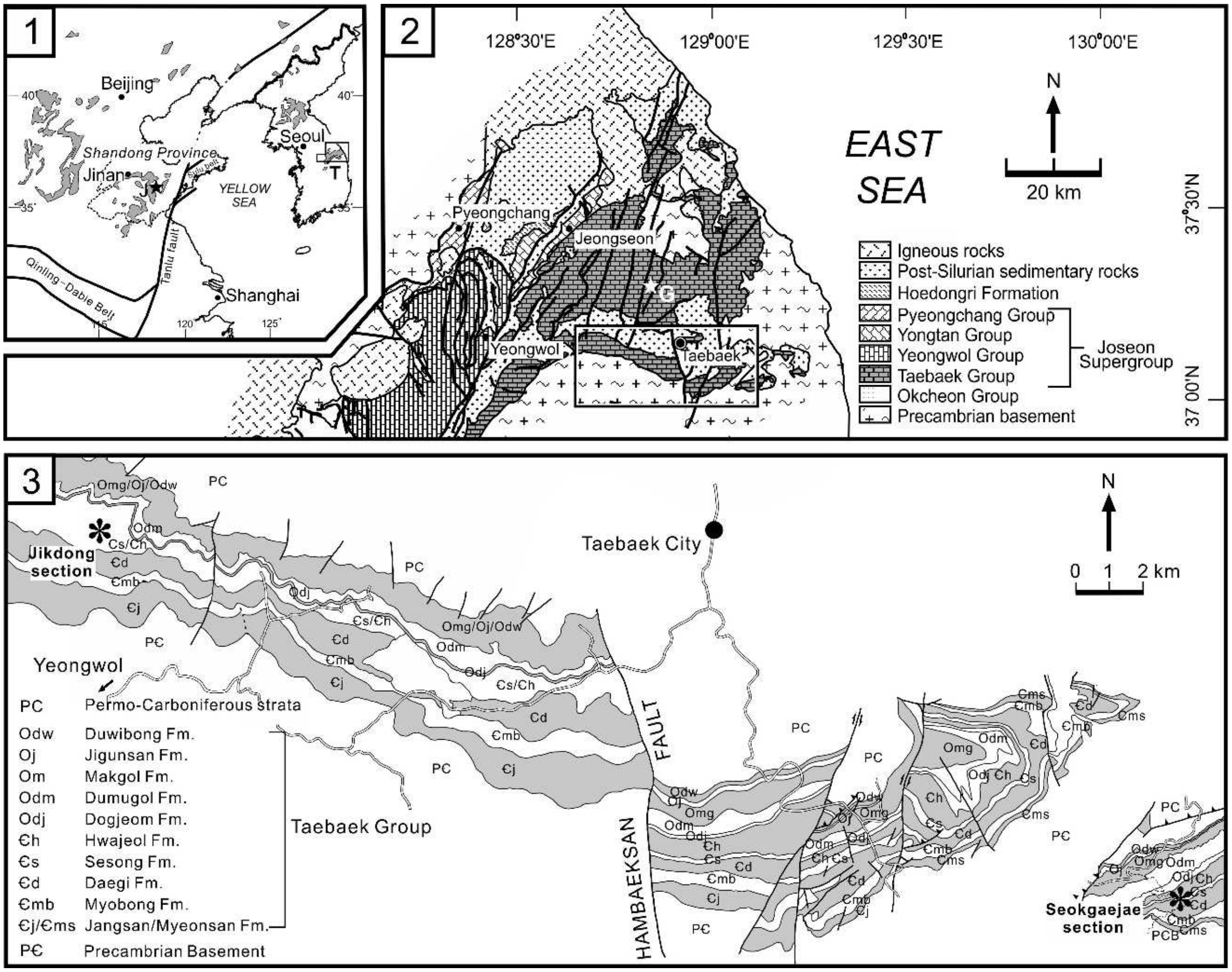

FIGURE *1*—Locality maps. *1*, index map showing the distribution of Cambro–Ordovician strata in the Korean peninsula and adjacent area; star with 'J' denotes the location of the Jiulongshan section; and 'T' indicates the location of the Taebaeksan Basin; *2*, simplified geological map of the Taebaeksan Basin which shows the distribution of the lower Paleozoic Joseon Supergroup in the Taebaeksan Basin; star with 'G' indicates the location of the Gadeoksan section; the rectangle in the south represents the location of the Taebaek area represented in *3*; *3*, geological map of the Taebaek area. The asterisks indicate the locations of the Jikdong and Seokgaejae sections from which the material for this study was collected.

The occurrence of *Jiulongshania* species from Korea is significant in that it may be used for correlation among widely separated sections in Korea and North China. The aim of this study is to describe trilobite faunas from the lower part of the Sesong Formation, and to revise the biostratigraphy accordingly. A detailed documentation of the occurrence of *Jiulongshania* species is expected to provide a high resolution correlation of the Cambrian sequence of Korea with those of North China.

FOSSIL LOCALITIES AND MATERIAL

Detailed description on the geologic setting of the Sesong Formation has been given in previous studies (Choi et al., 2004; Park et al., 2008b; Park and Choi, 2011). The material for this study was collected from the lower part of the Sesong Formation at two different sections: the Jikdong section (E 128°47′05″, N 37°10′16″) and the Seokgaejae section (E 129°08′45.05″, N 37°04′27.9″) (Fig. 1). The two sections are approximately 35 km apart (Fig. 1).

The Seokgaejae section is located approximately 25 km southeast of Taebaek City and exposes a nearly complete succession of the lower Paleozoic of the Taebaek Group. A detailed lithologic description of the section was given by Choi et al. (2004). However, the Sesong Formation and the lower part of the overlying Hwajeol Formation are not well exposed in this section. Choi et al. (2004) only provided the stratigraphic log of the lower 5 m of the Sesong Formation. However, an additional approximately 6 m interval of the lower part of the formation has been found recently; its stratigraphic description is included in this study (Fig. 2).

The Taebaek Group outcrops sporadically in the Jikdong section. The lowest 50 m of the Sesong Formation is well exposed in this section, and consists dominantly of shale, lime mudstone, and sandstone, with frequent intercalations of intraclastic conglomerate layers. In this section, diceratocephalid trilobites, *Cyclolorenzella convexa* (Resser and Endo *in* Endo and Resser, 1937) and *Diceratocephalus cornutus* (Endo *in* Endo and Resser, 1937), were recovered from the *Neodrepanura* Zone (Park et al., 2008b; Park and Choi, 2010), and three new biozones were established above the *Neodrepanura* Zone (Park and Choi, 2011).

Limestone blocks from the lowest 20 m (including a 9-m thick concealed interval) of the Sesong Formation at the Seokgaejae section, and the lowest 4 m of the Sesong Formation at the Jikdong section were dissolved in hydrochloric acid. Silicified trilobite sclerites were collected from the residues of eight horizons of the Seokgaejae section and two horizons of the

