

Original article

Trilobite faunal successions across the base of the Furongian Series in the Taebaek Group, Taebaeksan Basin, Korea[☆]

Les faunes de trilobites de la base de la série furongienne du Groupe Taebaek, Bassin de Taebaeksan, Corée

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Abstract

The base of the Furongian Series in the Sino-Korean Block has not been clearly defined due to the lack of the index taxon, *Glyptagnostus reticulatus*. The Sesong Formation of the Taebaek Group, Taebaeksan Basin, Korea, has been known to range from the Guzhangian Stage of the Cambrian Series 3 to the middle Furongian Series, hence embracing the base of the Furongian Series. Silicified polymerid trilobites were recovered from the middle part of the Sesong Formation. Described are a total of 18 polymerid species of 13 genera: *Neodrepanura* sp. 1, *Teinistion* sp. 1, *Huzhuia* sp. 1, *Huzhuia* sp. 2, *Liostracina simesi*, *Liostracina* sp. 1, *Parachangshania monkei*, *Parachangshania rectangularis* nov. sp., *Placosema bigranulosum*, *Fenghuangella laevis* nov. sp., *Baikadamaspis jikdongensis* nov. sp., *Baikadamaspis* sp. 1, *Prochuangia mansuyi*, *Maladioides coreanicus*, *Alataspis sesongensis* nov. gen., nov. sp., *Chuangia* sp. 1, and ceratopygids genus and species indeterminate 1 and 2. The stratigraphic occurrence of these trilobites provides a basis for recognition of five zones across the base of the Furongian Series (in ascending order): the *Neodrepanura*, *Liostracina simesi*, *Fenghuangella laevis*, *Prochuangia mansuyi*, and *Chuangia* zones. The *Neodrepanura* and *Chuangia* zones are provisionally adopted from the previous biostratigraphic scheme, while the three other ones are newly proposed. The recommended base of the Furongian Series in the Taebaek Group of Korea coincides with the base of the *Fenghuangella laevis* Zone, which appears to represent an episode of profound trilobite faunal turnover. © 2011 Elsevier Masson SAS. All rights reserved.

Keywords: Cambrian; Polymerid trilobites; Korea; Biostratigraphy

Résumé

Dans le bloc sino-coréen, la base de la Série furongienne n'a pas été clairement définie du fait de l'absence du taxon-index, *Glyptagnostus reticulatus*. La Formation Sesong du Groupe Taebaek, Bassin de Taebaeksan, Corée, est connue pour s'étendre de l'étage Guzhangien (Cambrien, Série 3), au milieu de la Série furongienne, dont elle contient de ce fait la base. Des trilobites polymérides silicifiés ont été retrouvés dans la partie médiane de la Formation Sesong. Dix-huit espèces appartenant à 13 genres sont décrites: *Neodrepanura* sp. 1, *Teinistion* sp. 1, *Huzhuia* sp. 1, *Huzhuia* sp. 2, *Liostracina simesi*, *Liostracina* sp. 1, *Parachangshania monkei*, *Parachangshania rectangularis* nov. sp., *Placosema bigranulosum*, *Fenghuangella laevis* nov. sp., *Baikadamaspis jikdongensis* nov. sp., *Baikadamaspis* sp. 1, *Prochuangia mansuyi*, *Maladioides coreanicus*, *Alataspis sesongensis* nov. gen., nov. sp., *Chuangia* sp. 1, et les cératopygidés gen. et sp. indet. 1 et 2. La distribution stratigraphique de ces trilobites permet la reconnaissance de cinq zones sur l'intervalle traversant la base de la Série furongienne (dans l'ordre ascendant): les zones à *Neodrepanura*, *Liostracina simesi*, *Fenghuangella laevis*, *Prochuangia mansuyi* et à *Chuangia*. Les zones à *Neodrepanura* et à *Chuangia* sont retenues provisoirement sur la base du schéma biostratigraphique précédent; les zones à *Liostracina simesi*, *Fenghuangella laevis* et à *Prochuangia mansuyi* sont nouvelles. La base de la Série furongienne au sein du Groupe Taebaek, Corée, correspond à la base de la Zone à *Fenghuangella laevis*, qui semble représenter un épisode de renouvellement faunique marqué chez les trilobites. © 2011 Elsevier Masson SAS. Tous droits réservés.

Mots clés : Cambrien ; Trilobites polymérides ; Corée ; Biostratigraphie

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1. Introduction

In 2004, the global standard stratotype section and point (GSSP) for the base of the Furongian Series, uppermost series of the Cambrian System, was ratified by the International Union of Geological Sciences (IUGS). This point coincides with the first appearance datum (FAD) of *Glyptagnostus reticulatus* (Angelin, 1851), corresponding to a contemporaneous, worldwide mass extinction of polymerid trilobites (Peng et al., 2004b). However, the absence of *Glyptagnostus reticulatus* and the lack of detailed biostratigraphic control around this time-interval in the Sino-Korean Block have hindered pinpointing the base of the Furongian Series in this region. The base of the Changshanian Stage was considered as equivalent to the base of the Furongian Series in North China (Peng et al., 2004b). However, there have been some discrepancies in recognizing the base of the Changshanian Stage *per se*: e.g., Peng et al. (2004a) marked the lower boundary of the Furongian Series at the base of the *Chuangia* Zone, referring the *Prochuangia* Zone to the latest middle Cambrian (Cambrian Series 3), whereas Geyer and

Shergold (2000) regarded the base of the *Prochuangia* Zone as the lower boundary of the Furongian Series.

The Sesong Formation is a member of the Taebaek Group in the Taebaeksan Basin, which is located in the central-eastern part of the Korean peninsula (Fig. 1). The formation has been known to range from the upper part of the Cambrian Series 3 to the middle Furongian (Sohn and Choi, 2005), hence embracing the base of the Furongian Series. Trilobites from the formation were reported by Kobayashi (1935, 1960), but no subsequent studies on the trilobites of the Sesong Formation have been done, apart from recent works on diceratocephalid trilobites by Park et al. (2008) and Park and Choi (2010). Unfortunately, Kobayashi (1935, 1960) failed to provide precise stratigraphic data for his collections: he collected specimens from different localities and set up the biozones, and then arranged those biozones in a stratigraphical order in reference to the then already known biostratigraphy of North China. Consequently, the biozones of the Sesong Formation have remained merely as composite faunal lists of taxa, without any information on the faunal changes within the formation.

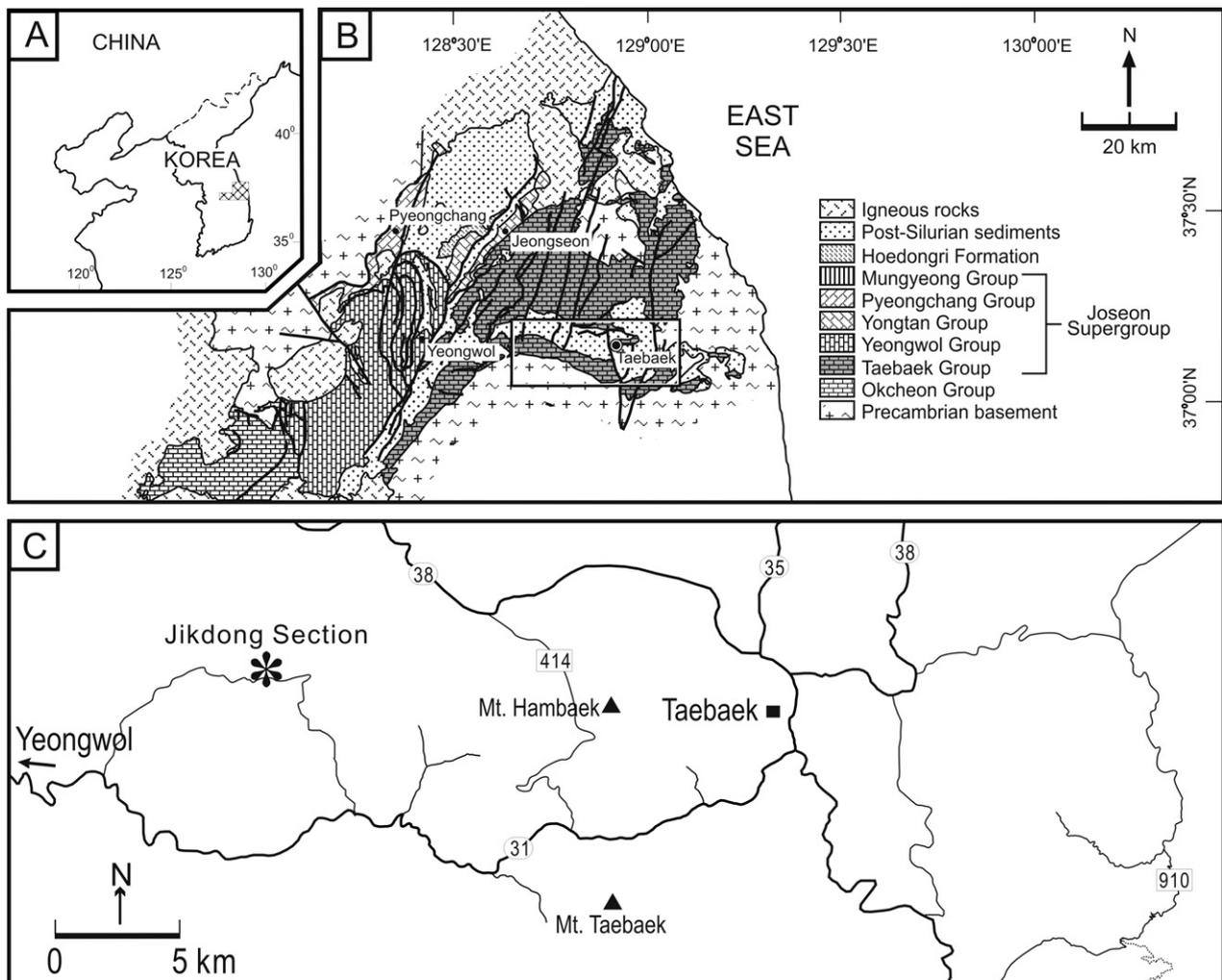


Fig. 1. Location maps. A. Index map showing the location of B. B. Simplified geological map of the Taebaeksan Basin, showing the location of the Taebaek area (rectangle). C. Road map of the Taebaek area showing the location of the Jikdong section.

The aim of this study is to refine the biostratigraphy for the interval across the putative base of the Furongian Series in the Taebaek Group of Korea, based on the detailed documentation of trilobite faunal successions in the middle part of the Sesong Formation. The interval is considered to span from the *Neodrepanura* Zone (formerly *Drepanura* Zone; see Özdikmen, 2006) to the *Chuangia* Zone. The trilobite faunal assemblages comprise three agnostoid genera and eighteen polymerid species belonging to thirteen genera. The associated agnostoid genera, *Pseudagnostus* Jaekel, 1909, *Kormagnostus* Resser, 1938, and *Ammagnostus* Öpik, 1967, are poorly preserved, and in general, these agnostoids are not useful for determining the base of the Furongian Series, as they occur both in the Cambrian Series 3 and in the Furongian. Therefore, polymerid trilobites of the Sesong Formation are here used for zonal subdivision, intercontinental correlation, and determination of the stratigraphic position of the base of the Furongian Series in Korea.

2. Geology and stratigraphy

The lower Paleozoic sedimentary rocks in Korea, Joseon Supergroup, are well exposed in the Taebaeksan Basin, which is located in the central-eastern part of the Korean peninsula (Fig. 1). The Taebaeksan Basin was a shallow marine, mixed siliciclastic-carbonate system with progressively greater depth to the west in the early Paleozoic times (Chough et al., 2000). The Joseon Supergroup rests unconformably on the Precambrian granitic gneiss and metasedimentary rocks and is in turn overlain unconformably by the upper Paleozoic sedimentary rocks. The Joseon Supergroup has been divided into the Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups, respectively, each with a unique lithologic succession and geographic distribution (Kobayashi, 1966; Choi, 1998; Choi and Chough, 2005).

The Taebaek Group occupies the eastern half of the Taebaeksan Basin and is subdivided in ascending order into the Jangsan/Myeonsan, Myobong, Daegi, Sesong, Hwajeol, Dongjeom, Dumugol, Makgol, Jigunsan, and Duwibong formations (Choi et al., 2004). The Cambrian-Ordovician boundary was drawn conventionally at the boundary between the Hwajeol and Dongjeom formations (Kobayashi, 1966), but Choi et al. (2003) suggested recently that the Cambrian-Ordovician boundary should be placed within the lowermost part of the Dongjeom Formation.

The Sesong Formation was established for the interval of purple to grey slate with interbedded thin sandstone and limestone layers in the Taebaeksan Basin (Kobayashi, 1930, 1935), but later the Geological Investigation Corps of Taebaeksan Region (GICTR, 1962) and Cheong (1969) lowered its lithostratigraphic rank to that of a member and regarded it as the lowermost member of the Hwajeol Formation. However, Choi et al. (2004) and Choi and Chough (2005) considered the Sesong Formation is a lithologically distinctive unit.

Kobayashi (1935, 1966) established two biozones, the *Stephanocare* and *Neodrepanura* zones, within the Sesong Formation, and five biozones, the *Prochuangia*, *Chuangia*,

Kaolishania, *Dictyites*, and *Eoorthis* zones, within the overlying Hwajeol Formation. Subsequently, Sohn and Choi (2005) redefined the concept of the Sesong and Hwajeol formations in accordance with their dominant lithologic associations: the Sesong Formation is characterized by dark grey slate with occasional intercalations of sandstone and limestone conglomerate layers, whereas the Hwajeol Formation is an alternating succession of limestone, marlstone/shale, and limestone conglomerate beds. The base of the Hwajeol Formation is defined by the first appearance of light brown limestone-shale couplets. Sohn and Choi (2005) also documented the *Kaolishania* Zone in the uppermost part of the Sesong Formation and the *Asioptychaspis* Zone in the lowermost part of the Hwajeol Formation. Accordingly, the biostratigraphy of the Sesong Formation has been modified greatly to comprise five biozones (in ascending order): the *Stephanocare*, *Neodrepanura*, *Prochuangia*, *Chuangia*, and *Kaolishania* zones.

3. Fossil locality and material

The material studied in this work was recovered from the Sesong Formation in the Jikdong Section (128° 46' 30.8 "E, 37° 10' 31.1" N), which is exposed along a mountain trail located approximately 20 km west of Taebaek (Fig. 1). The investigated interval consists predominantly of siliciclastic sedimentary rocks with a coarsening upward trend: the lower part is of limestone nodule-bearing dark-grey shale with occasional intercalations of limestone conglomerate beds, whereas the upper part is dominated by sandstones.

The studied interval (Fig. 2) is a 13 m-thick sequence with nodule-bearing black shale, limestone conglomerate, and light grey laminated fine-grained sandstone, and occupies 25–38 m above the base of the Sesong Formation. Fossils were collected from seventeen horizons, marked from bottom to top as JDA10 to JDA26 (Fig. 2). Blocks of limestone conglomerate beds and limestone nodules were digested with 7% hydrochloric acid, after which silicified trilobite sclerites were recovered from the residues. The amount of silicified fossils recovered from the horizons is variable, but the stratigraphically lower horizons yield more specimens than the upper ones. The upper part of the studied interval consists largely of fine-grained sandstone with rare limestone conglomerate beds and is poorly fossiliferous.

More than seven hundred specimens were examined for this study. Fossils shorter than 2.5 mm in length were coated with gold, and the images were taken using a scanning electron microscope, while larger specimens were photographed with a digital camera.

4. Systematic paleontology

The descriptive terminology applied herein generally follows that of Whittington and Kelly (1997), but the glabella used herein excludes the occipital ring. Descriptive terms for lateral glabellar furrows and facial sutures are quoted from Henningsmoen (1957). Terms for orientation are always indicated in reference to standard plane: length means sagittal

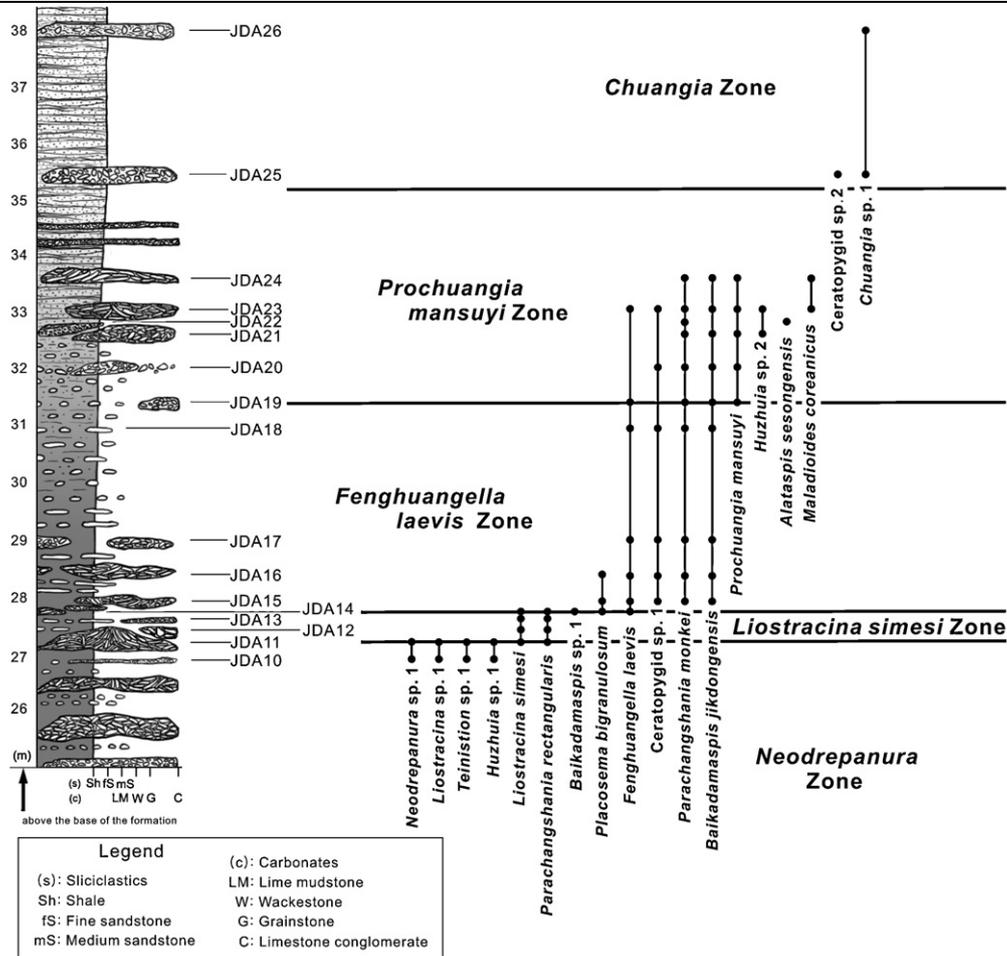


Fig. 2. Graphic log of the Sesong Formation at the Jikdong section including. Lithologic succession, stratigraphy, sample horizons, and ranges of the trilobites described in this study.

or exsagittal distance, while width refers to transverse distance. All of the specimens are repositied in the paleontological collection of Seoul National University with registered SNUP numbers.

In this section the full systematic description is restricted to those taxa that are newly erected and emended, while the remaining taxa are described and illustrated in Appendix A (Figs. S1–S10). Those additional taxa include: *Chuangia* sp. 1, *Prochuangia mansuyi* Kobayashi, 1935, *Neodrepanura* sp. 1, *Teinistion* sp. 1, ceratopygid genus and species indeterminate 1, ceratopygid genus and species indeterminate 2, *Liostracina simesi* Jago and Cooper, 2005, *Liostracina* sp. 1, *Huzhuia* sp. 1, and *Huzhuia* sp. 2. In addition, some undetermined trilobite sclerites are also described in the supplementary content.

