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Cambrian Series 3 trilobites from the lower part of the Machari Formation, Deoksang section, Yeongwol, Korea

영월 덕상 단면 마차리층 하부에서 산출된

캄브리아기 제3통 삼엽충

2014년 8월

서울대학교 대학원

지구환경과학부

홍 발

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Cambrian Series 3 trilobites from the lower part of the Machari Formation, Deoksang section, Yeongwol, Korea

Paul S. Hong

A dissertation submitted to Graduate School of
Seoul National University in partial fulfillment of
the requirement for the degree of Doctor of Philosophy

School of Earth and Environmental Sciences
Seoul National University

August, 2014

ABSTRACT

Cambrian Series 3 trilobites from the lower part of the Machari Formation, Deoksang section, Yeongwol, Korea

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The biostratigraphy of the Cambrian Series 3-equivalent part of the Machari Formation of Korea has not been well known compared to that of its Furongian interval due to scarce occurrence of trilobites: only three biozones, *Tonkinella*, *Lejopyge armata*, and *Glyptagnostus stolidotus* zones, have been established for the Cambrian Series 3. Well-preserved agnostoid trilobites were collected from a newly discovered locality about 12 km northwest of Yeongwol where the lowermost 10 m interval of the Machari Formation is well exposed. A total of 13 species from 14 horizons of two neighboring sections are identified: *Peronopsis taitzhuhoensis*, *Ptychagnostus sinicus*, *Ptychagnostus atavus, Yakutiana ovale*, *Hypagnostus parvifrons*, *Diplagnostus planicauda*, *Tomagnostella exsculpta*, *Lejopyge*

armata, *Kormagnostus minutus*, *Nahannagnostus nganasanicus*, *Pseudagnostus idalis*, *Glyptagnostus stolidotus*, and *Glyptagnostus reticulatus*. The lower part (ca. 5.8 m thick) is characterized by a massive bioclastic grainstone and yields the Cambrian Stage 5 trilobites previously known from the *Tonkinella* Zone. The middle part (ca. 1.7 m thick) is composed of dark gray wacke- to packstone and black shale. *Peronopsis taitzhuhoensis* and *Ptychagnostus sinicus* occur successively from the lower 1.2 m interval of the wacke- to packstone beds, while *Ptychagnostus atavus*, the index taxon of the base of the Drumian Stage, appears scarcely along with abundant *Yakutiana ovale* in the upper 0.5 m interval of the beds. The upper part (ca. 2.5 m thick) is a succession of laminated lime mudstone, and relatively diverse species including *Yakutiana ovale*, *Hypagnostus parvifrons*, *Diplagnostus planicauda*, *Tomagnostella exsculpta*, *Kormagnostus minutus*, and *Nahannagnostus nganasanicus* are recovered from the lower 1.4 m interval. Notably, *Lejopyge armata* is yielded at 1.2 m above the base of the interval, indicating that the boundary between the Drumian and the Guzhangian stages lies somewhere within the interval. *Glyptagnostus stolidotus* is recorded from the 1.6 m level, while *Glyptagnostus reticulatus* appears at the top of the interval. In short, the 10 m-thick interval of the section spans from the Cambrian Stage 5 to the lower part of the Paibian Stage. Two new biozones in ascending order, *Ptychagnostus sinicus* and *Ptychagnostus atavus* zones, are established

between the previously-known *Tonkinella* and *Lejopyge armata* zones.

This study reports the successive occurrence of *Ptychagnostus sinicus* Lu, 1957 and *Ptychagnostus atavus* (Tullberg, 1880) from the lower part of the Machari Formation. Morphometric approaches employing the landmark and principal component analyses make it possible to differentiate *P. sinicus* from *P. atavus* with clarity. Recognition of *P. atavus*, for the first time in Korea, allows define the base of the Drumian Stage in Korea and its correlation with other parts of the world.

Appearance of trilobite taxa endemic to North China as *Cyclolorenzella* and *Peronopsis taitzuhoensis* from the Yeongwol area extended the geological time of co-occurring endemic trilobite taxa between Yeongwol and North China from the Ordovician and Furongian ages to the older geological times of Cambrian Series 3.

…….....

Keywords: Machari Formation, trilobites, Cambrian Series 3, Yeongwol, geometric morphometrics

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Chapter 1

Introduction

1. 1. General statement

Despite the long history of paleontological studies on the Cambrian-Ordovician rocks of the Taebaeksan Basin in eastern-central Korean Peninsula (Fig. 1) as early as the 1930s (Kobayashi, 1934), the Cambrian Series 3 interval has received less attention in biostratigraphic studies than Furongian and Ordovician sequences. Acquiring biostratigraphic data is important because faunal contents often offer inferences to the geologic time, paleogeographic affinity, and paleoenvironmental characteristics of the region. Previous analyses on Cambrian-Ordovician faunal assemblages from the Taebaeksan Basin have already indicated close connections to North China (Choi et al., 2001; Choi and Kim, 2006; Choi, 2011). However, North China faunal signature does become weaker in the Furongian for the western side of the Basin where a deeper spatial setting is evident from its changes in lithology, and from the dominance of pandemic species over endemic ones in faunal contents. Combined with the ongoing argument on where the collisional suture of North and South China runs through in the Korean Peninsula, the western part of the Basin has sometimes been viewed as a separate sedimentary sequence more preferable to the South China in origin (Kobayashi, 1967; Cluzel et al., 1991).

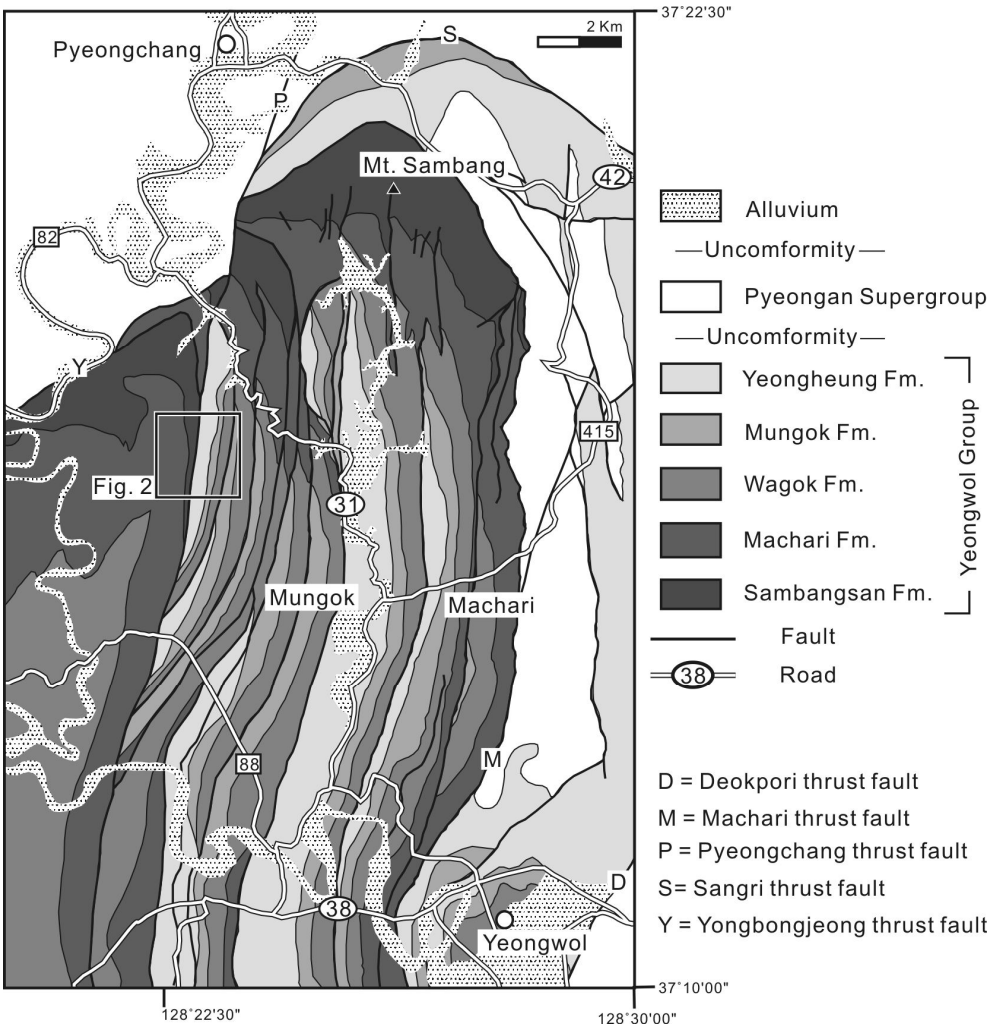

Figure 1. Geologic map of the Yeongwol area of the Taebaksan Basin in east-central Korean Peninsula. The black open box in the middle of the map represents the location of the fossil locality (Fig. 2).

A new locality in the western part of the Basin was uncovered recently that displayed continuous sequences of Cambrian Series 3 trilobites previously unknown from Korea (Fig. 2). The dissertation compiled herein is biostratigraphic works on the new materials with a prediction that the fauna will be mainly composed of cosmopolitan species, but will include few key taxa restricted to North China. Through these works, paleogeographic evidence for western Taebaeksan Basin's affinity to North China can be extended from Ordovician and Furongian intervals to the Cambrian Series 3 times when degree of provincialism for trilobite faunae must have been stronger (Fortey and Owens, 1997).

Field works on the locality produced a geologic map of the area, and lithologic, sedimentologic features from outcrop sections were described and analyzed. Fossils were systematically collected from the sections, and later prepared and photographed in the lab for species identification.

In the first chapter, occurrence of an index fossil that defines the base of the sixth Cambrian stage (Drumian Stage) is reported for the first time in Korea, and landmark based morphological analyses were implemented on the species and a successively older cosmopolitan species to illustrate the significant shape differences of the two species. In the second chapter, trilobite species identified from the new locality is described, and new trilobite biozones are established from the species occurrence data yielded from the sections. The biozones are then correlated with other

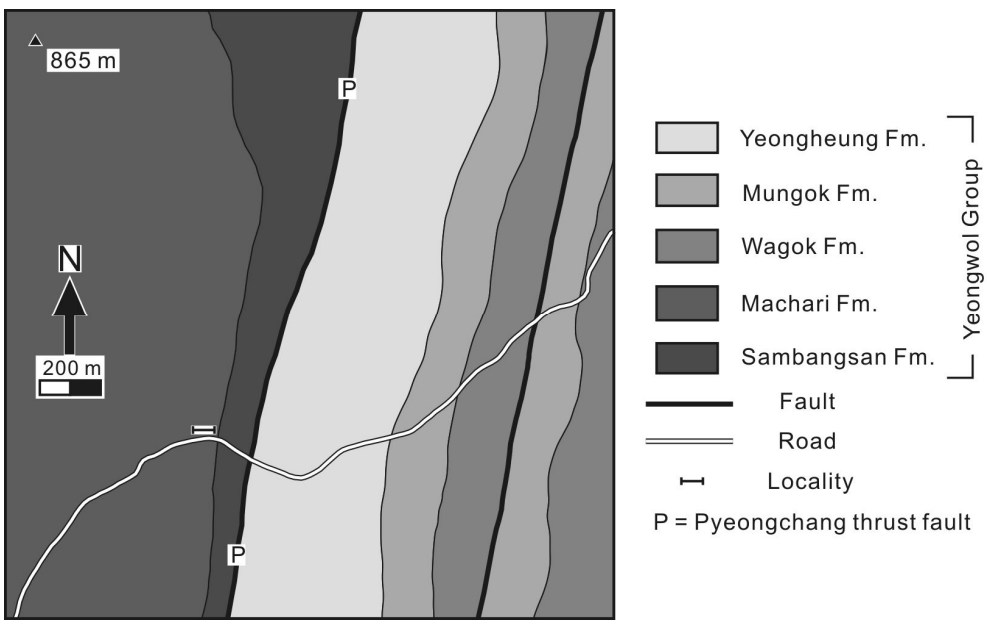

Figure 2. Geologic map near the fossil locality in the Yeongwol area, Taebaksan Basin, east-central Korean Peninsula.

biostratigraphic units around the world. In the third chapter, paleogeographic implications of the region are drawn from analyses of worldwide spatial ranges of species that comprise the trilobite fauna of this study.

1. 2. Geological settings

The Joseon Supergroup that forms the Cambrian-Ordovician sequence in the Taebaeksan Basin at the central-eastern part of the Korean Peninsula is composed of siliciclastic and carbonate rocks. Lithologically distinct Taebaek and Yeongwol groups each occupies eastern- and western-halves of the Taebaeksan Basin, with the Yeongwol Group representing a deeper environment than the Taebaek Group in a shallow marine setting at the margin of the North China Platform (Choi, 1998, 2009, 2011, 2014; Choi and Chough, 2005; Kwon et al., 2006; Kwon, 2012). The Yeongwol Group comprises, in ascending order, Sambangsan, Machari, Wagok, Mungok, and Yeongheung formations. The lowermost Sambangsan Formation is predominantly siliciclastic, whereas the other four overlying formations are carbonateous. Nineteen trilobite biozones from the Cambrian Series 2 to the Lower Ordovician Series can be recognized from the Yeongwol Group sequence with the Wagok-Mungok formation boundary closely paralleling the Cambrian-Ordovician boundary (Kobayashi, 1962; Choi et al., 1994, 1999, 2004, 2008; Lee and Choi, 1994, 1995, 1996, 1997; Kim and Choi,

2000a, b; Sohn and Choi, 2002; Hong et al., 2003, in press; Choi, 2014).

Lithological and biostratigraphical summary of the Machari Formation, and general information on the locality will be detailed in the second chapter of the dissertation.

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CHAPTER 2

Cambrian Series 3 agnostoid trilobites *Ptychagnostus sinicus* and *Ptychagnostus atavus* from the Machari Formation, Yeongwol Group, Taebaeksan Basin, Korea

2. 1. Introduction

The Machari fauna of Korea has been well known to paleontologists in yielding abundant invertebrate fossils of Cambrian age (Kobayashi, 1962). The Machari fauna denotes the macroinvertebrate fossil assemblage from the Machari Formation of the Yeongwol Group, Taebaeksan Basin, Korea, and comprises diverse trilobites of Cambrian Series 3 to Furongian, with some inarticulate brachiopods, monoplacophorans, gastropods, and hyoliths. It was partly introduced by Kobayashi (1935) and later was comprehensively dealt with by him (Kobayashi, 1962). The Machari fauna has been intensively studied during the last two decades, with studies including taxonomic revision, biostratigraphy, and paleogeographic reconstructions (Lee and Choi, 1994, 1995, 1996; Choi and Lee, 1995; Hong et al., 2003a, b; Choi et al., 2004, 2008; Choi and Kim, 2006). A total of ten trilobite biozones have been established in the Machari Formation, and in ascending order, comprise the *Tonkinella*, *Lejopyge armata*, *Glyptagnostus stolidotus*, *G. reticulatus*, *Proceratopyge tenuis*, *Hancrania brevilimbata*, *Eugonocare longifrons*, *Eochuangia hana*, *Agnostotes*

orientalis, and *Pseudoyuepingia asaphoides* zones (Choi and Chough, 2005).

First appearance data of agnostoid trilobite species offer precise reference points for high-resolution global correlation in the upper half of the Cambrian System. For instance, *Ptychagnostus* Jaekel, 1909, includes such types of cosmopolitan species that occur in ascending order in the lower to middle interval of the traditional middle Cambrian (Robison, 1982, 1984): namely, *Ptychagnostus praecurrens* (Westergård, 1936), *Ptychagnostus gibbus* (Linnarsson, 1869), *Ptychagnostus atavus* (Tullberg, 1880), and *Ptychagnostus punctuosus* (Angelin, 1851). Of these, *P. atavus* exhibits a global distribution, and consequently has been selected by the International Subcommission on Cambrian Stratigraphy to define the Global Stratotype Section and Point (GSSP) of the middle stage of the tripartite Cambrian Series 3, i.e., the Drumian Stage (Babcock et al., 2007).

In this study, we report, for the first time in eastern Asia, the successive occurrences of *Ptychagnostus sinicus* Lu, 1957 and *P. atavus* from the lower part of the Machari Formation, in a newly discovered section in the western part of Yeongwol. This study also attempts to evaluate the species concept of *P. sinicus* and to reveal how it differs significantly from *P. atavus*.