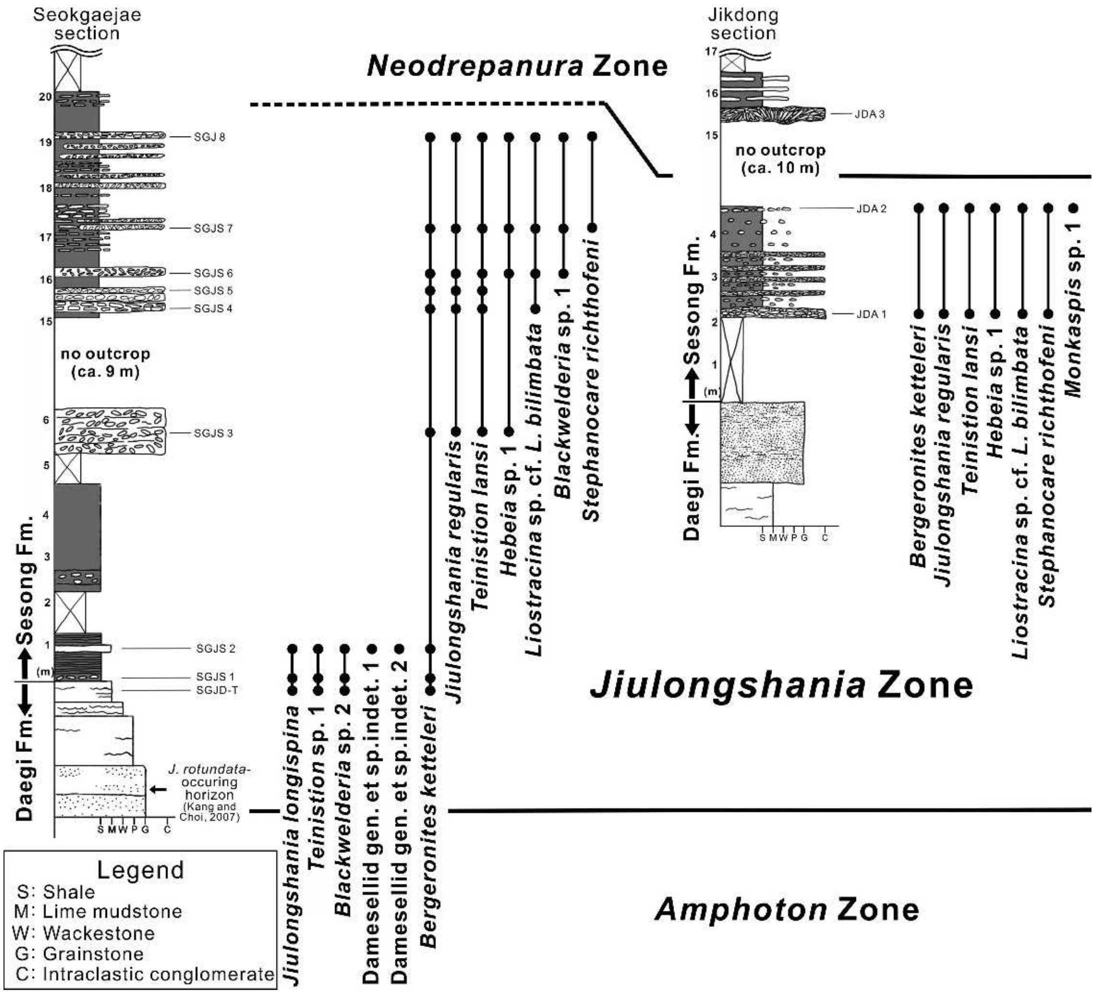

FIGURE 2—Graphic logs of the lower part of the Sesong Formation at the Seokgaejae and Jikdong sections. The sampling horizons, occurrences of trilobites, and the biozones are indicated. The boundary between the *Jiulongshania* Zone and the *Neodrepanura* Zone is currently indeterminate at the Seokgaejae section, and hence is indicated by a dotted line. Note that JDA 3 horizon of the Jikdong section has been known to yield the fauna of the *Neodrepanura* Zone (see Park and Choi, 2010).

Jikdong section, which were marked from bottom to top as SGJS 1 to SGJS 8, and JDA 1 and JDA 2, respectively (Fig. 2). In addition, in the Seokgaejae section, a limestone block from the uppermost horizon of the underlying Daegi Formation, marked as SGJD-T, was found to contain silicified trilobite sclerites comparable to those of the lowermost part of the Sesong Formation (Fig. 2). Fragments of agnostoids have also been collected, but they are in general stratigraphically long-ranging genera, and are too poorly-preserved to be described. Most of the specimens have suffered from tectonic distortion, but those from the Jikdong section have been more strongly distorted than those from the Seokgaejae section (e.g., Figs. 3.4, 3.9–11, 4.13, 4.29, 5.21, 6.9, 6.10).

SYSTEMATIC PALEONTOLOGY

The morphological terms employed in this study basically follow those of Whittington and Kelly (1997). All of the specimens are reposited in the paleontological collections of the Korea Polar Research Institute, with registered number prefixed with KOPRIF.

Family DAMESELLIDAE Kobayashi, 1935

Remarks.—The Damesellidae is the only family in the Superfamily Dameselloidea Kobayashi, 1935, but the phylogenetic relationships of the Damesellidae with other major trilobite groups is contentious. Damesellid trilobites were regarded as the primitive sister group of the lichid/odontopleurid trilobites (Fortey, 2001). However, the observation of the featureless protaspid morphology of the damesellid trilobite, *Shantungia spinifera* Walcott, 1905, cast doubt on the proposed lichid/odontopleurid affinity of the Damesellidae (Park et al., 2008a).

Genus BERGERONITES Sun *in* Kuo, 1965

Type species.—*Drepanura ketteleri* Monke, 1903 from the Gushan Formation, Shandong Province, North China.

Remarks.—The cranidial morphology of this genus displays a remarkable resemblance to that of *Palaeadotes* Öpik, 1967, often causing confusion in taxonomic assignment (reviewed by Peng et al., 2004). Peng et al. (2004) mentioned that *Palaeadotes* can be distinguished from *Bergeronites* in having a forwardly tapering glabella, a birfucate S1, weakly defined bacculae, and a pair of posterolateral accessory lobules on L1. These differences may be ascribable to the lack of well-preserved specimens of *Bergeronites*, because, except for the presence of lobules on L1, all the features supposedly characterizing *Palaeadotes* as mentioned by Peng et al. (2004) are seen in the new material of *Bergeronites ketteleri* (Monke, 1903) illustrated herein. The only notable difference in cranidial morphology is the more rounded forward anteriorly protruding cranidial margin of *Bergeronites*. However,

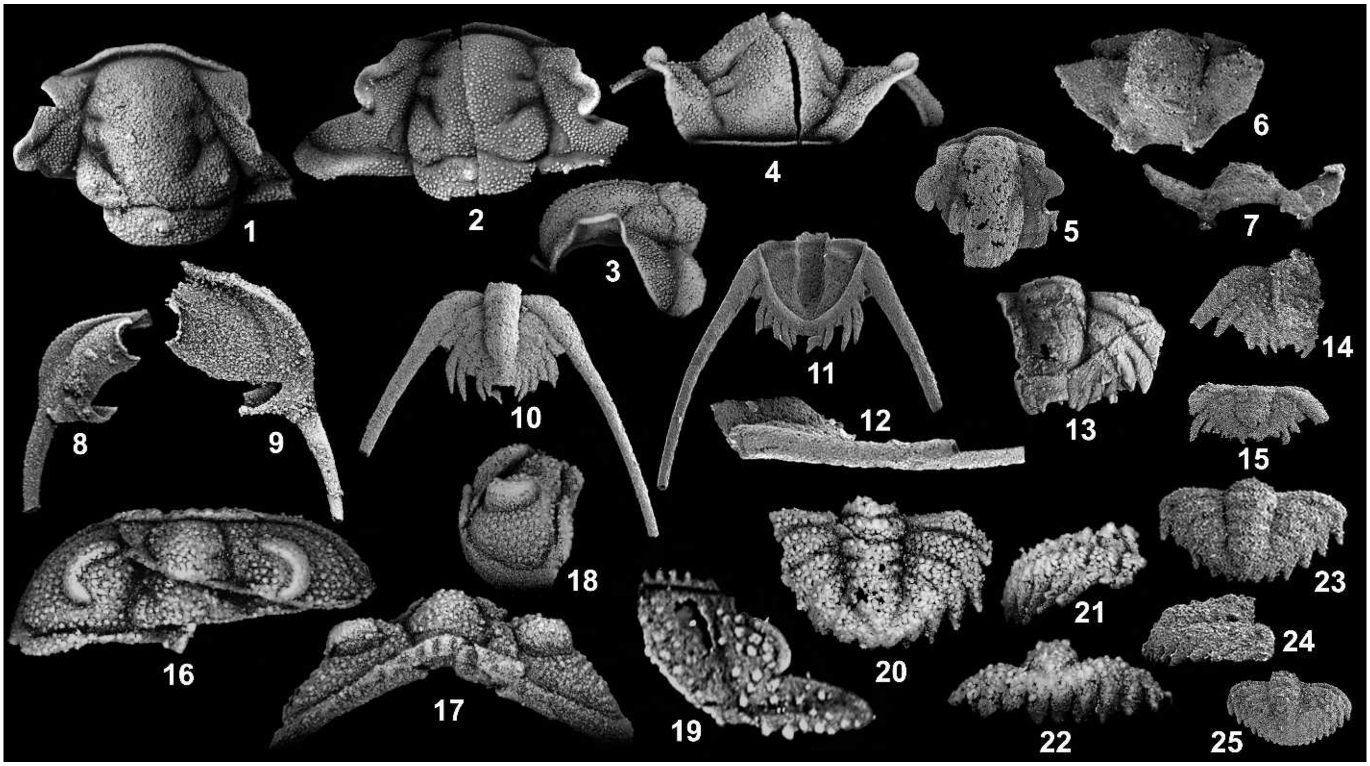

FIGURE 3—Damesellid trilobites from the *Jiulongshania* Zone of the Sesong Formation. Specimens are from the Seokgaejae section if not otherwise indicated. *1–15*, *Bergeronites ketteleri* (Monke, 1903): *1–5*, cranidia: *1*, KOPRIF1001; *2–4*, KOPRIF1002, dorsal, lateral and anterior views; *5*, KOPRIF1003, from the Jikdong section; *6*, *7*, hypostome, KOPRIF1004, dorsal and posterior views; *8*, *9*, free cheeks: *8*, KOPRIF1005; *9*, KOPRIF1006; *10–15*, pygidia: *10–12*, KOPRIF1007, from the Jikdong section, dorsal, ventral and lateral views; *13*, KOPRIF1008; *14*, KOPRIF1009, from the Jikdong section; *15*, KOPRIF1010, from the Jikdong section; *16–25*, *Stephanocare richthofeni* Monke, 1903: *16–19*, cranidia: *16–18*, free cheek-retained cranidium, KOPRIF1011, dorsal, anterior and lateral views; *19*, fragmentary cranidium, KOPRIF1012; *20–25*, pygidia: *20–22*, KOPRIF1013, dorsal, lateral and posterior views; *23–24*, KOPRIF1014, dorsal and lateral views; *25*, immature pygidium, KOPRIF1015. Magnifications: *1–4*, *13*, ×4; *5–12*, ×8; *14–25*, ×10.

as noted by Peng et al. (2004), these two genera show significant differences in pygidial morphology: i.e., the pygidial axis of *Bergeronites* is much wider than that of *Palaeadotes* and the pygidial spines of *Bergeronites* are not fused at the base, rendering the doublure not as wide as that of *Palaeadotes*. This latter feature also makes the pygidium of *Bergeronites* look more transverse than that of *Palaeadotes*.