Superfamily ANOMOCAROIDEA Poulsen, 1927.

Family PTEROCEPHALIIDAE Kobayashi, 1935.

Genus *Maladioides* Kobayashi, 1933.

Type species: *Maladioides asiaticus* Kobayashi, 1933 from the *Chuangia* Zone of Paichiashan, Wuhutsui Basin, Liaoning, China (by original designation).

Emended diagnosis: Cranium with broad, forward-tapering glabella, oblique-backward directed S1 and S2,

weakly truncated or rounded glabellar front; broadly round or angulate anterior cranial border; large palpebral lobes located at or anterior to glabellar mid-length; pygidium with a pair of short, broad-based posterior spines.

Remarks: the pygidial morphology of the present collection is markedly different from that of the type species, *M. asiaticus* Kobayashi, 1933, in bearing a pair of broad-based posterior spines. The pygidium assigned originally to *M. asiaticus* (Kobayashi, 1933: pl. 15, Fig. 12) lacks pygidial spines and is morphologically similar to *Changshania conica* Sun, 1924. We suggest that the pygidial assignment is doubtful and that pygidia assigned to *Maladioides coreanicus* in this study are correct, thereby emending the generic concept of *Maladioides*.

We note that *Maladioides* is comparable to *Dicanthopyge* Palmer, 1965 from the Great Basin of Laurentia in cranial and pygidial morphology. The pygidium of *Dicanthopyge* possesses a pair of broad-based and long posterior spines. *Maladioides* has comparatively shorter pygidial spines than *Dicanthopyge*. Palmer (1965: Fig. 11) suggested a possible evolutionary lineage from *Aphelaspis* Resser, 1935 to *Dicanthopyge* in which the rounded posterior pygidial margin of *Aphelaspis* evolved into the long and posteriorly directed pygidial spines of *Dicanthopyge*. As *Maladioides* possesses

shorter pygidial spines compared to those of *Dicanthopyge*, *Maladioides* may represent an intermediate morphology between *Aphelaspis* and *Dicanthopyge*.

Maladioides coreanicus Kobayashi, 1935

Fig. 3.

1935. *Maladioides coreanicus* nov. sp. – Kobayashi, p. 283, pl. 8, figs. 5, 6.

1989. *Maladioides?* sp. – Zhu and Wittke, p. 215, pl. 9, figs. 3, 4.

1994. *Anderssonella primitiva* nov. sp. – Qian, p. 134, pl. 34, fig. 11.

Material, horizon, and locality: ten cranidia, two pygidia, and one librigena; *Prochuangia mansuyi* Zone; JDA23–JDA24 of the Jikdong Section, Korea.

Lectotype: originally two syntypes were illustrated by Kobayashi (1935) and one of the cranidia [PA1157, Kobayashi, 1935: pl. 8, fig. 6; refigured here in Fig. 3(1)] is herein selected as the lectotype for the species.

Diagnosis: a species of *Maladioides* with angulate anterior border, broadly rounded glabellar front, large palpebral lobes located slightly anterior to glabellar mid-point, and a pair of broad-based pygidial spines.

Description: Cranidium subtriangular to subtrapezoidal, with gently angulate anterior margin, length 70 to 80% of posterior cranidial width. Glabella relatively large, weakly convex, tapering weakly forwards, with broadly rounded glabellar front, occupying three-fifths and one-third of

cranidial length and width, respectively; S1 oblique rearwards; S2 and S3 faintly impressed. LO subrectangular, slightly arched rearward, ca. one-fifth of cranidial length, as wide as glabellar base; SO shallow, simple, straight. Frontal area differentiated into frontal field and anterior cranial border by shallow anterior border furrow, ca. one-fifth of cranidial length; frontal field weakly convex, longer than anterior border; anterior border boomerang-shaped, longest medially, progressively shortening abaxially. Palpebral lobes large, about one-third of cranidial length, crescentic, situated anterior to glabellar midpoint, defined by shallow palpebral furrow; palpebral area moderately broad, one-half as wide as glabella. Posterior area short, as wide as glabella, with broadly rounded posterolateral projection. Facial sutures opisthoparian; anterior branch of facial suture divergent straight to weakly convex; posterior branch of facial suture strongly divergent, convex to sinuous. Surface smooth.

Librigena with moderately broad genal field and lateral border; genal field downsloping abaxially, broader than lateral border; lateral border weakly convex; genal spine moderately long; doublure narrower than lateral border; eye socle narrow and elevated.

Pygidium inversely trapezoidal, with broadly rounded antero-lateral corners and broadly indented posterior margin; sagittal length ca. 70% of maximum width; posterolateral borders expanded to form a pair of broad-based, posteriorly directed spines. Axis convex, slender, tapering rearwards, with 5 to 6 axial rings and a terminal piece, not reaching to posterior

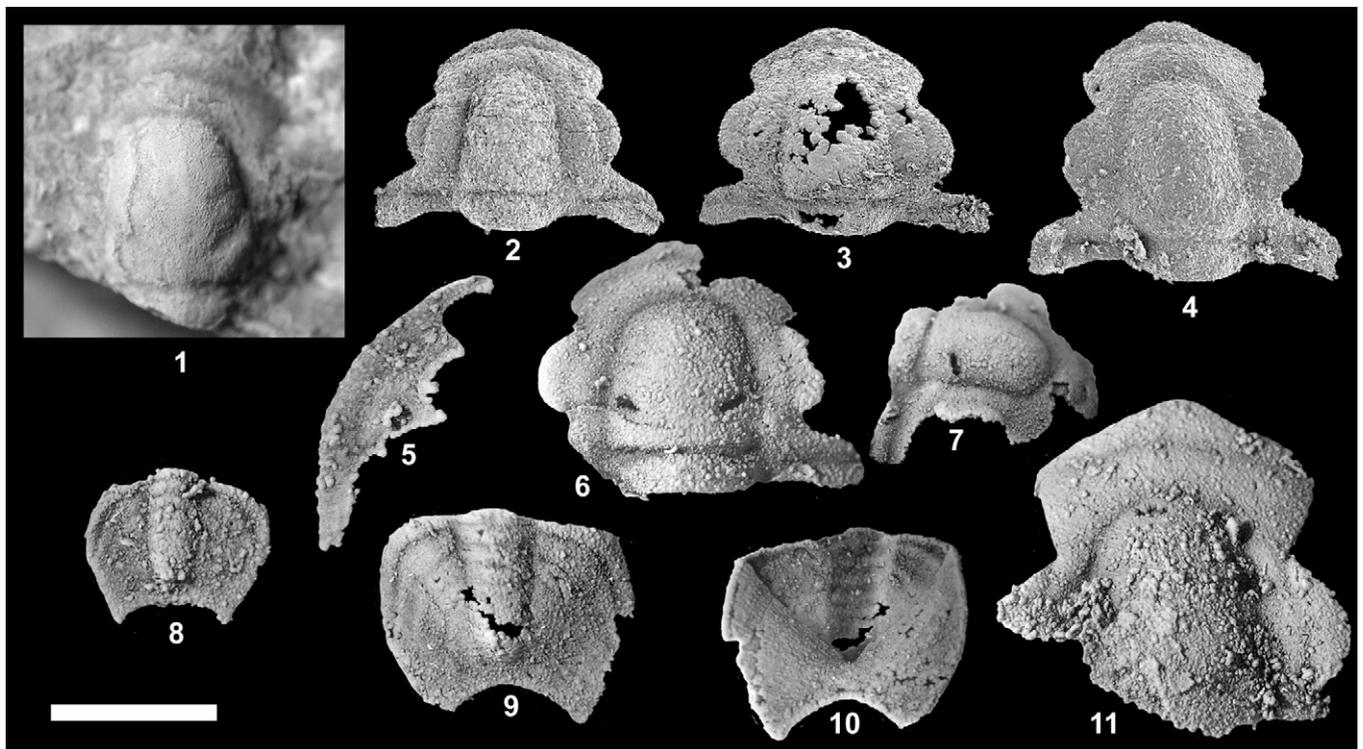


Fig. 3. 1–11. *Maladioides coreanicus* Kobayashi, 1935; *Prochuangia mansuyi* Zone, Korea. 1, lectotype of *M. coreanicus* designated herein, housed in the University Museum, University of Tokyo, Japan, PA1157 (Kobayashi, 1935: pl. 8, Fig. 6); 2, SNUP4538, cranidium; 3, SNUP4539, cranidium; 4, SNUP4540, cranidium; 5, SNUP4541, librigena; 6, 7, SNUP4542, cranidium, dorsal and oblique lateral views; 8, SNUP4543, pygidium; 9, 10, SNUP4544, pygidium, dorsal and ventral views; 11, SNUP4545, cranidium. Scale bar = 4 mm (1), 1.33 mm (2–4), 2 mm (5–6), 2.5 mm (7–11).

margin. Pleural field narrower than axis, with 5 to 6 pleurae; pleural furrows moderately incised, extending onto posterolateral border. Surface smooth.

Remarks: the type material of *M. coreanicus* (Fig. 3(1)) is incompletely preserved, which apparently prevented later workers from identifying the species with confidence. *Maladioides?* sp. from Tangshan, China (Zhu and Wittke, 1989) share key features with *M. coreanicus* including the short lateral glabellar furrows and crescentic palpebral lobes and is here considered conspecific with *M. coreanicus*. *Anderssonella primitiva* Qian, 1994 from the *Chuangia* Zone of Liaoning Province is identical to *M. coreanicus* in having an angulate anterior cranial border and oblique rearward-directed S1 and hence is considered a junior synonym of *M. coreanicus*. *Maladioides asiaticus* differs from *M. coreanicus* in possessing a broadly rounded anterior cranial border.

Superfamily PTYCHOPARIOIDEA Matthew, 1887.

Family CHANGSHANIIDAE Kobayashi, 1935.

Genus *Parachangshania* Chien, 1958.

Type species: *Parachangshania hsiaoshihensis* Chien, 1958 from the Changshan Formation, Liaoning Province, China (by original designation).

Emended diagnosis: Changshaniid trilobites having truncato-conical glabella, flat to weakly convex preglabellar field, large palpebral lobes located away from glabella and posterior to glabellar mid-point, upturned or flat anterior border, and semi-circular pygidium with six to nine axial rings.

Remarks: *Parachangshania* is restricted to North China with an exceptional occurrence from Spain (Shergold and Szalay, 1991). The original generic diagnosis of Chien (1958) includes only the upturned anterior border, whereas *P. monkei* and *P. rectangularis* nov. sp. possess relatively flat anterior border. Hence, the generic diagnosis is emended.

Parachangshania monkei (Kobayashi, 1935).

Fig. 4.

1935. *Asaphiscus monkei*. nov. sp. – Kobayashi, p. 293, pl. 8, figs. 1–4.

1962. *Pseudoliostracina monkei* (Kobayashi) – Kobayashi, p. 82.

Material, horizon, and locality: more than one hundred specimens of cranidia, librigenae, and pygidia; *Fenghuangella laevis* and *Prochuangia mansuyi* zones; JDA15-24 of the Jikdong Section, Korea.

Lectotype: four syntypes were illustrated by Kobayashi (1935). The lectotype for this species is designated here as the cranidium [PA1160; Kobayashi, 1935: pl. 8, fig. 3; refigured here in Fig. 4(1)] which was collected from the *Prochuangia* Zone, Sesongni, Korea.

Diagnosis: a species of *Parachangshania* with a flat preglabellar field and slender glabella.

Description: Cranidium weakly convex, subtrapezoidal in outline, slightly longer than wide. Glabella convex, slender, width 65 to 75% of length, 54 to 56% of cranial length, 30 to 35% of palpebral cranial width, slightly tapering forwards, defined by deep axial furrow and rounded to truncated glabellar front; S1, S2 and S3 faintly impressed. LO subrectangular, one-

tenth of cranial length, defined by weakly impressed occipital furrow. Preglabellar field relatively long, 15 to 18% of cranial length, flat to weakly convex. Anterior border moderately long, shortening abaxially, flat, broadly arched forwards; anterior border furrow indicated by change in slope. Palpebral lobes large, bean-shaped, four-fifths of glabellar length, located behind glabellar midpoint, defined by clearly impressed palpebral furrow; eye ridges not visible; palpebral area flat, ca. Fifteen percent of palpebral cranial width. Posterior fixigenal field very short; posterior border shorter than occipital ring, widening abaxially, delineated by moderately incised posterior border furrow. Facial sutures opistharian; anterior branch of facial suture strongly divergent convex; posterior branch of facial suture nearly transverse.

Librigena crescentic in outline; genal field narrow, down-sloping abaxially; genal spine as long as genal area; lateral border narrow, defined by shallow border furrow; eye socle narrow, elevated; eye socle furrow moderately incised; cephalic doublure broader than border.

Thoracic segment consisting of moderately convex axis and flat pleurae. Axis ca. one-fourth of width; ring slightly longer than articulating half ring; ring furrow slightly arched forward, shallow; axial furrow shallow; pleural furrow shallow, running almost horizontally; anterior band shorter than posterior bands; pleural spine pointy rearward.

Pygidium semicircular to subtriangular in outline, twice as wide as long. Axis subconical, rounded posteriorly, reaching beyond posterior border furrow; axial furrow indicated by change in slope; pleural field wider than axis, gently convex; pleural furrow faintly impressed, directed oblique backwards; lateral and posterior borders moderately wide, flat, indicated by change in slope. Doublure very broad, twice as broad as border.

Remarks: this species was originally assigned to *Asaphiscus* Meek, 1873, and was later transferred to *Pseudoliostracina* Kobayashi, 1938. *Asaphiscus* is distinct from *Parachangshania* in lacking a genal spine. *Pseudoliostracina* was subsumed to *Lioparia* Lorenz, 1906 (Öpik, 1967: p. 297), which was described as to have a median furrow on the preglabellar field (Zhang and Jell, 1987). Cranidia of *Changshanocephalus majus* (Dames, 1883) illustrated by Schrank (1975: pl. 5, figs. 7–9; pl. 6, fig. 3) are comparable to those of *P. monkei*, but the associated pygidia (Schrank, 1975: pl. 6, figs. 1–2, 4, 6) and librigenae (Schrank, 1975: pl. 5, fig. 6; pl. 6, figs. 5, 7) differ in having well-developed pleural furrows and a shorter eye socle and genal spine, respectively.

Parachangshania rectangularis nov. sp.

Fig. 5.

Etymology: from Latin, *rectangularis*, referring to the rectangular shape of glabella.

Material, horizon, and locality: Holotype cranidium, SNUP4614 (Fig. 5(10–11)); and paratypes SNUP4605–4613, SNUP4615–4622; more than one hundred specimens of cranidia, librigenae, and pygidia; *Liostracina simesi* Zone; JDA11–14 of the Jikdong Section, Korea.

Diagnosis: a species of *Parachangshania* with a flat and short preglabellar field and a relatively wide glabella.

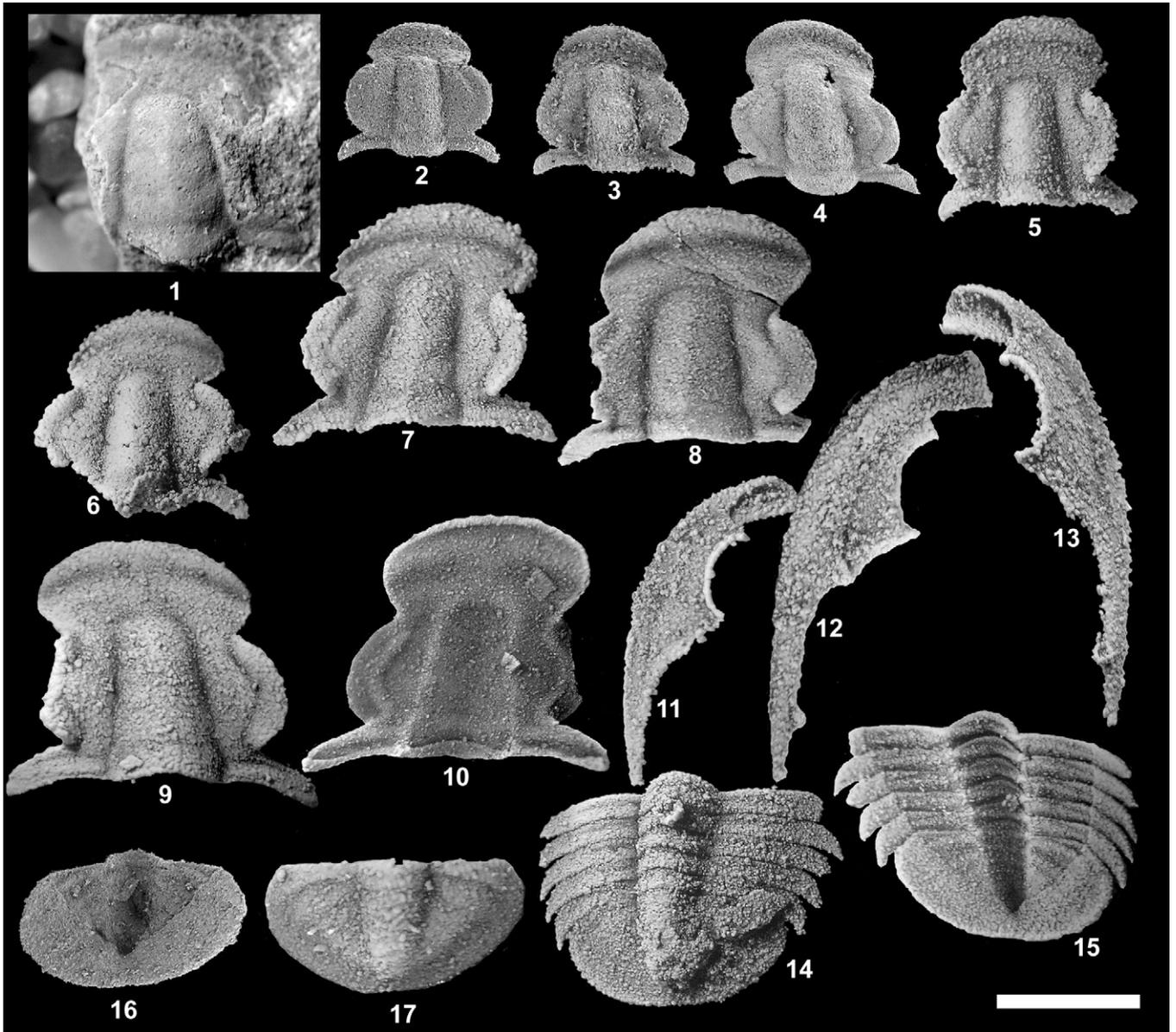


Fig. 4. 1–17. *Parachangshania monkei* (Kobayashi, 1935); *Fenghuangella laevis* and *Prochuangia mansuyi* zones, Korea. 1, lectotype of *P. monkei* designated herein, housed in the University Museum, University of Tokyo, Japan, PA1160 (Kobayashi, 1935: pl. 8, Fig. 3); 2, SNUP4592, cranidium; 3, SNUP4593, cranidium; 4, SNUP4594, cranidium; 5, SNUP4595, cranidium; 6, SNUP4596, cranidium; 7, SNUP4597, cranidium; 8, SNUP4598, cranidium; 9, 10, SNUP4599, cranidium, dorsal and ventral views; 11, SNUP4600, librigena; 12, 13, SNUP4601, librigena, ventral and dorsal views; 14, 15, SNUP4602, pygidium with five thoracic segments retained, dorsal and ventral views; 16, SNUP4603, pygidium, ventral view; 17, SNUP4604, pygidium. Scale bar = 3.33 mm (1, 8), 2 mm (2–4, 16–17), 2.5 mm (5–7, 9–13), 2.86 mm (14–15).