2. 2. General geology and fossil locality

The Taebaeksan Basin occupies the mid-eastern region of the Korean Peninsula and comprises the Cambrian-Ordovician Joseon Supergroup and

the Carboniferous-Permian Pyeongan Supergroup, which are separated by a ~140-myr-long hiatus (Chough et al., 2000). The Joseon Supergroup is a mixed carbonate-siliciclastic succession of shallow marine origin and has been divided into the Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups (Choi, 1998; Choi and Chough, 2005).

The Yeongwol Group is divided, in ascending order, into the Sambangsan, Machari, Wagok, Mungok, and Yeongheung formations (Yosimura, 1940; Kobayashi, 1966; Choi, 1998; Choi and Chough, 2005). The lowermost Sambangsan Formation is composed exclusively of siliciclastic sediments, whereas the upper four formations are dominated by carbonates. The base of the Machari Formation comprises thick-bedded bioclastic grainstone/packstone beds which contain well preserved middle Cambrian trilobites belonging to the genera *Tonkinella*, *Olenoides*, *Dorypyge*, and *Peronopsis*. These beds are succeeded by dark gray dolomitic limestone and black shale in the lower part of the formation. The middle part is characterized by laminated dark gray to black shale with occasional intercalations of thin dolomitic limestone layers and yields diverse trilobites of Furongian age (Lee and Choi, 1994, 1995, 1996; Choi et al., 2004, 2008). The upper part displays a conspicuous banded appearance, composed of alternating units of thin-bedded, light gray dolomitic limestone and black shale layers. The banded structure becomes obscure in the uppermost part of the formation and grades upwards into massive dolostone

of the overlying Wagok Formation. The lower and middle parts of the Machari Formation are richly fossiliferous, whereas the upper part is generally poorly fossiliferous.

The newly discovered Deoksang section (37°16'50"N, 128°22'40"E), is located at a road cut about 13 km northwest from Yeongwol (Fig. 3) where the Sambangsan Formation and the lower part of the Machari Formation occur in superpositional order. The lowermost 10 m thick interval of the Machari Formation is particularly well exposed: the lower 6 m thick interval of massive bioclastic grainstone beds yields well-preserved trilobites of the *Tonkinella* Zone and the overlying 4 m thick interval is characterized by alternating units of dark gray wacke- to packstone and black shale. This upper interval yields well preserved trilobites belonging to Cambrian Stage 5 to the Paibian Stage. *Ptychagnostus sinicus* occurs at three fossil horizons, 6 m, 6.8 m, and 6.9 m above the base of the formation, while *P. atavus* is restricted to one fossil horizon 7.0 m above the base of the formation. *Ptychagnostus sinicus* is associated with *Peronopsis taitzuhoensis* Lu (1957) at the lowermost horizon, whereas *P. atavus* is associated with *Yakutiana ovale* (Yang, 1982).

2. 3. Systematic paleontology

Morphological terms used herein are adopted from Whittington and Kelly (1997) and from Peng and Robison (2000). Specimens are stored at

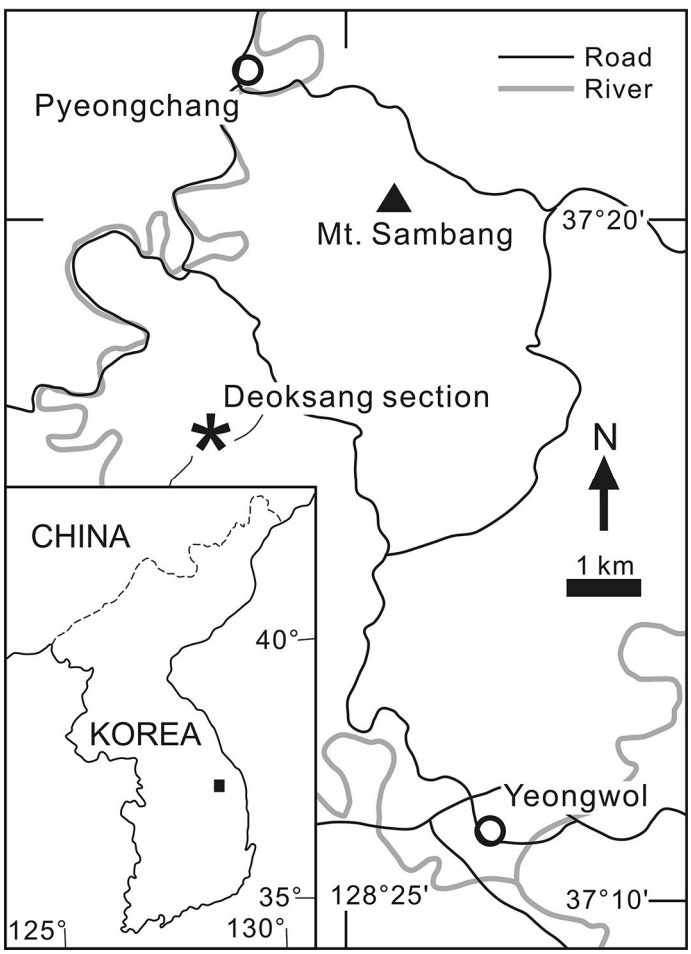

Figure 3. Locality map. An asterisk denotes the location of the Deoksang section from which the material for this study was collected. A small solid square in the inset indicates the approximate location of the fossil horizons.

the Seoul National University in Korea with designated SNUP numbers.

Class TRILOBITA Walch, 1771

Order AGNOSTIDA Salter, 1864

Family PTYCHAGNOSTIDAE Kobayashi, 1939

Genus ***Ptychagnostus*** Jaekel, 1909

Type species: *Agnostus punctuosus* Angelin, 1851 from the *P. punctuosus* Zone of the Alum Shale (Drumian), Sweden (by original designation). Official ruling on the conservation of accepted usage of *A. punctuosus* as the type species was given by the International Commission on Zoological Nomenclature, 1993.

Remarks: There are disparate views on the taxonomy of the genus *Ptychagnostus* and its relationship with other genera or subgenera that include *Acidusus* Öpik (1979), *Triplagnostus* Howell (1935), *Yakutiana* Özdikmen (2009) among others. Monophyly of these taxa had been rejected (Westrop et al., 1996) or accepted (Laurie, 2008), presumably due to differences in morphological characters selected for analyses. A complete taxonomic assessment of *Ptychagnostus* is beyond the scope of this study, and a more broad definition of *Ptychagnostus* suggested by Peng and Robison (2000) is herein followed.

Ptychagnostus atavus (Tullberg, 1880)

Fig. 4(1–8)

1880. *Agnostus atavus* nov. sp. – Tullberg, p. 14, pl. 1, figs. 1a–1d.

1880. *Agnostus intermedius* nov. sp. – Tullberg, p. 17, pl. 1, figs. 4a–4b.

1909. *Ptychagnostus atavus* (Tullberg) – Jaekel, p. 400.

1980. *Ptychagnostus intermedius* (Tullberg) – Ergaliev, p. 69–70, pl. 1, figs. 18–20.

1988. *Acidusus atavus* (Tullberg) – Laurie, p. 180, fig. 5.

2000. *Ptychagnostus atavus* (Tullberg) – Peng and Robison, p. 69–70, fig. 52.

2006. *Acidusus atavus* (Tullberg) – Fletcher, pl. 34, figs. 43, 44.

2007. *Ptychagnostus atavus* (Tullberg) – Ahlberg, Axheimer, and Robison, p. 710–713, figs. 2.1–2.12 (for additional synonymy).

2007. *Ptychagnostus atavus* (Tullberg) – Babcock, Robison, Rees, Peng, and Saltzman, figs. 6B–6D, 7B.

2008. *Ptychagnostus atavus* (Tullberg) – Høyberget and Bruton, p. 49–50, pl. 7, figs. G–M.

2009. *Acidusus atavus* (Tullberg) – Weidner and Nielsen, p. 259–260, figs. 8A–8D, 10A, 10B.

2014. *Acidusus atavus* (Tullberg) – Weidner and Nielsen, p. 32–35, figs. 9, 10A–D, 11A–H, 12F–H.

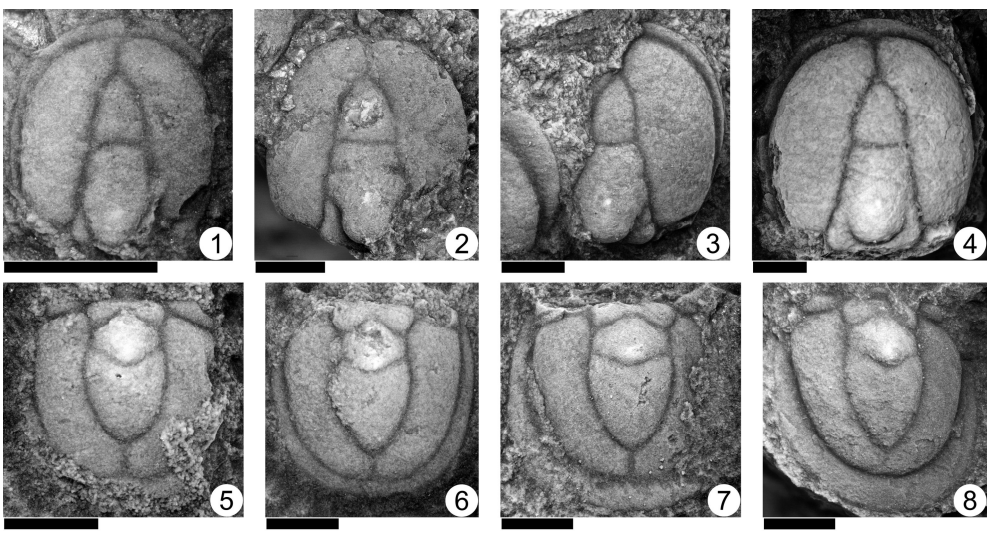

Figure 4. *Ptychagnostus atavus* (Tullberg, 1880) from the lower part of the Machari Formation in the Deoksang section, Yeongwol, Korea. *1–4*, cephala, SNUP6311–6314; *5–8*, pygidia, SNUP6315–6318. All scale bars represent 1 mm.

Occurrence: Ten cephala and 22 pygidia from the horizon 7.0 m above the base of the Machari Formation at the Deoksang section.

Remarks: The first appearance datum of *P. atavus* defines the base of the Drumian Stage of Cambrian Series 3 (Babcock et al., 2007), and this species has been thoroughly treated by Peng and Robison (2000) and Ahlberg et al. (2007).

Ptychagnostus atavus differs from other species of *Ptychagnostus* in lacking cephalic and pygidial spines and surface granules, and in having a hexagonal M2 on the pygidial axis. Although variations in the degree of scrobiculation on the genae have been known to range from smooth to moderately scrobiculate (Robison, 1982, pl.1. figs. 1–9; 1984, fig. 11), all the specimens from the Deoksang section are uniformly smooth. In addition, the width of the pygidial border is variable.

Ptychagnostus sinicus Lu, 1957

Fig. 5(1–16)

1954. *Ptychagnostus richmondensis* (Walcott) – Palmer, p. 61–62, pl. 13, fig. 5 (part).

1957. *Ptychagnostus sinicus* nov. sp. – Lu, p. 259, pl. 137, figs. 17–19.

1965. *Ptychagnostus sinicus* Lu – Lu, Chang, Chu, Chien, and Hsiang, p. 37–38, pl. 3, figs. 16–18.

1979. *Ptychagnostus* (*Ptychagnostus*) *idmon* nov. sp. – Öpik, p. 95–96,

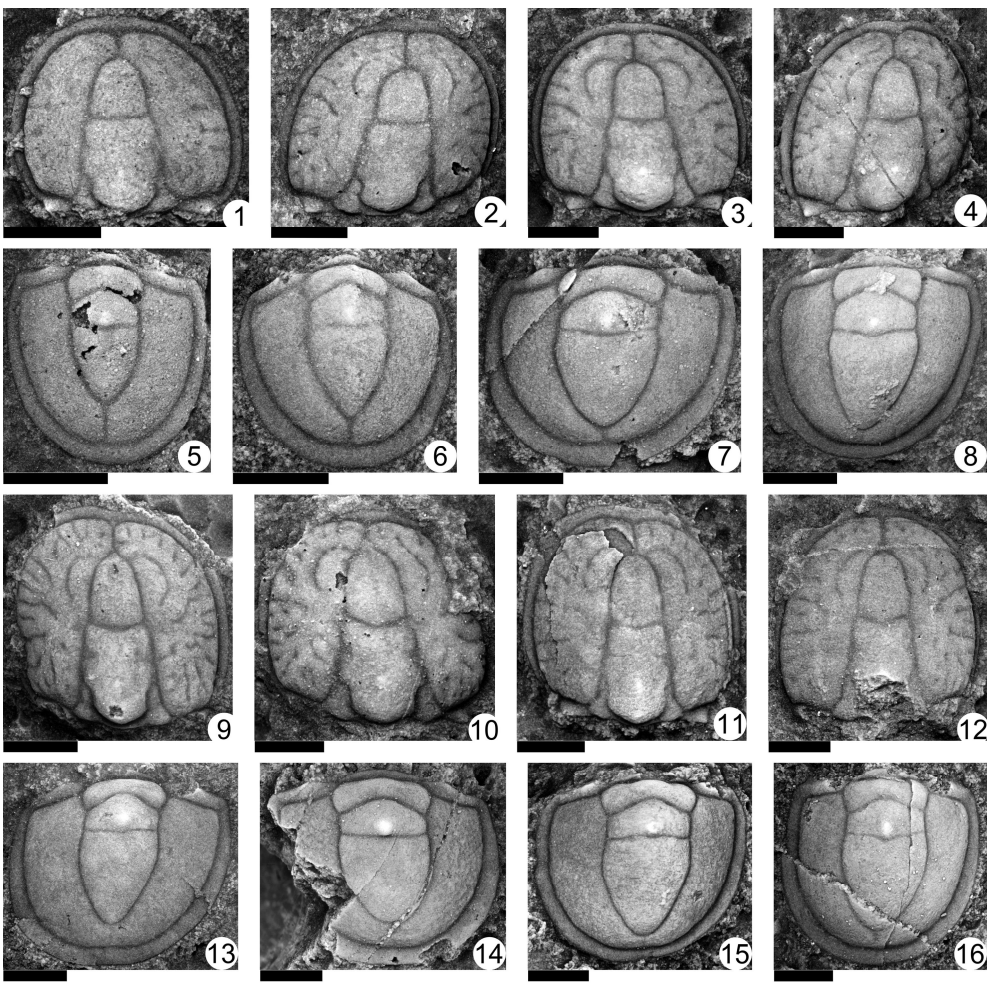

Figure 5. *Ptychagnostus sinicus* Lu, 1957 from the lower part of the Machari Formation in the Deoksang section, Yeongwol, Korea. *1–4*, *9–12*, cephala, SNUP6319–6322, SNUP6327–6330; *5–8*, *13–16*, pygidia, SNUP6323–6326, SNUP6331–6334. All scale bars represent 1 mm.

pl. 43, figs. 5–8.

1979. *Ptychagnostus* (*Ptychagnostus*) *intermedius* (Tullberg) – Öpik, p. 95, pl. 41, fig. 8.

1979. *Ptychagnostus* (*Ptychagnostus*) *scarifatus* nov. sp. – Öpik, p. 96–97, pl. 44, figs. 1–5, pl. 58, fig. 2.

1979. *Ptychagnostus* (*Ptychagnostus*) sp. aff. *scarifatus* – Öpik, p. 97, pl. 44, fig. 6.

1980. *Ptychagnostus sinicus* Lu – Nan, p. 484, pl. 200, figs. 7, 8.

1980. *Ptychagnostus atavus* (Tullberg) – Ergaliev, P. 67–69, pl. 1, figs. 13–17.

1982. *Ptychagnostus intermedius* (Tullberg) – Robison, 1982, p. 143–145, pl. 3, figs. 1–9.

1982. *Ptychagnostus intermedius* (Tullberg) – Rowell, Robison, and Strickland, p. 161–182.

non 1983. *Ptychagnostus sinicus* Lu – Qiu, Lu, Zhu, Bi, Lin, Zhou, Zhang, Qian, Ju, Han, and Wei, p. 37, pl. 12, fig. 15 (?=*P. atavus*).