Palaeadotes displays a wide paleogeographic distribution within Gondwana including South China, Iran, Australia, Kazakhstan, France and Siberia (Peng et al., 2004), whereas *Bergeronites* has been known to occur exclusively in the Sino-Korean Block.

BERGERONITES KETTELERI (Monke, 1903)
Figure 3.1–3.15

1903 *Drepanura premesnili* Bergeron, 1899; MONKE, p. 149, pl. 8, fig. 7.
1905 *Drepanura ketteleri*; WOODWARD, p. 253, pl. 13, fig. 4.
1913 *Drepanura premesnili* Bergeron; WALCOTT, p. 129, pl. 10, fig. 2.
1913 *Drepanura ketteleri*; WALCOTT, p. 129, pl. 10, fig. 3, 3a–c.
?1916 *Drepanura ketteleri tonkinensis* MANSUY, p. 23, pl. 2, fig. 7.
1916 *Drepanura* cf. *premesnili* Bergeron; MANSUY, p. 23, pl. 2, fig. 8, pl. 3, fig. 1.
1937 *Drepanura intermedia* RESSER AND ENDO *in* ENDO AND RESSER, p. 215, pl. 51, fig. 3.
1937 *Drepanura mina* RESSER AND ENDO *in* ENDO AND RESSER, p. 216, pl. 50, fig. 16.
1941 *Drepanura ketteleri*; KOBAYASHI, p. 38, pl. 1, figs. 3–6.
1965 *Drepanura ketteleri*; LU, CHANG, CHU, CHIEN AND HSIANG, p. 399, pl. 75, figs. 4–7.
1965 *Bergeronites ketteleri* (Monke); KUO, p. 637.
1976 *Drepanura ketteleri*; NAN, p. 339, pl. 196, fig. 6.
1987 *Bergeronites ketteleri* (Monke); ZHANG AND JELL, p. 222, pl. 106, fig. 11, pl. 107, figs. 5–9, pl. 108, figs. 1, 2.
non1996 *Bergeronites ketteleri* (Monke); GUO, ZAN AND LUO, p. 129, pl. 64, fig. 16.
2005 *Bergeronites ketteleri* (Monke) DUAN, AN, LIU, PENG AND ZHANG, p. 184, pl. 39, figs. 1, 2, pl. 53, fig. 7.

Material.—Forty-two cranidia, 21 free cheeks, and 23 pygidia including immature specimens.

Occurrence.—SGJD-T, SGJS 1–SGJS 8 of the Seokgaejae section, and JDA 1 and JDA 2 of the Jikdong section.

Remarks.—Silicified cranidia display a sagittally wider anterior cranidial border than those of *Palaeadotes*. The border of this species has seldom been illustrated in the literature, except for Monke (1903). The anterior cranidial border is slightly upturned.

This species has long been regarded as a species of the genus *Drepanura* (now *Neodrepanura*; see Özdikmen, 2006). *Bergeronites* is easily distinguished from *Neodrepanura* by the presence of the anterior cranidial border and the more posteriorly situated palpebral lobes.

STEPHANOCARE Monke, 1903

Type species.—*Stephanocare richthofeni* Monke, 1903 from the Gushan Formation, Shandong Province, North China.

Remarks.—The cranidial morphology of this genus is characterized by the serrated anterior margin or the vincular sockets as described by Öpik (1967), which must have been a coaptive structure that, when enrolled, fitted into the spinose posterior margin of the pygidium. Öpik (1967, p. 327) noted that *S. richthofeni* is the only Cambrian trilobite with a frontal vincular apparatus.

A number of species have been assigned to this genus, albeit many of them with reservation. They include: *S.* (?) *sinensis* (Bergeron, 1899), *S. chione* (Walcott, 1905), *S.* (?) *monkei* Walcott, 1911, *S.* (?) *sinensis* Mansuy, 1916, *S.* (?) *quinquespina* Kobayashi, 1935, *S. bergeroni* Kobayashi, 1935, *S. inutilis* (Resser and Endo *in* Endo and Resser, 1937), *S. ordosensis* Chu, 1959, and *S. fuxianensis* Guo et al., 1996. Most of the species have been established on the basis of poorly preserved pygidia. Of these, *Stephanocare* (?) *sinensis* was synonymized with *Shantungia spinifera* Walcott, 1905 by Zhang and Jell (1987). Kobayashi (1941) treated *S. chione* (Walcott, 1905) as a junior synonym of *S. richthofeni*. Cranidia of *S. fuxianensis* are indistinguishable from those of *S. richthofeni*. The pygidia on the basis of which *S. fuxianensis* was established probably belong to *Hebeia*. *Stephanocare chione* (Walcott, 1905) was established based on a single pygidium with a long pygidial spine on the right side of the fourth pygidial segment, and may represent an abnormal variant of *S. richthofeni*. It should be noted that only *S. richthofeni* retains a relatively stable taxonomic status within the genus *Stephanocare*.

STEPHANOCARE RICHTHOFENI Monke, 1903
Figure 3.16–3.25

1903 *Stephanocare richthofeni* MONKE, p. 136, pl. 8, figs. 1–17.
1905 *Olenoides richthofeni* (Monke); WOODWARD, p. 254, pl. 13, figs. 1, 2, 6.
1913 *Stephanocare richthofeni*; WALCOTT, p. 114, pl. 7, fig. 17a, 17b, 17d.
1915 *Stephanocare richthofeni*; MANSUY, p. 2.
1916 *Stephanocare richthofeni*; MANSUY, p. 19.
1924 *Stephanocare richthofeni* Monke; SUN, p. 32, pl. 2, fig. 5a–5c.
1931 *Stephanocare richthofeni*; KOBAYASHI, p. 174, pl. 22, fig. 2.
1935 *Stephanocare richthofeni*; KOBAYASHI, p. 167, pl. 13, figs. 4–7.
1941 *Stephanocare richthofeni*; KOBAYASHI, p. 47.
1957 *Stephanocare richthofeni*; LU, p. 274, pl. 143, figs. 12, 13.
1965 *Stephanocare richthofeni*; LU ET AL., p. 388, pl. 73, figs. 2–6.
1967 *Stephanocare richthofeni*; ÖPIK, p. 327, pl. 44, figs. 5, 6.
1987 *Stephanocare richthofeni*; ZHANG AND JELL, p. 215, pl. 104, figs. 1–8.
1995 *Stephanocare richthofeni*; ZHANG, XIANG, LIU AND MENG, p. 76, pl. 34, figs. 2–8.
2009 *Stephanocare richthofeni*; LUO, HU, HOU, GAO, ZHAN AND LI, p. 154, pl. 42, figs. 10, 11.

Material.—Four cranidia, one free cheek, and two pygidia including fragmentary specimens.

Occurrence.—SGJS 3–SGJ 8 of the Seokgaejae section, and JDA1 and JDA 2 of the Jikdong section.

Remarks.—Specimens assigned to *S. richthofeni* from the Sesong Formation are fragmentary, but show many features of the species, including the serrated anterior cranidial margin and ventrally projecting pygidial spines. An immature pygidium belonging to this species possesses eight or nine pairs of pygidial spines (Fig. 3.25), while holaspid pygidia of this species retain six pairs of pygidial spines.

Genus TEINISTION Monke, 1903

Type species.—*Teinistion lansi* Monke, 1903 from the Gushan Formation, Shandong Province, North China.