Description: Cranidium weakly convex, subtrapezoidal in dorsal view, as wide as long. Glabella convex, width 80 to 85% of length, 55 to 57% of cranial length, 38 to 40% of palpebral cranial width, gently tapering forwards, defined by deep axial furrow and truncated glabellar front; lateral glabellar furrows not recognized. LO subrectangular, 15% of cranial length, slightly curved backwards; SO composite, shallow. Preglabellar field ca. one-tenth of cranial length, flat. Anterior border slightly shorter than preglabellar field, elevated, flat, strongly arched forward; anterior border furrow indicated by change in slope. Palpebral lobes large, three-fourths of glabellar length, bean-shaped, located behind glabellar midpoint, and defined by

clearly impressed palpebral furrow; eye ridges not indicated; palpebral area weakly convex, 15% of palpebral cranial width. Posterior fixigenal field very short; posterior border one-tenth of cranial length, widening abaxially, delineated by moderately incised posterior border furrow. Facial sutures opisthoparian; anterior branch of facial suture divergent, convex; posterior branch of facial suture strongly divergent to nearly transverse.

Librigena crescentic in outline; genal field broad and convex, downsloping abaxially; lateral border moderately broad, defined by shallow border furrow; genal spine as long as genal area; eye socle narrow and elevated; eye socle furrow

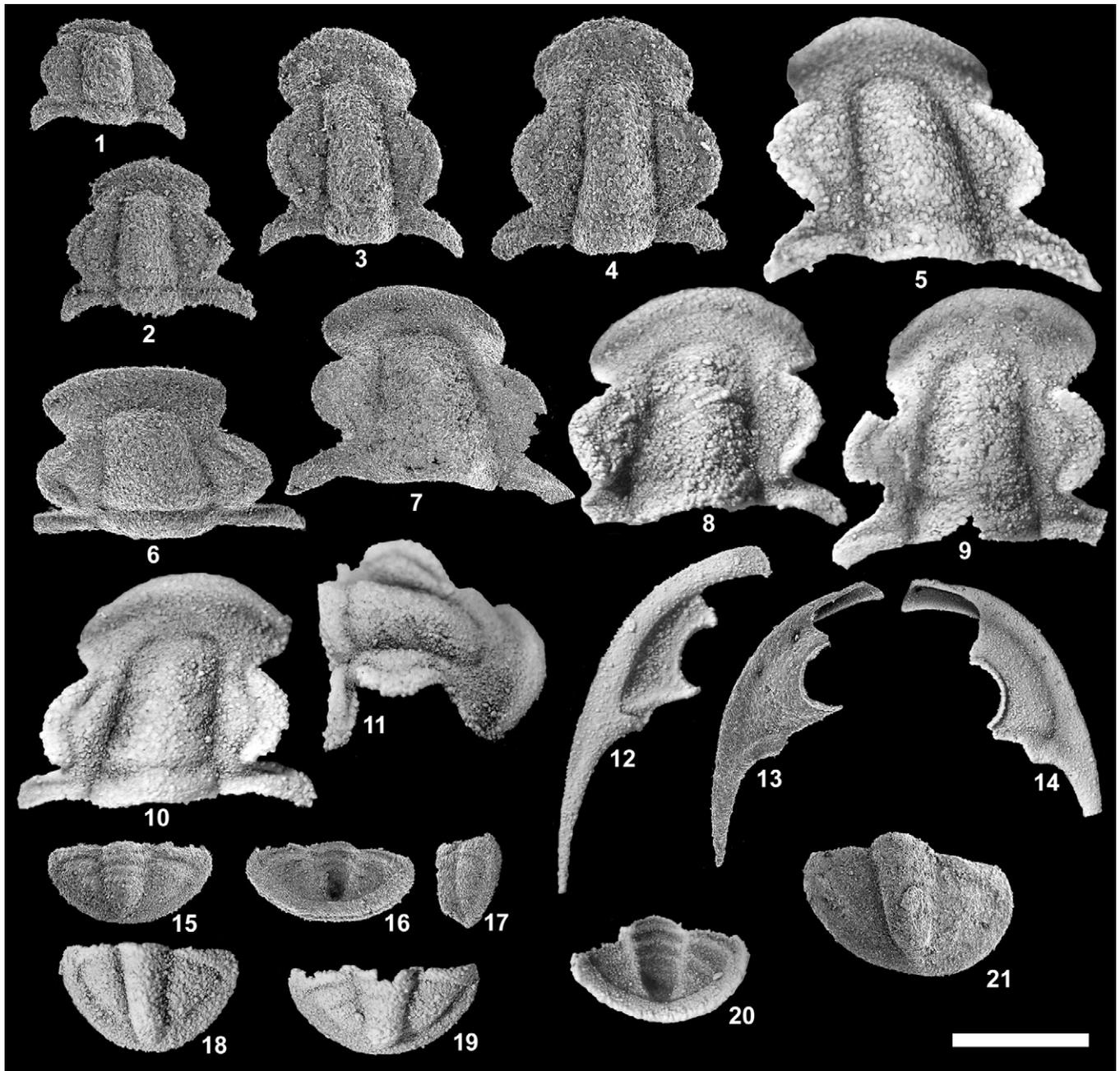


Fig. 5. 1–21. *Parachangshania rectangularis* nov. sp.; *Liostracina simesi* Zone, Korea. 1, SNUP4605, cranidium; 2, SNUP4606, cranidium; 3, SNUP4607, cranidium; 4, SNUP4608, cranidium; 5, SNUP4609, cranidium; 6, SNUP4610, cranidium; 7, SNUP4611, cranidium; 8, SNUP4612, cranidium; 9, SNUP4613, cranidium; 10, 11, holotype, SNUP4614, cranidium, dorsal and oblique lateral views; 12, SNUP4615, librigena, ventral view; 13, SNUP4616, librigena; 14, SNUP4617, librigena; 15–17, SNUP4618, pygidium, dorsal, ventral, and lateral views; 18, SNUP4619, pygidium; 19, SNUP4620, pygidium; 20, SNUP4621, pygidium, ventral view; 21, SNUP4622, pygidium. Scale bar = 1.33 mm (1–5), 2 mm (6–11, 13), 4 mm (12, 14), 2.86 mm (15–21).

moderately incised; cephalic doublure as broad as lateral border.

Pygidium semicircular in dorsal view, moderately effaced, length ca. one-half of width. Axis subconical, rounded posteriorly, reaching beyond posterior border furrow, with three to four faintly visible axial rings and a semicircular terminal piece; pleural field wider than axis, gently convex; pleural furrow moderately incised, directed oblique backward; border moderately wide, flat, uniform in width; doublure as wide as border.

Remarks: *Parachangshania rectangularis* nov. sp. is similar to *P. monkei*, but differs in having a wider glabella and a shorter preglabellar field. These features render the cranidium of this species shorter than that of *P. monkei*. The cephalic and pygidial doublures of the new species are narrower than those of *P. monkei*.

Family MENOMONIIDAE Walcott, 1916.

Genus *Alataspis* nov. gen.

Etymology: from Latin, *alatus*, winged; *aspis*, shield; referring to wing-like shield of cranium.

Type species: *Alataspis sesongensis* nov. gen., nov. sp. from the *Prochuangia mansuyi* Zone of the Sesong Formation, Korea.

Diagnosis: Menomoniid having a strongly forward-tapering glabella with effaced lateral glabellar furrows and anteriorly-located elevated palpebral lobes.

Remarks: *Alataspis* nov. gen. resembles *Ampullatocephalina* Lu and Qian, 1983 in overall cranial outline and glabellar shape. However, *Ampullatocephalina* is characterized by its more posteriorly located palpebral lobes, more constricted glabella, and deeply incised glabellar furrows and axial furrows. In addition, *Ampullatocephalina* has so far been reported to occur in the younger *Kaolishania* Zone of North China (Lu and Qian, 1983; Qian, 1994). Another similar-looking genus, *Xiaoshiella* Lu and Qian, 1983, was reported to occur along with *Prochuangia* in the lower part of the *Chuangia* Zone of Northeast China, but can be distinguished from *Alataspis* in having a well-defined preglabellar field and more posteriorly located palpebral lobes.

As for the familial assignment, Qian (1994) assigned *Ampullatocephalina* to the Yinitidae Hupé, 1953 and *Xiaoshiella* to the Anomocaridae Poulsen, 1927, which were subsequently reassigned to Leiostegiidae and Pterocephaliidae, respectively, by Jell and Adrain (2003). The narrow distance between the palpebral lobes, the strongly forward-tapering glabella, the constricted frontal part of glabella, and the transversely narrow anterior border suggest that *Alataspis* nov. gen., *Ampullatocephalina*, and *Xiaoshiella* should be assigned to the Menomoniidae.

Alataspis sesongensis nov. gen., nov. sp.

Figs. 6 and 7.

Etymology: from the Sesong Formation, where this species was recovered.

Material, horizon, and locality: Holotype cranium SNUP4677 (Fig. 6(22–27)); paratypes SNUP4661–4676, SNUP4678–4692; 17 protaspides and 45 immature cranidia, two mature cranidia, four librigenae, two thoracic segments, 11 pygidia including immature pygidia, and one hypostome; *Prochuangia mansuyi* Zone; JDA22 of the Jikdong section, Korea.

Description: Cranium subtriangular in dorsal view, moderately convex, length 70% of posterior cranial width. Glabella poorly defined, weakly convex, long, reaching to anterior cranial border, strongly tapering forward, abruptly down-sloping in anterior part, maximum glabellar width ca. one-third of posterior cranial width; axial furrow moderately deep near palpebral lobes, becoming obsolete posteriorly; lateral glabellar furrows not recognized. LO subrectangular, defined by a shallow, poorly defined occipital furrow occupying ca. one-sixth of cranial length. Anterior cranial border short, less than one-tenth of cranial length, broadly rounded anteriorly, flat to slightly upturned, defined by change in slope. Palpebral lobes semicircular in outline, occupying one-fifth of cranial length, strongly elevated abaxially, located close to

glabellar front; palpebral area very narrow. Posterior area triangular in dorsal view, as long as wide, with acuminate posterolateral projection, directed slightly rearwards, down-sloping abaxially. Facial sutures opisthoparian; anterior branch of facial suture short, convergent, weakly convex; posterior branch of facial suture divergent, weakly convex. Posterior border poorly defined by weakly incised posterior border furrow, becoming longer and deflected postero-laterally.

Librigena with wide and weakly convex genal field and narrow lateral border; genal field poorly differentiated from lateral border by faint border furrows; eye socle narrow, elevated, defined by shallow eye socle furrow; genal spine very short; cephalic doublure narrow, as wide as lateral border.

Hypostome shield-shaped with slight constriction at anterior one-third of hypostomal length in dorsal view; middle body ovoid, weakly convex; middle furrow weakly incised; anterior margin transverse, flat; anterior border furrow slightly arched forward; lateral border narrow, defined by shallow lateral border furrow.

Thoracic segment with axis about one-third of total width of segment; pleural furrow slightly inscribed; articulating half-ring short with weakly rounded anterior margin; ring furrow straight, narrow, shallowly incised; lateral margin slightly pointed rearward; panderian notch and panderian protuberance present.

Pygidium semi-circular in dorsal view, moderately convex, with slightly effaced pleural region, length about three-fifths of width. Axis ca. one-fourth of pygidial width, tapering backward, comprising six axial rings, not reaching to posterior margin; pleural field weakly convex; posterior marginal border unrecognizable.

Remarks: the thoracic segment arched forward in outline (Fig. 7(7, 8)) would have been situated more posteriorly than the straight one when articulated. Interestingly, no other polymerid trilobites are associated with this trilobite, except rare occurrences of *Parachangshania monkei*, which may imply a unique biofacies represented by this trilobite.

Protaspides are divided into three stages on the basis of size and morphological features (Fig. 8). For morphologically immature cranidia, “groups” rather than “degrees” are used (Fig. 9), as no articulated specimens have been found. Cranidia shorter than 1.5 mm in sagittal length are considered morphologically immature.

Protaspide stage 1 (Fig. 6(1, 2)): Exoskeleton circular in outline; 0.37–0.43 mm long; 0.39–0.45 mm wide; a pair of short posterior fixigenal spines situated at the rear of exoskeleton, directing slightly inward; distance between posterior marginal spines about one-fourth of exoskeletal width; posterior exoskeletal margin between posterior marginal spines slightly indented; axial furrow not distinguishable.

Protaspide stage 2 (Fig. 6(3, 4)): exoskeleton semi-circular in outline, 0.46–0.53 mm long, 0.48–0.58 mm wide; axis ca. one-fourth of exoskeletal width, defined by weakly incised axial furrows in the median part of exoskeleton; distance between posterior marginal spines about 45% of exoskeletal width; posterior exoskeletal margin between posterior marginal spines nearly transverse. Hypostome shield-shaped in outline, bearing laterally projecting spines.

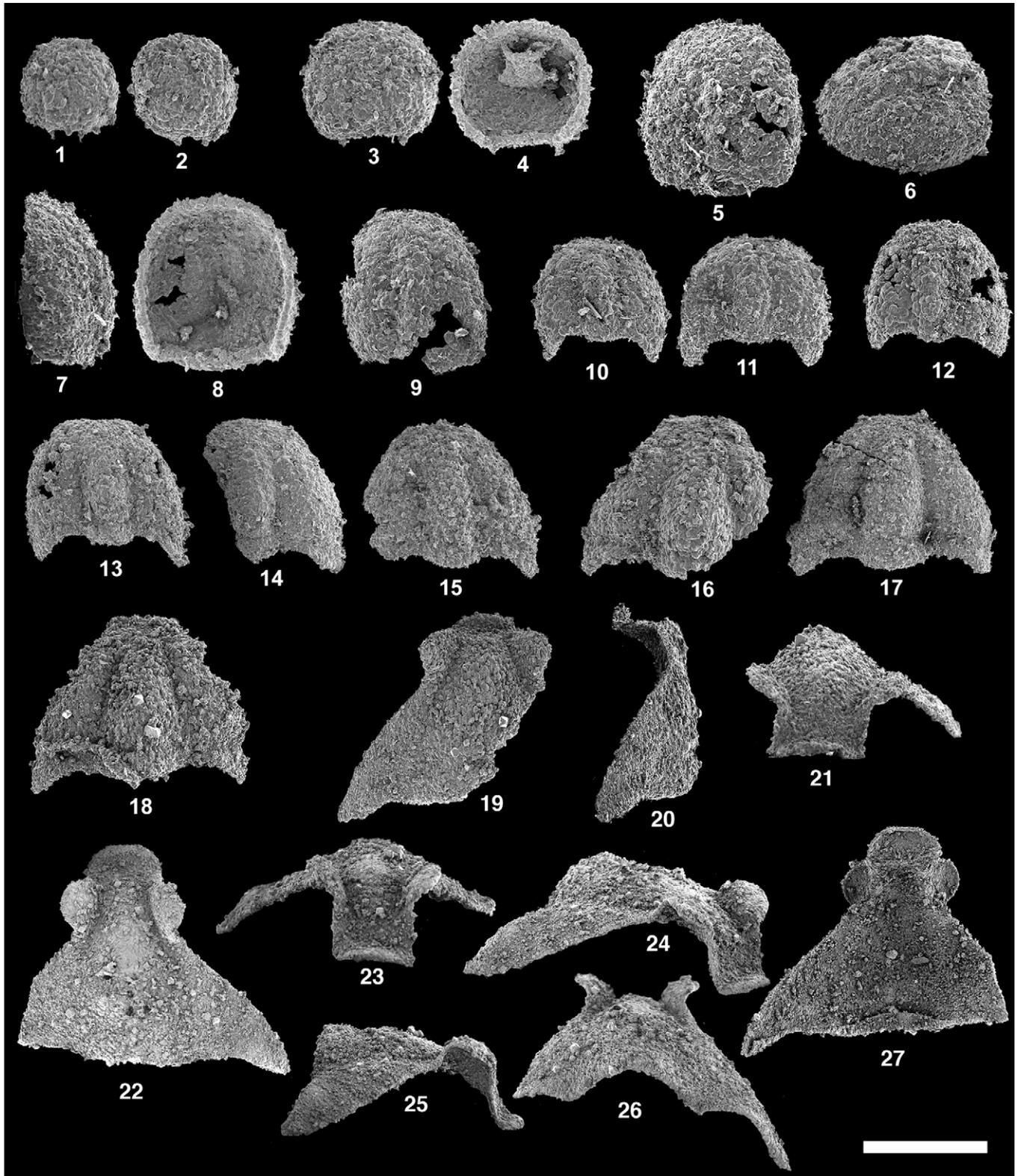


Fig. 6. 1–27. *Alataspis sesongensis* nov. gen., nov. sp.; *Prochuangia mansuyi* Zone, Korea. 1, SNUP4661, protaspis at stage 1; 2, SNUP4662, protaspis at stage 1; 3, SNUP4663, protaspis at stage 2; 4, SNUP4664, protaspis at stage 2 with hypostome retained, ventral view; 5–8, SNUP4665, protaspis at stage 3; 9, SNUP4666, protaspis at stage 3; 10, SNUP4667, cranidium of morphologically immature group 1; 11, SNUP4668, cranidium of morphologically immature group 1; 12, SNUP4669, cranidium of morphologically immature group 2; 13, SNUP4670, cranidium of morphologically immature group 2; 14, SNUP4671, cranidium of morphologically immature group 3; 15, SNUP4672, cranidium of morphologically immature group 3; 16, SNUP4673, cranidium of morphologically immature group 4; 17, SNUP4674, cranidium of morphologically immature group 4; 18, SNUP4675, cranidium of morphologically immature group 5; 19–21, SNUP4676, cranidium; dorsal, lateral, and anterior views; 22–27, holotype, SNUP4677, cranidium; dorsal, anterior, oblique antero-lateral, lateral, oblique posterior, and ventral views. Scale bar = 0.5 mm (1–9), 0.57 mm (10–11), 0.67 mm (12–15), 0.8 mm (16–17), 1 mm (18), 1.33 mm (19–21), 2 mm (22–27).