1984. *Ptychagnostus intermedius* (Tullberg) – Robison, p. 25–28, figs. 15.1–15.7.

1988. *Ptychagnostus intermedius* (Tullberg) – Lisogor, Rozov, and Rozova, p. 56–57, pl. 4, figs. 1–4.

1988. *Zeteagnostus scarifatus* (Öpik) – Laurie, p. 178, figs. 4A–H.

1989. *Ptychagnostus sinicus* Lu – Sun, p. 76–77, pl. 4, figs. 9–21.

1994. *Ptychagnostus intermedius* (Tullberg) – Robison, p. 56–57, figs. 27.7, 27.8.

1996. *Ptychagnostus sinicus* Lu – Guo, Zan, and Luo, p. 50, pl. 1, figs. 1–6.

1999. *Ptychagnostus sinicus* Lu – Luo, pl. 7, figs. 1, 2.

2000. *Ptychagnostus intermedius* (Tullberg) – Peng and Robison, p. 80.

2007. *Ptychagnostus sinicus* Lu – Ahlberg, Axheimer, and Robison, p. 712.

2007. *Ptychagnostus intermedius* (Tullberg) – Bordonaro and Banchig, figs. 2N–P.

2008. *Ptychagnostus intermedius* (Tullberg) – Bordonaro, Banchig, Pratt, and Raviolo, p. 121, figs. 4N–P.

2012. *Ptychagnostus* (*Acidusus*) *sinicus* Lu – Yuan, Li, Mu, Lin, and Zhu, p. 62–63, pl. 4, figs. 1–16, pl. 5, figs. 1–4.

Diagnosis: A species of *Ptychagnostus* with pentagonal pygidial M2, smooth acrolobe surfaces without pustules or granules, and no border spines on the cephalon or pygidium.

Description: Cephalon semielliptical, with narrow border and border furrow, without posterolateral spines. Acrolobe unconstricted; genal field scrobiculate, with a pair of crescent-shaped furrows opposite anteroglabella, without pustules or granules; median preglabellar furrow well developed.

Glabella about four-fifths of cephalic length; anteroglabella about two-fifths of glabellar length, subtriangular in outline; F3 posteriorly curved medially; posteroglabella tapering forward, constricted near F3; F2 weakly impressed near axial furrow; axial glabellar node, small, circular, positioned posterior to M2 mid-length. Basal lobe elongate, weakly divided.

Pygidium semielliptical, with moderately broad border and narrow border furrow, without posterolateral spines. Acrolobe unconstricted; pleural field smooth, without pustules or granules; postaxial median furrow moderately to weakly developed. Axis about one-third of pygidial width, constricted across M2, with maximum width at anterior quarter of posteroaxial length; anteroaxis about two-fifths of axial length; M1 arched, of even length (sag., exsag.) or slightly shorter medially; F1 anteriorly curved, of even depth or slightly shallower medially; M2 pentagonal in outline; median tubercle small, circular, positioned near F2; F2 straight to slightly flexed toward posterior; posteroaxis with pointed to rounded posterior end.

Types: A cephalon from the Tangshih Formation in Benxi, east-central Liaoning, North China (Lu, 1957, pl. 137, fig. 17; re-illustrated by Lu et al., 1965, pl. 3, fig. 16) has been selected as the lectotype by Yuan et al (2012, p. 63).

Occurrence: Eighty-two cephala and more than one hundred pygidia were collected from three horizons, 6.0 m, 6.8 m, and 6.9 m above the base

of the Machari Formation in the Deoksang section. Aside from the type locality in east-central Liaoning, occurrences in North China include the *Bailiella* Zone (Nan, 1980; Sun, 1989) and the *Crepicephalina* Zone (Guo et al., 1996) of the Hsuchuang Formation, southern Liaoning, and the upper *Tonkinella flabelliformis–Poriagraulos nanus* Zone and the lower *Bailiella lantenoisi* Zone of the Changhsia Formation, central Shandong (Yuan et al., 2012). This species has also been known to occur in the *P. intermedius* Zone in the Kyrshabakty section of Malyi Karatau, Kazakhstan (Ergaliev, 1980; Lisogor et al., 1988; Ergaliev et al., 2008); *P. atavus* and *Euagnostus opimus* zones of the Inca Formation, Queensland, Australia (Öpik, 1979); *P. gibbus* Zone of the Wheeler Formation and coeval formations in Utah and Nevada, USA (Palmer, 1954; Robison, 1982; Babcock et al., 2007); the Henson Gletscher Formation, northern Greenland (Robison, 1984, 1994); and the Alojamiento Formation, Precordillera, Argentina (Bordonaro and Banchig, 2007).

Remarks: *Ptychagnostus sinicus* and *P. atavus* differ from all other species of the genus in having smooth acrolobe surfaces without pustules or granules and in lacking border spines on the cephalon and pygidium. However, it has been difficult to differentiate the two species, because *P. atavus* has been known to display a wide range of variation in morphological characters such as scrobiculation of the genal region, whether arcuate scrobicules are present opposite anteroglabella, position of the

median node on glabellar M2, and relative width of the pygidial border (Robison, 1982; Ahlberg et al., 2007).

Morphological variation in the pygidial F2 of *P. atavus* has been responsible for the taxonomic confusion of the species with other species including *P. intermedius*, *P. sinicus*, and *P. affinis* (Brøgger, 1878). *Ptychagnostus atavus* and *P. intermedius* were established by Tullberg in 1880 among the collections from the *P. atavus* Zone of the Alum Shale in the Andrarum area of southern Sweden. Tullberg (1880) differentiated the two species based on the difference in the course of the pygidial F2 furrow. As is clear from the plates of Tullberg (1880) and illustrations of Tullberg's syntypes by Westergård (1946), *P. atavus* possesses a V-shaped F2 furrow, whereas F2 furrow of *P. intermedius* is more or less straight. Accordingly, *Ptychagnostus* species with comparatively straight F2 documented subsequently in Laurentia, Australia, Kazakhstan, and Argentina were referred to as *P. intermedius*. However, re-examination of Tullberg's original collections by Ahlberg et al. (2007) revealed that the degree of flexure of the F2 furrow in specimens assigned to *P. intermedius* is well within the range of variation of *P. atavus*. Tullberg's hand-drawn figures of *P. intermedius* did not show the true degree of the curvature, and re-illustration of the original collections by Westergård (1946) widely referenced by subsequent researchers were found to be retouched to emphasize the straightness of the F2 furrow (Ahlberg et al., 2007, p. 712). In addition, original materials of *P.*

atavus and *P. intermedius* by Tullberg (1880) were collected from the *P. atavus* Zone (Ahlberg et al., 2007), whereas non-Baltic specimens assigned previously to *P. intermedius* all occur in zones equivalent to the *P. gibbus* Zone that lies immediately below the *P. atavus* Zone. The relatively less known species, *P. sinicus,* was established by Lu in 1957 from the *Bailiella* Zone (approximately equivalent to the *P. gibbus* Zone) of the Tangshih Formation of Liaoning, China. It is characterized by a straight F2 furrow on the pygidium and hence non-Baltic specimens that were previously assigned to *P. intermedius* should be reassigned to *P. sinicus*.

Landmark-based geometric morphometrics were employed to test the significance of shape differences between *P. atavus* and *P. sinicus*. Nine landmarks were selected on the M1 and M2 of the pygidium which correspond to right/left, antero-/postero-lateral corners and three axial points of M1 and M2 (Fig. 6.1). A total of 66 specimens were digitized using the NIH ImageJ software (Abràmoff et al., 2004) and all analytical processes were performed with the IMP software series (Sheets, 2012): three specimens of *P. atavus* and 13 specimens of *P. sinicus* from the Deoksang section, and 28 specimens of *P. atavus* and 22 specimens of *P. sinicus* from illustrations of previous studies (see Supplementary Data 1). Superimposition of the mid-point landmark of the F2 furrow displays the visual difference between the two species (Fig. 6.2). Regressions of partial Procrustes distance against the natural logarithm of the centroid size for

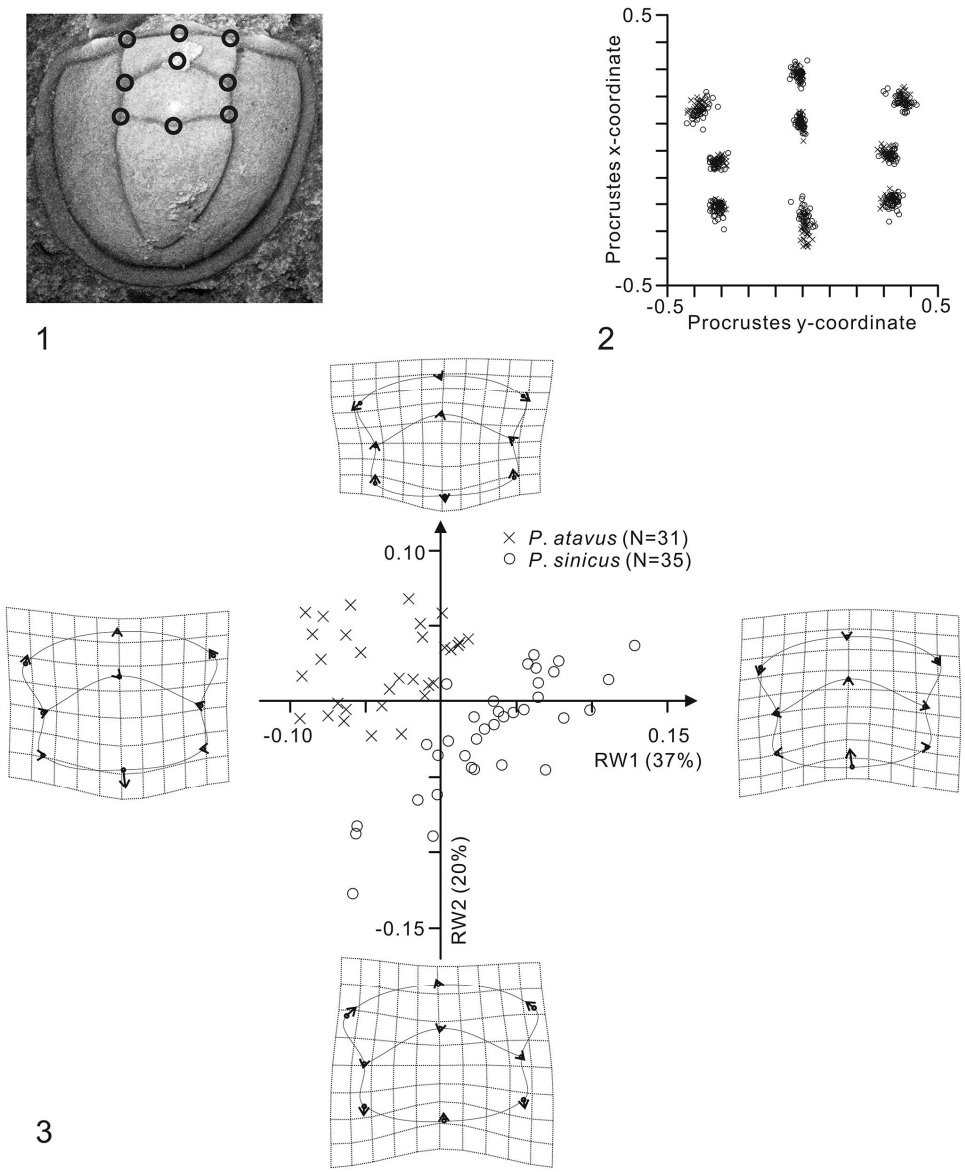

Figure 6. Landmark data analyses employing 31 pygidia of *Ptychagnostus atavus* (Tullberg, 1880) and 35 pygidia of *Ptychagnostus sinicus* Lu, 1957. *1*, location of nine landmarks recorded from each pygidium at dorsal view; *2*, partial Procrustes superimposition of 66 specimens; *3*, bivariate plot of the specimens on the first two relative warps RW1 and RW2 from the principal component analysis of warp scores; RW1 and RW2 explain 37% and 20%

of the total shape variance, respectively; thin-plate spline deformation grids depict shape variation along each relative warp; and arrows on landmarks of thin-plate spline deformation grids express relative displacements (Zelditch et al., 2004).

both species did not identify any significant shape changes with size increase, and suggest that shape variations present in the dataset is not due to ontogeny. The amount of shape deviation for each specimen can be quantified by assessing the displacement vectors of landmarks from the reference form (in this case, the consensus of all configurations in a partial Procrustes superimposition). Following the thin-plate spline method, the deviation matrix of all specimens are first decomposed into mathematically independent styles of deformation (warps) and its contribution to each deformation (warp scores), and then the principal component analysis is performed on the warp scores to examine the structure of the shape variations present in a dataset (Webster and Sheets, 2010). Results (Fig. 6.3) show that the first and second principal components (termed relative warps) account for 37 % and 20 % of the total shape variance, respectively, and that the two species are significantly different with the degree of flexure of the pygidial F2 furrow being the major component in the morphological variations, and with abaxial-widening and posteriorly-arching of the anterolateral regions of the pygidial M1 being the second component. Although variations in the pygidial F2 furrow of the two species overlap (Fig. 6.2), the two species are clearly differentiated when the information on the shape of anterolateral regions of the pygidial M1 (Fig. 6.3) is considered.

In summary, *P. atavus* and *P. sinicus* can be distinguished on the basis of the shape of M1 and the course of pygidial F2 furrow in association with the

median tubercle on the pygidial M2: *P. atavus* has a broadly-arching M1, a chevron-shaped pygidial F2, and a prominent median tubercle that medially flexes the posterior margin of M2, whereas *P. sinicus* is characterized by having a relatively narrow M1, a transverse pygidial F2, and a weakly developed tubercle on M2.

2. 4. Biostratigraphic significance

Ptychagnostus sinicus and *P. atavus* occur successively and do not overlap in their stratigraphic distribution in the Deoksang section. Such occurrences have also been documented in Kazakhstan (Ergaliev, 1980; Ergaliev et al., 2008) and North America (Robison, 1982; Babcock et al., 2007). However, in Kazakhstan and North America *P. sinicus* has been known to occur in association with *P. gibbus*. The co-occurrence of *P. sinicus* and *P. gibbus* has also been reported in Australia (Öpik, 1979) and Greenland (Robison, 1984, 1994). In Australia, Öpik (1979) reported the occurrences of *Ptychagnostus* from the Inca Formation of the Georgina Basin in which one locality (M208) yielded *P. sinicus*, *P. gibbus*, and *P. atavus*, while three localities (M149, M170, and M176) produced *P. sinicus* and *P. gibbus*.

In North America, *P. sinicus* and *P. gibbus* first appeared in the *P. gibbus* Zone (Robison, 1982, 1984; Babcock et al., 2007): *P. sinicus* is restricted to the *P. gibbus* Zone, while *P. gibbus* is extendeds into the overlying *P. atavus*

Zone. In North China, *P. sinicus* occurs in the *Tonkinella flabelliformis*-*Poriagraulos nanus* and *Bailiella lantenoisi* zones in Shandong province, both of which can be correlated with the *P. gibbus* Zone of South China (Yuan et al., 2012). Therefore, it can be concluded that the stratigraphic occurrences of *P. sinicus* appear to be restricted within an age equivalent to the *P. gibbus* Zone and can be employed as a guide fossil for intercontinental correlation. In Korea, the boundary between the Cambrian Stage 5 and the Drumian Stage can be confidently drawn at the *P. atavus*-yielding horizon, 7 m above the base of the Machari Formation at the Deoksang section.