Remarks.—The genus *Teinistion* has been often involved in taxonomic confusion with *Dorypygella* Walcott, 1905. The genus *Dorypygella* was established on the basis of *D. typicalis* Walcott, 1905 from the Gushan Formation, but later the *Dorypygella* was synonymized with *Teinistion* by Walcott (1913). On the other hand, Kobayashi (1941) retained *Dorypygella* as a separate genus, an opinion followed by Zhu (1959), Lu et al. (1965), and Öpik (1967). Subsequently, *Dorypygella* was treated as a junior synonym of *Teinistion* by Zhang and Jell (1987), Guo et al. (1996), and Peng et al. (2004). Peng et al. (2004) went further to suggest that *Metashantungia* Zhang, 1957, *Histiomona* Öpik, 1967, and *Jiawangaspis* Zhang *in* Qiu et al., 1983 are the junior synonyms of *Teinistion*. Peng et al. (2004) concept is basically followed in this study, but the taxonomic position of *Metashantungia* needs further investigation.

TEINISTION LANSI Monke, 1903
Figure 4.1–4.22

1903 *Teinistion lansi* MONKE, p. 117, pl. 4, figs. 1–17, pl. 9, fig. 3.
1913 *Teinistion lansi*; WALCOTT, p. 111, pl. 9, fig. 1, 1a, 1b.
1935 *Teinistion lansi*; KOBAYASHI, p. 255.
1937 1*Teinistion truncatus*, ENDO *in* ENDO AND RESSER, p. 337, pl. 64, fig. 7, pl. 65, figs. 1–3.
1955 *Teinistion lansi*; KOBAYASHI, p. 93.
1959 *Teinistion tangshilingensis* CHU, p. 62, pl. 2, figs. 24, 25.
1965 *Teinistion lansi*; LU ET AL., p. 408, pl. 77, figs. 14–18.
1965 *Teinistion tangshilingensis* (Chu); LU ET AL., p. 409, pl. 78, figs. 1, 2.
1965 *Teinistion truncatus* (Endo *in* Endo and Resser); LU ET AL., p. 411, pl. 78, figs. 10, 11.
1996 *Teinistion tangshilingensis* (Chu); GUO ET AL., p. 128, pl. 64, fig. 3.

Material.—Forty-six cranidia, 15 free cheeks, and 43 pygidia including immature specimens.

Occurrence.—SGJS 3–SGJ 8 of the Seokgaejae section, and JDA 1 and JDA 2 of the Jikdong section.

Remarks.—This species is distinguished from other species of *Teinistion* in having a slightly posteriorly curved anterior cranidial margin and posteriorly situated palpebral lobes. The anterior cranidial margin of the original material (Monke, 1903, pl. 4, fig. 14) is curved more rearward than the specimens from the Sesong Formation, but the degree of rearward curvature of the anterior cranidial margin should be treated as intraspecific variation. The pygidia of this species are characterized by a pair of long anterior-most pygidial spines and five pairs of shorter spines behind them. However, it is possible that some of these pygidia may be assignable to *Hebeia* sp. 1 no pygidia of which have been identified in this study.

TEINISTION sp. 1
Figure 4.23–4.26

Material.—Six cranidia, and four pygidia including fragmentary immature specimens.

Occurrence.—SGJD-T, SGJS 1, and SGJS2 of the Seokgaejae section.

Remarks.—The specimens are too fragmentary to be assigned

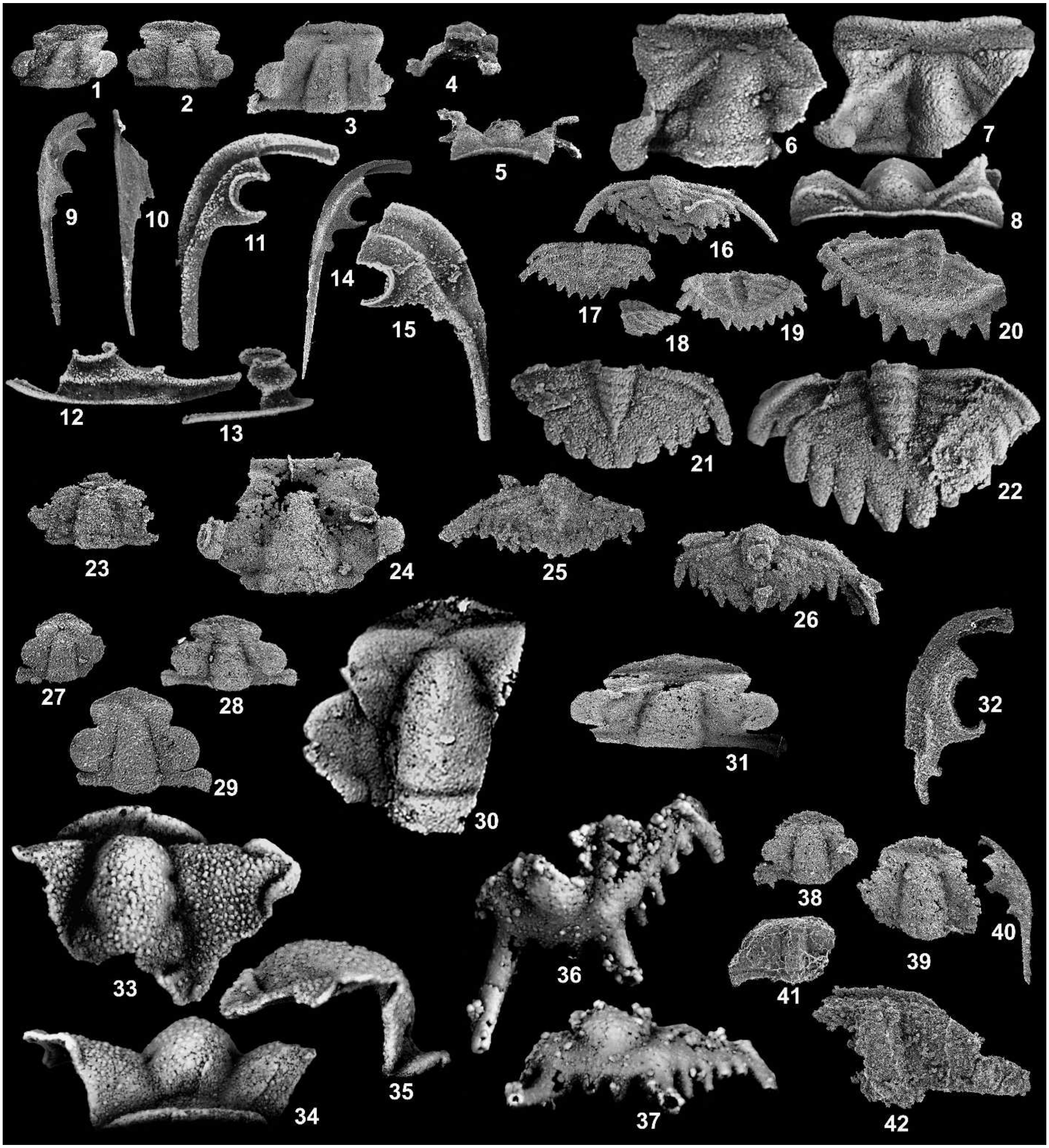

FIGURE 4—Damesellid trilobites from the *Jiulongshania* Zone of the Sesong Formation and the uppermost part of the Daegi Formation. Specimens are from the Seokgaejae section if not otherwise indicated. *1–22*, *Teinistion lansi* Monke, 1903: *1–8*, cranidia: *1*, KOPRIF1016; *2*, KOPRIF1017; *3–5*, KOPRIF1018, dorsal, lateral and anterior views; *6*, KOPRIF1019; *7*, *8*, KOPRIF1020, dorsal and anterior views; *9–15*, free cheeks: *9*,*10*, KOPRIF1021, dorsal and lateral views; *11–13*, KOPRIF1022, dorsal, lateral and anterior views; *14*, KOPRIF1023, from the Jikdong section; *15*, KOPRIF1024; *16–22*, pygidia: *16*, KOPRIF1025, from the Jikdong section; *17–19*, KOPRIF1026, dorsal, lateral and ventral views; *20*, KOPRIF1027, ventral view; *21*, KOPRIF1028; *22*, KOPRIF1029; *23–27*, *Teinistion* sp. 1: *23*, *24*, cranidia: 23, KOPRIF1030; *24*, KOPRIF1031; *25*, *26*, pygidia: *25*, KOPRIF1032; *26*, KOPRIF1033; *27–32*, *Hebeia* sp. 1: *27–31*, cranidia: *27*, KOPRIF1034; *28*, KOPRIF1035; *29*, KOPRIF1036; *30*, KOPRIF1037; *31*, KOPRIF1038, from the Jikdong section; *32*, free cheek, KOPRIF1039; *33–35*, *Blackwelderia* sp. 1, fragmentary cranidium, KOPRIF1040, dorsal, anterior and lateral views; *36*, *37*, *Blackwelderia* sp. 2, fragmentary pygidium, KOPRIF1041, dorsal and posterior views; *38–40*, damesellid gen. and sp. indet. 1: *38*, *39*, cranidia: *38*, KOPRIF1042; *39*, KOPRIF1043; *40*, free cheek, KOPRIF1044; *41*, *42*, damesellid gen. and sp. indet. 2: *41*, KOPRIF1045; *42*, KOPRIF1046. Magnifications: *1–10*, *16–24*, *27–40*, ×10; *11–15*, ×5; *25*, *26*, ×15; *41*, *42*, ×20.

to specific level. The fragmentary cranidium assigned to *Teinistion* sp. 1 is characterized by having a strongly forward-tapering glabella which is reminiscent of *T. nanhaitouensis* Guo et al., 1996. This specimen possesses comparatively smaller palpebral lobes than other species of *Teinistion*. The pygidium is similar to that of *T. typicalis* (Walcott, 1905) in having a pair of long anteriormost pygidial spines, and six pairs of short pygidial spines. However, the short pygidial spines of *T. typicalis* are in general shorter and have broader bases than those of *Teinistion* sp. 1.