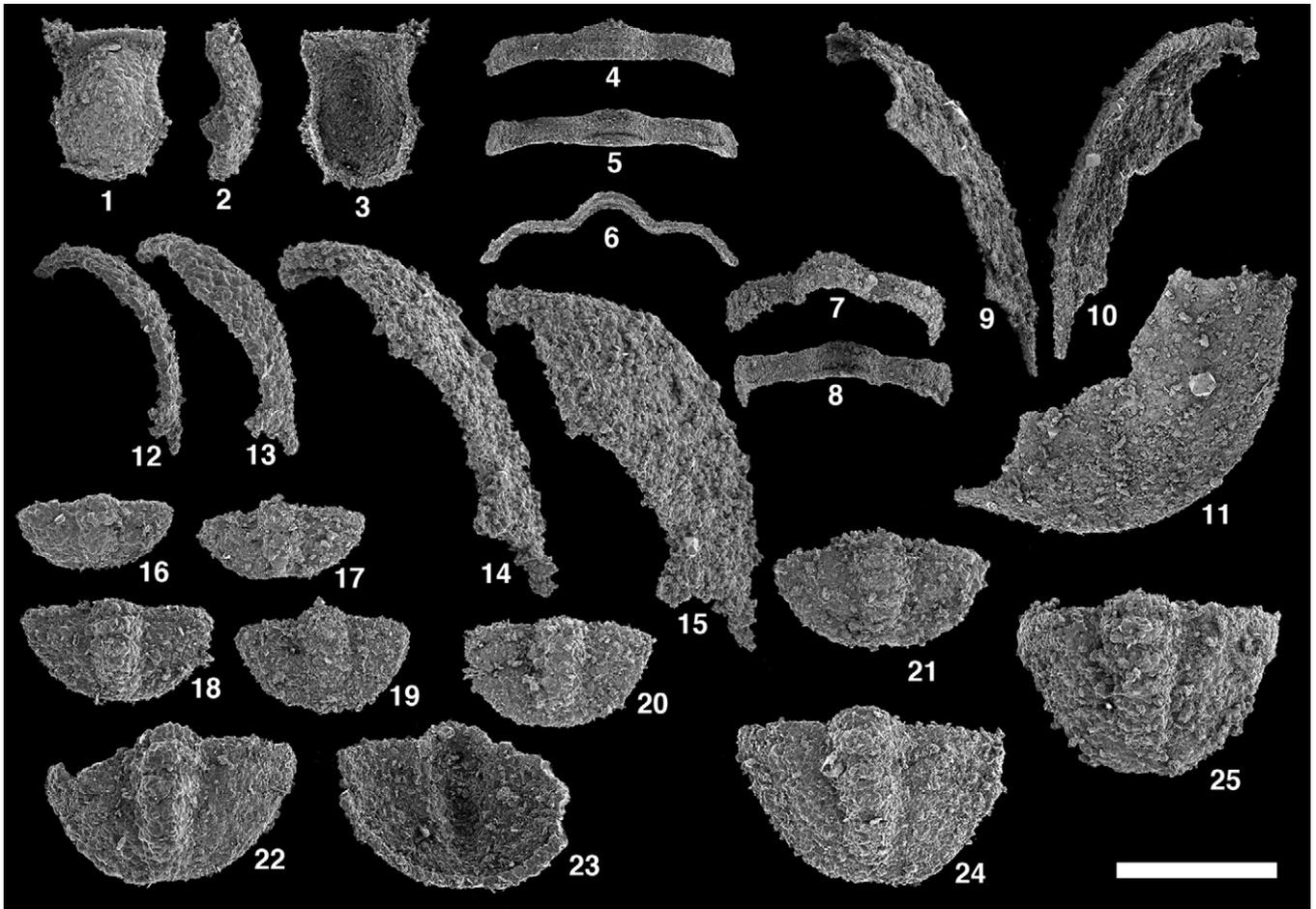


Fig. 7. 1–25. *Alataspis sesongensis* nov. gen., nov. sp.; *Prochuangia mansuyi* Zone, Korea. 1–3, SNUP4678, hypostome; ventral, lateral, and dorsal views; 4–6, SNUP4679, thoracic segment; dorsal, ventral, and posterior views; 7, 8, SNUP4680, thoracic segment, dorsal and ventral views; 9–11, SNUP4681, librigena; dorsal, ventral, and lateral views; 12, 13, SNUP4682, librigena, dorsal and oblique lateral views; 14, 15, SNUP4683, librigena, dorsal and oblique lateral views; 16, SNUP4684, pygidium; 17, SNUP4685, pygidium; 18, SNUP4686, pygidium; 19, SNUP4687, pygidium; 20, SNUP4688, pygidium; 21, SNUP4689, pygidium; 22, 23, SNUP4690, pygidium, dorsal and ventral views; 24, SNUP4691, pygidium; 25, SNUP4692, pygidium. Scale bar = 1 mm (1–3), 1.33 mm (4–11), 0.67 mm (12–24), 0.8 mm (25).

Protaspid stage 3 (Fig. 6(5–9)): exoskeleton oval in dorsal view; 0.62–0.70 mm long, 0.58–0.67 mm wide; axial furrow slightly expanding forward; occipital ring distinguishable; sagittal length of cranium 0.85 of exoskeletal length; posterior cranial margin running abaxially obliquely backward; protopygidium short and transverse.

Morphologically immature crania, Group 1 (Fig. 6(10, 11)): Cranium semi-circular in outline; 0.47–0.56 mm long, 0.61–0.69 mm wide; glabella parallel-sided, ca. one-fourth of cranial width, but expanding forward in anteriormost part; occipital ring is delineated by shallow occipital furrow; posterior border is delimited by moderately incised posterior border furrow; posterolateral projections of fixigenae pointed rearwards.

Morphologically immature crania, Group 2 (Fig. 6(12, 13)): Cranium semi-circular in dorsal view, 0.55–0.73 mm long and 0.74–0.96 mm wide; glabella parallel-sided, expanding forward in frontal part; occipital ring weakly arched backward; posterior border furrow shallower than that of group 1.

Morphologically immature crania, Group 3 (Fig. 6(14, 15)): Cranium sub-trapezoidal in outline, 0.72–0.85 mm in length and 0.97–1.25 mm in width; axial furrow somewhat obsolete in frontal part; occipital ring arched backward, occipital furrow moderately incised.

Morphologically immature crania, Group 4 (Fig. 6(16, 17)): Cranium sub-trapezoidal in outline, 0.93–1.11 mm long and 1.31–1.56 mm wide; glabella broad, occupying one-third of cranial width, tapering forward; occipital ring moderately arched backward, occipital ring furrow shallow; anterior cranial margin transverse; palpebral lobes weak but distinguishable.

Morphologically immature crania, Group 5 (Fig. 6(18)): Cranium sub-trapezoidal in outline, weakly convex, 1.31–1.37 mm long and 1.71–1.78 mm wide; glabella ca. one-third of cranial width, tapering forward; occipital ring slightly arched backward, occipital furrow shallow; anterior border furrow slightly incised, delimiting short anterior cranial border; palpebral lobes small, situated anteriorly; anterior branch of facial suture very short, convergent straight; posterior branch of

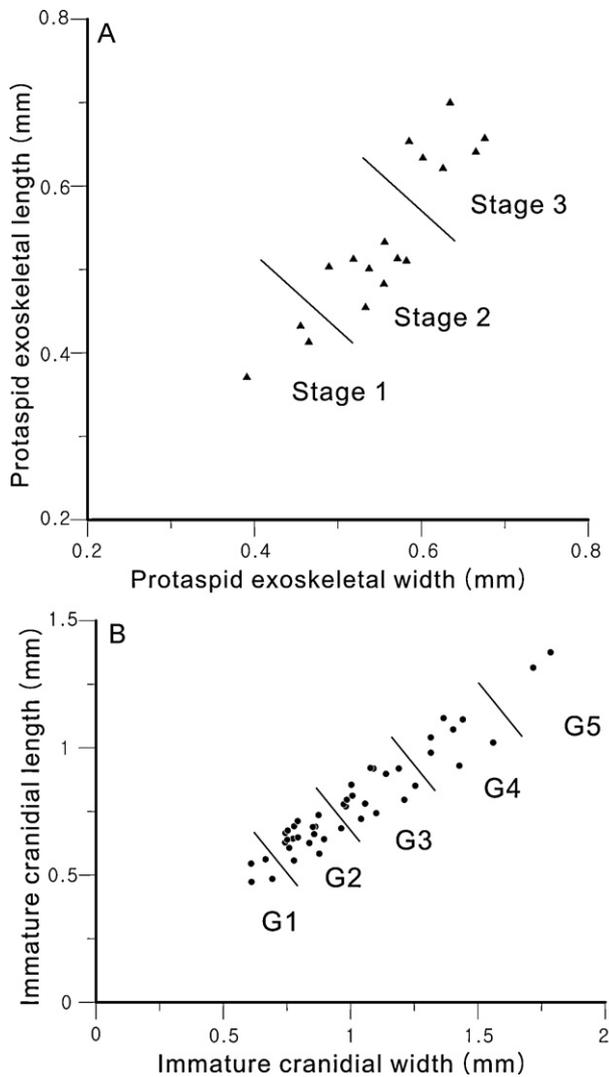


Fig. 8. Scatter plots of length versus width for protaspis exoskeletons (A) and morphologically immature post-protaspis cranidia (B) of *Alataspis sesongensis* nov. gen., nov. sp. G1 to G5 denote the groupings made for the purpose of description.

facial suture divergent convex; posterior border becoming longer abaxially to form rearward-directed acuminate posterolateral projection; posterior cranidial border furrow clearly incised.

Ontogenetic development of librigenae (Fig. 7(9–15)): the most noticeable morphological change of librigena during growth is the enlargement of genal field. It is easily visible when comparing the smallest librigena (Fig. 7(12, 13)) with the largest one (Fig. 7(9–11)). The eye socle is visible only in the large specimens.

Ontogenetic development of post-protaspis pygidia (Fig. 7(16–25)): the smallest meraspis pygidium examined in this study (Fig. 7(16)) is 0.31 mm long and 0.58 mm wide. It is semi-elliptical in outline and bears three axial rings. With growth, immature pygidia become longer and bear up to six axial rings (Fig. 7(17–25)).

It is worth comparing the ontogeny of *Alataspis sesongensis* nov. gen., nov. sp., with that of the late middle Cambrian menomoniid trilobite, *Bolaspidella housensis* (Walcott, 1886)

(Lee and Chatterton, 2005). Although *B. housensis* is markedly different from *A. sesongensis* nov. gen., nov. sp., in holaspis morphology, the two menomoniid trilobites show close similarities in early ontogenetic stages. The three protaspis stages of *B. housensis* are closely comparable to those of *A. sesongensis* nov. gen., nov. sp., in having simple morphology of stage 1 protaspis, weakly impressed axial furrows of stage 2 protaspis, and forwardly expanding axis and small protopygidium of stage 3 protaspis. The comparable morphological features in the small morphologically immature post-protaspis cranidia include: axial furrows becoming shallow anteriorly and the posteriorly acuminate posterolateral projection of fixigenae. Subsequent divergence in morphological development leads to the significantly different holaspis morphology of the two menomoniid trilobites.

Family DICERATOCEPHALIDAE Lu, 1954.

Genus *Fenghuangella* Yang in Zhou et al., 1977.

Type species: *Fenghuangella laochatianensis* Yang in Zhou et al., 1977 from the Huaqiao Formation, South China; subsequently designated by Yang (1978).

Remarks: the generic concept of *Fenghuangella* followed herein was comprehensively treated by Peng et al. (2004a) who reduced the number of valid species (including subspecies) within *Fenghuangella* to five.

Fenghuangella laevis nov. sp.

Fig. 9.

Etymology: from Latin *laevis*, smooth, referring to the smooth prosopon of the species.

Material, horizon, and locality: Holotype cranidium, SNUP4641 (Fig. 9(9–12)); and paratypes SNUP4635–4640, SNUP4642–4644. Fifty cranidia and one pygidia; *Fenghuangella laevis* and *Prochuangia mansuyi* zones; JDA14–19 and JDA23 of the Jikdong section, Korea.

Diagnosis: a species of *Fenghuangella* having smooth surface and a short occipital spine and lacking lateral glabellar furrows and eye ridges.

Description: Cranidium convex, subtriangular in outline, two-thirds as long as wide. Glabella strongly convex, bell-shaped, sharply-pointed anteriorly, lacking lateral glabellar furrows; axial furrow wide, deep. LO subrectangular, relatively long, one-fifth of cranidial length, with a short stout occipital spine; SO simple, transverse, deep. Preglabellar area with a pair of incomplete, divergent furrows emerging from tip of glabella. Palpebral lobes indistinguishable. Fixigenal field moderately convex, downsloping peripherally. Posterior border one-half as long as occipital ring adaxially, becoming longer up to as long as occipital ring abaxially. Posterior border furrow clearly incised, transverse, but deflected forwards laterally. Facial suture converging forward, weakly convex. Surface smooth.

Pygidium semi-circular in outline, convex, two-thirds as long as wide. Axis tapering slightly rearwards, defined by shallow axial furrow, with three or four axial rings. Pleural field weakly convex, downsloping marginally; border narrow, poorly defined by faint border furrow.

Remarks: *Fenghuangella laevis* nov. sp. is easily distinguished from other species of *Fenghuangella* by its smooth

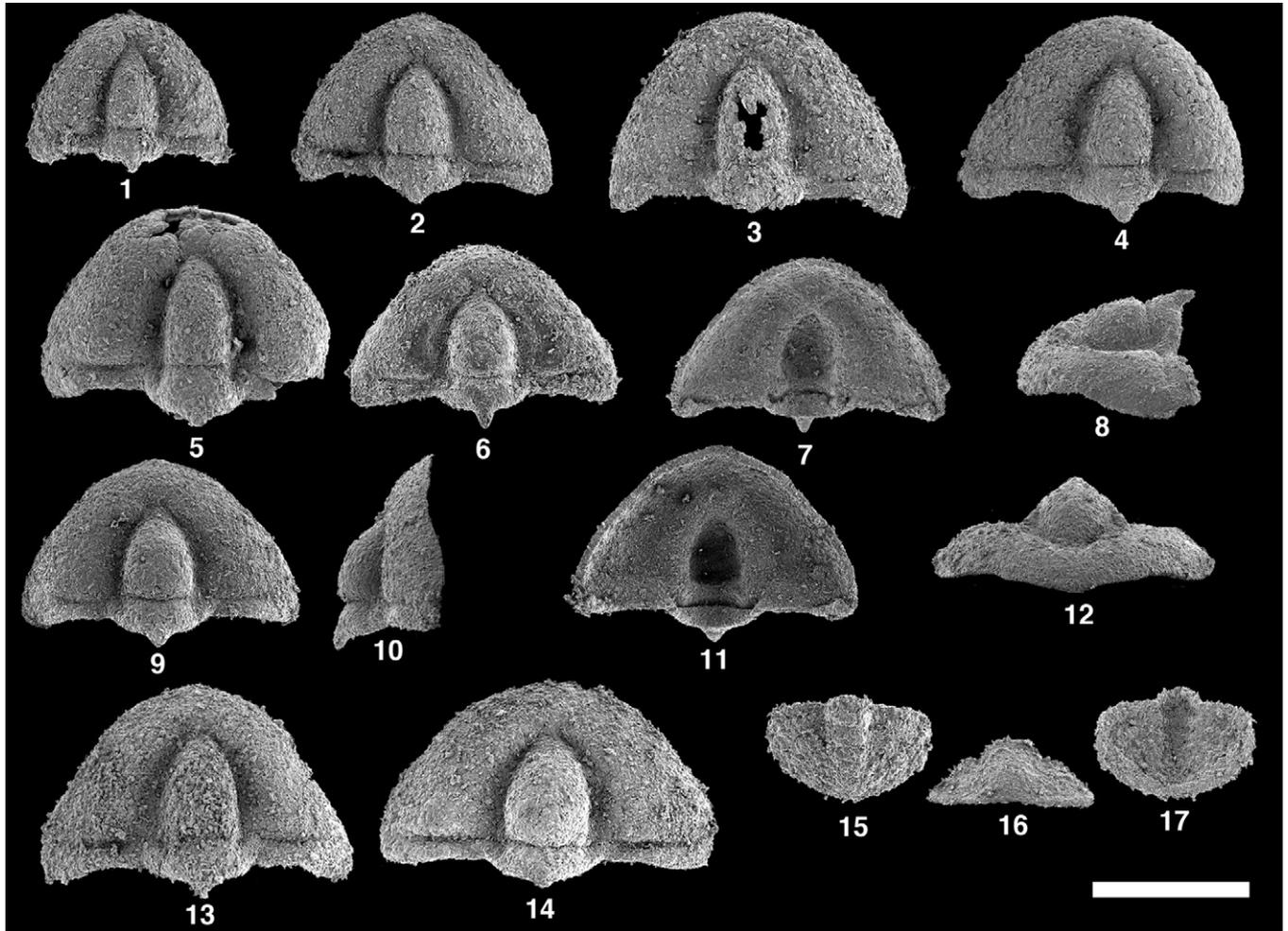


Fig. 9. 1–17. *Fenghuangella laevis* nov. sp.; *Fenghuangella laevis* and *Prochuangia mansuyi* zones, Korea. 1, SNUP4635, cranidium; 2, SNUP4636, cranidium; 3, SNUP4637, cranidium; 4, SNUP4638, cranidium; 5, SNUP4639, cranidium; 6–8, SNUP4640, cranidium; dorsal, ventral, and oblique lateral views; 9–12, holotype, SNUP4641, cranidium; dorsal, lateral, ventral, and anterior views; 13, SNUP4642, cranidium; 14, SNUP4643, cranidium; 15–17, SNUP4644, pygidium; dorsal, posterior, and ventral views. Scale bar = 1.33 mm (1–14), 1 mm (15–17).

surface and the lack of lateral glabellar furrows and eye ridges. *Fenghuangella fusilis* Peng, Babcock and Lin, 2004 has a smooth surface also, but is characterized by a single pit-like median furrow on the preglabellar field.

Suborder HARPINA Whittington, 1959.

Family HARPIDIDAE? Whittington, 1950.

Genus *Baikadamaspis* Ergaliev, 1980.

Type species: *Baikadamaspis proprius* Ergaliev, 1980 from the *Glyptagnostus reticulatus* to *Homagnostus longiformis* zones, Malyi Karatau, Kazakhstan (by original designation).

Remarks: the generic concept of *Baikadamaspis* has been thoroughly treated by Peng et al. (2004a), which is followed in this study. Peng et al. (2004a) mentioned the possibility of *Baikadamaspis* being a junior synonym of *Sailoma* Schrank, 1975. Apparently, the incomplete type specimen of *Sailoma loma* Schrank, 1975 hinders reliable comparison with *Baikadamaspis*, and a reconstruction of the cranidium of *S. loma* (Schrank, 1975: text-fig. 3) shows long palpebral lobes. Therefore, we suggest a restriction of the generic concept of *Sailoma* to the type material of *S. loma*.

Baikadamaspis jikdongensis nov. sp.

Fig. 10.

Etymology: after the Jikdong section from which the present material was collected.

Material, horizon, and locality: Holotype cranidium SNUP4645 (Fig. 10(1–4)); paratypes SNUP4646–SNUP4657; 16 cranidia, 15 librigenae, eight thoracic segments, and 13 pygidia; *Fenghuangella laevis* and *Prochuangia mansuyi* zones; JDA15–21, 23, and 24 of the Jikdong section, Korea.

Diagnosis: a species of *Baikadamaspis* with short preglabellar field, parallel-sided to convergent anterior branches of facial suture, densely spaced granules, and absence of eye ridges.