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Supplementary Data 1

Order	Species	Reference	Figure	Specimen number	Locality	Species designation in reference
1	*P. sinicus* Lu, 1957	Nan, 1980	pl. 200, fig. 8	-	PH4, Mopanshan, Liaoning. Hsuchuang Fm, Middle Cambrian.	*P. sinicus* Lu, 1957
2	*P. sinicus* Lu, 1957	Lu et al., 1965	pl. 3, fig. 17	-	Tangshih Fm in Benxi, east-central Liaoning, North China	*P. sinicus* Lu, 1957
3	*P. sinicus* Lu, 1957	Lu et al., 1965	pl. 3, fig. 18	-	Tangshih Fm in Benxi, east-central Liaoning, North China	*P. sinicus* Lu, 1957
4	*P. sinicus* Lu, 1957	Sun, 1989	pl. 4, fig. 13	IGP89070	LM5A, *Bailiella* Zone, Hsuchuang Fm. Mopanshan, Fuxian, Liaoning.	*P. sinicus* Lu, 1957
5	*P. sinicus* Lu, 1957	Sun, 1989	pl. 4, fig. 14	IGP89071	LM5A, *Bailiella* Zone, Hsuchuang Fm. Mopanshan, Fuxian, Liaoning.	*P. sinicus* Lu, 1957
6	*P. sinicus* Lu, 1957	Sun, 1989	pl. 4, fig. 15	IGP89072	LM5A, *Bailiella* Zone, Hsuchuang Fm. Mopanshan, Fuxian, Liaoning.	*P. sinicus* Lu, 1957
7	*P. sinicus* Lu, 1957	Sun, 1989	pl. 4, fig. 16	IGP89073	LM5A, *Bailiella* Zone, Hsuchuang Fm. Mopanshan, Fuxian, Liaoning.	*P. sinicus* Lu, 1957
8	*P. sinicus* Lu, 1957	Sun, 1989	pl. 4, fig. 20	IGP89077	LM5A, *Bailiella* Zone, Hsuchuang Fm. Mopanshan, Fuxian, Liaoning.	*P. sinicus* Lu, 1957
9	*P. sinicus* Lu, 1957	Sun, 1989	pl. 4, fig. 21a	IGP89078	LM5A, *Bailiella* Zone, Hsuchuang Fm. Mopanshan, Fuxian, Liaoning.	*P. sinicus* Lu, 1957
10	*P. sinicus* Lu, 1957	Robison, 1982	figs. 3.3a, b	KUMIP153953	379, basal 6 m of Wheeler Fm, House Range, western Utah. rare to abundant (136, 137, 195, 379, 3414-CO, 3415-CO)	*P. intermedius* (Tullberg, 1880)
11	*P. sinicus* Lu, 1957	Robison, 1982	figs. 3.6a, b	KUMIP153954	379, basal 6 m of Wheeler Fm, House Range, western Utah. rare to abundant (136, 137, 195, 379, 3414-CO, 3415-CO)	*P. intermedius* (Tullberg, 1880)

12	*P. sinicus* Lu, 1957	Robison, 1982	fig. 3.7	KUMIP153957	379, basal 6 m of Wheeler Fm, House Range, western Utah. rare to abundant (136, 137, 195, 379, 3414-CO, 3415-CO)	*P. intermedius* (Tullberg, 1880)
13	*P. sinicus* Lu, 1957	Robison, 1982	figs. 3.8a, b	KUMIP153956	137, basal 6 m of Wheeler Fm, House Range, western Utah. rare to abundant (136, 137, 195, 379, 3414-CO, 3415-CO)	*P. intermedius* (Tullberg, 1880)
14	*P. sinicus* Lu, 1957	Robison, 1982	figs. 3.9a, b	KUMIP153958	126, basal 12m of Secret Canyon Fm, northern Egan Range, Nevada. abundant (125, 126, 128-133, 37l)	*P. intermedius* (Tullberg, 1880)
15	*P. sinicus* Lu, 1957	Robison, 1984	figs. 15.4a-c	MGUH16.272	GGU 271489, upper 3m, type section of Fm 2, Brønlund Fjord Group, North Greenland	*P. intermedius* (Tullberg,
16	*P. sinicus* Lu, 1957	Robison, 1984	figs. 15.5a, b	MGUH16.273	GGU 271489, upper 3m, type section of Fm 2, Brønlund Fjord Group, North Greenland	*P. intermedius* (Tullberg,
17	*P. sinicus* Lu, 1957	Robison, 1984	figs. 15.7a-c	MGUH16.275	GGU 271492, upper 3m, type section of Fm 2, Brønlund Fjord Group, North Greenland	*P. intermedius* (Tullberg,
18	*P. sinicus* Lu, 1957	Robison, 1994	fig. 27.8	MGUH21.441	GGU298970. middle Henson Gletscher Fm, Nyeboe Land, Greenland	*P. intermedius* (Tullberg,
19	*P. sinicus* Lu, 1957	this study	(not figured)	(Deoksang A section, 24.0-02-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
20	*P. sinicus* Lu, 1957	this study	Fig. 5.5	SNUP6323 (Deoksang A section, 24.0-03-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
21	*P. sinicus* Lu, 1957	this study	(not figured)	(Deoksang A section, 24.0-04-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
22	*P. sinicus* Lu, 1957	this study	Fig. 5.7	SNUP6325 (Deoksang A section, 24.0-04-3)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
23	*P. sinicus* Lu, 1957	this study	(not figured)	(Deoksang A section, 24.0-07-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957

24	*P. sinicus* Lu, 1957	this study	(not figured)	(Deoksang A section, 24.0-08-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
25	*P. sinicus* Lu, 1957	this study	Fig. 5.15	SNUP6333 (Deoksang A section, 24.0-10-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
26	*P. sinicus* Lu, 1957	this study	Fig. 5.8	SNUP6326 (Deoksang A section, 24.0-11-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
27	*P. sinicus* Lu, 1957	this study	Fig. 5.16	SNUP6334 (Deoksang A section, 24.0-14-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
28	*P. sinicus* Lu, 1957	this study	Fig. 5.6	SNUP6324 (Deoksang A section, 24.0-14-2)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
29	*P. sinicus* Lu, 1957	this study	(not figured)	(Deoksang A section, 24.0-15-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
30	*P. sinicus* Lu, 1957	this study	(not figured)	(Deoksang A section, 24.0-18-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
31	*P. sinicus* Lu, 1957	this study	Fig. 5.13	SNUP6331 (Deoksang A section, 24.0-20-1)	Deoksang A section, 24.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. sinicus* Lu, 1957
32	*P. sinicus* Lu, 1957	Öpik, 1979	pl. 43, fig. 7	CPC14232	M208, Inca Fm, NW Queensland, Australia	*P. idmon* Öpik, 1979
33	*P. sinicus* Lu, 1957	Öpik, 1979	pl. 44, fig. 5	CPC14237	M176, Current Bush Limestone, NW Queensland, Australia	*P. scarifatus* Öpik, 1979
34	*P. sinicus* Lu, 1957	Laurie, 1988	fig. 4G	CPC25680	M176, Current Bush Limestone, NW Queensland, Australia	*Zeteagnostus scarifatus* (Öpik, 1979)
35	*P. sinicus* Lu, 1957	Laurie, 1988	fig. 4H	CPC25676	M176, Current Bush Limestone, NW Queensland, Australia	*Zeteagnostus scarifatus* (Öpik, 1979)
36	*P. atavus* (Tullberg, 1880)	Weidner and Nielsen, 2009	fig. 8C	PMU25073	Mörbylilla conglomerate, beach at Mörbylilla, Öland	*Acidusus atavus* (Tullberg, 1880)

37	*P. atavus* (Tullberg, 1880)	Weidner and Nielsen, 2009	fig. 8D	PMU25074	Mörbylilla conglomerate, beach at Mörbylilla, Öland	*Acidusus atavus* (Tullberg, 1880)
38	*P. atavus* (Tullberg, 1880)	Høyberget and Bruton, 2008	pl. 7, fig. L	PMO212.001	Roykenvika, Oslo Region, Norway	*P. atavus* (Tullberg, 1880)
39	*P. atavus* (Tullberg, 1880)	Høyberget and Bruton, 2008	pl. 7, fig. M	PMO212.002	Ringstrand, Oslo Region, Norway	*P. atavus* (Tullberg, 1880)
40	*P. atavus* (Tullberg, 1880)	Babcock et al., 2007	fig. 6C	KUMIP153933	196, Wheeler Fm, 27m above base, House Range, Utah.	*P. atavus* (Tullberg, 1880)
41	*P. atavus* (Tullberg, 1880)	Babcock et al., 2007	fig. 6D	KUMIP153930	114, Wheeler Fm, c. 100 below top, "Swayey Spring quarry", east flank of House Range, Utah.	*P. atavus* (Tullberg, 1880)
42	*P. atavus* (Tullberg, 1880)	Babcock et al., 2007	fig. 7B	KUMIP204579	62m above base, Wheeler Fm, Stratotype Ridge section, Drum Mountains, Utah.	*P. atavus* (Tullberg, 1880)
43	*P. atavus* (Tullberg, 1880)	Ahlberg et al., 2007	fig. 2.3	LO355T	loose stinkstone at Forsemölla, Andrarum area, Scania, southern Sweden	*P. atavus* (Tullberg, 1880)
44	*P. atavus* (Tullberg, 1880)	Ahlberg et al., 2007	fig. 2.8	LO3432t	alum shale at an undetermined stratigraphical level at the Verke rivulet, Andrarum area, Scania, southern Sweden	*P. atavus* (Tullberg, 1880)
45	*P. atavus* (Tullberg, 1880)	Ahlberg et al., 2007	fig. 2.9	LO9690t	alum shale at an undetermined stratigraphical level at the Verke rivulet, Andrarum area, Scania, southern Sweden	*P. atavus* (Tullberg, 1880)
46	*P. atavus* (Tullberg, 1880)	Ahlberg et al., 2007	fig. 2.10	LO9691t	alum shale at an undetermined stratigraphical level at the Verke rivulet, Andrarum area, Scania, southern Sweden	*P. atavus* (Tullberg, 1880)
47	*P. atavus* (Tullberg, 1880)	Ahlberg et al., 2007	fig. 2.11	LO9692t	alum shale at an undetermined stratigraphical level at the Verke rivulet, Andrarum area, Scania, southern Sweden	*P. atavus* (Tullberg, 1880)

48	*P. atavus* (Tullberg, 1880)	Ahlberg et al., 2007	fig. 2.12	LO9693t	alum shale at an undetermined stratigraphical level at the Verke rivulet, Andrarum area, Scania, southern Sweden	*P. atavus* (Tullberg, 1880)
49	*P. atavus* (Tullberg, 1880)	Axheimer, and Ahlberg, 2003	fig. 5C	LO9196t	23.27m, *Tomagnostus fissus-P. atavus* Zone ~ *Hypagnostus parvifrons* Zone. Almbacken, Södra Sandby, Scania, S Sweden	*P. atavus* (Tullberg, 1880)
50	*P. atavus* (Tullberg, 1880)	Peng and Robison, 2000	fig. 52.6	NIGP124110	W56.7, Wancun, NW Hunan. Huaqiao Fm	*P. atavus* (Tullberg, 1880)
51	*P. atavus* (Tullberg, 1880)	Peng and Robison, 2000	fig. 52.7	NIGP124111	P84.3, Paibi, NW Hunan. Huaqiao Fm	*P. atavus* (Tullberg, 1880)
52	*P. atavus* (Tullberg, 1880)	Peng and Robison, 2000	fig. 52.8	NIGP124112	P84.3, Paibi, NW Hunan. Huaqiao Fm	*P. atavus* (Tullberg, 1880)
53	*P. atavus* (Tullberg, 1880)	Pegel, 2000	fig. 11.13	W-33/17a	CNIGR10112, Ust' Maya Fm, Maya River, SE Siberian Platform. Lower Slope, Agnostid Biofacies. Late Middle Cambrian.	*P. atavus* (Tullberg, 1880)
54	*P. atavus* (Tullberg, 1880)	Shergold and Laurie, 1997	fig. 223.2	CPC14248	northwestern Mt. Isa district, western Queensland	*Acidusus atavus* (Tullberg, 1880)
55	*P. atavus* (Tullberg, 1880)	Westrop et al., 1996	fig. 15.4	GSC113218	WRI640, White Rock Islets(JamesStevens1986), NW Newfoundland. Downes Point Member, Shallow Bay Fm, Cow Head Group	*P. atavus* (Tullberg, 1880)
56	*P. atavus* (Tullberg, 1880)	Dong, 1991	pl. 1, fig. 5	DT 88003	P32-1, Paibi section, Huaqiao Fm. Huayuan, western Hunan	*P. atavus* (Tullberg, 1880)
57	*P. atavus* (Tullberg, 1880)	Lu and Lin, 1989	pl. 7, fig. 12	66256	GD10, Yangliugang section, Jiangshan, Zhejiang	*P. atavus* (Tullberg, 1880)
58	*P. atavus* (Tullberg, 1880)	Laurie, 1988	fig. 5B	CPC25684	M425, NE of Flora Downs, Inca Fm, NW Queensland, Australia	*Acidusus atavus* (Tullberg, 1880)
59	*P. atavus* (Tullberg, 1880)	Robison, 1984	figs. 11.1a-e	KUMIP204219	114, middle Wheeler Fm, House Range, Utah	*P. atavus* (Tullberg, 1880)

60	*P. atavus* (Tullberg, 1880)	Robison, 1984	figs. 11.3a-c	KUMIP204220	775, lower Marjum Fm, House Range, Utah	*P. atavus* (Tullberg, 1880)
61	*P. atavus* (Tullberg, 1880)	Robison, 1984	fig. 11.5	KUMIP204223	789, middle Geddes Limestone, Eureka mining district, Nevada	*P. atavus* (Tullberg, 1880)
62	*P. atavus* (Tullberg, 1880)	Robison, 1984	fig. 11.6	KUMIP204224	114, middle Wheeler Fm, House Range, Utah	*P. atavus* (Tullberg, 1880)
63	*P. atavus* (Tullberg, 1880)	Robison, 1984	figs. 7.2a, b	KUMIP204202	168, 303m abouv base of Secret Canyon Fm, northern Egan Range	*P. acidusus* Öpik, 1979
64	*P. atavus* (Tullberg, 1880)	this study	Fig. 4.6	SNUP6316 (Deoksang A section, 25.0-04-1)	Deoksang A section, 25.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. atavus* (Tullberg, 1880)
65	*P. atavus* (Tullberg, 1880)	this study	Fig. 4.5	SNUP6315 (Deoksang A section, 25.0-04-2)	Deoksang A section, 25.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. atavus* (Tullberg, 1880)
66	*P. atavus* (Tullberg, 1880)	this study	Fig. 4.7	SNUP6317 (Deoksang A section, 25.0-07-1)	Deoksang A section, 25.0, lower Machari Fm, Yeongwol, Taebaeksan Basin, Korea	*P. atavus* (Tullberg, 1880)

CHAPTER 3

Middle Cambrian (Cambrian Series 3) agnostoid trilobites from the Machari Formation, Yeongwol, Korea

3. 1. Introduction

The Machari Formation of Korea is well kown to yield diverse trilobites of Cambrian Series 3 and Furongian (Kobayashi, 1962). The biostratigraphic scheme for the upper-half of the formation has been revised into eight trilobite zones (Choi et al., 2004), while only two zones, *Tonkinella* and *Lejopyge armata* zones, have been identified for the lower-half of the formation. Recently discovered trilobites from a continuous section of the lower part of the Machari Formation at the Deoksang locality provided recognition of new trilobite assemblages in Korea (Hong and Choi, in press), and accordingly new biozones are proposed in this study.

3. 2. Geology and stratigraphy

General geology of the region has been given in a recent study (Hong and Choi, in press).

3. 3. Fossil locality

The Deoksang locality (37°16'50"N, 128°22'40"E) is situated at about 13 km northwest from Yeongwol in the Taebaeksan Basin, east-central

Korean Peninsula. General information on the locality has been given in a previous study (Hong and Choi, in press). In addition to the roadcut section (Deoksang A section) described in the previous study, a supplementary section (Deoksang B section) approximately 200 m north uphill from the original section has been measured and collected for additional trilobite specimens. The north-south trending strata of both sections are laterally equivalent and represent the lowermost 10 m interval of the Machari Formation.

