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Furongian trilobites from the *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea

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ABSTRACT: This paper describes the upper Furongian trilobites from the Hwajeol Formation and, based on these trilobite faunal assemblages, proposes formally two trilobite biozones, the *Asioptychaspis* and *Quadraticephalus* zones. A total of 14 species belonging to ten genera are described: i.e., *Micragnostus* sp., *Pseudagnostus planulatus*, *Koldinioidia* sp., *Hamashania pulchera*, *Hamashania* sp. cf. *H. busiris*, *Asioptychaspis subglobosa*, *Changia* sp., *Quadraticephalus elongatus*, ptychaspidid genus and species indeterminate, *Lophosaukia orientalis*, *Lophosaukia*? sp., *Tsinania canens*, *Tsinania* sp., and *Haniwa sosanensis*. The *Asioptychaspis* Zone is characterized by predominance of *Asioptychaspis subglobosa*, while the succeeding *Quadraticephalus* Zone is dominated by *Quadraticephalus elongatus*, *Lophosaukia orientalis*, *Haniwa sosanensis*, and *Micragnostus* sp. The *Asioptychaspis* and *Quadraticephalus* zones are well correlated with the *Ptychaspis-Tsinania* and *Changia* (or *Quadraticephalus*) zones of North China, respectively. These two trilobite assemblages of the Hwajeol Formation support a strong paleogeographical link between the Taebaeksan Basin and North China Platform during the late Furongian.

Key words: trilobites, Cambrian, Furongian, Taebaeksan Basin, biostratigraphy

1. INTRODUCTION

The Taebaek Group is a mixed siliciclastic-carbonate succession representing a shallow marine facies of the Taebaeksan Basin in the early Paleozoic (Choi and Chough, 2005). Trilobites are among the most abundant and diverse fossil groups in the Taebaek Group. The biostratigraphy of the Taebaek Group mainly based on trilobites was established by Kobayashi (1935, 1966) with recent modification for the Ordovician biozones by Kim et al. (1991) and Choi et al. (2003). Lately, Choi and Chough (2005) summarized 19 biozones within the Taebaek Group: they are, in ascending order, the *Redlichia*, *Elrathia*, *Mapania*, *Bailiella*, *Megagraulos*, *Solenoparia*, *Olenoides*, *Stephanocare*, *Drepanura*, *Prochuangia*, *Chuangia*, *Kaolishania*, *Dictyites*, *Eoorthis*, *Pseudokainella*, *Asaphellus*, *Protopliomerops*, *Kayseraspis*, and *Dolerobasilicus* zones. The lower 14 zones were assigned to the Cambrian, and the upper five to the Ordovician.

During the last several years, extensive search for trilobites from the Taebaek Group have accumulated a considerable number of trilobite specimens from the Sesong and Hwajeol formations. A preliminary report (Sohn and Choi, 2005b) suggests that the revised lithostratigaphy and biostratigraphy of the Sesong and Hwajeol formations are different from those proposed by Kobayashi (1966). Kobayashi (1966) originally recognized two biozones (*Stephanocare* and *Drepanura* zones) in the Sesong Formation and five biozones (*Prochuangia*, *Chuangia*, *Kaolishania*, *Dictyites*, and *Eoorthis* zones) in the Hwajeol Formation, respectively. Meanwhile, Sohn and Choi (2005b) reported four trilobite faunal assemblages across the boundary between the Sesong and Hwajeol formations: namely, the *Kaolishania*, *Ptychaspis*, *Quadraticephalus*, and saukiid-dominated faunas in ascending order. They went on further to suggest that the *Kaolishania* fauna belongs to the Sesong Formation, whereas the upper three faunas are comparable to the previously poorly-defined *Dictyites* and *Eoorthis* zones.

Species previously assigned to *Ptychaspis* from the Hwajeol Formation are morphologically distinct from the *Ptychaspis* species from Laurentia. The former is transferred to *Asioptychaspis* Kobayashi, 1933. Accordingly, the *Ptychaspis* and *Quadraticephalus* faunas of Sohn and Choi (2005b) are herein renamed as the *Asioptychaspis* and *Quadraticephalus* zones. This paper systematically describes the trilobites from the *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation and discusses their biostratigraphic significance.