Description: Cranidium semicircular to subtrapezoidal in dorsal view, strongly convex, length one-half of posterior cranial width. Glabella truncato-conical, widest at glabellar base, tapering steadily forwards, 50 to 55% and 30% of cranial length and width respectively; three pairs of lateral glabellar furrows connecting to axial furrows; S1 oblique rearwards, geniculate; S2 transverse; S3 pit-like; axial furrows shallow, but clearly incised; preglabellar furrow faint, indicated by change in slope. LO semi-elliptical, ca. 15% of cranial

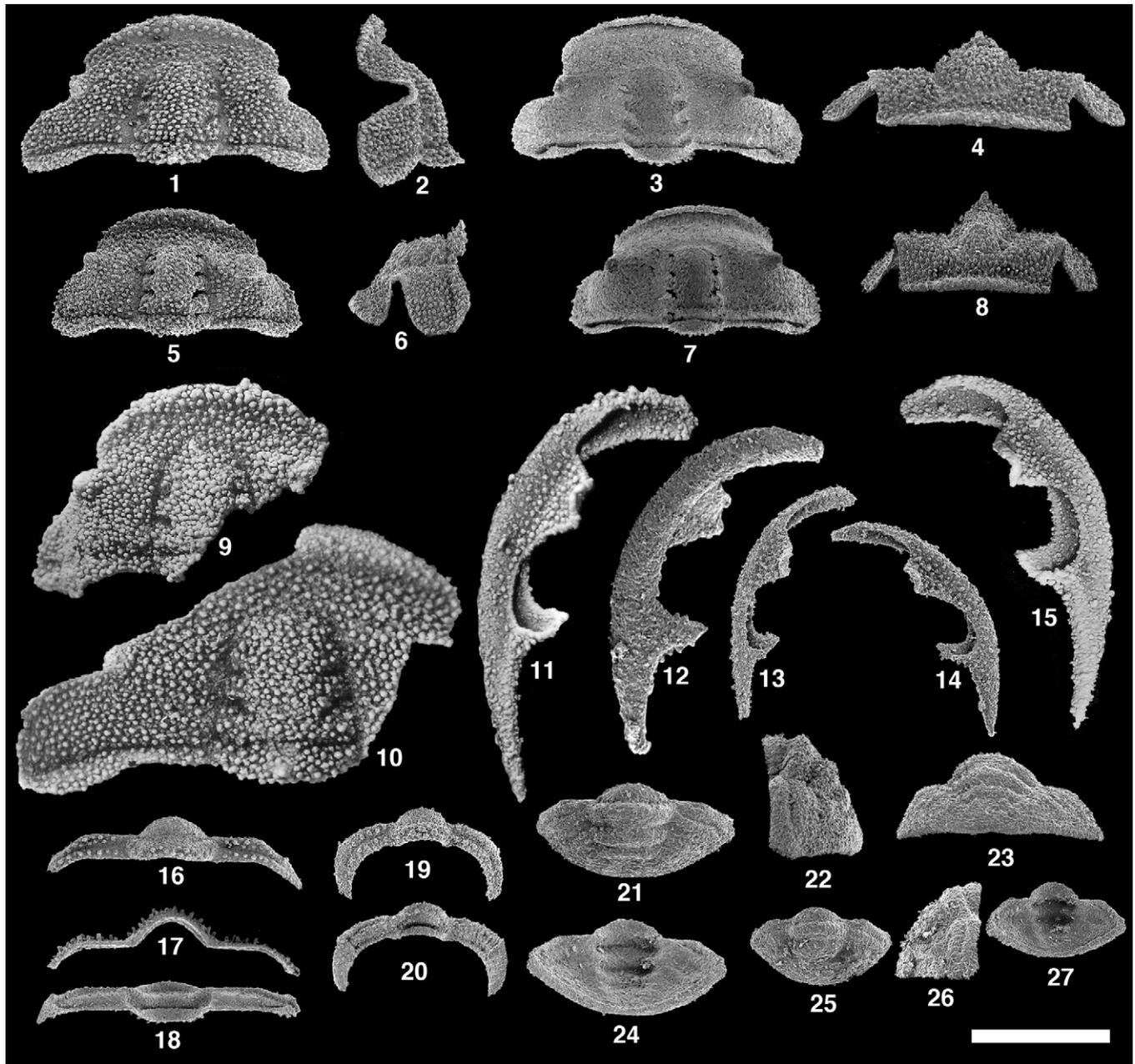


Fig. 10. 1–27. *Baikadamaspis jikdongensis* nov. sp.; *Fenghuangella laevis* and *Prochuangia mansuyi* zones, Korea. 1–4, Holotype, SNUP4645, cranidium; dorsal, lateral, ventral, and anterior views; 5–8, SNUP4646, cranidium; dorsal, lateral, ventral, and anterior views; 9, SNUP4647, cranidium; 10, SNUP4648, cranidium; 11, SNUP4649, librigena; 12, SNUP4650, librigena, ventral view; 13, SNUP4651, librigena; 14, SNUP4652, librigena; 15, SNUP4653, librigena; 16–18, SNUP4654, thoracic segment; dorsal, posterior, and anterior views; 19, 20, SNUP4655, thoracic segment, dorsal and ventral views; 21–24, SNUP4656, pygidium; dorsal, lateral, posterior, and ventral views; 25–27, SNUP4657, pygidium; dorsal, lateral, and ventral views. Scale bar = 2 mm (1–9), 2.22 mm (10), 1.33 mm (11–14, 21–27), 2 mm (15–20).

length, as wide as glabellar base, with a small median node located posteriorly; SO shallow, simple, straight. Preglabellar field short, ca. 15% of cranidial length, downsloping anteriorly. Anterior border convex, upturned, ca. 10% of cranidial length, becoming shorter abaxially. Palpebral lobes small, bulb-like, located slightly in front of cranidial mid-length; eye ridges not indicated; palpebral area as broad as glabella. Posterior field wider than long, strongly downsloping abaxially. Posterior border proximally 50% of length of occipital ring, becoming as long as occipital ring abaxially, deflected strongly forwards connecting to lateral border; posterior border furrow shallow,

short, transverse to slightly bent rearwards, and then strongly deflected forwards and merging with lateral border furrow; lateral border partly indicated in abaxial ends of posterior field. Facial sutures opisthoparian; anterior branch of facial suture parallel-sided to convergent convex; posterior branch of facial suture divergent convex; posterolateral projection broadly rounded, directed slightly rearwards. Surface covered with closely spaced coarse granules.

Librigena with narrow librigenal field and comparatively broad lateral border; lateral border weakly convex, wider than librigenal field; lateral border prolonged into a stout genal

spine; genal spine 50 to 70% of cranial length; doublure as wide as or slightly wider than lateral border; eye socle narrow and elevated, clearly defined by shallow eye socle furrow. Dorsal surface granulate.

Thoracic segment consisting of strongly convex axis and nearly flat pleurae. Axis ca. 35% of segment; articulating half ring semi-elliptical, convex; ring slightly longer than articulating half ring, ornamented with prominent pustules in posterior portion; ring furrow transversely straight, shallow; axial furrow shallow, indicated by change in slope; pleural furrow shallow, running diagonally postero-laterally; anterior band slightly longer than posterior band, both bands sculptured with transversely linearly aligned prominent pustules; fulcrum located at ca. one-half of pleural width; panderian protuberance and weak panderian notch present.

Pygidium transversely elliptical in plan view, strongly convex, sagittal length ca. one-half of maximum width. Axis inflated above pleural field, tapering strongly rearwards, nearly reaching to posterior margin, with two axial rings and a small terminal piece; articulating half ring as long as first ring; ring furrows deep and transverse; axial furrow shallow, indicated by change in convexity. Pleural field downsloping marginally; pleural furrow shallow; border not clearly defined; doublure evenly narrow, ca. 10% of pygidial length. Surface smooth.

Remarks: *Baikadamaspis jikdongensis* nov. sp. is comparable to *B. proprius* Ergaliev, 1980 and *B. granulosa* (Yuan and Yin, 1998) in overall cranial morphology. It can be distinguished from *B. proprius* in having a forward-tapering glabella, shorter preglabellar field, smaller palpebral lobes, and parallel-sided to convergent anterior branch of facial suture and in the absence of eye ridges. *Baikadamaspis jikdongensis* nov. sp. differs from *B. granulosa* in lacking eye ridges and a transverse ridge or paradoublural line on the preglabellar field. It is easily differentiated from other species of *Baikadamaspis*, such as *B. sinensis* (Yang in Zhou et al., 1977), *B. linearis* Peng, Babcock and Lin, 2004, and *B. paibiensis* Peng, Babcock and Lin, 2004, all of which have strongly divergent anterior branches of facial suture, sparsely-spaced small granules, and distinct eye ridges.

Baikadamaspis sp. 1.

Fig. 11.

Material, horizon, and locality: two cranidia and one librigena; *Fenghuangella laevis* Zone; JDA14 of the Jikdong section, Korea.

Remarks: *Baikadamaspis* sp. 1 includes a complete cranidium, a fragmentary cranidium, and a librigena. The complete cranidium (Fig. 11(1–3)) most closely resembles *B. proprius* Ergaliev, 1980 in having comparable palpebral lobes and facial suture patterns, but differs in possessing shorter preglabellar field, longer anterior cranial border, and less densely distributed granules. *Baikadamaspis* sp. 1 occurs in a horizon stratigraphically lower than *B. jikdongensis* in the Jikdong section.

5. Biostratigraphy

The succession of polymerid trilobites in the Jikdong section (Fig. 2) is used for a subdivision of the strata into five biozones (in ascending order; Fig. 12): the *Neodrepanura*, *Liostracina simesi*, *Fenghuangella laevis*, *Prochuangia mansuyi*, and *Chuangia* zones, of which the *L. simesi*, *F. laevis*, and *P. mansuyi* zones are new. The *Neodrepanura* and *Chuangia* zones are treated as informal and provisional due to insufficient documentation of trilobite occurrences. The *Neodrepanura* and *Chuangia* zones are supposed to be roughly equivalent to the same name-bearing zones proposed by Kobayashi (1935, 1966). However, a more accurate correspondence needs to be confirmed by more extensive collections.

5.1. Neodrepanura Zone

Kobayashi (1966) reported 15 trilobite species and a few brachiopod and gastropod taxa from the *Neodrepanura* Zone of the Sesong Formation and correlated it with the *Neodrepanura* Zone of North China. In this study, the *Neodrepanura* Zone is recognized in the two lowermost horizons (JDA10 and JDA11) of the Jikdong section (Fig. 2) and comprises four species: *Neodrepanura* sp. 1, *Liostracina* sp. 1, *Teinistion* sp. 1, and *Huzhuia* sp. 1. These genera are mainly known from the Cambrian Series 3 in other areas. *Neodrepanura* occurs abundantly in the *Neodrepanura* Zone of North China (Zhang and Jell, 1987), and the genus was recently reported with reservation from the *Linguagnostus reconditus* Zone of South China (Peng et al., 2004a). *Liostracina* has been widely documented and often employed as a zonal taxon in China; it is documented from the *Neodrepanura* Zone of North China (Monke, 1903; Zhang and Jell, 1987), *Liostracina bella* Zone of South China (Peng et al., 2004a), and *Liostracina* Zone of

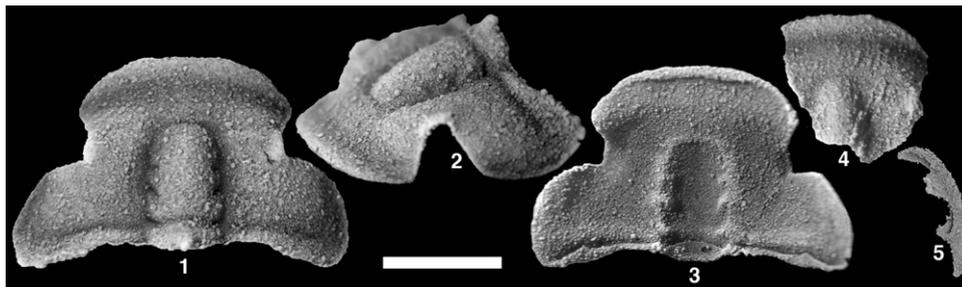


Fig. 11. 1–5. *Baikadamaspis* sp. 1; *Fenghuangella laevis* Zone, Korea. 1–3, SNUP4658, cranidium; dorsal, oblique antero-lateral, and ventral views; 4, SNUP4659, incomplete cranidium; 5, SNUP4660, librigena. Scale bar = 2.22 mm (1–4), 2 mm (5).

Series	Stage	TAEBAEK	NORTH CHINA		SOUTH CHINA		AUSTRALIA
		This study	Qian (1994)	Zhang and Jell (1987)	Peng (1992), Peng and Robison (2000)	Peng et al. (2004a)	Öpik (1967)
Furongian	Paibian	<i>Chuangia</i>	<i>Chuangia</i>	<i>Chuangia</i>	<i>Agnostus inexpectans-Proceratopyge protracta</i>	<i>Shengia quadrata</i>	<i>Proceratopyge cryptica</i>
		<i>Prochuangia mansuyi</i>	<i>Prochuangia mansuyi</i>		<i>Glyptagnostus reticulatus</i>	<i>Chuangia subquadrangulata</i>	
		<i>Fenghuangella laevis</i>	<i>Luotuolingia</i>				<i>Glyptagnostus stolidotus</i>
Series 3	Guzhangian	<i>Liostracina simesi</i>	<i>Neodrepanura</i>	<i>Neodrepanura</i>	<i>Glyptagnostus stolidotus</i>	<i>Liostracina bella</i>	<i>Glyptagnostus stolidotus</i>
		<i>Neodrepanura</i>			<i>Linguagnostus reconditus</i>		<i>Acmarharchis quasivespa</i>

Fig. 12. Zonal correlation of Cambrian Series 3/Furongian Series transitional interval of the Taebaek Group, Korea, with those of North China, South China, and Australia.

Xinjiang (Lin et al., 1992). The genus *Liostracina* is also known to occur in the *Glyptagnostus stolidotus* Zone of Australia (Öpik, 1967) and Antarctica (Jago and Cooper, 2005). *Teinistion* has a relatively long range from the upper part of the *Damesella* Zone to the *Neodrepanura* Zone in North China (Zhang and Jell, 1987; Guo et al., 1996; Zhou and Zhen, 2008), while it is more or less restricted to the *Liostracina* Zone of Xinjiang (Lin et al., 1992) and the *Wanshan* *wanshanensis* and *Liostracina bella* zones of South China (Peng et al., 2004a). *Huzhuia* has a very long stratigraphic range from the *Taitzui*-*Poshania* Zone to *Chuangia subquadrangulata* Zone of South China and western North China (Zhou and Zhen, 2008). The *Neodrepanura* Zone of Korea is rather confidently correlated with the *Neodrepanura* Zone of North China (Zhang and Jell, 1987) and the uppermost biozones of the Guzhangian Stage elsewhere (Peng et al., 2009; Fig. 12).

5.2. *Liostracina simesi* Zone (new)

Composition: The *Liostracina simesi* Zone is defined by the first appearance datum (FAD) of the eponymous species and comprises two species, *L. simesi* and *Parachangshania rectangularis*.

Stratigraphic occurrence: The *L. simesi* Zone occurs in a relatively narrow interval (ca. 0.5 m-thick) of the section, represented by four horizons (JDA11 to JDA14). The limestone blocks dissolved in this study consist of limestone conglomerate in lithology, presumably formed by diagenetic processes (Kwon et al., 2002), and hence the horizons JDA11 and JDA14 are considered to contain mixed trilobite faunal assemblages from adjacent strata.

Correlation: this zone yields only two trilobite species and, thus, is not easy to correlate with the biozones of other parts of the world. *Liostracina* species are known largely from the Guzhangian Stage of China (Zhang and Jell, 1987; Lin et al., 1992; Peng et al., 2004a). It is, however, noted that *L. simesi* occurs in association with *Glyptagnostus stolidotus* in Antarctica (Jago and Cooper, 2005), which provides a basis

for correlation of the *L. simesi* Zone with the *G. stolidotus* Zone and equivalents (Fig. 12). *Parachangshania* has hitherto been exclusively known from the *Chuangia* Zone of North China (Chien, 1958; Qian, 1994) and thereby *P. rectangularis* represents the oldest occurrence of the genus.

5.3. *Fenghuangella laevis* Zone (new)

Composition: the *Fenghuangella laevis* Zone is established on the first occurrence of *Placosema bigranulosum* and *Fenghuangella laevis*, and comprises six trilobite taxa: *Baikadamaspis jikdongensis*, *B. sp. 1*, *Parachangshania monkei*, a ceratopygid gen. and sp. indeterminate 1, and the two species mentioned above.

Stratigraphic occurrence: this zone is represented by five horizons, ranging from JDA14 to JDA18 of the Jikdong section. Two species (*Placosema bigranulosum* and *B. sp. 1*) are restricted to this zone, while the remaining four species extend their stratigraphic ranges upwards into the *Prochuangia mansuyi* Zone.

Correlation: *Placosema bigranulosum* was reported to occur in South China and Antarctica (Peng et al., 2004a). In South China, it has a stratigraphic range from the upper part of the *Liostracina bella* Zone to the lower part of the *Chuangia subquadrangulata* Zone, equivalent to the *Glyptagnostus stolidotus* Zone to the lower part of the *G. reticulatus* Zone (Fig. 13). This species was also documented as *Pagodia* sp. in Antarctica (Cooper et al., 1996) from the horizon overlying the *G. reticulatus*-yielding strata. *Fenghuangella* has been reported from the *Wanshan* *wanshanensis* through *Chuangia subquadrangulata* zones of South China (Peng et al., 2004a) and from the *G. stolidotus* Zone in Kazakhstan (Ergaliev, 1980). *Parachangshania* has been known to occur exclusively in the *Chuangia* Zone of North China (Qian, 1994), which is in part correlated with the *G. reticulatus* Zone. *Baikadamaspis* was originally reported from the *G. reticulatus* Zone and *Homagnostus longiformis* Zone of Kazakhstan (Ergaliev, 1980), but was widely documented from the *Linguagnostus*

reconditus to *Glyptagnostus reticulatus* zones of South China and western North China (Yuan and Yin, 1998; Peng et al., 2004a; Zhou and Zhen, 2008).

The *Fenghuangella laevis* Zone can be correlated with the lower part of the *Chuangia* (or *Prochuangia*) Zone of North China and the *Glyptagnostus reticulatus* Zone of South China and Kazakhstan. The correlation of the *Fenghuangella laevis* Zone with the *G. reticulatus* Zone of the Paibi section at Hunan, South China (Peng et al., 2004b) warrants that the base of the Furongian Series in the Taebaek Group can be drawn at the base of the *Fenghuangella laevis* Zone.

5.4. *Prochuangia mansuyi* Zone (new)

Composition: This zone is recognized by the FAD of the eponymous species and comprises eight species: *Fenghuangella laevis*, *Parachangshania monkei*, *Baikadamaspis jikdongensis*, *Prochuangia mansuyi*, *Huzhuia* sp. 2, *Alataspis sesongensis*, *Maladioides coreanicus*, and ceratopygid gen. and sp. indeterminate 1.

Stratigraphic occurrence: this zone is represented by six horizons, spanning from JDA19 to JDA24 of the Jikdong section. Four species, which appeared in the *Fenghuangella laevis* Zone, extend their stratigraphic ranges into the *P. mansuyi* Zone, while the remaining four species are restricted to this zone.

Correlation: the stratigraphic ranges of the four species which also occur in the *Fenghuangella laevis* Zone are described above. *Prochuangia mansuyi* was also employed as a zonal taxon in North China (Qian, 1994), which was correlated with the upper part of the *Glyptagnostus reticulatus* Zone and the lower part of the *Innitagnostus inexpectans-Proceratopyge protracta* Zone of South China (Peng, 1992). The specimens referable to *Maladioides coreanicus* were reported from the *Chuangia* Zone of North China (Zhu and Wittke, 1989; Qian, 1994). The *Prochuangia mansuyi* Zone can be equated with the *Prochuangia mansuyi* Zone of North China and less convincingly with the *Glyptagnostus reticulatus* and *Innitagnostus inexpectans-Proceratopyge protracta* zones of South China (Fig. 12).

5.5. *Chuangia* Zone

Kobayashi (1966) documented ten trilobite species from the *Chuangia* Zone and assigned it to the Changshanian Stage of North China. In this study, the *Chuangia* Zone is rather vaguely recognized, based on the observation of two poorly preserved trilobite specimens in the JDA25 and JDA26 horizons of the Jikdong section: *Chuangia* sp. and ceratopygid gen. and sp. indeterminate 2. The poor occurrence of trilobite taxa in the zone does not allow a reliable correlation of the *Chuangia* Zone of Korea with the biozones of other parts of the world, albeit it broadly corresponds to the *Chuangia* Zone of North China (Fig. 12).

In summary, the *Neodrepanura* and *Liostracina simesi* zones are characterized by the occurrence of typical Guzhangian trilobites of the Sino-Korean Block. None of the species of these zones extend their ranges into the overlying zone. The

base of the *Fenghuangella laevis* Zone appears to represent the bioevent of profound faunal turnover by colonization of a new Furongian trilobite faunal assemblage in the Taebaeksan Basin. Comparable faunal turnovers have been widely documented in North China, South China, Kazakhstan, and Laurentia (Peng et al., 2004b).

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Appendix A. Supplementary data

Supplementary data (Text and Fig. S1–S10) associated with this article can be found, in the online version, at doi:10.1016/j.geobios.2011.02.003.