3. 4. Biostratigraphy and correlation

The Machari Formation ranges in age from the Cambrian Series 3 to the Furongian, and biostratigraphy for the Furongian has been well established comprising seven trilobite zones (Choi et al., 2004). However, biozonations for the Cambrian Series 3 strata are less detailed with three trilobite zones identified: i.e., the Cambrian Stage 5 *Tonkinella* Zone (Kobayshi, 1962), the Drumian-Guzhangian boundary *Lejopyge armata* Zone (Hong et al., 2003a), and the uppermost Guzhangian *Glyptagnostus stolidotus* Zone (Lee and Choi, 1994). Information about these trilobite zones has been described in detail in previous studies (Choi and Lee, 1995; Lee and Choi, 1994, 1995, 1996, 1997, 1999; Choi, 1998, 2009, 2011; Hwang et al., 2000; Lee et al., 2001; Hong et al., 2003a, 2003b; Choi et al., 2004, 2008; Choi and Chough, 2005; Hwang and Choi, 2005; Choi and Kim, 2006; Jung and Choi, 2007),

and will not be repeated herein.

The Deoksang section yields trilobites spanning from the *Tonkinella* Zone to the *G. reticulatus* Zone. Based on the straigraphic occurrence ranges of trilobites in the section, two new biozones, in ascending order *Ptychagnostus sinicus* and *Ptychagnostus atavus* zones, are established in the interval between the *Tonkinella* Zone and the *L. armata* Zone. The base of each zone is defined by the first appearance of the eponymous taxon, and its top is equivalent to the base of the succeeding zone. The stratigraphic ranges of agnostoid trilobites of the Deoksang section are illustrated in Figure 7. Regional and global correlations of these biozones are summarized in Figure 8.

3. 4. 1. Tonkinella *Zone*

The *Tonkinella* Zone has been established by Kobayashi (1962) for the thick-bedded bioclastic grainstone to packestone beds at the lowermost part of the Machari Formation that contain middle Cambrian trilobites such as *Tonkinella*, *Olenoides*, *Dorypyge*, and *Peronopsis*. The fauna has yet to be systematically described, and in this study *Peronopsis taitzuhoensis* Lu, 1957 that first appears 5.8 m above base of the Machari Formation at Deoksang A section is tentatively assigned to the *Tonkinella* Zone. *Peronopsis taitzuhoensis* ranges into the lower part of the overlying *P. sinicus* Zone at Deoksang A section. Based on global occurrence records of

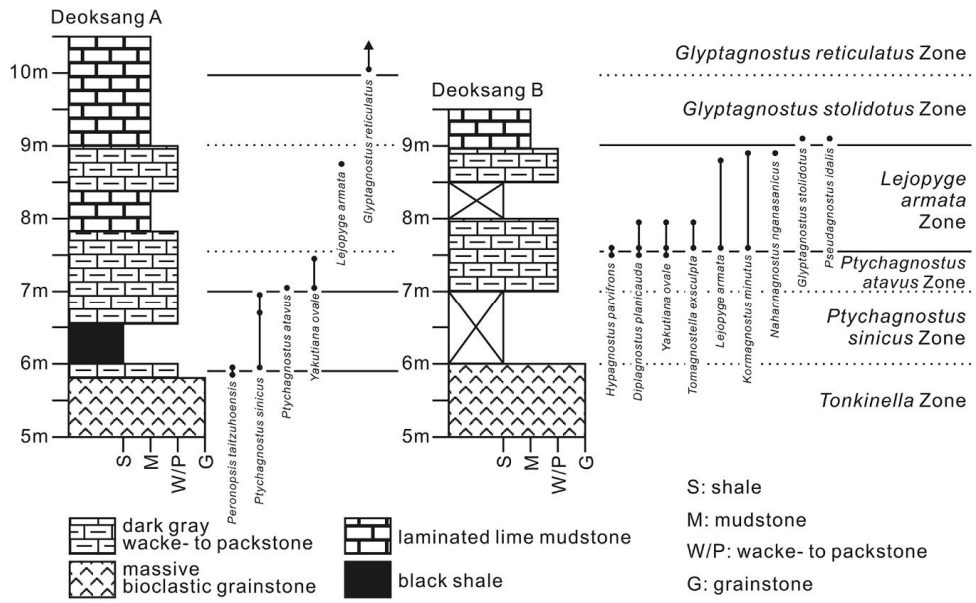

Figure 7. Stratigraphic sections Deoksang A and B of the lower Machari Formation at the Deoksang locality, with trilobite species occurrence ranges and biozonations.

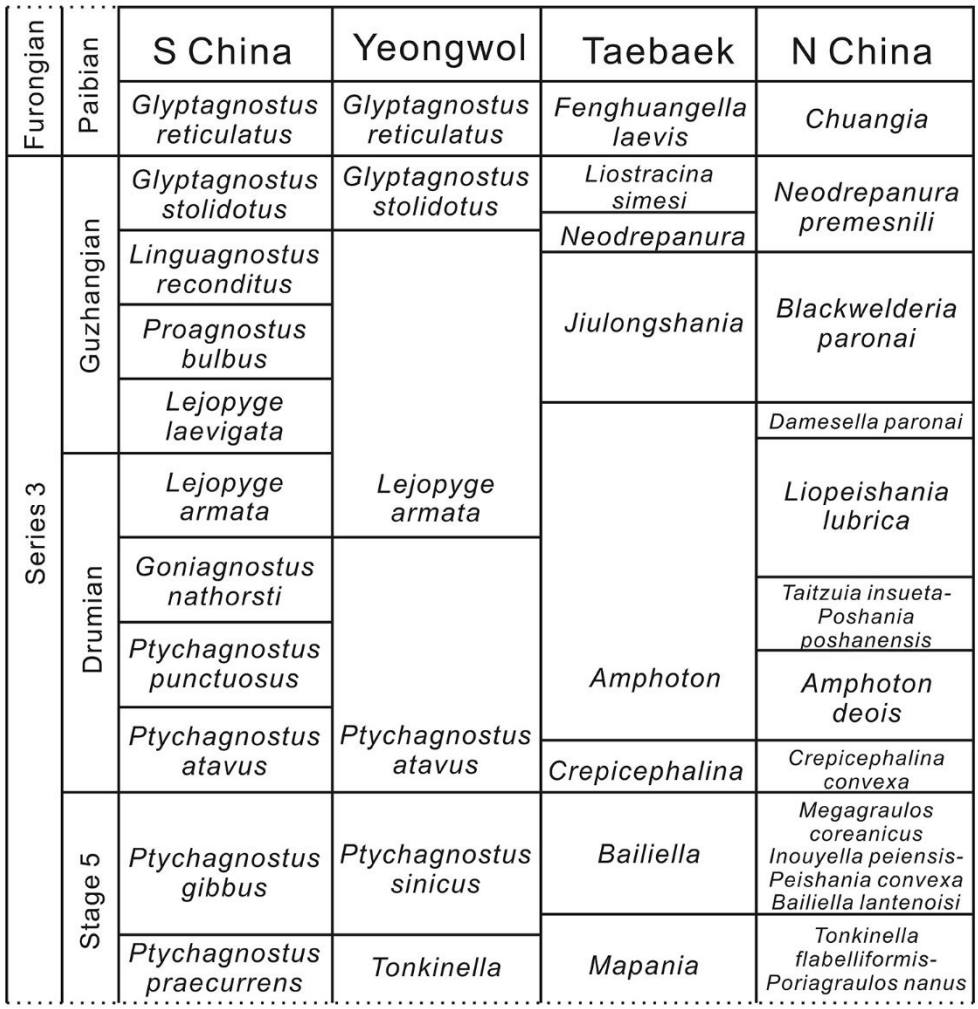

Figure 8. Correlation of trilobite biozones of the lower parts of the Machari Formation at the Yeongwol region (this study) in western Taebaeksan Basin with coeval strata at the Taebaek area (Kang and Choi, 2007; Park et al., 2013) in eastern Taebaeksan Basin, and with those of North China (Yuan et al., 2012) and South China (Peng and Robison, 2000; Peng et al., 2009; Zhao et al., 2014).

Tonkinella species (Sundberg, 2006) and reference to the overlying *P. sinicus* Zone (Hong and Choi, in press), the *Tonkinella* Zone can be assigned to the Cambrian Stage 5.

3. 4. 2. Ptychagnostus sinicus *Zone*

The *P. sinicus* Zone occupies the interval of 6.0–6.9 m above the base of the Machari Formation at Deoksang A section. *Ptychagnostus sinicus* Lu, 1957 co-occurs with *P. taitzuhoensis* at the lowermost part of the Zone, and is confined within the Zone. The *P. sinicus* Zone is correlated with the upper *Tonkinella flabelliformis-Poriagraulos nanus* and lower *Bailiella lantenoisi* zones of North China, and the *Ptychagnostus gibbus* Zone in other parts of the world (Hong and Choi, in press).

3. 4. 3. Ptychagnostus atavus *Zone*

The *P. atavus* Zone covers the interval of 7.0–7.5 m above the base of the Machari Formation at Deoksang A section, and a bed 7.5 m above the base at Deoksang B section. *Yakutiana ovale* (Yang, 1982) co-occurs with *Ptychagnostus atavus* (Tullberg, 1880) at the lowermost part of the Zone at Deoksang A section. *Ptychagnostus atavus* has not been recovered from the Deoksang B section, but *Hypagnostus parvifrons* (Linnarsson, 1869) and *Diplagnostus planicauda* (Angelin, 1851) occur earlier than *Lejopyge armata* (Linnarsson, 1869) that defines the *L. armata* Zone at the section.

The two species are provisionally included as components of the *P. atavus* Zone. *Ptychagnostus atavus* is confined to the zone, whereas all of other component species of the zone extend into the overlying *L. armata* Zone. The *P. atavus* Zone has been employed to define the base of the Drumian Stage (Babcock et al., 2007), and correlation of the *P. atavus* Zone of Korea may extend into the *Ptychagnostus punctuosus* and *Goniagnostus nathorsti* zones, or the *Yakutiana ovale* Zone established elsewhere (Peng et al., 2009a, 2012).

3. 4. 4. Lejopyge armata *Zone*

The *L. armata* Zone is recognized at the bed 8.7 m above the base of the Machari Formation at Deoksang A section, and at the interval of 7.6–8.8 m above the base at Deoksang B section. *Kormagnostus minutus* (Schrank, 1975) and the four species from the underlying *P. atavus* Zone occur in association with *L. armata* at Deoksang B section. *Nahannagnostus nganasanicus* (Rozova, 1964) does not co-occur with *L. armata* at Deoksang B section, but it predates *Glyptagnostus stolidotus* Öpik, 1961 that defines the overlying *Glyptagnostus stolidotus* Zone. Therefore, *N. nganasanicus* is treated as a component of the *L. armata* Zone. All component species of the zone does not range into the overlying *G. stolidotus* Zone. *Lejopyge armata* is known to occur earlier than *Lejopyge laevigata* (Dalman, 1828) that defines the base of the Guzhangian Stage

(Peng et al., 2009a). The *L. armata* Zone correlates with the global *L. armata* Zone, and correlation may extend into the *L. laevigata*, *Proagnostus bulbus*, and *Linguagnostus reconditus* zones identified elsewhere (Peng et al., 2009a, 2012).

3. 4. 5. Glyptagnostus stolidotus *Zone*

The *G. stolidotus* Zone is recognized at the bed 9.1 m above base of the Machari Formation at Deoksang B section. *Pseudagnostus idalis* Öpik, 1967 co-occurs with *G. stolidotus*. Both species are confined to the zone. The *G. stolidotus* Zone has been known to represent the uppermost part of Guzhangian Stage (Peng et al., 2004).

3. 4. 6. Glyptagnostus reticulatus *Zone*

The *Glyptagnostus reticulatus* Zone is recognized by the first appearance of *Glyptagnostus reticulatus* (Angelin, 1851) at the bed 10.0 m above the base of the Machari Formation at Deoksang A section. The *G. reticulatus* Zone defines the base of the Paibian Stage (Peng et al., 2004).

3. 5. Systematic paleontology

Morphological terms used herein are adopted from Whittington and Kelly (1997) and from Peng and Robison (2000). Specimens are stored at the Seoul National University in Korea with designated SNUP numbers.

Full descriptions of *P. atavus* and *P. sinicus* from the Deoksang locality have been given in a separate paper (Hong and Choi, in press).

Class TRILOBITA Walch, 1771

Order AGNOSTIDA Salter, 1864

Family AGNOSTIDAE M'Coy, 1849

Genus ***Pseudagnostus*** Jaekel, 1909

Type species: *Agnostus cyclopyge* Tullberg, 1880 from the lowermost part of the *Pseudagnostus cyclopyge* Zone (uppermost Paibian to lowermost Jiangshanian) of the Alum Shale Formation, Andrarum, Skåne, southern Sweden (by original designation).

Pseudagnostus idalis Öpik, 1967

Fig. 9(1)

1967. *Pseudagnostus idalis* nov. sp. – Öpik, p.153–154, pl. 62, figs. 8, 9, pl. 63, figs. 1, 2.

1995. *Pseudagnostus idalis* Öpik – Lee and Choi, p. 16–18, pl. 2, figs. 1–7 (additional symonymy).

?1998. *Pseudagnostus idalis* Öpik – Han et al., p. 154–155.

2000. *Pseudagnostus josepha* (Hall) – Peng and Robison, p. 16–18, figs. 10.1, 2, 4, 6–10 (part) (additional synonymy on *P. idalis*).

2006. *Pseudagnostus* (*Pseudagnostus*) *idalis* Öpik – Varlamov et al., p.

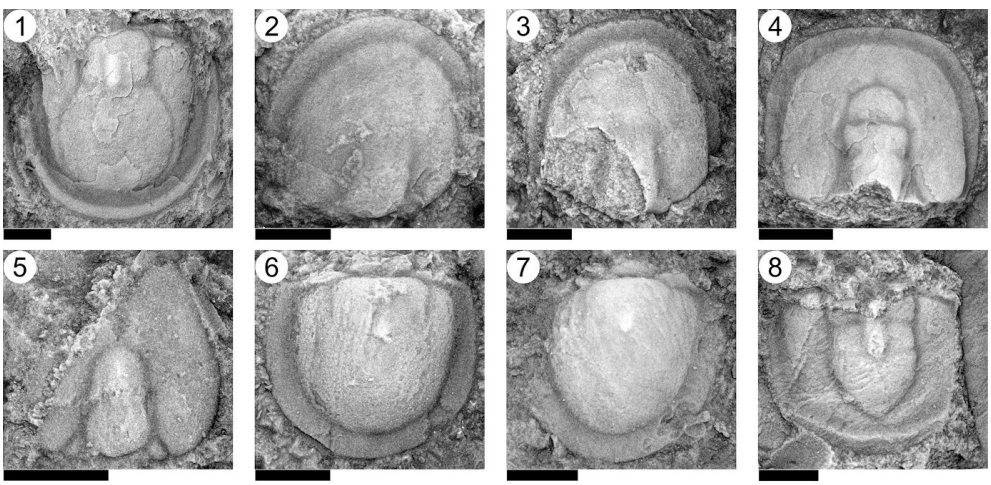

Figure 9. **1**. *Pseudagnostus idalis* Öpik, 1967. Pygidium (latex cast), DSB9.1, SNUP 6327. **2**, **3**, **6**, **7**. *Kormagnostus minutus* (Schrank, 1975). **2**. Cephalon, DSB8.9, SNUP 6329. **3**. Cephalon, DSB7.6, SNUP 6330. **6**. Pygidium, DSB7.6, SNUP 6331. **7**. Pygidium, DSB8.9, SNUP 6332. **4**, **8**. *Diplagnostus planicauda* (Angelin, 1851). **4**. Cephalon, DSB7.6, SNUP 6333. **8**. Pygidum, DSB7.5, SNUP 6334. **5**. *Nahannagnostus nganasanicus* (Rozova, 1964). Cephalon, DSB8.9, SNUP 6328. All scale bars represent 1 mm.

S31–S32, pl. 1, figs. 5–10.

Material, horizon, and locality: A single pygidium is collected from the horizon DSB9.1 of the *G. stolidotus* Zone.