Genus Hebeia Guo and Duan, 1978

Type species.—*Hebeia conica* Guo and Duan, 1978 from the Kushanian Stage, northeastern Hebei, China.

Remarks.—This genus has been assigned to the family Polycyrtaspididae Öpik, 1967 since its establishment (Guo and Duan, 1978; Qiu et al., 1983; Duan et al., 2005). However, not only does this genus have a spinose pygidium which is characteristic of the family Damesellidae, but it also shares many morphological features with *Shantungia* Walcott, 1905, namely: posteriorly situated large palpebral lobes; a weak plectrum-like rearward extension from the anterior border of the cranidium; a pair of thin ridges running anterolaterally from the anterolateral corners of glabella; a pair of long pygidial spines originating from the anteriormost pygidial segment; and a pair of long broad-based posterior-most pygidial spines (see Park et al., 2008a for the morphology of *Shantungia spinifera* Walcott, 1905, and Duan et al., 2005 for that of *Hebeia*). These morphological features suggest that *Hebeia* must be phylogenetically closely related to the Damesellidae. Hence it is treated herein as a member of that family. If *Hebeia* is also closely related to Polycyrtaspididae, it can be concluded that the Polycyrtaspididae may have originated from the Damesellidae. Alternatively, the morphological similarities between *Polycyrtaspis flexuosa* Öpik, 1967 and *Hebeia* could have been the result of a convergent evolution.

Hebeia sp. 1
Figure 4.27–4.32

Material.—Ten cranidia and a single free cheek including immature and fragmentary specimens.

Occurrence.—SGJS 3, SGJS 5– SGJS 7 of the Seokgaejae section, and JDA 1 and JDA 2 of the Jikdong section.

Remarks.—*Hebeia* sp. 1 is similar to other species of *Hebeia* in having a plectrum-like backward extension from the anterior cranidial border and large (length more than 40% of cranidial length) palpebral lobes centered at about one third of the distance to the anterior from the occipital furrow. Unlike other species, *Hebeia* sp. 1 has a conical glabella, while others have a slightly or moderately truncated glabellar frontal margin. However, due to the lack of well-preserved mature specimen, these specimens are left in open nomenclature. A single free cheek has a narrow genal field, a short genal spine, the length of which is about 25 percent that of the genal field, a moderately wide lateral border defined by a shallow, wide border furrow, a large eye socle, moderately incised eye socle furrow, and a cephalic doublure which is slightly narrower than the lateral border, but becomes wider adaxially.

Genus Blackwelderia Walcott, 1913

Type species.—*Calymmene*? *sinensis* Bergeron, 1899 from North China; the locality and formation not known (see Peng et al., 2004).

Remarks.—Many authors have discussed *Blackwelderia* (Walcott, 1913; Kobayashi, 1942; Lu et al., 1965) but its generic concept has remained ambiguous. This is because many of the specimens assigned to this genus have come from weathered-out surfaces of the so-called "bat-stone", the *Neodrepanura*-bearing rocks from the Gushan Formation of North China (see Peng, 2007). This incompletely understood morphology of *Blackwelderia* has resulted in some taxonomic confusion involving closely related genera. For example, *B. spectabilis* (Resser and Endo *in* Endo and Resser, 1937) from North China (see Zhang and Jell, 1987, p. 214) is morphologically similar to *Damesella hunanensis* Peng, Babcock, and Lin, 2004 from South China. A detailed morphological and taxonomic assessment of this genus, based on well preserved material is needed, especially given the fact that the generic name, *Blackwelderia*, has long been used as a zonal name in the Kushanian Stage in China (see Zhang and Jell, 1987).

Blackwelderia sp. 1
Figure 4.33–4.35

Material.—A single fragmentary cranidia.

Occurrence.—SGJS 6–SGJS 8 of the Seokgaejae section.

Remarks.—The illustrated fragmentary cranidium is reminiscent of *Blackwelderia sinensis* in having a gently forwardly tapering glabella with a truncated anterior margin, well impressed glabellar furrows and highly elevated palpebral lobes. However, this cranidium has been left in open nomenclature because of the lack of well-preserved specimen.

Blackwelderia sp. 2
Figure 4.36, 4.37

Material.—Three fragmentary pygidia.

Occurrence.—SGJD-T, SGJS 1, and SGJS2 of the Seokgaejae section.

Remarks.—These fragmentary pygidia are relatively large and have seven pairs of pygidial spines, the first and sixth of which are macropleural and so are similar to *B. spectabilis* (Resser and Endo *in* Endo and Resser, 1937), but they are too fragmentary to be identified confidently.

Damesellid genus and species indeterminate 1
Figure 4.38–4.44

Material.—Two immature cranidia and a free cheek.

Occurrence.—SGJS 2 of the Seokgaejae section.

Remarks.—Two morphologically immature cranidia are comparable to an immature cranidium of *Shantungia spinifera* (Walcott, 1905) reported by Park et al. (2008a, fig. 3.14) or an associated immature form of *Teinistion* sp. 1. However, this cranidium is significantly different from the immature cranidia of *T. lansi* of similar size (Fig. 4.1, 4.2) and is hence left in open nomenclature. This cranidium is also comparable to the immature cranidia of *Hebeia* sp. 1 (Fig. 4.27–4.29), but no mature specimen of *Hebeia* sp. 1 has been recovered in association so far.

Damesellid genus and species indeterminate 2
Figure 4.41, 4.42

Material.—Two fragmentary immature cranidia.

Occurrence.—SGJS 2 of the Seokgaejae section.

Remarks.—These immature cranidia are too fragmentary to be identified even at generic level, although the conterminant glabellar condition is indicative of damesellid trilobites. The smaller specimen (Fig. 4.41) has no anterior cranidial border, and a forwardly diverging glabella frontal lobe.

Family Inouyiidae Chang, 1963
Jiulongshania Park, Han, Bai and Choi, 2008

Type species.—*Agraulos acalle* Walcott, 1905 from the Gushan Formation (middle Cambrian), Yanzhuang, Shandong Province, China.

Remarks.—See Park et al. (2008b) for detailed discussion of this genus.