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Trilobite faunal successions across the base of the Furongian Series in the Taebaek Group, Taebaeksan Basin, Korea

Les faunes de trilobites de la base de la Série furongienne du Groupe Taebaek, Bassin Taebaeksan, Corée

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Matériel supplémentaire / *Supplementary materials*

Supplementary text: Systematic description of the polymerid trilobite taxa which were previously described in the literature or are treated under open nomenclature in this study.

Figure S1. 1–10. *Chuangia* sp. 1; *Chuangia* zone, Korea.

Figure S2. 1–8. *Prochuangia mansuyi* Kobayashi, 1935; *Prochuangia mansuyi* Zone, Korea.

Figure S3. 1–8. *Neodrepanura* sp. 1; *Neodrepanura* zone, Korea.

Figure S4. 1–10. *Teinistion* sp. 1; *Neodrepanura* zone, Korea.

Figure S5. 1–21. Ceratopygid genus et species indeterminate 1; *Fenghuangella laevis* and *Prochuangia mansuyi* zones, Korea; **22–24.** Ceratopygid genus et species indeterminate 2; *Chuangia* zone, Korea.

Figure S6. 1–32. *Liostracina simesi* Jago and Cooper, 2005; *Liostracina simesi* Zone, Korea.

Figure S7. 1–12. *Liostracina* sp. 1; *Neodrepanura* zone, Korea.

Figure S8. 1–8. *Huzhuia* sp. 1; *Neodrepanura* zone, Korea.

Figure S9. 1–9. *Placosema bigranulosum* Peng et al., 2004; *Fenghuangella laevis* Zone, Korea.

Figure S10. 1–3. Indeterminate protaspis; *Prochuangia mansuyi* Zone, Korea. **4–6.** Indeterminate cranidium; *Liostracina simesi* Zone, Korea. **7–12.** Indeterminate hypostome 1; *Fenghuangella laevis* Zone, Korea. **13–15.** Indeterminate hypostome 2; *Neodrepanura* zone, Korea. **16, 17.** Indeterminate thoracic segment; *Neodrepanura* zone, Korea. **18–20.** Indeterminate pygidium; *Fenghuangella laevis* Zone, Korea.

Supplementary text: Systematic description of the polymerid trilobite taxa which were previously described in the literature or are treated under open nomenclature in this study.

Superfamily LEIOSTEGIOIDEA Bradley, 1925

Family LEIOSTEGIIDAE Bradley, 1925

Subfamily LEIOSTEGIINAE Bradley, 1925

Genus *Chuangia* Walcott, 1911

Type species: *Ptychoparia? batia* Walcott, 1905 from the Changshan Formation, Shandong, China (by original designation).

Chuangia sp. 1

Fig. S1

Material, horizon, and locality: Four incomplete cranidia, one librigena, three incomplete pygidia, and one hypostome; *Chuangia* Zone; JDA25-26 of the Jikdong Section, Korea.

Description: Cranidium trapezoidal in outline, moderately convex, with granulate prosopon. Glabella rectangular, two-thirds as wide as long, gently tapering forward, anteriorly weakly constricted in large specimens, defined by clearly incised axial furrows; lateral glabellar furrows faintly visible in large specimens. LO semi-elliptical; SO composite, moderately deep. Preglabellar field absent; anterior border upturned, weakly arched forwards; anterior border furrow deep. Palpebral lobes crescentic, medium-sized, located at glabellar mid-length, defined by moderately deep palpebral furrow. Fixigenae ca. one-half as wide as glabella. Facial suture opisthoparian; anterior branch of facial suture subparallel or slightly convergent convex; posterior branch of facial suture divergent convex. Posterior border short, defined by moderately deep border furrow.

Librigena crescentic in outline; genal field moderately wide, downsloping abaxially; genal spine short; lateral border moderately wide, defined by shallow border furrow; eye socle large; eye socle furrow moderately incised; doublure as broad as lateral border.

Hypostome subrectangular in outline with moderate convexity; middle body elongate; middle furrow weakly incised; anterior lobe oval in outline; posterior lobe crescentic; anterior margin broadly rounded; anterior border very short, ridge-like, delimited by shallow anterior border furrow; anterior wing short, triangular in outline; lateral border narrow, defined by moderately incised lateral border furrow.

Pygidium semi-elliptical in outline; axis weakly tapering backwards; pleural furrows poorly defined.

Remarks: Specimens available are too poorly preserved to be identified to the species level. One large cranidium (Fig. S1(4, 5)) has a granulate prosopon and weakly incised lateral glabellar furrows; however, these features are regarded as highly variable as seen in cranidia of *C. batia* (Zhang and Jell, 1987), and can be treated as intraspecific variation.

Subfamily PAGODIINAE Kobayashi, 1935

Genus *Prochuangia* Kobayashi, 1935

Type species: *Prochuangia mansuyi* Kobayashi, 1935 from the *Prochuangia* Zone, Sesongni, Korea; by original designation.

Prochuangia mansuyi Kobayashi, 1935

Fig. S2

1915. *Chuangia nais* Walcott - Mansuy, p. 20, pl. 2, fig. 14a–g.

1935. *Prochuangia mansuyi* nov. sp. - Kobayashi, p. 186, pl. 8, fig. 8; pl. 10, figs. 1–7.

1965. *Prochuangia mansuyi* Kobayashi - Lu et al., p. 414, pl. 78, figs. 18–21.

1994. *Prochuangia mansuyi* Kobayashi - Qian, p. 129, pl. 31, figs. 1–7.

Material, horizon, and locality: Two incomplete cranidia, one juvenile cranidium, two incomplete pygidia, and one librigena; *Prochuangia* Zone; JDA19-21, 23, 24 of the Jikdong Section, Korea.

Remarks: Although the fragmentary specimens make it difficult to compare with other species of *Prochuangia*, they are referred to *P. mansuyi*, as the orientation of posterolateral pygidial spines is comparable to that of *P. mansuyi*.

Superfamily DAMESELLOIDEA Kobayashi, 1935

Family DAMESELLIDAE Kobayashi, 1935

Subfamily DREPANURINAE Hupé, 1953

Genus *Neodrepanura* Özdikmen, 2006

Type species: *Drepanura premesnili* Bergeron, 1899 from the Kushan Formation of North China.

Remarks: The name *Drepanura* was preoccupied by a collembolan insect (Schoett, 1891) and Özdikmen (2006) proposed *Neodrepanura* to replace *Drepanura* Bergeron, 1899.

Neodrepanura sp. 1

Fig. S3

Material, horizon, and locality: Seven cranidia and one incomplete juvenile pygidium; *Neodrepanura* Zone; JDA10-JDA11 of the Jikdong Section, Korea.

Description: Cranidium subtrapezoidal in dorsal view, twice as wide as long. Glabella convex, three-fourths of cranidial length, parallel-sided at posterior half and abruptly tapering in anterior half, but parallel-sided in smaller cranidia; three pairs of lateral glabella furrows; S1 oblique rearwards, convex, deeply incised; S2 short, oblique rearwards, straight; S3 indistinct. LO transversely elliptical, relatively long, ca. one-fourth of cranidial length, with a median node; SO composite, clearly incised. A pair of faint bacculae flanking L1 separated from glabella by deep axial furrow. Anterior cranidial border very short; no preglabellar field. Palpebral lobes crescentic, medium in size, upsloping abaxially, located at anterior one-fourth of cranidial length, close to glabella; palpebral area narrow; palpebral furrow indistinct. Posterior field subtriangular, wider than long, weakly downsloping abaxially. Posterior border one-half as long as occipital ring, becoming longer abaxially; posterior border furrow moderately incised. Facial suture opisthoparian; anterior branch of facial suture absent; posterior branch of facial suture divergent convex.

Immature pygidium retaining the posteriormost thoracic segment, bearing a pair of long anterior marginal spines and five pairs of short marginal spines. Axis tapering backwards, not reaching to posterior margin.

Remarks: The largest cranidium in the collection is about 2.8 mm long and has a strongly forward-tapering glabella (Fig. S3(5–8)). Without complete holaspide pygidia, it is not possible to make identification to the species level. The immature pygidium at hand (Fig. S3(4)) retains the posterior-most thoracic segment, and it is considered to represent the meraspide degree 11, given the fact that *Neodrepanura* possessed twelve thoracic segments (Zhang and Jell, 1987: p. 207). This meraspide pygidium possesses five pairs of short marginal spines behind the macropleural spines, which is one pair less than so-far reported pygidia of *Neodrepanura* (cf. Zhang and Jell, 1987), probably due to its not yet proliferated posterior-most spine pair.

Subfamily DORYPYGELLINAE Kobayashi, 1935

Genus *Teinistion* Monke, 1903

Type species: *Teinistion lansi* Monke, 1903 from the Kushan Formation, Yan-tzy-yai, Shandong, China [subsequently designated by Vogdes (1925)].

Teinistion sp. 1

Fig. S4

Material, horizon, and locality: Six cranidia, three librigenae, and two pygidia; *Neodrepanura* Zone; JDA10-JDA11 of the Jikdong Section, Korea.

Description: Cranidium subrectangular in dorsal view, as long as wide, but wider than long in smaller specimens. Glabella convex, weakly tapering forwards, with rounded glabellar front; lateral glabellar furrows indistinct; axial furrows deep and clearly incised, becoming shallower anteriorly; preglabellar furrow weakly defined. LO crescentic, short, wider than glabellar base; SO simple, straight. Preglabellar field very short, flat. Anterior cranial border slightly upturned; anterior cranial margin weakly angulate. Palpebral lobes kidney-shaped, highly elevated, defined by moderately shallow palpebral furrow, located at glabellar mid-length; eye-ridges faintly visible. Facial sutures opisthoparian; anterior branch of facial suture divergent, straight; posterior branch of facial suture transverse adaxially, curved smoothly backwards distally. Posterior border shorter than occipital ring, becoming longer abaxially, with acute genal angle; posterior border furrow transverse, clearly incised.

Librigena crescentic in outline; genal field narrow, downsloping abaxially; genal spine more than 1.5 times long as genal area, but as long as genal area in small librigena; lateral border moderately wide, defined by distinct border furrow which continues down to genal angle; eye socle large, elevated; eye socle furrow moderately incised; cephalic doublure slightly wider than lateral border; adaxial tip of cephalic doublure straight.

Pygidium semicircular in dorsal view, with six pairs of marginal spines; length of marginal spines progressively shorter posteriorly, but fourth marginal spine slightly longer than third one. Axis strongly convex, narrow, tapering rearwards, with four axial rings and a terminal piece, reaching to posterior margin by post-axial ridge; first two pleural furrows clearly defined.

Remarks: The small cranidia resemble those of *Teinistion posterocostum* (Yang in Zhou et al., 1977) in having an angulate anterior cranial margin, but differ in showing a poorly defined glabellar front. The largest cranidium (Fig. S4(3–5)) is unique in displaying strong convexity with highly elevated palpebral lobes. The illustrated pygidium (Fig. S4(6)) has six pairs of pleural spines, while the pygidium of *Teinistion posterocostum* was known to have seven pairs of pleural spines (Peng et al., 2004).

Superfamily ASAPHOIDEA Salter, 1864

Family CERATOPYGIDAE Linnarsson, 1869

Ceratopygid genus and species indeterminate 1

Fig. S5(1–21)

Material, horizon, and locality: Eighteen cranidia, five hypostomes, 11 librigenae, and five pygidia; *Fenghuangella laevis* and *Prochuangia mansuyi* zones; JDA15-18, 20, 23, and 24 of the Jikdong section, Korea.

Description: Cranidium sub-trapezoidal in dorsal view, weakly convex. Glabella subtrapezoidal, tapering forwards with truncated to broadly rounded glabellar front; three-fourths and one-third of cranial length and width respectively; glabellar furrows obsolete; S1 oblique backwards and shallow. LO crescentic to subrectangular, slightly arched rearwards; SO composite, moderately incised. Preglabellar field flat, shorter than, or as long as anterior cranial border; anterior cranial border convex, arched forward, defined by

weakly impressed anterior border furrow. Palpebral lobes medium-sized, one-fourth to one-third of cranial length, crescentic, located at glabellar midpoint, close to but not attached to glabella, defined by faint palpebral furrow; palpebral area flat. Posterior fixigena short and weakly downsloping rearward. Posterior border short, shorter than occipital ring, becoming longer abaxially, defined by clearly impressed posterior border furrow. Facial sutures opisthoparian; anterior branch of facial suture weakly divergent, straight; posterior branch of facial suture strongly divergent to nearly transverse, convex.

Hypostome semi-circular in outline with high convexity, but smaller specimens elongate in outline; circular middle body divided by wide and shallow middle furrows; anterior lobe circular; posterior lobe crescentic in outline. Anterior margin indented rearward in the middle; anterior border moderately downsloping forward; anterior border furrow wide and moderately deep. Anterior wing slightly pointed outward, directed obliquely upward, continued to lateral border; lateral border narrow, delimited by moderately deep lateral border furrow. Posterior wing moderately long, pointing upward. Posterior border narrow, delimited by posterior border furrow, continued from lateral border furrow.

Librigena with narrow and abaxially downsloping genal field differentiated from lateral border by shallow border furrows; lateral border wide, weakly convex; posterior border short; genal spine short; eye socle crescentic, elevated; cephalic doublure as wide as lateral border, becoming broader adaxially.

Pygidium semicircular, weakly convex, gently effaced; length about three-fifths of width. Axis narrow and moderately convex, one-fourth of pygidial width, tapering rearwards, not reaching to posterior margin of pygidium; axial rings indiscernible. Pleural field very weakly convex; posterior border indistinguishable; pygidial doublure moderately wide, narrowing abaxially.

Remarks: The cranidia resemble those of *Yuepingia glabra* Palmer, 1968, but differ in having a smaller glabella and longer preglabellar field. When articulated, the adaxially widening cephalic doublures of librigenae probably form a tumid angle in the center pointing rearward, which would have fitted to the indented anterior margin of the hypostome, suggesting that this primitive ceratopygid group possessed a conterminant hypostomal condition.

Ceratopygid genus and species indeterminate 2

Fig. S5(22–24)

Material, horizon, and locality: One cranidium and one immature pygidium; *Chuangia* Zone; JDA25 of the Jikdong section, Korea.

Remarks: The cranidium is poorly preserved, but can be distinguished from ceratopygid genus and species indeterminate 1 by its shorter preglabellar field and more strongly divergent anterior branch of facial suture. The associated pygidium possesses a pair of short posterior spines, but is very small, less than 0.8 mm in length, presumably representing a meraspid stage.

Superfamily TRINUCLEOIDEA Hawle and Corda, 1847

Family LIOSTRACINIDAE Raymond, 1937

Genus *Liostracina* Monke, 1903

Type species: *Liostracina krausei* Monke, 1903 from the *Neodrepanura* Zone, Kushan Formation, near Yanzhuang, Shandong, China (by original designation).

Remarks: Öpik (1967) thoroughly discussed the generic concept of *Liostracina*, which is followed here. Fortey and Chatterton (1988) suggested *Liostracina* as a candidate for the Cambrian sister group of the Ordovician trinucleoids. Chatterton et al. (1994) found the subtriangular rostral plate in the Ordovician trinucleoid protaspides, which is lost with

subsequent growth. They suggested that this transient subtriangular rostral plate may have occurred in the phylogeny, which means that the possible ancestral sister taxa of the Trinucleoidea would have had the subtriangular rostral plate in adult stage. In this respect, it is interesting to observe the subtriangular rostral plate in one enrolled juvenile specimen of *Liostracina simesi* in this study: i.e., an enrolled specimen of *L. simesi* representing the degree 2 meraspis reveals the empty space for a subtriangular rostellum (Fig. S6(31–32)). The obliquely truncated anterior end of cephalic doublure (Fig. S6(15–20)) also suggests that the rostellum or a triangular rostral plate persisted throughout ontogeny, supporting the interpretation of Chatterton et al. (1994). However, the presence of the rostellum in *L. simesi* is not consistent with the presence of the ventral median suture in *L. volens* Öpik, 1967. In addition, a cranidium of *Liostracina* sp. 1 illustrated in this study shows a bizarre structure in the place of rostral plate (Fig. S7(9–12)), which has not previously been observed in other trilobites.

Liostracina simesi Jago and Cooper, 2005

Fig. S6

2005. *Liostracina simesi* nov. sp. - Jago and Cooper, p. 671, fig. 4A–E.

Material, horizon, and locality: More than two hundred specimens of cranidia, librigenae, and pygidia; *Liostracina simesi* Zone; JDA11-14 of the Jikdong Section, Korea.

Description: The cranidial morphology was well described by Jago and Cooper (2005). Descriptions for newly discovered pygidia and librigenae are added below.

Librigena crescentic in dorsal view; genal field narrow, convex, downsloping abaxially; lateral border relatively broad, poorly defined by shallow border furrow; eye socle small, weakly elevated; cephalic doublure slightly broader than lateral border; rostral plate presumably subtriangular. Surface ornamented with pustules.

Pygidium semi-elliptical, length ca. 0.4 width. Axis convex, conical, tapering gradually backwards, reaching to border furrow; three axial rings and a rounded terminal piece; axial rings bearing a pair of tubercles in smaller specimens. Pleural field flat, wider than axis; pleurae bearing transversely aligned pustules; pleural furrows reaching border furrow; border very narrow, uniform in width.

Remarks: The present specimens are nearly identical to the type material of *L. simesi* from Antarctica (Jago and Cooper, 2005). The pustules on cranidial surface are more densely distributed in the pre-ocular area. The intensity of pustules seems to vary with ontogeny as tubercles are prominent on the glabella and pygidial axis of smaller specimens, and somewhat reduced in larger specimens.

Liostracina sp. 1

Fig. S7

Material, horizon, and locality: Three cranidia and four librigenae; *Neodrepanura* Zone; JDA10-JDA11 of the Jikdong Section, Korea.

Remarks: The illustrated cranidia are similar in outline to *L. krausei*, but differ in having higher convexity and shorter preglabellar field with deeply incised median preglabellar furrow, and in lacking bacculae. The librigena is crescentic in outline and has a moderately wide lateral border defined by deeply incised border furrow. The genal spine initially projects backward, and then curves smoothly inward, forming a broadly arched librigena. The cephalic doublure bears rows of terrace lines sub-parallel to the margin. One cranidium (Fig. S7(7–12)) displays a peculiar ventral structure which may be a fused rostral plate or a ventral extension of the anterior cranial border.

Superfamily ASAPHISCOIDEA Raymond, 1924

Family CATILLICEPHALIDAE Raymond, 1938

Genus *Huzhuia* Chu, 1965

Type species: *Huzhuia typica* Chu, 1965 from the middle Cambrian at Xiaoshiwan, Huzhu, Qinghai Province, China (by original designation).

Huzhuia sp. 1

Fig. S8(1–8)

Material, horizon, and locality: Five cranidia and one putative pygidium; *Neodrepanura* Zone; JDA10-JDA11 of the Jikdong Section, Korea.

Description: Cranidium convex, subtrapezoidal in outline, with broadly rounded anterior margin; wider than long. Glabella convex, rectangular, width ca. 80% of length, 40% of cranidial width, clearly defined by parallel-sided axial furrows and rounded glabellar front; axial furrows not defined. LO crescentic with stout median spine; SO transverse, simple. Preglabellar field very short, shorter than anterior cranidial border, flat. Anterior cranidial border short, weakly convex, broadly bent forwards; anterior border furrow shallow, but clearly impressed. Palpebral lobes small, located at anterior two-thirds of cranidial length; eye ridges faintly visible; palpebral area convex, ca. two-thirds of glabellar width. Posterior fixigenal field long and wide; posterior border shorter than occipital ring, widening abaxially, defined by nearly transverse, clearly incised posterior border furrow. Facial suture opisthoparian; anterior branch of facial suture convergent straight; posterior branch of facial suture divergent straight.