Remarks: Although the partially exfoliated pygidum is the only specimen found from the *G. stolidotus* Zone of the Deoksang section, it clearly shows the diagnostic characters of the species: subovoid cephalic and pygidial outlines, a pair of small margial spine in the pygidial border at about one-third pygidial height, deeply incised and wide border furrows, and pygidial axial furrows that commonly extend near to the posterior portion of the border furrow. The species has previously been described from the Paibian *Proceratopyge tenuis*, *Hancrania brevilimata*, and *Eugonocare longifrons* zones of the Machari Formation at Deogu and Bundeokjae sections (Lee and Choi, 1995). *Pseudagnostus* cf. *P. idalis* (Westrop and Eoff, 2012) from the "*Innitagnostus*" *inexpectans* Fauna (lower Paibian) of northwestern Newfoundland slightly differs by having a narrower and a shallower pygidial border furrow with a less constricted acrolobe. *Pseudagnostus leei* Lee and Choi, 1994 is the only species that co-occurs with *G. stolidotus* in the Deogu section about 9 km southwest of the Deoksang locality, but it differs from *P. idalis* by lacking marginal spines in the pygidial border. *Pseudagnostus josepha* (Hall, 1863) has thinner borders, shallower border furrows, a narrower cephalon, and a wider pygidium that is more effaced (Westrop and Eoff, 2012). *Pseudagnostus idalis* has a long

stratigraphic range that spans from the *L. reconditus* Zone (upper Guzhangian Stage; Peng and Robison, 2000) to the uppermost Paibian Stage in Korea, Australia, Tasmania, South China, Kazakhstan, Siberia, and Argentina.

Genus ***Nahannagnostus*** Pratt, 1992

Type species: *Pseudagnostus nganasanicus* Rozova, 1964 from the Nganasanian Horizon (lower Kulyumbean Stage), Kulyumbe River, northwestern Siberian Platform, Russia (by original designation).

Nahannagnostus nganasanicus (Rozova, 1964)

Fig. 9(5)

1964. *Pseudagnostus nganasanicus* nov. sp. – Rozova, p. 27–28, pl. 16, figs. 3, 4.

1992. *Nahannagnostus nganasanicus* (Rozova) – Pratt, p. 36–337, pl. 6, figs. 10–18 (additional synonymy).

2000. *Nahannagnostus nganasanicus* (Rozova) – Stitt and Perfetta, p. 204, figs. 6.7, 6.8, 6.12.

2000. *Nahannagnostus nganasanicus* (Rozova) – Peng and Robison, p. 23, fig. 16 (additional synonynmy).

2001b. *Nahannagnostus nganasanicus* (Rozova) – Peng et al., pl. 2, fig. 4.

2001a. *Nahannagnostus nganasanicus* (Rozova) – Peng et al., fig. 8.17.

Material, horizon, and locality: A single cephalon is collected from the horizon DSB8.9 of the uppermost *L. armata* Zone.

Remarks: Although the fragmentary cephalon illustrated [Fig. 9(5)] is the sole specimen in the collection, it clearly displays the morphological features of *N. nganansanicus* such as the semielliptical outline of the cephalon, effacement of the anteroglabella, and the presence of a prominent median preglabellar furrow that extends posteriorly close to the anterior margin of posteroglabella. Other species of *Nahannagnostus* include *Nahannagnostus logani* Pratt, 1992 and *Nahannagnostus pratti* Choi et al., 2004. *Nahannagnostus logani* has a semicircular cephalon and a small anteroglabella, and *N. pratti* has a small anteroglabella and a broadly expanding posteroaxis encircled by axial furrow in the pygidium. In addition, *N. logani* occurs stratigraphically lower than *N. nganasanicus* in the *Cedaria minor* Zone and its equivalence in Laurentia, and *N. pratti* in significantly younger, upper Paibian to lower Jiangshanian zones (Pratt, 1992; Choi et al., 2004). *Nahannagnostus nganasanicus* has been reported from the upper Guzhangian Stage of northwestern China (Zhou et al., 1996), *G. stolidotus* Zone of Australia (Öpik, 1967; Shergold, 1977), *P. bulbus* Zone of the Paibian Stage in South China (Peng, 1987; Lu and Lin, 1989; Peng and Robison, 2000), *Kormagnostus simplex* (=*K. seclusus*) Zone of Kazakhstan (Ergaliev, 1980), *Cedaria selwyni* Zone to the *Cedaria*

brevifrons Zone, or the *Crepicephalus* Zone of Laurentia (Robison and Palmer, 1968; Kindle, 1982; Pratt, 1992; Stitt and Perfetta, 2000), and the lower Kulyumbean Stage of Siberia (Rozova, 1964).

Family AMMAGNOSTIDAE Öpik, 1967

Genus ***Kormagnostus*** Resser, 1938a

Type species: *Kormagnostus simplex* Resser, 1938a (=*Agnostus seclusus* Walcott, 1884; Robison, 1988) from the Nolichucky Formation (upper Steptoean Stage) of Tennessee (by original designation).

Kormagnostus minutus (Schrank, 1975)

Fig. 9(2, 3, 6, 7)

1975. *Litagnostoides minutus* nov. sp. – Schrank, p. 593–594, pl. 1, figs. 4–10.

1982. *Kormagnostella minutus* (Schrank) – Shergold, p. 24–25

2000. *Kormagnostus minutus* (Schrank) – Peng and Robison, p. 33–35, fig. 24 (additional synonymy).

2001a. *Kormagnostus minutus* (Schrank) – Peng et al., figs. 8.9, 8.10

Material, horizon, and locality: Five cephala and seven pygidia are collected from DSB7.6 and DSB8.9 of the *L. armata* Zone.

Remarks: The holotype of the species comes from the *Prochuangia* fauna of Liaoning, North China (Schrank, 1975) which is correlatable to the

G. reticulatus Zone. *Kormagnostus minutus* is also present in South China, from the *P. bulbus* Zone to the *L. reconditus* Zone (Peng, 1987; Dong, 1991; Peng and Robison, 2000).

Family DIPLAGNOSTIDAE Shergold, Laurie, and Sun, 1990

Genus ***Diplagnostus*** Whitehouse, 1939

Type species: *Agnostus planicauda* Angelin, 1851 from the *Lejopyge laevigata* Zone (lowermost Guzhangian Stage) of Andrarum Limestone, Andrarum, Skåne, southern Sweden (by original designation).

Diagnosis: See Peng and Robison, 2000, p. 48–49.

Diplagnostus planicauda (Angelin, 1851)

Fig. 9(4, 8)

1851. *Agnostus planicauda* nov. sp. – Angelin, p. 7, pl. 6, fig. 9.

1909. *Diplagnostus planicauda* (Angelin) – Jaekel, p. 396, fig. 14

2000. *Diplagnostus planicauda* (Angelin) – Peng and Robison, p. 49, fig. 35 (additional synonymy).

2003. *Diplagnostus planicauda* (Angelin) – Axheimer and Ahlberg, p. 144, figs. 4A–4D.

2006. *Diplagnostus planicauda* (Angelin) – Axheimer et al., fig. 6m.

2008. *Diplagnostus planicauda* (Angelin) – Ergaliev and Ergaliev, p. 156, pl. 13, figs. 13–15.

2008. *Diplagnostus planicauda* (Angelin) – Høyberget and Bruton, p. 23, pl. 1, figs. R–X, pl. 2, figs. A, B.

2009b. *Diplagnostus planicauda* (Angelin) – Peng et al., p. 18–19, fig. 10.

2011. *Diplagnostus planicauda* (Angelin) – Gozalo et al., figs. 6G–6I, 8A, 8B.

Material, horizon, and locality: Three cephala and three pygidia are collected from DSB7.5, DSB7.6, and DSB8.0, ranging from the upper *P. atavus* Zone to the lower *L. armata* Zone.

Remarks: Robison (1988) illustrated a range of variations in morphological characters for the species including the depth of preglabellar furrow, roundness of the posterior outline of the glabella, degree of scrobicules on the gena, and the location of median tubercle in the pygidium. Most of the previous species and subspecies of *Diplagnostus* that had been defined by minor morphological differences have been synonymized with *D. planicauda*. *Diplagnostus* sp. of South China (Peng and Robison, 2000) and *Diplagnostus* sp. indet. of Himalaya (Peng et al., 2009b) slightly differs from *D. planicauda* by having a sinuous anterior border ridge in the pygidium. *Diplagnostus planicauda* has a wide geographical distribution that includes Korea, northwestern China, Australia, South China, Himalaya, Kazakhstan, Siberia, Greenland, Precordillera, southeastern Newfoundland, Baltica, and the Iberian Chains. It ranges from the *P. atavus* Zone to the *L.*

laevigata Zone.

Family GLYPTAGNOSTIDAE Whitehouse, 1936

Genus ***Glyptagnostus*** Whitehouse, 1936

Type species: *Glyptagnostus toreuma* Whitehouse, 1936 [=*Glyptagnostus reticulatus* (Angelin, 1851); Westergård, 1947] from the Georgina Limestone (Idamean) of western Queensland, Australia. Ruling on the conservation of the accepted usage of *Glyptagnostus* has been made by the International Commission on Zoological Nomenclature (1993).

Glyptagnostus reticulatus (Angelin, 1851)

Fig. 10(1, 2, 5)

1851. *Agnostus reticulatus* nov. sp. – Angelin, p. 8, pl. 6, fig. 10.

1936. *Glyptagnostus reticulatus* (Angelin) – Whitehouse, p. 103.

2001a. *Glyptagnostus reticulatus* (Angelin) – Peng et al., figs. 10.1, 10.2.

2001b. *Glyptagnostus reticulatus* (Angelin) – Peng et al., pl. 4, figs. 1–4, pl. 5, figs. 1–3, pl. 6, figs., 1, 6, 14.

2003. *Glyptagnostus reticulatus* (Angelin) – Ahlberg, figs. 3E–3G.

2006. *Glyptagnostus reticulatus* (Angelin) – Varlamov et al., p. S29–S31, pl. 1, figs. 1–3.

2012. *Glyptagnostus reticulatus* (Angelin) – Ahlberg and Terfelt, figs. 3a, 3b.

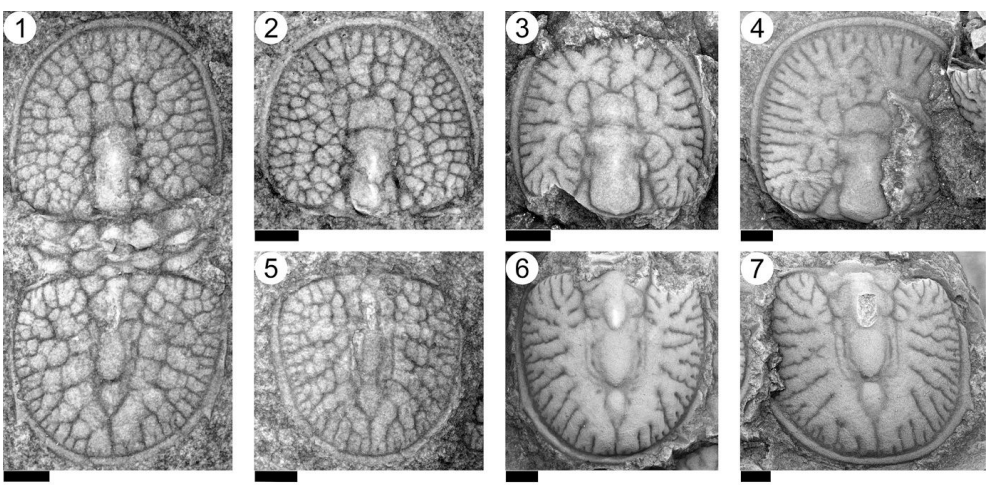

Figure 10. **1**, **2**, **5**. *Glyptagnostus reticulatus* (Angelin, 1851). Exoskeleton, cephalon, pygidium, DSA19.0, SNUP 6335–6337. **3**, **4**, **6**, **7**. *Glyptagnostus stolidotus* Öpik, 1961. **3**, **4**. Cephala, DSB9.1, SNUP 6338, 6339. **6**, **7**. Pygidia, DSB9.1, SNUP 6340, 6341. All scale bars represent 1 mm.

2012. *Glyptagnostus reticulatus* (Angelin) – Westrop and Eoff, p. 235, figs. 22.9–22.15 (additional synonymy).

Material, horizon, and locality: More than twenty specimens are collected from DSA10.0 and higher horizons in the *G. reticulatus* Zone.

Remarks: First appearance datum of *G. reticulatus* defines the base of the Paibian Stage and consequently the base of the Furongian Series (Peng et al., 2004). The species has been thoroughly reviewed in previous studies (Palmer, 1962; Choi and Lee, 1995; Peng and Robison, 2000; Peng et al., 2004).

Glyptagnostus stolidotus Öpik, 1961

Fig. 10(3, 4, 6, 7)

1961. *Glyptagnostus stolidotus* nov. sp. – Öpik, p. 432, pl. 70, figs. 1–8, text-fig. 16.

2000. *Glyptagnostus stolidotus* Öpik – Peng and Robison, p. 88–89, fig. 72 (additional synonymy).

2001a. *Glyptagnostus stolidotus* Öpik – Peng et al., fig. 8.13.

2001b. *Glyptagnostus stolidotus* Öpik – Peng et al., pl. 2, figs. 1–3.

2004. *Glyptagnostus stolidotus* Öpik – Peng et al., figs. 8A, 8B.

2005. *Glyptagnostus stolidotus* Öpik – Jago and Cooper, p. 667, figs. 2O–V.

2008. *Glyptagnostus stolidotus* Öpik –Ergaliev and Ergaliev, p. 88, pl.

25, figs. 1–7.

Material, horizon, and locality: More than twenty cephala and pygidia from DSB9.1 of the *G. stolidotus* Zone.

Remarks: The Deoksang locality documents the second section after the Deogu section that yields *G. stolidotus* in Korea. Previous studies (Palmer, 1962; Choi and Lee, 1995; Peng and Robison, 2000; Peng et al., 2004) have extensively dealt with the morphology and stratigraphic importance of the species together with *G. reticulatus*.

Family PERONOPSIDAE Westergård, 1936

Genus ***Peronopsis*** Hawle and Corda, 1847

Type species: *Battus integer* Beyrich, 1845 from the *Paradoxides gracilis* Zone (Drumian Stage) of the Jince Formation, Jince, Czech Republic (by monotypy).

Peronopsis taitzuhoensis Lu, 1957

Fig. 11(1–11)

1957. *Peronopsis taitzuhoensis* nov. sp. – Lu, p. 258, pl. 137, figs. 4, 5.

1989. *Peronopsis taitzuhoensis* Lu – Sun, p. 93–94 (additional synonymy).

2012. *Peronopsis fallax* (Linnarsson) – Yuan et al., p. 70–71, pl. 5, figs. 11–23, pl. 6, figs. 16–20.

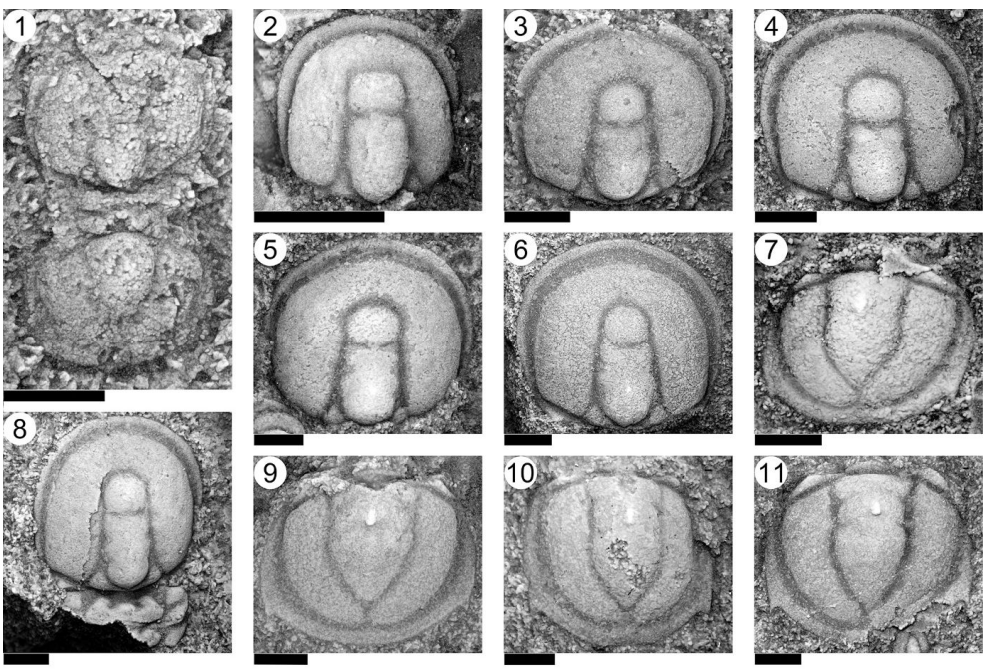

Figure 11. *Peronopsis taitzuhoensis* Lu, 1957. **1**. Exoskeleon, DSA5.8, SNUP 6342. **2**–**6**. Cephala, DSA5.8, SNUP 6343–6347. **7**, **9**–**11**. Pygidia, DSA5.8, SNUP 6348–6351. 8. Cephalon with two thoracic segments, DSA5.8, SNUP 6352. All scale bars represent 1 mm.