2. GEOLOGY AND STRATIGRAPHY

The lower Paleozoic sedimentary rocks in Korea, Joseon Supergroup, are largely exposed in the Taebaeksan Basin, which occupies 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 (Yeongwol area) 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 Carboniferous-Permian sedimentary rocks. The Joseon Supergroup has been divided into the Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups based

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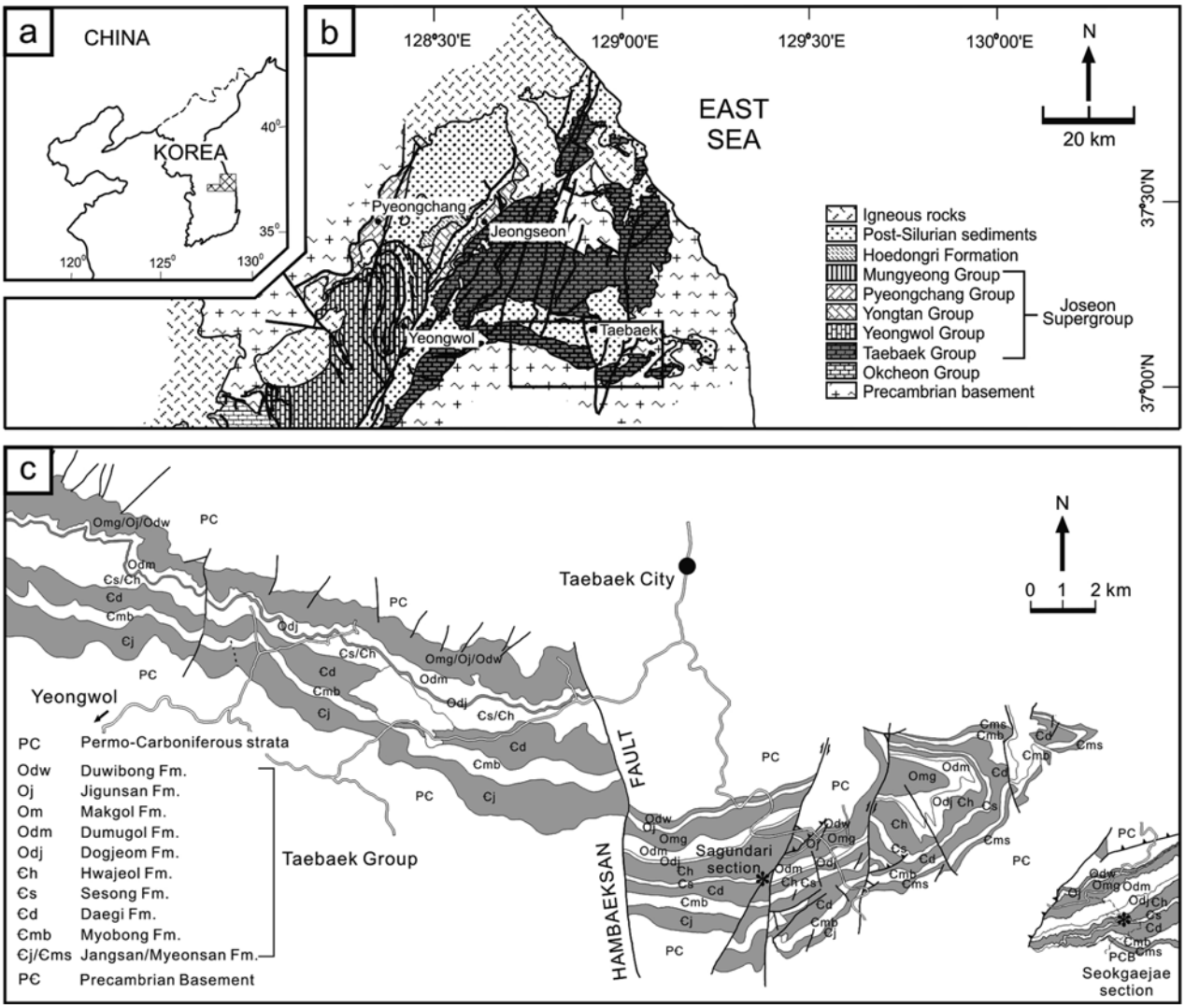