Pygidium semielliptical in outline, weakly convex; axis tapering rearwards with two or three axial rings and a terminal piece; pleural and interpleural furrows faintly incised.

Remarks: *Huzhuia* sp. 1 may be comparable to *Liaotropis tropis* Schrank, 1975 or *Huzhuia curvata* Peng et al., 2004 in having small palpebral lobes, broadly arched anterior cranidial border, and very short preglabellar field. However, assignment to either species is not possible due to poor preservation of the present material.

Huzhuia sp. 2

Fig. S8(9–11)

Material, horizon, and locality: Two juvenile cranidia; *Prochuangia mansuyi* Zone; JDA21 and 23 of the Jikdong Section, Korea.

Remarks: The two immature cranidia are similar in outline to *Huzhuia* sp. 1, but are too small to make a confident identification to the species level, hence left in open nomenclature. The specimens are small, less than 1.2 mm in length, and show narrow eye ridges.

Genus *Placosema* Öpik, 1967

Type species: *Placosema caelatum* Öpik, 1967 from the *Eridiaspis eretes* and *Acmahachis quasivespa* zones (Mindyallan) of Queensland, Australia (by original designation).

Remarks: *Placosema* was erected on the basis of cranidia having a forwardly steeply downsloping subquadrate glabella, small palpebral lobes situated at glabellar mid-length, absence of preglabellar field, transverse anterior cranidial border, and convergent anterior branches of facial sutures. Pratt (1992) treated *Placosema* as a junior synonym of *Genevievella* Lochman, 1936, but the latter is considered to be distinct from the former in having a more strongly tapering glabella, larger palpebral lobes, broadly arched anterior cranidial border, and transverse, rather than divergent convex, posterior branches of facial

sutures. *Placosema* has been documented from Australia (Öpik, 1967), South China (Peng et al., 2004), and Korea (this study), whereas *Genevievella* is restricted to Laurentia.

Placosema bigranulosum Peng, Babcock and Lin, 2004

Fig. S9

1996. *Pagodia* sp. - Cooper, Jago, and Begg, p. 379, fig. 7I–K, P, Q, T.

2004. *Placosema bigranulosum* nov. sp. - Peng, Babcock, and Lin, p. 68, pl. 26, figs. 1–7.

Material, horizon, and locality: Four cranidia, one fragmentary pygidium, and two fragmentary librigenae; *Fenghuangella laevis* Zone; JDA14-16 of the Jikdong section, Korea.

Remarks: The specimens at hand are closely similar to *Placosema bigranulosum* from the *Liostracina bella* and *Chuangia subquadrangulata* zones of Hunan Province, South China (Peng et al., 2004). Notably the largest specimen (Fig. S9(6)) is indistinguishable from the specimens from China, but the associated smaller specimens lack granules which characterize *P. bigranulosum*. The lack of granules in smaller specimens, however, may be a morphological feature of immature specimen of this species. They also bear a strong resemblance to *Pagodia* sp. from the northern Victoria Land, Antarctica (Cooper et al., 1996), which was known to occur from the strata above the *Glyptagnostus reticulatus*-occurring horizon. *Onchonotellus convexus* Qian, 1994 from the *Chuangia* Zone of Liaoning Province, North China is also comparable to this species, but its poor preservation makes it difficult to recognize the morphological details.

A fragmentary pygidium and two incomplete librigenae are provisionally assigned to this species. The axis of the pygidium is comparatively wide with three or four axial rings and a terminal piece, and the librigenae have very broad lateral border which becomes progressively narrower forwardly.

Undetermined trilobite sclerites

Family uncertain

Indeterminate protaspis

Fig. S10(1–3)

Material, horizon, and locality: One protaspis exoskeleton; *Prochuangia mansuyi* Zone; JDA22 of the Jikdong Section, Korea.

Remarks: The illustrated exoskeleton is too poorly preserved to be described in detail. The protaspis is inverted triangular in outline and has a moderate convexity and three pairs of marginal spines. This protaspis is not as bulbous as the asaphoid protaspides, but certainly more bulbous than the middle Cambrian ptychopariid protaspides (see Fortey and Chatterton, 1988; Chatterton and Speyer, 1997).

This protaspis is associated with *Alataspis sesongensis* and a few fragments of *Parachangshania monkei*. It is distinct from the protaspides of *A. sesongensis* in having three pairs of marginal spines, and thus this protaspis might be assignable to *Parachangshania monkei*. However, without concrete evidence for the protaspis of *P. monkei*, this protaspis is left in open nomenclature.

Indeterminate cranidium

Fig. S10(4–6)

Material, horizon, and locality: One small cranidium; *Liostracina simesi* Zone; JDA12 of the Jikdong section, Korea.

Description: Cranidium trapezoidal in outline, moderately convex. Glabella sub-parallel, downsloping in frontal part; axial furrow moderately deep; S1 deep, directing obliquely backward, S2, S3 not recognizable due to poor preservation; Occipital ring sub-

rectangular, defined by deep occipital furrow. Anterior cranial border transverse, short, defined by moderately incised border furrow. Posterior border widening outward; posterior border furrow moderately incised. Palpebral lobe medium to small sized, elevated, kidney-shaped, located in front of glabellar midlength. Anterior branch of facial suture slightly converging forward. Posterior branch of facial suture diverging significantly rearward.

Remarks: The illustrated cranidium is about 1 mm in length, thus probably representing a juvenile stage. This cranidium is associated with *Liostracina simesi* and *Parachangshania rectangularis*, and neither of these species is morphologically comparable to this juvenile cranidium.

Indeterminate hypostome 1

Fig. S10(7–12)

Material, horizon, and locality: Two hypostomes; *Fenghuangella laevis* Zone; JDA16 of the Jikdong section, Korea.

Description: Semi-circular in outline, with high convexity; middle body sub-rectangular; middle furrow moderately incised; anterior lobe semi-circular in outline; posterior lobe crescentic, short, one-sixth of hypostomal length. Anterior margin straight; anterior border narrow, slightly downsloping forward. Anterior wing moderately long, directed obliquely upward, with lateral margin rounded, continued to lateral border; lateral border moderately wide, defined by well incised lateral border furrow. Posterior wing short, pointing upward, with rounded tip.

Remarks: The high convexity, circular outline, and stratigraphic association suggest that these hypostomes may belong to either *Fenghuangella laevis* or *Placosema bigranulosum*.

Indeterminate hypostome 2

Fig. S10(13–15)

Material, horizon, and locality: Two hypostomes; *Neodrepanura* Zone; JDA10 and 11 of the Jikdong section, Korea.

Description: Semi-oval in outline with moderate convexity; middle body elongate; middle furrow weakly incised; anterior lobe subrectangular in outline; posterior lobe subtriangular. Anterior margin bearing tongue-like anterior extension downsloping forward; anterior border moderately wide, delimited by wide and shallow anterior border furrow. Anterior wing extending outward as far as one half length of hypostome, slightly curved forward; anterior border furrow continuing on anterior wing. Lateral border wide defined by well incised lateral border furrow. Posterior border moderately wide, rounded; posterior border furrow well incised. Posterior wing pointing upward.

Remarks: The illustrated hypostome is characterized by a tongue-like extension in the middle of anterior margin and long anterior wings. The tongue-like structure extending forward from this hypostome has not been reported in trilobites. The closely comparable example would be the tongue-like structure extending rearward from rostral plate of an Ordovician proetid *Dimeropyge* (Chatterton, 1994: fig. 6.5). The downsloping tongue-like structure of this hypostome may have connected to the rostral plate or doublure when articulated.

Indeterminate thoracic segments

Fig. S10(16, 17)

Material, horizon, and locality: Two thoracic segments; *Neodrepanura* Zone; JDA10 and 11 of the Jikdong section, Korea.

Description: Rectangular in outline excluding pleural spine. Axis convex, occupying over 80% of width; a few pustules distributed on surface; articulating half ring slightly curved forward. Pleural field flat, narrow, bearing small node-like structure where pleural spine begins. Pleural spine projecting from anterior band, moderately upturned outward, directing obliquely backward. Pleural spine as long as 80% of width of thorax excluding pleural spine.

Indeterminate pygidium
Fig. S10(18–20)

Material, horizon, and locality: One pygidium; *Fenghuangella laevis* Zone; JDA16 of the Jikdong section, Korea.

Description: Semi-oval in outline with moderate convexity. Axis moderately tapering rearward, not reaching posterior margin; at least five axial lobes present including terminal piece; posterior margin slightly indented forward. Four pairs of pleural furrows moderately incised, continuing onto four pairs of short pleural spines; interpleural furrows weakly incised.

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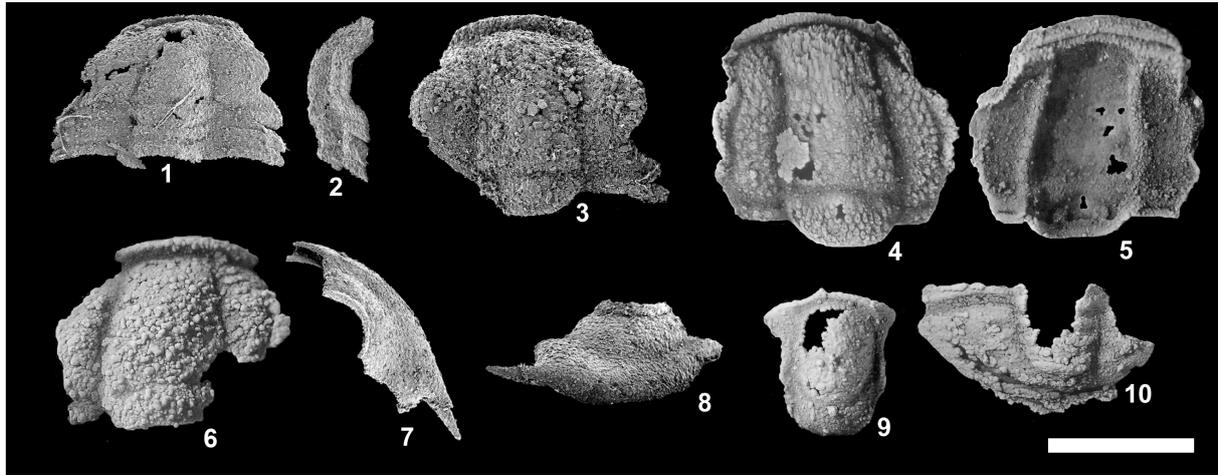


Figure S1. 1–10. *Chuangia* sp. 1; *Chuangia* zone, Korea. 1, 2, SNUP4515, cranidium with first two thoracic segments retained; dorsal and lateral views; 3, SNUP4753, cranidium; 4, 5, SNUP4516, cranidium; dorsal and ventral views; 6, SNUP4517, cranidium; 7–8, SNUP4754, librigena; dorsal and lateral views; 9, SNUP4518, hypostome; 10, SNUP4519, pygidium. Scale bar = 1.33 mm (1–3), 2.5 mm (4–5, 7–8, 10), 2 mm (6), 2.22 mm (9).

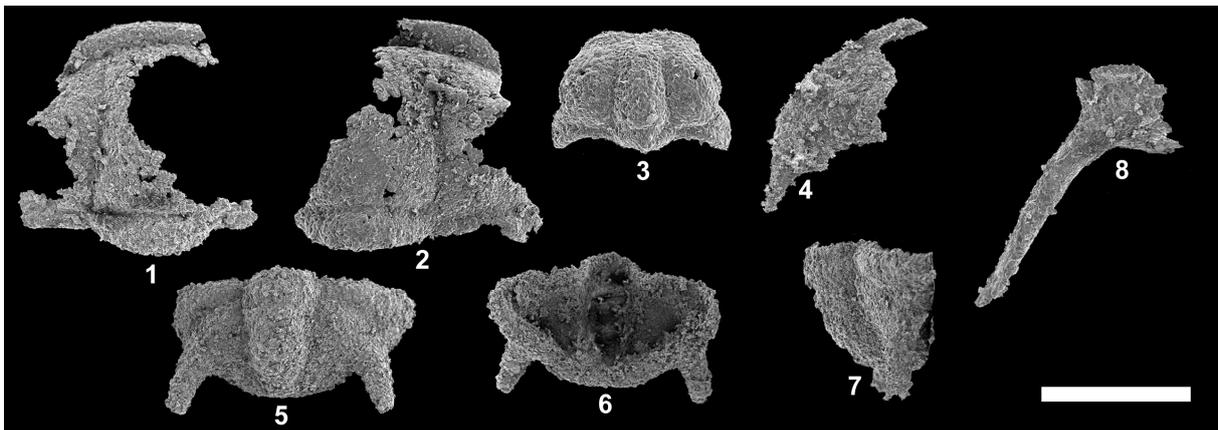


Figure S2. 1–8. *Prochuangia mansuyi* Kobayashi, 1935; *Prochuangia mansuyi* Zone, Korea. 1, SNUP4521, cranidium; 2, SNUP4522, cranidium; 3, SNUP4523, immature cranidium; 4, SNUP4524, librigena; 5–7, SNUP4525, pygidium; dorsal, ventral, and lateral views; 8, SNUP4526, fragmentary pygidium. Scale bar = 1.33 mm (1–2, 4–8), 1 mm (3).

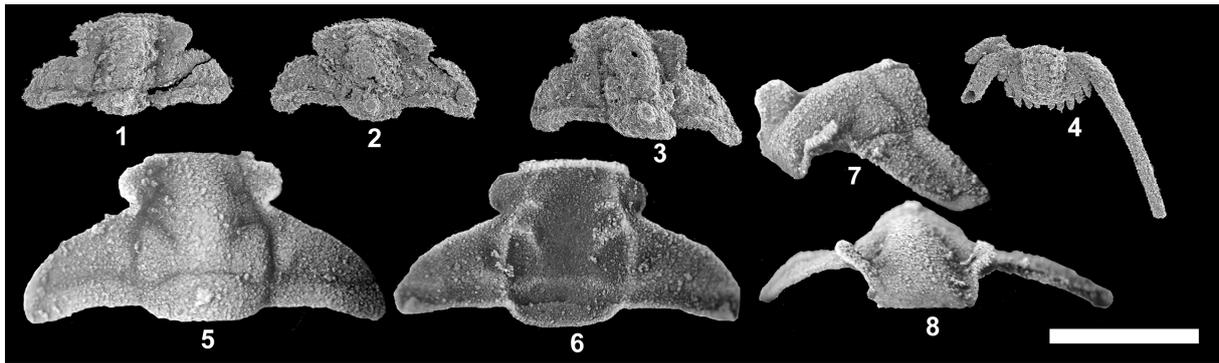


Figure S3. 1–8. *Neodrepanura* sp. 1; *Neodrepanura* zone, Korea. 1, SNUP4527, cranidium; 2, SNUP4528, cranidium; 3, SNUP4529, cranidium; 4, SNUP4530, degree 11 meraspid pygidium; 5–8, SNUP4531, cranidium; dorsal, ventral, oblique antero-lateral, and anterior views. Scale bar = 1.33 mm (1–4), 2.5 mm (5–8).

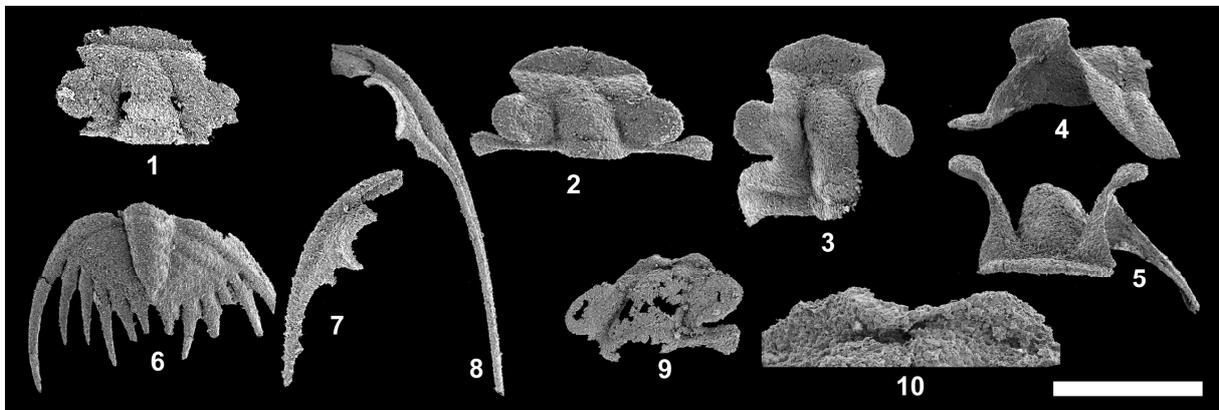


Figure S4. 1–10. *Teinistion* sp. 1; *Neodrepanura* zone, Korea. 1, SNUP4532, incomplete cranidium; 2, SNUP4533, cranidium. 3–5, SNUP4534, cranidium; dorsal, lateral, and anterior views; 6, SNUP4535, pygidium; 7, SNUP4536, librigena; 8, SNUP4849, librigena; 9, 10, SNUP4537, cranidium with teratological structure; 9, cranidium; 10, magnified view of the anterior cranial border with teratological structure. Scale bar = 2 mm (1–7, 9), 2.5 mm (8), 0.5 mm (10).

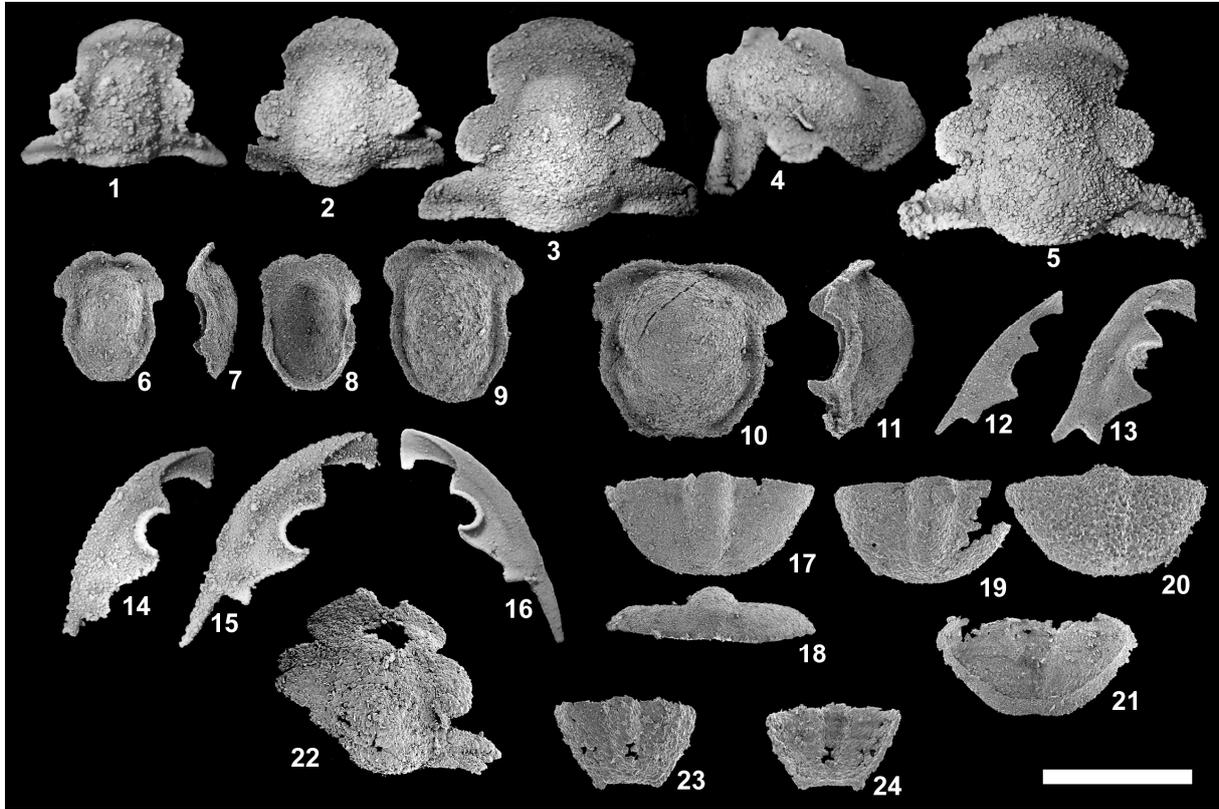


Figure S5. 1–21. Ceratopygid genus et species indeterminate 1; *Fenghuangella laevis* and *Prochuangia mansuyi* zones, Korea. 1, SNUP4546, cranidium; 2, SNUP4547, cranidium; 3, 4, SNUP4548, cranidium; dorsal and oblique lateral views; 5, SNUP4549, cranidium; 6–8, SNUP4550, hypostome; ventral, lateral, and dorsal views; 9, SNUP4551, hypostome; 10, 11, SNUP4552; hypostome; ventral and lateral views; 12, SNUP4553, librigena; 13, SNUP4554, librigena; 14, SNUP4555, librigena; 15, SNUP4556, librigena; 16, SNUP4557, librigena; 17, 18, SNUP4558, pygidium; dorsal and posterior views; 19, SNUP4559, pygidium; 20, SNUP4560, pygidium; 21, SNUP4561, pygidium; ventral view. 22–24. Ceratopygid genus et species indeterminate 2; *Chuangia* zone, Korea. 22, SNUP4562, cranidium; 23, 24, SNUP4563, immature pygidium; dorsal and ventral views. Scale bar = 2.86 mm (1–5), 2 mm (6–11, 17–21), 2.5 mm (12–13), 4 mm (14–16), 1.33 mm (22–24).