2012. *Peronopsis universalis* – Yuan et al., p. 72, pl. 5, figs. 5–10.

Diagnosis: A species of *Peronopsis* with narrow glabella, evenly-rounded cephalic anterior margin, well-defined pygidial F1 and F2 adjacent to the axial furrow, v-shaped posterior end in the pygidial posteroaxis, moderately long median postaxial furrow, and a pair of sharp posterolateral pygidial spines.

Material, horizon, and locality: Forty-nine cephala, forty-five pygidia, one exoskeleton, and one cephalon with two articulated thoracic segments are collected from DSA5.8 and DSA6.0, ranging from the *Tonkinella* Zone to the base of the *P. sinicus* Zone. *Peronopsis taitzuhoensis* has been reported from the *Bailiella-Lioparia* Zone of the Dangshi Formation in Benxi, east-central Liaoning Province, North China (Lu, 1957; Lu et al., 1965; Sun, 1989), and from the *T. flabelliformis–P. nanus* and lower *B. lantenoisi* zones of the Changhia Formation in Zibo, central Shandong Province (Yuan et al., 2012).

Remarks: *Peronopsis taitzuhoensis* Lu, 1957 is based on two syntypes from the east-central Liaoning, China. The pygidial specimen (Lu, 1957, pl. 137, fig. 5; Lu et al., 1965, pl. 5, fig. 22) is herein selected as the lectotype of the species. Compared to other *Peronopsis* species, the glabellar width of *P. taitzuhoensis* is comparatively narrow with about 25% of the cephalic width. The relative length of the glabella is about 65% of the cephalic length. A small axial node on the glabella is visible in well-preserved specimens,

and is located at M2, close to F1.

Peronopsis fallax (Linnarsson, 1869) is a junior synonym of *Peronopsis acadica* (Hartt in Dawson, 1868) (Robison, 1995). *Peronopsis acadica* differs from *P. taitzuhoensis* in having more subquadratic cephalon, wider (trans.) glabella, larger basal lobes, longer (sag. and exsag.) posterior pygidial border, posteriorly rounded pygial axial furrow, wider (trans.) pygidial axis, and larger pygidial axial node (Laurie, 1990; Robison, 1995; Naimark, 2012). Specimens assigned to *P. fallax* (Yuan et al., 2012, pl. 5, figs. 11–23, pl. 6, figs. 16–20) and *Peronopsis universalis* Yuan et al., 2012 (pl. 5, figs. 5–10) from the *T. flabelliformis–P. nanus* and lower *B. lantenoisi* zones of North China have all the diagnostic features of *P. taitzuhoensis*, and are therefore treated as junior synonyms of the latter species.

Peronopsis interstricta (White, 1874) (Robison, 1964, 1982, 1994; Young and Ludvigsen, 1989; Westrop, Ludvigsen, and Kindle, 1996; Laurie, 2004, 2006) and *Peronopsis gaspensis* Rasetti, 1948 (Robison, 1978) are comparable to *P. taitzuhoensis*, but are distinguishable in having weak to absent F1 and F2, larger axial node on M2, and weakly-developed marginal spines. In addition, cephalic margins of *P. interstricta* and *P. gaspensis* become straight at the anteromedian area, and the glabella is relatively wide (trans.). Young and Ludvigsen (1989) commented on the indentation of the cephalic border at the anteromedian region for larger *P. interstricta*

specimens, but anteromedian portion of the cephalic margin for *P. taitzuhoensis* is uniformly rounded in all observed specimens. Naimark (2012, p. 981, p. 1001) treated *P. taitzuhoensis* as a subspecies of *P. gaspensis* in terms of geographical variations, but due to consistant differences in morphological characters mentioned above, including relative width of the glabella being too wide (trans.) for *P. gaspensis* (about 30% of cephalic width), *P. taitzuhoensis* is treated as a separate species.

Other comparable species are differentiated with the following morphological differences: *Peronopsis opimus* (Whitehouse, 1936) has axial furrows effaced around the anteroglabella (Jell and Robison, 1978); *Peronopsis taijianganensis* Huang and Yuan, 1994 has a shorter (sag.) median postaxial furrow (Laurie, 2004, 2006); and *Peronopsis brighamensis* (Resser, 1938b) has transverse F1 and F2 in the pygidium (Robison, 1978). *Pentagnostus krusei* Laurie, 2006 and *Doryagnostus deltoides* Robison, 1978 resemble *P. taitzuhoensis*, but both species have a median preglabellar furrow, and *Pentagnostus krusei* has transverse F1 and F2 in the pygidium.

Other middle Cambrian species previously described from Korea include *Baltagnostus rakuroensis* (Kobayashi, 1935). Its holotype occurs with *Ptychoparia* (?) *coreanica* Kobayashi, 1935 in Pyeongannam-do, northwestern Korean Peninsula, and is different from *P. taitzuhoensis* in having an incipient median preglabellar furrow with angular glabellar culmination and a wide (sag. and exsag.) posterior pygidial border. Other

specimens previously assigned to *B. rakuroensis* from the *Tonkinella* Zone of the Machari Formation in the Taebaeksan Basin (Kobayashi, 1935, pl. 14, figs. 17–18, 1962, pl. 3, figs. 1–3) have relatively wide (sag.) glabellar width, pygidial posteroaxis that may or may not reach to the border furrow, and do not have median preglabellar furrows. Therefore, the specimens from the Machari Formation may not belong to *B. rakuroensis*, but presumably represent a single or multiple *Peronopsis* species not excluding *P. taitzuhoensis*. Definite species assignment is reserved until taxonomic revision of trilobites from the *Tonkinella* Zone is made. Another middle Cambrian agnostoid trilobite from Korea is *Ammagnostus laiwuensis* (Lorenz, 1906) that occurs in the *Crepicephalina* and *Amphoton* zones of Daegi Formation, Taebaek Group, eastern Korean Peninsula (Kang and Choi, 2007). *Ammagnostus laiwuensis* mainly differs from *P. taitzuhoensis* in having a round posterior margin in the posteroaxis that nearly reaches to the border furrow, and its geological age is younger than that of *P. taitzuhoensis*.

Genus ***Hypagnostus*** Jaekel, 1909

Type species: *Agnostus parvifrons* Linnarsson, 1869 from the *Hypagnostus parvifrons* Zone (lower Drumian) of the Alum Shale Formation, Kinnekulle, Västergötland, south-central Sweden (by original designation).

Hypagnostus parvifrons (Linnarsson, 1869)

Fig. 12(1–4)

1869. *Agnostus parvifrons* nov. sp. – Linnarsson, p. 82, pl. 2, figs. 56, 57.

1909. *Hypagnostus parvifrons* (Linnarsson) – Jaekel, p. 399, fig. 17.

2004. *Hypagnostus parvifrons* (Linnarsson) – Sloan and Laurie, p. 197, figs. 2F, 2I, 2J.

2014. *Hypagnostus parvifrons* (Linnarsson) – Weidner and Nielsen, p. 48–49, figs. 21C, 21D, 22P (additional synonymy).

Material, horizon, and locality: Four cephala and seven pygidia are collected from DSB7.5 and DSB7.6, ranging from the upper *P. atavus* Zone to the base of the *L. armata* Zone.

Remarks: *Hypagnostus parvifrons* differs from *Hypagnostus brevifrons* (Angelin, 1851) in having a prominent postaxial median furrow and medial expansion of the posterior border of pygidium. The smaller specimens show that the relative length of pygidial axis increases with growth. Cephala of *H. parvifrons* and *Tomagnostella sulcifera* (Wallerius, 1895) are very similar in overall shape, but the posteroglabella in *H. parvifrons* is oval rather than angular in outline, relatively short in sagittal length, and the cephalon has no trace of preglabellar median furrow. The species is widespread in distribution, and has a long stratigraphic range from the base of the *P. atavus* Zone to the *P. bulbus* Zone.

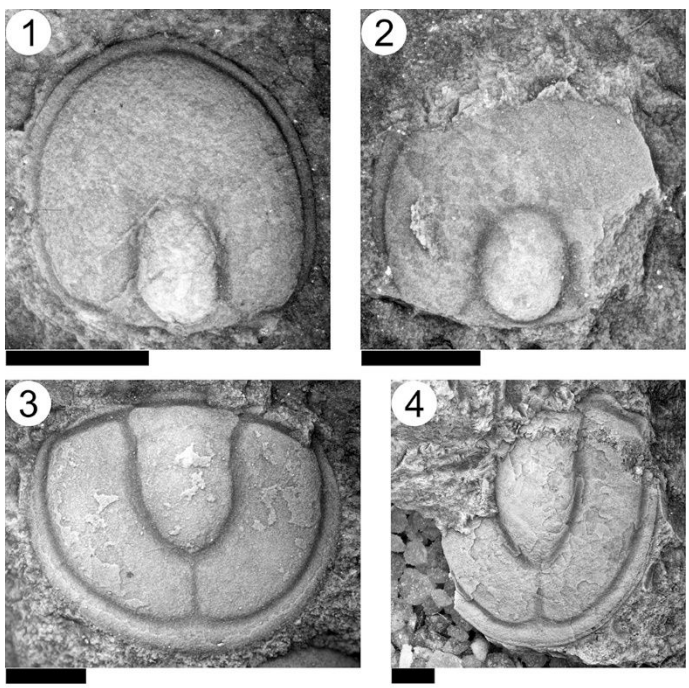

Figure 12. *Hypagnostus parvifrons* (Linnarsson, 1869). **1**, **2**. Cephala, DSB7.6, SNUP 6353, 6354. **3**. Pygidium, DSB7.5, SNUP 6355. 4. Pygidium, DSB7.6, SNUP 6356. All scale bars represent 1 mm.

Family PTYCHAGNOSTIDAE Kobayashi, 1939

Genus ***Lejopyge*** Hawle and Corda, 1847

Type species: *Battus laevigatus* Dalman, 1828 from the *Lejopyge laevigata* Zone (Guzhangian) of Alum Shale Formation, Västergötland, south-central Sweden (by monotypy).

Lejopyge armata (Linnarsson, 1869)

Fig. 13(1, 2, 5, 6)

1869. *Agnostus laevigata* var. *armata* nov. sp. – Linnarsson, p. 82, pl. 2, figs. 58, 59.

1983. *Lejopyge armata* (Linnarsson) – Lu and Lin, pl. 1, figs. 7, 8.

2003a. *Lejopyge armata* (Linnarsson) – Hong et al., p. 901, figs. 4.17–4.20.

2006. *Lejopyge armata* (Linnarsson) – Axheimer et al., p. 453, figs. 6c1, 6c2, 6d1, 6d2.

2006. *Lejopyge armata* (Linnarsson) – Peng et al., figs. 8A–8D.

2008. *Lejopyge armata* (Linnarsson) – Høyberget and Bruton, p. 58–59, pl. 10, figs. D–G, I, J, N (additional synonymy).

2009a. *Lejopyge armata* (Linnarsson) – Peng et al., figs. 9A–9D.

2009b. *Lejopyge armata* (Linnarsson) – Peng et al., p. 25, fig. 14.1–14.4 (additional synonymy).

2011. *Lejopyge armata* (Linnarsson) – Peng et al., figs. 5B–5D.

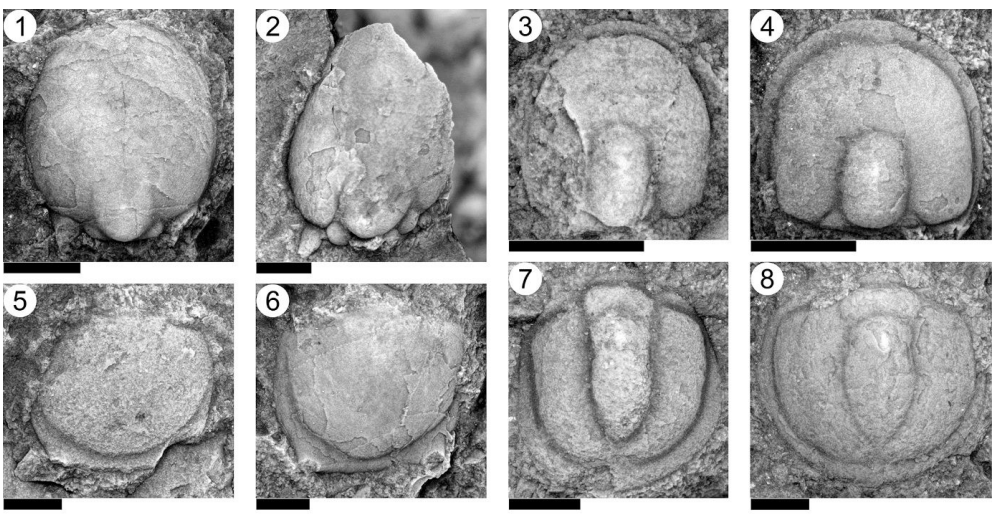

Figure 13. **1**, **2**, **5**, **6**. *Lejopyge armata* (Linnarsson, 1869). **1**, Cephalon, DSB8.8, SNUP 6357. **2**. Cephalon, DSB7.5, SNUP 6358. **5**. Pygidium, DSB7.6, SNUP 6359. **6**. Pygidium, DSB8.8, SNUP 6360. **3**, **4**, **7**, **8**. *Tomagnostella exsculpta* (Angelin, 1851). **3**, Cephalon, DSB7.6, SNUP 6361. **4**. Cephalon, DSB7.5, SNUP 6362. **7**. Pygidium, DSB8.0, SNUP 6363. **8**. Pygidium, DSB7.6, SNUP 6364. All scale bars represent 1 mm.

2011. *Lejopyge armata* (Linnarsson) – Jago et al., p. 19–21, fig. 3D.

Material, horizon, and locality: Three cephala and two pygidia are collected from DSA8.7, DSB7.6, and DSB8.8 of the *L. armata* Zone.

Remarks: Aside from Laurentia, *L. armata* globally occurs stratigraphically higher than *Lejopyge laevigata*, which is used to define the base of the Guzhangian Stage (Peng et al, 2009a). *Lejopyge armata* is the only species of *Lejopyge* in having marginal spines both in the cephalon and in the pygidium. Phosphatized specimens of *L. armata* have been reported from the name-bearing zone of the Eudungol section located about 8 km northeast of the Deoksang section (Hong et al., 2003a). *Lejopyge armata* has been reported from the *L. armata* Zone to the *P. bulbus* Zone of Korea, northwestern China, Australia, Tasmania, South China, Himalaya, Kazakhstan, Siberia, Greenland, North America, Baltica, and Antarctica.

Genus ***Tomagnostella*** Kobayashi, 1939

Type species: *Agnostus exsculptus* Angelin, 1851 from the *Lejopyge laevigata* Zone (lowermost Guzhangian Stage) of Andrarum Limestone, Andrarum, Skåne, southern Sweden (by original designation).

Tomagnostella exsculpta (Angelin, 1851)

Fig. 13(3, 4, 7, 8)

1851. *Agnostus exsculptus* nov. sp. – Angelin, p. 7, pl. 6, fig. 8 (part;

cephalon only).

1939. *Tomagnostella exsculpta* (Angelin) – Kobayashi, p. 150–151.

2012. *Tomagnostella exsculpta* (Angelin) – Yuan et al., p.82–83, pl. 13, figs. 23–26 (additional synonymy).

Material, horizon, and locality: Five cephala and five pygidia are collected from DSB7.6 and DSB8.0 of the lower *L. armata* Zone.