Fig. 1. Location maps. (a) Index map showing the position of (b) (hatched box). (b) Simplified geologic map of the Taebaeksan Basin showing the distribution of the lower Paleozoic Joseon Supergroup and the position of (c) (rectangular box). (c) Geologic map of the study area showing the fossil localities indicated by asterisks (*). Modified from Choi (1998), Chough et al. (2000), and Woo et al. (2006).

on their geographic distribution and lithologic successions (Kobayashi, 1966; Choi, 1998; Choi and Chough, 2005).

The Taebaek Group occupies the eastern half of the Taebaeksan Basin and comprises the Jangsan/Myeonsan, Myobong, Daegi, Sesong, Hwajeol, Dongjeom, Dumugol, Makgol, Jigunsan, and Duwibong formations in ascending order (Choi et al., 2004; Fig. 1). The Cambrian-Ordovician boundary was conventionally placed at the boundary between the Hwajeol and Dongjeom formations (Kobayashi, 1966), but it was recently suggested that the Cambrian-Ordovician boundary may lie within the lowermost part of the Dongjeom Formation (Choi et al., 2003).

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

The Hwajeol Formation was originally proposed by Kobayashi (1935) as the Hwajeol Group for the upper Cambrian strata composed mostly of an alternating succession of limestone and shale beds. GICTR (1962) lowered its rank to a formation. Kobayashi (1966) divided the formation into four members: the basal member (ca. 60 m thick) is an alternating sequence of black shale, limestone, sandstone and slate; the lower member (25 m thick) was described to comprise reddish calcareous sandstone and quartzite, containing the *Kaolishania* fauna; the upper

member (ca. 80 m thick) is characterized by an alternation of reddish limestone and dark gray to black marl with occasional thin shale layers and yields the *Quadraticephalus* fauna; and the top member (ca. 40 m thick) was described to consist of dark reddish limestone and dark green marl with intercalations of shale and sandstone layers. Sohn and Choi (2005b) however interpreted that the lower two members are lithologically indistinguishable from, and consequently should be incorporated into, the Sesong Formation, which means that the Hwajeol Formation is restricted to the upper two members recognized by Kobayashi (1966).

The newly defined Hwajeol Formation is characterized by an alternating succession of calcareous shale, nodule-bearing shale, flaser wackestone to packstone, massive grainstone, limestone-shale couplet, and limestone pebble conglomerate beds (cf. Choi et al., 2004). The boundary between the Sesong and Hwajeol formations is drawn at the base of shale bed which overlies several meter thick fine-grained sandstone facies of the uppermost part of the Sesong Formation. The lower part of the Hwajeol Formation is characterized by thick limestone-shale couplets with intercalation of nodule-bearing shale and limestone pebble conglomerate beds. The upper part of the formation comprises nodule-bearing shale, limestone-shale couplet, laminated fine-grained sandstone, and calcareous shale with limestone pebble conglomerate. The top of the formation is placed at the base of thick intermingled fine-grained sandstone of the overlying Dongjeom Formation.