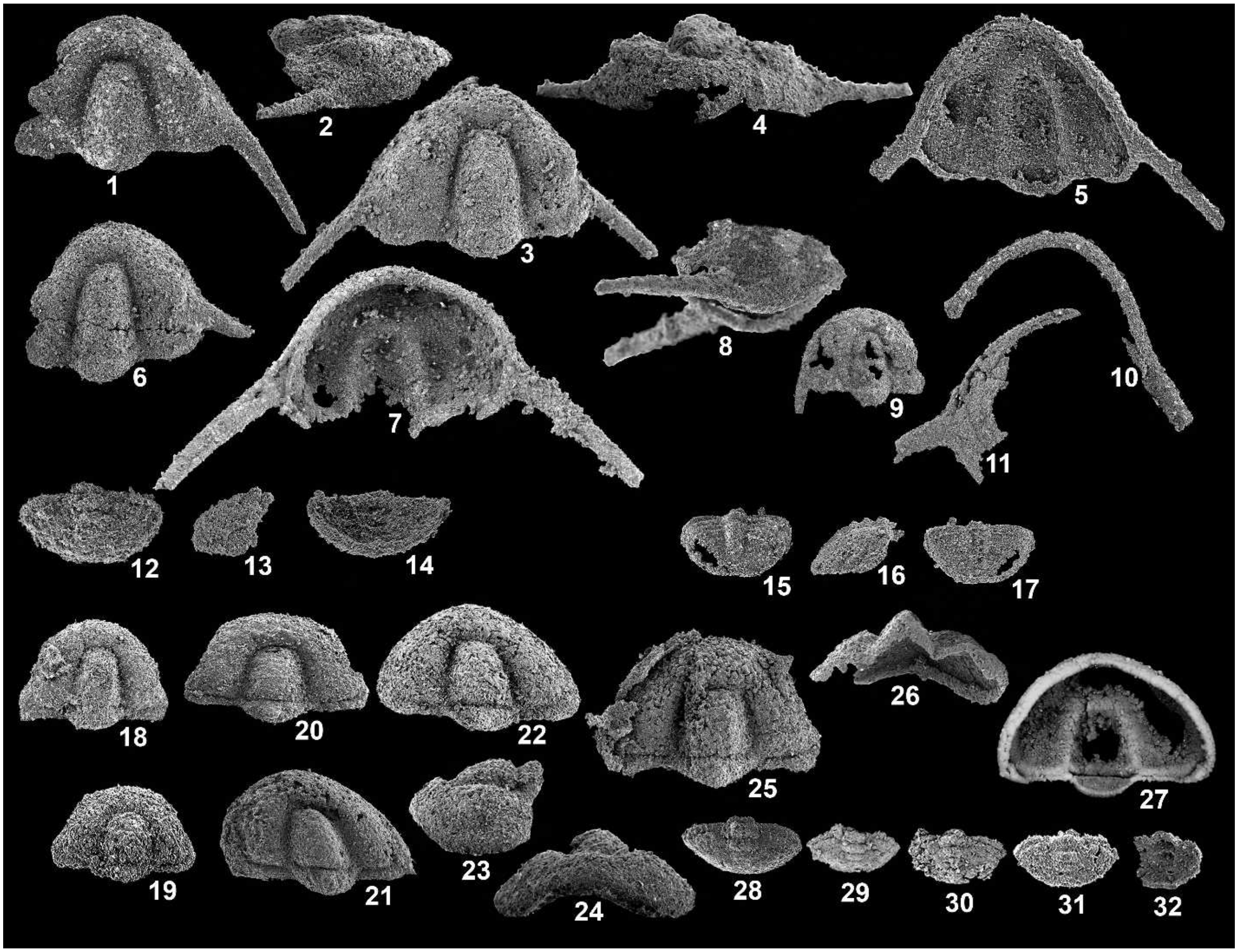

FIGURE 5—*Jiulongshania* from the *Jiulongshania* Zone of the Sesong Formation and the uppermost part of the Daegi Formation. Specimens are from the Seokgaejae section if not otherwise indicated. *1–17*, *Jiulongshania longispina* (Wittke and Zhu *in* Zhu and Wittke, 1989): *1–9*, cranidia with free cheeks retained: *1*, *2*, KOPRIF1047, dorsal and lateral views; *3–5*, KOPRIF1048, dorsal, anterior and ventral views; *6*, KOPRIF1049; *7*, *8*, KOPRIF1050, ventral and lateral views; *9*, KOPRIF1051; *10*, *11*, free cheeks: *10*, fragmentary yoked free cheek, KOPRIF1052; *11*, fragmentary free cheek, KOPRIF1053; *12–17*, pygidia: *12–14*, KOPRIF1054, dorsal, lateral and ventral views; *15–17*, immature (possibly meraspid) pygidium, KOPRIF1055, dorsal, lateral and ventral views; *18–32*, *Jiulongshania regularis* (Walcott, 1906): *18–27*, cranidia: *18*, KOPRIF1056; *19*, KOPRIF1057; *20*, KOPRIF1058, from the Jikdong section; *21*, KOPRIF1059, from the Jikdong section; 22–*24*, KOPRIF1060, dorsal, lateral and anterior views; *25*, KOPRIF1061; *26*, posteroventral view, KOPRIF1062; *27*, KOPRIF1063, ventral view; *28–32*, pygidia: *28*, KOPRIF1064; *29*, KOPRIF1065; *30*, KOPRIF1066; *31*, KOPRIF1067; *32*, KOPRIF1068, ventral view. Magnifications: *1–26*, ×15; *27*, ×10; *28–32*, ×20.

JIULONGSHANIA LONGISPINA (Wittke and Zhu *in* Zhu and Wittke, 1989)
Figure 5.1–5.17

1989 *Cyclolorenzella longispina* WITTKE AND ZHU *in* ZHU AND WITTKE, p. 213, pl. 3, fig. 13.

2008b *Jiulongshania longispina* (Wittke and Zhu *in* Zhu and Wittke); PARK, HAN, BAI AND CHOI, p. 260, fig. 7A–7Q.

Material.—Twenty-one cranidia and five pygidia including immature specimens.

Occurrence.—SGJD-T, SGJS 1, and SGJS 2 of the Seokgaejae section.

Remarks.—A detailed diagnosis for this species was given by Park et al. (2008b). *Jiulongshania longispina* is characterized by long genal spines projected posterolaterally; *J. longa* Park et al., 2008b and *J. acalle* (Walcott, 1905) have long genal spines directed posteriorly and are subparallel; *J. rotundata* (Walcott, 1906) possesses very short genal spines; and *J. regularis* (Walcott, 1906) generally has no genal spines (see Park et al., 2008b). The free cheek is apparently yoked, given the ventral views of free cheek-attached cranidia (Fig. 5.5, 5.7) and an isolated fragmentary free cheek (Fig. 5.10). The small cranidium with the left free cheek attached has the genal spine projecting posteriorly (Fig. 5.9) rather than posterolaterally as in large specimens.

JIULONGSHANIA REGULARIS (Walcott, 1906)
Figure 5.18–5.32

1906 *Agraulos regularis* Walcott, p. 578.

1913 *Inouyia*? *regularis* (Walcott); WALCOTT, p. 154, pl. 14, fig. 18.

1959 *Lorenzella pustulosa* CHU, p. 98, pl. 2, figs. 6–8.

1959 *Cyclolorenzella pustulosa* (Chu); KOBAYASHI, p. 389.

1960 *Latilorenzella regularis* (Walcott); KOBAYASHI, p. 390.

1965 *Cyclolorenzella pustulosa* (Chu); LU ET AL., p. 253, pl. 42, figs. 23, 24.

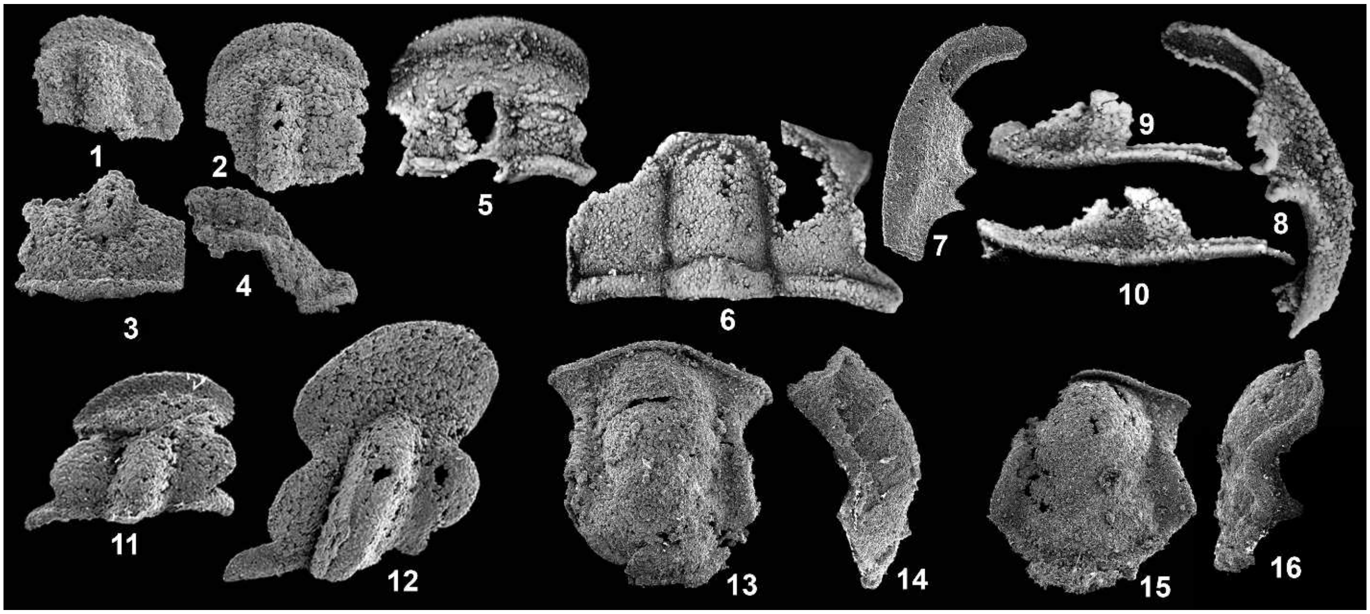

FIGURE 6—Other trilobites from the *Jiulongshania* Zone of the Sesong Formation. Specimens are from the Seokgaejae section if not otherwise indicated. *1–10*, *Liostracina* sp. cf. *L. bilimbata* Zhang *in* Qiu et al., 1983: *1–6*, cranidia: *1*, KOPRIF1069; *2–4*, KOPRIF1070, dorsal, anterior and lateral views; *5*, KOPRIF1071; *6*, KOPRIF1072; *7–10*, free cheeks: *7*, KOPRIF1073; *8–10*, KOPRIF1074, dorsal, anterior and lateral views; *11*, *12*, *Monkaspis* sp. 1: *11*, KOPRIF1075, from the Jikdong section; *12*, KOPRIF1076, from the Jikdong section; *13*, *14*, indeterminate hypostome 1, KOPRIF1077, dorsal and lateral views; *15*, *16*, indeterminate hypostome 2, KOPRIF1078, dorsal and lateral views. Magnifications: *1–4*, *9–14*, ×15; *5*, *6*, ×8; *7*, *8*, ×10.