Remarks: Two major variants of the species, *Agnostus parvifrons* var. *nepos* Brøgger, 1878 and *Agnostus exsculptus* forma *sulcifera* Wallerius, 1895 were variously treated in the previous studies: some elevated them to the species-level (Westergård, 1946; Høyberget and Bruton, 2008), while others (Robison, 1988; Peng and Robison, 2000) synonymized altogether or partially with *T. exsculpta*. Deoksang specimens show consistancy in some of the diagnostic features such as uniformly smooth acrolobe and relatively short (sag.) pygidial axis, whereas other morphological characters previously described as differential features for taxonomic division such as depth of the postaxial furrow and F2, convexity of the pygidial axis, and roundness of its posterior margin are proved to be gradational even within the small number of available specimens. Therefore, broader definition of *T. exsculpta* as in Robison, 1988 is adopted in this study. Cephalon of *H. parvifrons* bears some resemblance to that of *T. exsculpta*, but the posteroglabella is longer at about half-length of the cephalon and the F3 is angular in *T. exsculpta*. *Tomagnostella exsculpta* has been reported from the

P. punctuosus Zone to the *G. stolidotus* Zone of Korea, North China, northwestern China, Australia, South China, Himalaya, Kazakhstan, Siberia, Greenland, Precordillera, North America, eastern Avalonia, and Baltica.

Genus ***Yakutiana*** Özdikmen, 2009

Type species: *Pseudophalacroma crebra* Pokrovskaya, 1958 [=*Yakutiana dubium* (Whitehouse, 1936)] from the Mayan Stage of southeastern Sakha Republic, Russia.

Remarks: The agnostid generic name *Pseudophalacroma* was erected by Pokrovskaya in 1958, but was preoccupied by Jörgensen (1923) for a dinoflagellate genus. Özdikmen (2009) proposed the replacement name *Yakutiana* for *Pseudophalacroma* Pokrovskaya, 1958.

Yakutiana ovale (Yang, 1982)

Fig. 14(1–10)

1982. *Phalagnostus ovalis* nov. sp. – Yang, p. 302–303, pl. 2, fig. 1.

2000. *Pseudophalacroma ovale* (Yang) – Peng and Robison, p. 82–83, fig. 67 (additional synonymy).

2001a. *Pseudophalacroma ovale* (Yang) – Peng et al., fig. 8.6.

2009. *Yakutiana ovale* (Yang) – Özdikmen, p. 156.

Material, horizon, and locality: More than one hundred specimens of cephala and pygidia are collected from DSA7.0, DSA7.5, DSB7.5, DSB7.6,

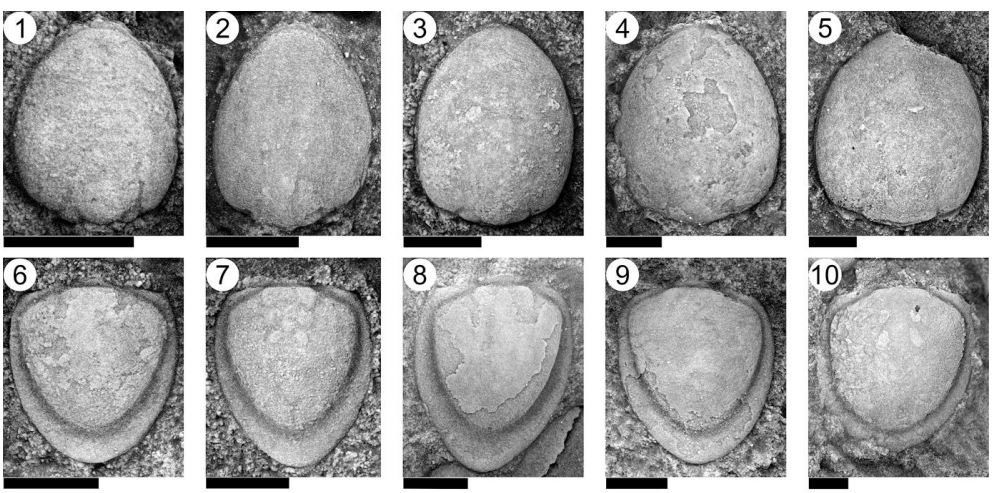

Figure 14. *Yakutiana ovale* (Yang, 1982). **1**–**5**. Cephala, DSA7.0, SNUP 6365–6369. **6**–**10**. Pygidia, DSA7.0, SNUP 6370–6374. All scale bars represent 1 mm.

and DSB8.0, ranging from the basal *P. atavus* Zone to the lower *L. armata* Zone. The species has hitherto been exclusively reported from China: *Yakutiana ovale* Zone, Kuruktag, eastern Xinjiang (Lin et al., 1992); *Ptychagnostus punctuosus* and *G. nathorsti* zones, northwestern Hunan (Lin, 1991; Peng and Robison, 2000; Peng et al., 2009a); *Yakutiana ovale* and *L. armata* zones of western Zhejiang (Lu and Lin, 1989).

Remarks: *Yakutiana ovale* and *Y. dubium* are the two effaced species of the genus, and the former differs from the latter in having more triangularly shaped cephalon and pygidium. Occurrence ranges of the two species are known to overlap in northwestern Hunan (Peng and Robison, 2000; Peng et al., 2009a) and western Zhejiang (Lu and Lin, 1989). Peng and Robison (2000, p. 83) suggested that both morphs may intergrade in the same collection. However, numerous specimens from Korea invariably show distinctly triangular shape and, therefore, are assigned to *Y. ovale*.

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CHAPTER 4

New Cambrian Series 3 trilobite faunas from the lower part of the Machari Formation and their paleogeographical implications

4. 1. Introduction

The occurrence data of trilobite species have been employed to reconstruct the Cambrian paleogeography of east Gondwana. Cambrian trilobites of the Taebaek Group show a close affinity with those of North China, whereas those of the Yeongwol Group have been suggested in the past to show some similarity with the South China faunas (Kobayashi, 1967). However, this apparent resemblance of Yeongwol Group with South China may largely be due to the effect of cosmopolitan species occupying relatively larger portion in the total number of South China taxa. Newly recovered trilobites from the lower part of the Machari Formation are employed to explore whether this faunal composition of the Machari Formation agrees with the suggestion of close paleogeographic connection between Yeongwol and North China.

4. 2. Previous studies

The number of Furongian genera that have been reported from South China but not from North China is 179, and 175 out of the total genera are known to be found in deeper-water settings (Zhou and Zhen, 2008). Many

of these deeper-water genera are in fact cosmopolitan taxa instead of being endemic to South China, so the Machari Formation which also yields many global trilobite taxa may mislead us into affiliating the Yeongwol Group to South China (Cluzel et al., 1991). In addition, rare occurrences of Furongian trilobite genera exclusively from North China such as *Changshania*, *Parachangshania*, and *Eochuangia* of the Machari Formation seem to affirm the close relationship of the Yeongwol Group with North China (Choi and Kim, 2006).

Aside from these fossil records, detrital zircon age spectra are widely being sought for the clues to the source areas of sediments. Recent attempts on the analyses of detrital zircons from the Yeongwol area also suggest its affinity to North China (McKenzie et al., 2011; Kim et al., 2013).

4. 3. Cambrian Series 3 polymerid trilobites from the Machari Formation

Agnostoid trilobites are abundantly recovered from the Machari Formation at the Deoksang section, whereas polymerid trilobites are scarce and show a low species diversity. Six polymerid genera have been identified from the section; *Amphoton* sp., *Cyclolorenzella* sp., *Dorypyge* sp., *Neoanomocarella* sp., *Palaeadotes* sp., and *Teinistion* sp.

Amphoton sp. occurs in the bed 7.0 m above the base of the Machari Formation in the lower *Ptychagnostus atavus* Zone of the Deoksang A

section, and *Dorypyge* sp. appears in horizons 7.5 m above the base at Deoksang A and B sections in the upper *P. atavus* Zone. *Cyclolorenzella* sp., *Neoanomocarella* sp., *Palaeadotes* sp., and *Teinistion* sp. occur in the lower *Lejopyge armata* Zone at 7.6 m above the base of the Machari Formation and the upper *Lejopyge armata* Zone at 8.9 m above the base of the Machari Formation in Deoksang B (Fig. 15).

Amphoton Lorenz, 1906, *Dorypyge* Dames, 1883, *Neoanomocarella* Hsiang in Egorova et al., 1963, *Palaeadotes* Öpik, 1967, and *Teinistion* Monke, 1903 are all cosmopolitan taxa with relatively long stratigraphic ranges, and these genera have been reported from South China (Peng et al., 2004), North China (Zhang and Jell, 1987), Australia (Öpik, 1967), Himalaya (Peng et al., 2009), France (Shergold et al., 2000), and Kazakhstan (Ergaliev, 1980). Therefore, these genera may not offer much information about the paleogeography of the study area. However, *Cyclolorenzella* has only been reported from North China and Korea (Park et al., 2008), and the occurrence of the genus in the Yeongwol area again supports the idea that the Taebaeksan Basin must have been the Sino-Korean Craton during the time equivalent to Cambrian Series 3.

4. 4. Conclusions

Occurrence of the trilobite genera endemic to North China such as *Cyclolorenzella* in the Yeongwol area expands our evidence on close

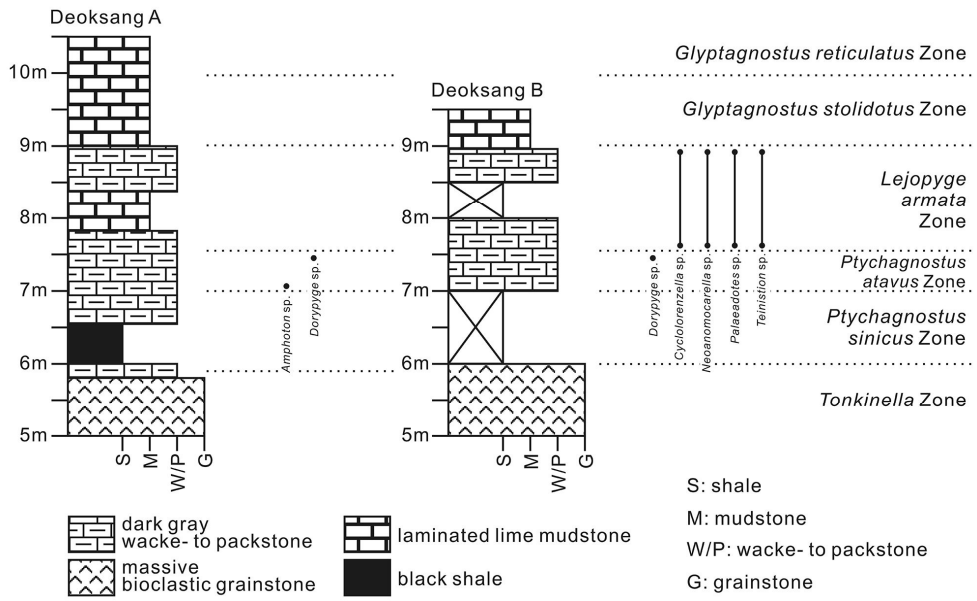

Figure 15. Stratigraphic sections Deoksang A and B of the lower Machari Formation at the Deoksang locality, with polymerid trilobite species occurrence ranges and biozonations.

paleogeographical relationship between Yeongwol and North China; from the previous reported Furongian trilobite genera of *Changshania*, *Parachangshania*, and *Eochuangia*, to the Cambrian Series 3 trilobites of *Cyclolorenzella*. In addition, occurrence of agnostoid trilobite species *Peronopsis taitzuhoensis* Lu, 1957 from the Deoksang section further support close Yeongwol-North China relationship since the species has only been reported from the *Bailiella* Zone of Shandong, North China.

The polymerid trilobite fauna from the lower part of the Machari Formation is of relatively low species diversity, and is dominated by cosmopolitan taxa. Nonetheless, occurrence of *Cyclolorenzella* not only stengthens the previous interepretation on close paleogeographical ties between Yeongwol and North China, but also extends the geological time of co-occurring endemic trilobite taxa between the two regions from the Ordovician (*Koraipsis* and *Yosimuraspis*) and Furongian (*Changshania*, *Parachangshania*, and *Eochuangia*) to older Cambrian Series 3 (*Cyclolorenzella* and *Peronopsis taitzuhoensis*). Further re-evalution of the trilobite fauna from the *Tonkinella* Zone of the lowermost Machari Formation, and review of polymerid species from the underlying Sambangsan Formation are expected to offer more information on the paleogeographical configuration of the Yeongwol region.

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초 록

캄브리아기 제3통에 대응하는 마차리층의 생층서는 삼엽충의 산출 부족으로 푸롱통의 그것에 비해 잘 알려져 있지 않다: 캄브리아기 제3통에 대해서는 오직 3개의 생층서대인 *Tonkinella*대, *Lejopyge armata*대, *Glyptagnostus stolidotus*대만 설정되어 있다. 영월 북서쪽 12 km에 위치한 새로운 화석 산출지는 마차리층 최하부 10 m가 잘 노출되어 있으며, 그곳에서 보존상태가 좋은 아그노스토이드 삼엽충이 수집되었다. 근처 두 단면의 14 화석 층준에서 총 13개의 종이 인지되었다: *Peronopsis taitzhuhoensis*, *Ptychagnostus sinicus*, *Ptychagnostus atavus, Yakutiana ovale*, *Hypagnostus parvifrons*, *Diplagnostus planicauda*, *Tomagnostella exsculpta*, *Lejopyge armata*, *Kormagnostus minutus*, *Nahannagnostus nganasanicus*, *Pseudagnostus idalis*, *Glyptagnostus stolidotus*, *Glyptagnostus reticulatus*. 하부(약 5.8 m 두께)는 괴상의 생물파편 기원의 grainstone이 특징적이며, 과거 *Tonkinella*대에서 나타나는 것으로 알려진 캄브리아기 제5조 삼엽충이 산출된다. 중부(약 1.7 m 두께)는 암회색 wacke- to packstone과 흑색 셰일로 이루어져 있다. *Peronopsis taitzhuhoensis*와 *Ptychagnostus sinicus*는 중부 구간의 하부 1.2 m의 wacke- to packstone 층준에서 순차적으로 나타나며, 드럼조의 기저를 지시하는 *Ptychagnostus atavus*는 중부 구간의 상부 0.5

m에서 다량의 *Yakutiana ovale*와 함께 소량 산출된다. 상부(약 2.5 m 두께)는 엽층리가 발달한 석회질 이암이 우세하며, 상부의 하부 1.4 m 구간에서는 상대적으로 종 다양성이 높으며, *Yakutiana ovale*, *Hypagnostus parvifrons*, *Diplagnostus planicauda*, *Tomagnostella exsculpta*, *Kormagnostus minutus*, *Nahannagnostus nganasanicus*가 인지되었다. 특히 *Lejopyge armata*는 상부 구간의 1.2m 높이에서 발견되었으며, 이는 드럼조와 구장조의 경계가 이 구간 내에 존재한다는 것을 의미한다. *Glyptagnostus stolidotus*는 상부 구간 1.6 m 높이에서 기록되었으며, *Glyptagnostus reticulatus*는 구간 최상부에서 나타난다. 그러므로 단면 10 m 두께의 구간은 캄브리아기 제5조에서부터 파이비조 하부에 해당한다. 하부로부터 *Ptychagnostus sinicus*대와 *Ptychagnostus atavus*대가 이미 알려진 *Tonkinella*대와 *Lejopyge armata*대 사이에 순차적으로 설정되었다.

*Ptychagnostus sinicus*와 *P. atavus*는 랜드마크 기반의 형태 분석과 주성분 북석을 통해 명확하게 구분될 수 있다. 이번 *P. atavus*의 첫 발견으로 한국의 드럼조 기저의 인지와 기타 지역과의 생층서 대비가 가능해졌다.

*Cyclolorenzella*와 *Peronopsis taitzuhoensis*와 같은 북중국 고유 삼엽충의 영월 산출은 영월-북중국 간 고유 삼엽충 종의 시기 분포를 오르도비스기와 푸롱통에 해당하는 지질시대에서

캄브리아기 제3통에 해당하는 시간까지 확장시켰다.

주요어 : 마차리층, 삼엽충, 캄브리아기 제3통, 영월, 기하학적 형태 계측

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