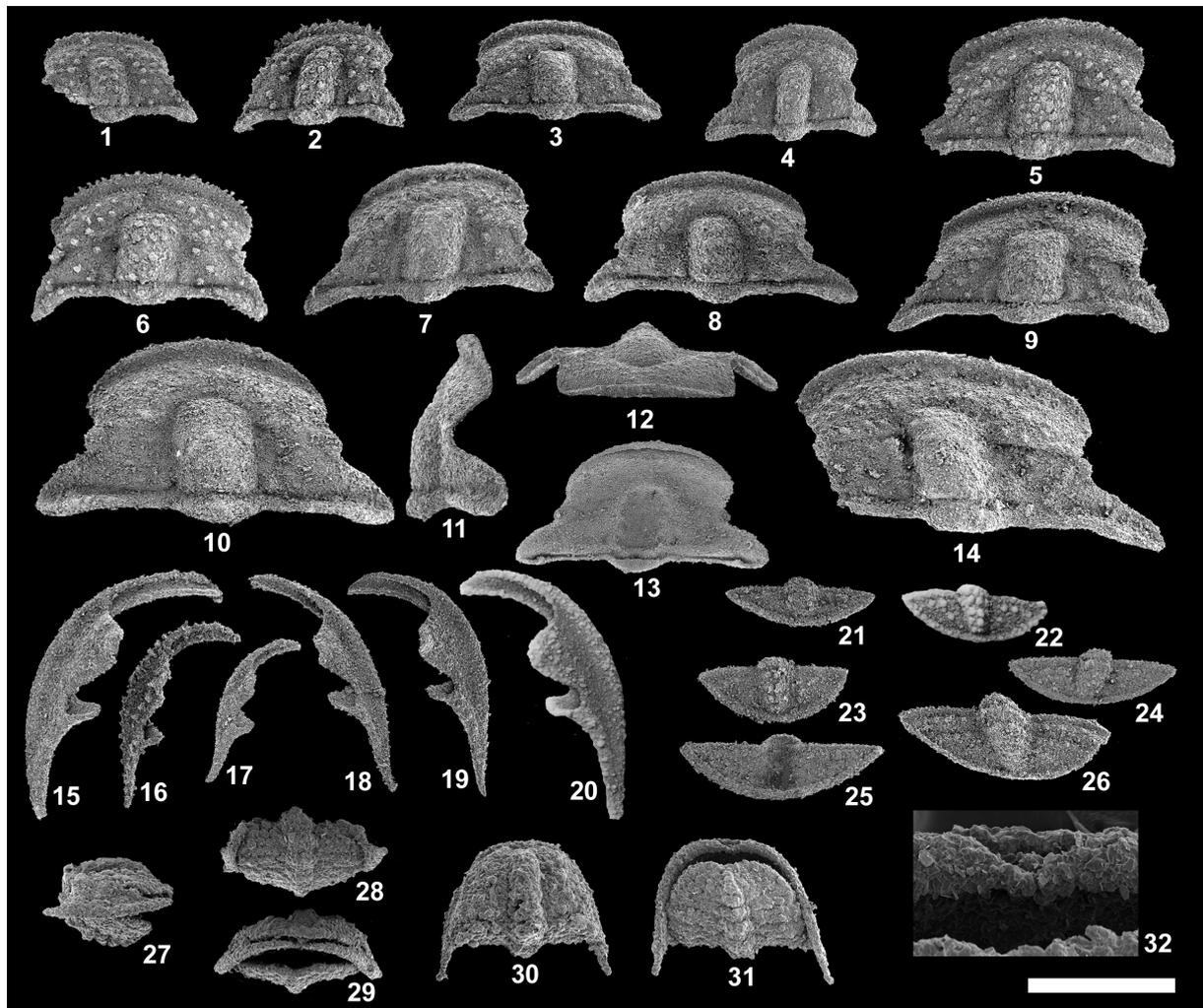


Figure S6. 1–32. *Liostracina simesi* Jago and Cooper, 2005; *Liostracina simesi* Zone, Korea. 1, SNUP4564, cranidium; 2, SNUP4565, cranidium; 3, SNUP4566, cranidium; 4, SNUP4567, cranidium; 5, SNUP4568, cranidium; 6, SNUP4569, cranidium; 7, SNUP4570, cranidium; 8, SNUP4571, cranidium; 9, SNUP4572, cranidium; 10–13, SNUP4573, cranidium; 10, dorsal view; 11, lateral view; 12, anterior view; 13, ventral view; 14, SNUP4574, cranidium; 15, SNUP4575, librigena; 16, SNUP4576, librigena; 17, SNUP4577, librigena; 18, SNUP4578, librigena; 19, SNUP4579, librigena; 20, SNUP4580, librigena; 21, SNUP4581, pygidium; 22, SNUP4582, pygidium; 23, SNUP4583, pygidium; 24, SNUP4584, pygidium; 25, SNUP4585, pygidium, ventral view; 26, SNUP4586, pygidium; 27–32, SNUP4587, articulated degree 2 meraspis in enrolled posture; lateral, posterior, anterior, dorsal, and ventral views; 32, magnified view of ventral side of cephalic doublure; note the space for sub-triangular rostral plate. Scale bar = 2 mm (1–11, 14–26), 2.86 mm (12–13), 1 mm (27–31), 0.2 mm (32).

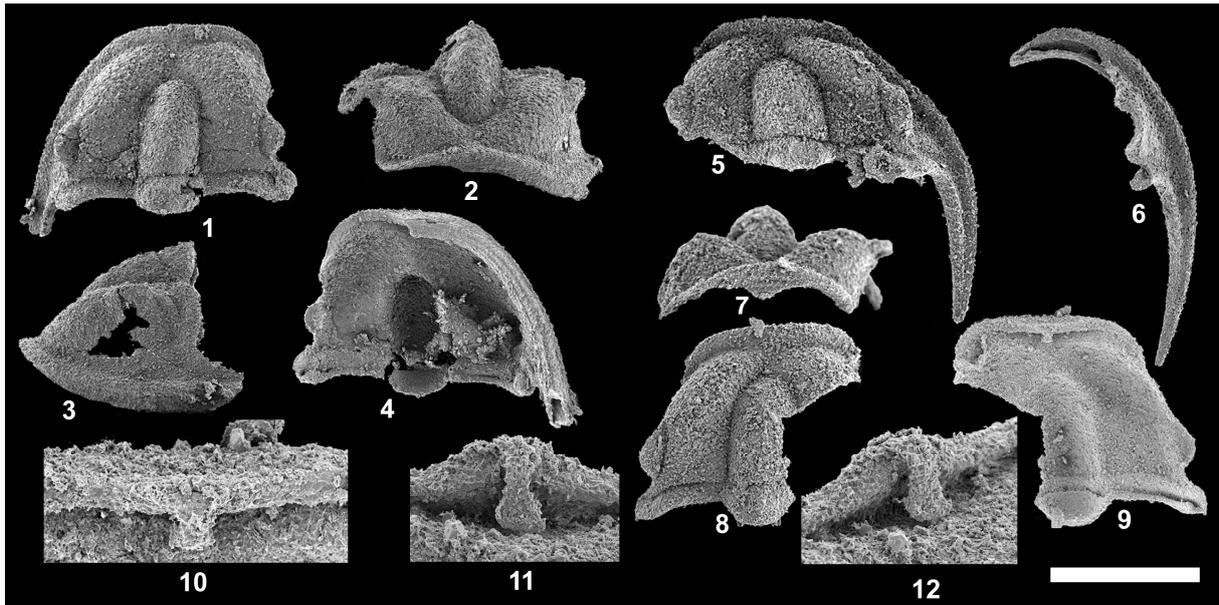


Figure S7. 1–12. *Liostracina* sp. 1; *Neodrepanura* zone, Korea. 1–4, SNUP4588, cranidium with left librigena articulated; dorsal, anterior, lateral, and ventral views; 5, SNUP4589, cranidium with right librigena articulated; 6, SNUP4590, librigena; 7–9, SNUP4591, cranidium; anterior, dorsal, and ventral views; 10–12, magnified views of the peculiar ventral structure which may be a fused rostral plate or a ventral extension of anterior cranial border; ventral, postero-ventral, and oblique postero-ventral views. Scale bar = 2 mm (1–9), 0.44 mm (10–12).

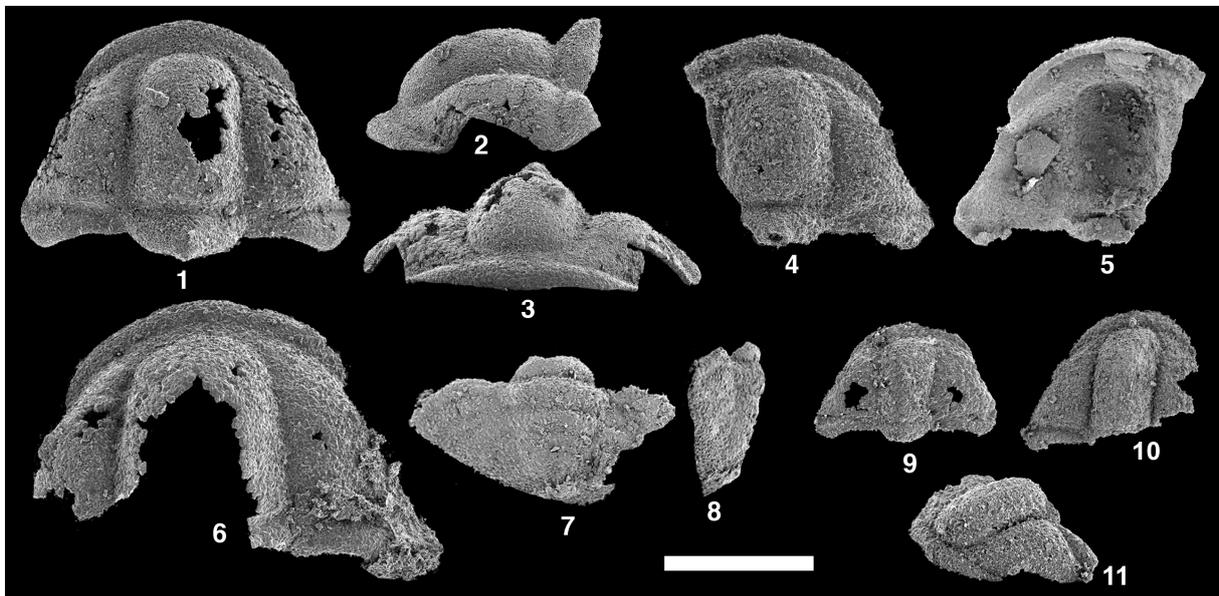


Figure S8. 1–8. *Huzhuia* sp. 1; *Neodrepanura* zone, Korea. 1–3, SNUP4623, cranidium; dorsal, lateral, and anterior views; 4–5, SNUP4624, cranidium; dorsal and ventral views; 6 SNUP4625, incomplete cranidium; 7–8, SNUP4850, fragmentary pygidium. 9–11. *Huzhuia* sp. 2; *Prochuangia mansuyi* Zone, Korea. 9, SNUP4626, cranidium; 10–11, SNUP4627, cranidium; dorsal and oblique antero-lateral views. Scale bar = 1.33 mm (1–6, 9–11), 2.86 mm (7–8).

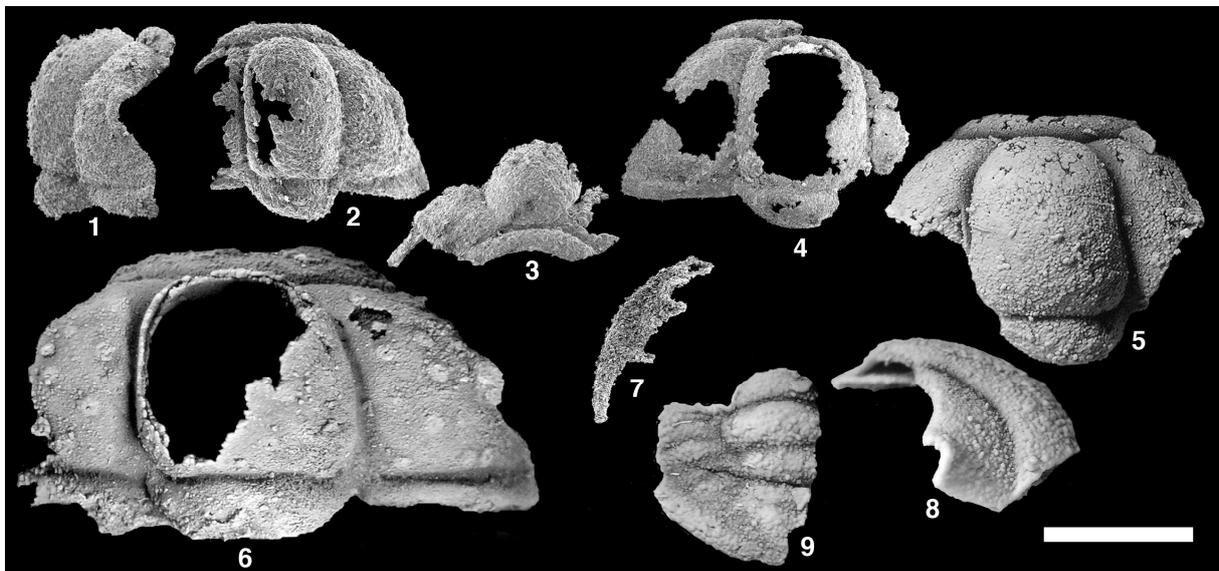


Figure S9. 1–9. *Placosema bigranulosum* Peng et al., 2004; *Fenghuangella laevis* Zone, Korea. 1–3, SNUP4628, cranidium; lateral, dorsal, and anterior views; 4, SNUP4629, incomplete cranidium; 5, SNUP4630, incomplete cranidium; 6, SNUP4631, cranidium; 7, SNUP4632, small librigena; 8, SNUP4633, incomplete librigena; 9, SNUP4634, incomplete pygidium. Scale bar = 1.33 mm (1–3), 2 mm (4, 7–9), 2.5 mm (5–6).

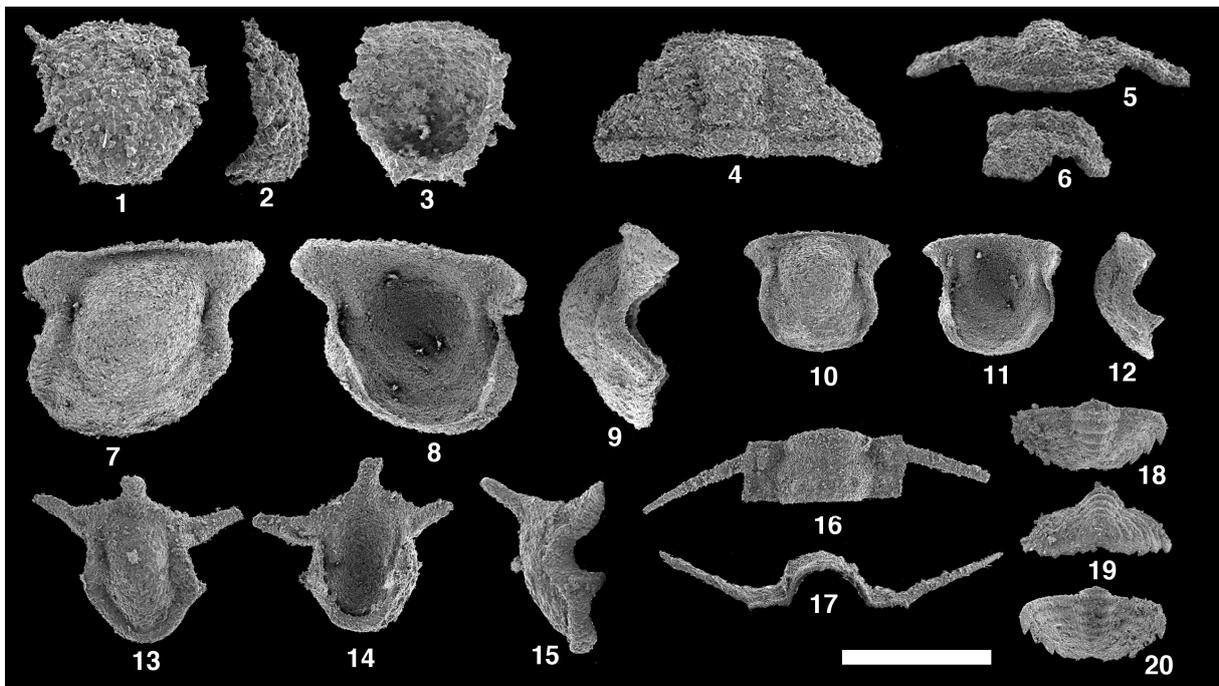


Figure S10. 1–3. Indeterminate protaspis; *Prochuangia mansuyi* Zone, Korea, SNUP4693; dorsal, lateral, and ventral views, note that the anteriormost spine was broken during the process of flipping over. 4–6. Indeterminate cranidium; *Liostracina simesi* Zone, Korea, SNUP4695; dorsal, anterior, and lateral views. 7–12. Indeterminate hypostome 1; *Fenghuangella laevis* Zone, Korea; 7–9, SNUP4695; ventral, dorsal, and lateral views; 10–12, SNUP4696; ventral, dorsal, and lateral views. 13–15. Indeterminate hypostome 2; *Neodrepanura* zone, Korea, SNUP4697; ventral, dorsal, and lateral views. 16, 17. Indeterminate thoracic segment; *Neodrepanura* zone, Korea, SNUP4698; dorsal and anterior views. 18–20. Indeterminate pygidium; *Fenghuangella laevis* Zone, Korea, SNUP4699; dorsal, posterior, and ventral views. Scale bar = 0.5 mm (1–3), 1 mm (4–6), 2 mm (7–12, 16–17), 1.33 mm (13–15, 18–20).