1965 *Cyclolorenzella regularis* (Walcott); LU ET AL., p. 253, pl. 42, figs. 25, 26.
1987 *Cyclolorenzella regularis* (Walcott); ZHANG AND JELL, p. 133, pl. 51, figs. 8, 9.
1996 *Cyclolorenzella regularis* (Walcott); GUO ET AL., p. 115, pl. 59, figs. 17, 18.
1995 *Cyclolorenzella yentaiensis* (Chu, 1959); ZHANG ET AL., p. 78, pl. 34, figs. 12–14.
2008b *Jiulongshania regularis* (Walcott); PARK ET AL., p. 260, fig. 9A–9H.
2009 *Jiulongshania regularis* (Walcott); PARK, KIM AND CHOI, p. 121, fig. 3.1–3.10.
2010 *Jiulongshania regularis* (Walcott); PARK, WOO AND CHOI, p. 176, fig. 3.6–3.8.

Material.—127 cranidia and 11 pygidia including immature specimens.

Occurrence.—SGJS3–SGJS8 of the Seokgaejae section, and JDA 1 and JDA 2 of the Jikdong section.

Remarks.—Park et al. (2008b) provided a diagnosis for this species. It is characterized by its small transverse cranidium. Generally genal spines are absent, but vestigial spines are sometimes observed (Fig. 5.21).

Family LIOSTRACINIDAE Raymond, 1937
LIOSTRACINA Monke, 1903

Type species.—*Liostracina krausei* Monke, 1903 from the *Drepanura* Zone of the Gushan Formation, Shandong Province, North China.

Remarks.—Detailed discussions of this genus were given by Zhang and Jell (1987) and Peng et al. (2004).

LIOSTRACINA SP. cf. L. BILIMBATA Zhang *in* Qiu et al., 1983
Figure 6.11, 6.12

cf.1983 *Liostracina bilimbata*, ZHANG *in* QIU ET AL., p. 117, pl. 67, figs. 4, 5.
cf.1983 *Liostracina suixiensis*, BI *in* QIU ET AL., pl. 67, fig. 2.

Material.—Five cranidia and two free cheeks including fragmentary specimens.

Occurrence.—SGJS 4– SGJS 8 of the Seokgaejae section, and JDA 1 and JDA 2 of the Jikdong section.

Remarks.—*Liostracina bilimbata* differs from other species of *Liostracina* in having a broad and parallel-sided glabella and a wide anterior cranidial border furrow. Although the specimens on hand are fragmentary, the two large and morphologically mature fragmentary cranidia show a wide anterior cranidial border furrow (Fig. 6.5) and a parallel-sided glabella (Fig. 6.6).

Family MONKASPIDIDAE Kobayashi, 1935
MONKASPIS Kobayashi, 1935

Type species.—*Anomocare*? *daulis* Walcott, 1905 from the Gushan Formation, North China.

Remarks.—Detailed discussions of this genus were given by Zhang and Jell (1987) and Peng et al. (2004).

MONKASPIS sp. 1
Figure 6.10

Material.—Two cranidia.

Occurrence.—JDA 2 of the Jikdong section.

Remarks.—Cranidia from the Jikdong section have a long, wide preglabellar field, an anterior branch of the facial suture which diverges forward and a rounded anterior cranidial margin, all of which warrant assignment of these specimens to *Monkaspis*. However, they are small and have been tectonically distorted, so identification to specific level is reserved. The smaller specimens are about 1.5 mm long and display a distinctive anterior cranidial border which is usually not known in *Monkaspis*, but it may be because the specimen is so small.

Indeterminate hypostome 1
Figure 6.13, 6.14

Material.—A single hypostome.

Occurrence.—SGJ 1 of the Seokgaejae section.

Remarks.—This hypostome displays a simple conservative

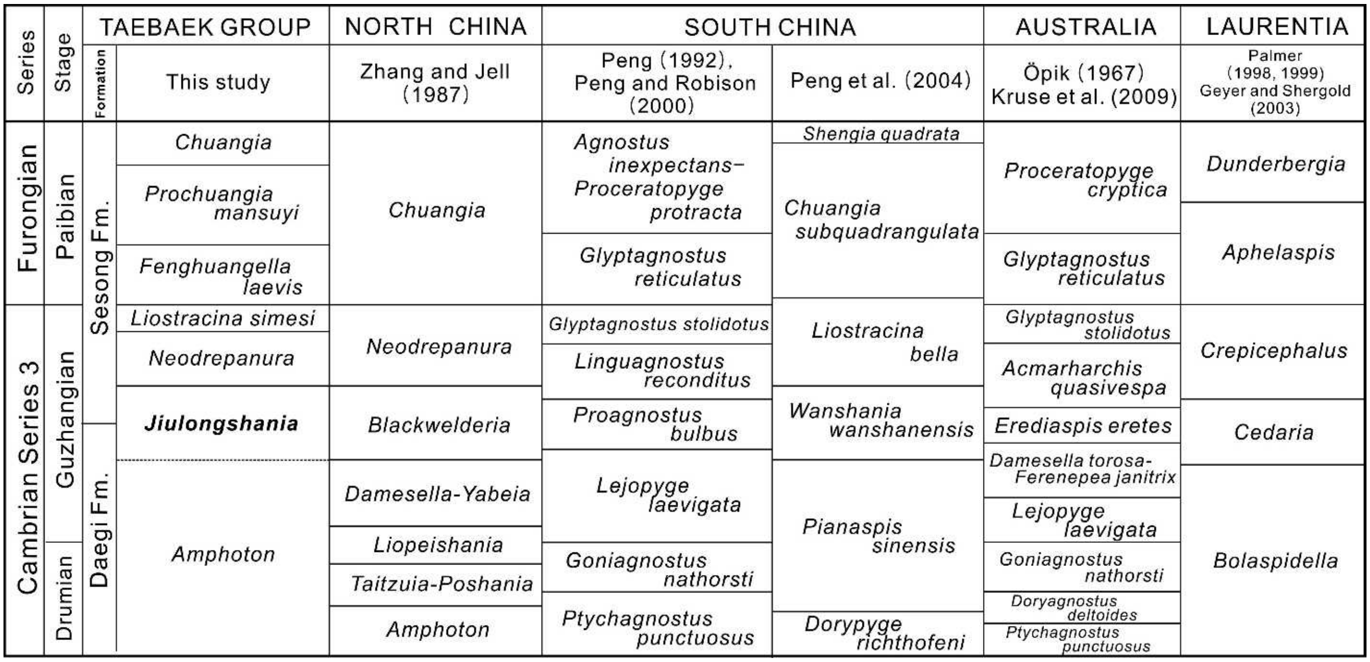

FIGURE 7—Biostratigraphical correlation of Cambrian Series 3/Furongian Series transitional interval of the Taebaek Group, Korea, with those of North China, South China, Australia, and Laurentia.

morphology in having an elongate oval middle body, narrow lateral border, and rounded posterior border.

Indeterminate hypostome 2
Figure 6.15, 6.16

Material.—A single hypostome.

Occurrence.—SGJ 2 of the Seokgaejae section.

Remarks.—This hypostome is similar to the indeterminate hypostome 1, but differs in having a wider lateral border which is more convex and more strongly arched in lateral view.

IMPLICATIONS FOR CORRELATION

The occurrences of the two species of *Jiulongshania* from the lower part of the Sesong Formation and the rare occurrence of *Stephanocare richthofeni* in this interval necessitate the suppression of the "*Stephanocare*" Zone and the extension of the *Jiulongshania* Zone of the Daegi Formation into the lower part of the Sesong Formation. This is particularly practical because, unlike *Stephanocare richthofeni*, the species of *Jiulongshania* do not overlap in occurrence with *Neodrepanura premesnili*, the eponymous trilobite for the overlying *Neodrepanura* Zone. Similar mutually exclusive occurrences of the *Jiulongshania* species and *Neodrepanura premesnili* have been also documented in Shandong Province, North China (Park et al., 2008b). The base of the *Jiulongshania* Zone should be defined at the FAD of *J. rotundata* at present, since the older species of *Jiulongshania*, such as *J. acalle* and *J. longa* (see Park et al., 2008b), have not been recovered from the Daegi Formation. It is noteworthy that *J. rotundata* is associated with *Blackwelderia* sp. in the Seokgaejae section, Korea (Kang and Choi, 2007), but *Blackwelderia* was not associated with *J. rotundata* in the Jiulongshan section, North China (Park et al., 2008b). Instead, the *Jiulongshania* species immediately preceding *J. rotundata*, *J. acalle* occurs in association with *Damesella* (Park et al., 2008b), the representative taxon of the *Damesella-Yabeia* Zone, which is overlain by the *Blackwelderia* Zone in North China. As the base of the *Jiulongshania* Zone is herein defined at the FAD of *J. rotundata* in Korea, the *Jiulongshania* Zone of the Taebaeksan Basin, Korea can be correlated with the *Blackwelderia* Zone of North China (Fig. 7). However, it should be noted that if the older species of *Jiulongshania* are discovered from the Daegi Formation, the lower boundary of the *Jiulongshania* Zone should be stratigraphically lowered.

The Daegi/Sesong formation boundary is characterized by an abrupt lithologic shift from shallow subtidal carbonate facies to transgressive shale and distal turbidite facies of sandstone and siltstone (Kwon et al., 2006). Kwon et al. (2006) recognized this abrupt deepening facies change as a 'type-3 sequence boundary', resulted from rapid landward backstepping of the carbonate factory and drowning of the platform. They went further to correlate this 'type-3 sequence boundary' with the tectonic tilting of the North China Platform (Meyerhoff et al.,1991; Meng et al.,1997), which is thought to have played a crucial role in the lithological change at the Zhangxia(Changhia)/Gushan formation boundary. In fact, the Zhangxia/Gushan formation boundary is closely comparable to the Daegi/Sesong formation boundary in that it also shows an abrupt shift from a carbonate-dominant facies to a shale-dominant facies. Notably, both the Zhangxia and Daegi formations contain microbial bioherms composed predominantly of calcimicrobes, such as *Epiphyton*, *Renalcis* and *Girvanella* (Woo and Chough, 2010; Woo et al., 2008; Hong et al., 2012), whereas the Gushan and Sesong formations are dominated by shale in lithology.

Because the species of *Jiulongshania* occur successively in Korea and North China (Fig. 8), the occurrence of *Jiulongshania* species can be used for a detailed correlation within the Sino-Korean Block. The correlation employing *Jiulongshania* species demonstrates that the Daegi/Sesong formation boundary is diachronous within the Taebaeksan Basin. The lowermost part of the Sesong Formation in the Seokgaejae section contains *J. longispina*, while that in the Jikdong section contains *J. regularis* (Fig. 2). *Jiulongshania regularis* was also recovered from the lowermost part of the Gadeoksan section, situated

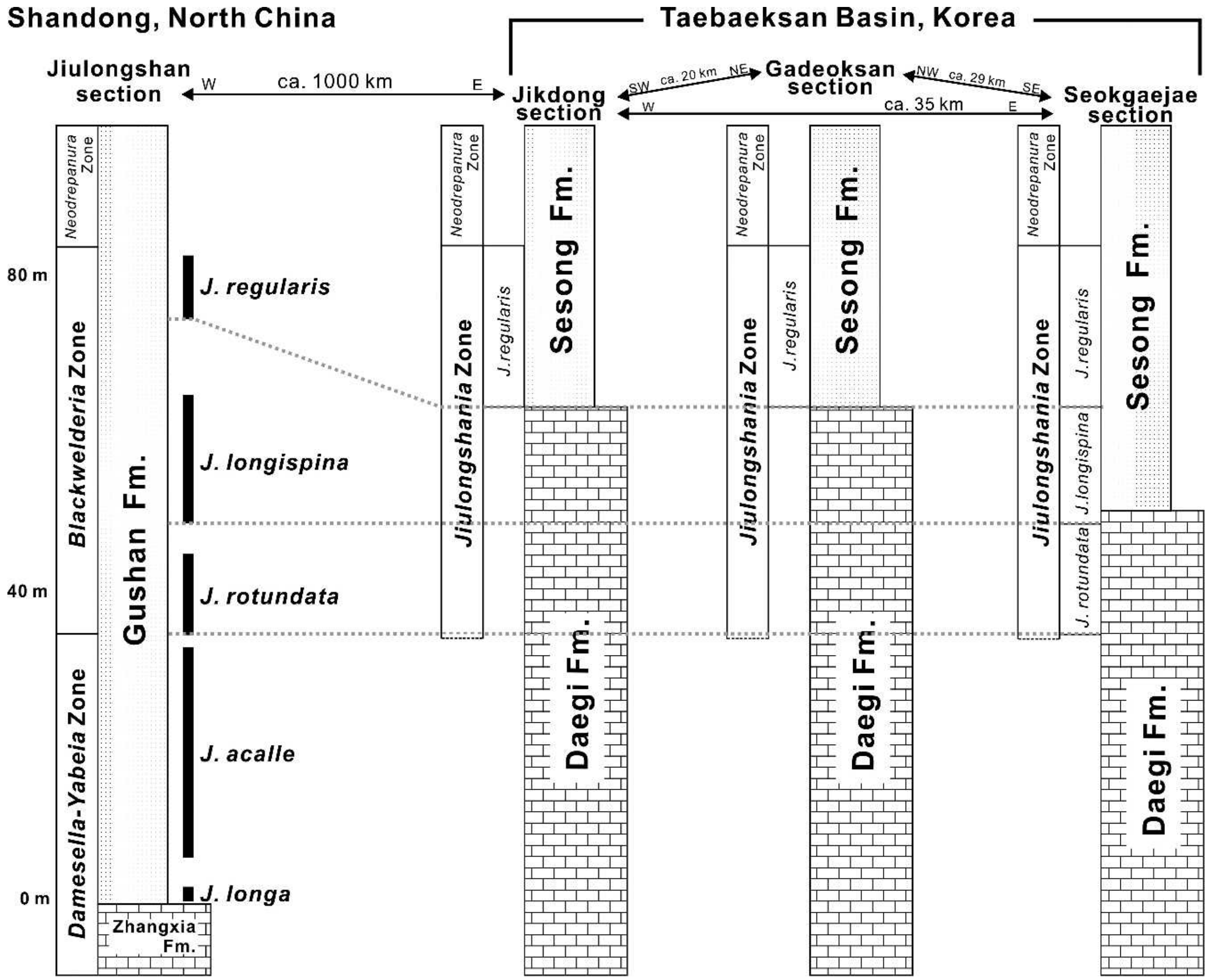

FIGURE 8—Correlation of schematic graphic logs of the Jiulongshan section (Shandong Province, North China), Jikdong section, Gadeoksan section, and Seokgaejae section (Taebaeksan Basin, Korea), using the stratigraphic occurrences of *Jiulongshania* species. The lower boundary of the *Jiulongshania* Zone is represented with a dotted line because it should be stratigraphically lowered if the older species of *Jiulongshania*, such as *J. acalle* and *J. longa* are discovered from the Daegi Formation.

about 12 km north of Taebaek City (Fig. 1). This indicates that the shift from a carbonate-dominant facies to a shale-dominant facies occurred earlier in the Seokgaejae section than at the other two sections (Fig. 8).

The occurrences of *Jiulongshania* species also demonstrate that the Daegi/Sesong formation boundary in Korea and the Zhangxia/Gushan formation boundary in North China differ significantly in age. The Jiulongshan Section (E 117°44′35″, N 36°48′42″), Shandong Province, North China lies approximately 1000 km west of the Jikdong section, Taebaeksan Basin, Korea (Fig. 1). The Gushan Formation at the Jiulongshan section measures about 110 m thick and yields *J. longispina* and *J. regularis* from the intervals 48 m–64 m and 75 m–82 m above the base of the formation, respectively (Park et al., 2008b). *Jiulongshania rotundata* occurs in the uppermost part of the Daegi Formation at the Seokgaejae section, Korea, and also has been recovered from the interval 34–43 m above the base of the Gushan Formation at the Jiulongshan section, North China (Park et al., 2008b). Therefore, it can be concluded that the Daegi/Sesong formation boundary at the Seokgaejae section is stratigraphically correlated to the middle part (about 48 m above the base) of the Gushan Formation, while those of the Jikdong and Gadeoksan sections are correlated to the upper part (about 75 m above the base) of the Gushan Formation (Fig. 8). In short, the occurrences of *Jiulongshania* species demonstrate that the lithologic change from a carbonate-dominant facies to a shale-dominant facies occurred significantly earlier in Shandong Province of North China than in Korea.

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