3. DESCRIPTION OF FOSSIL LOCALITIES

The Hwajeol Formation is well exposed at several localities in Taebaek area. Two sections, Sagundari and Seokgaejae sections, were selected for biostratigraphic zonation of the Hwajeol Formation (Fig. 1c). The Sagundari section is located at approximately 8 km south of Taebaek City. The section comprises the interval across the boundary between the Sesong and Hwajeol formations and measures ca. 20 m in thickness (Fig. 2). The Sesong Formation in the

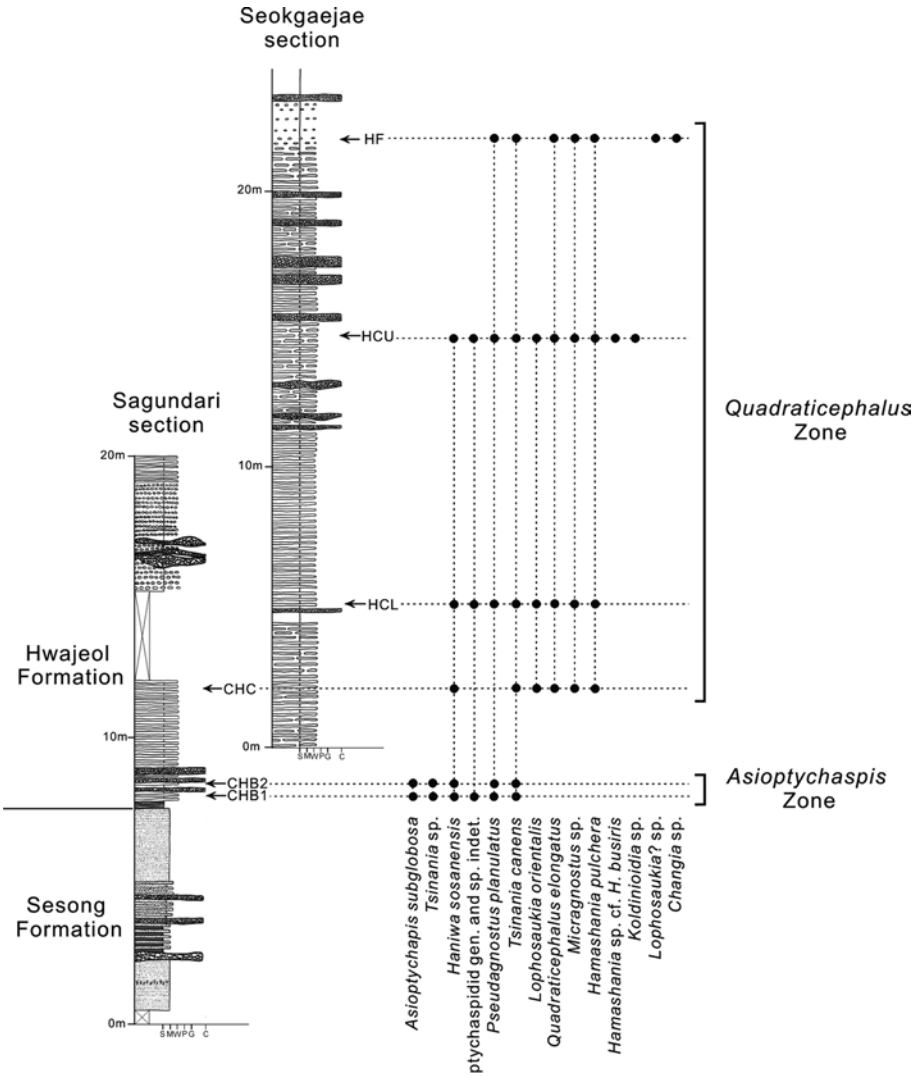

Fig. 2. Lithologic columns of the Hwajeol Formation in the Sagundari and Seokgaejae sections with occurrence of trilobites and stratigraphic distribution of the biozones.

section occupies the lowermost 7 meter thick interval of the section and consists of alternating fine-grained sandstone and limestone conglomerate beds. The succeeding 13 meter thick interval belongs to the lower part of the Hwajeol Formation and is mainly composed of limestone-shale couplet and limestone conglomerate. The upper part of the Hwajeol Formation is mostly covered by vegetation. The Hwajeol Formation in this section includes three fossiliferous horizons; CHB1, CHB2, and CHC in ascending order. The lower two horizons (CHB1 and CHB2) yield trilobites belonging to the *Asioptychaspis* fauna. Most fossils are silicified and relatively well-preserved, but disarticulated. The uppermost horizon (CHC) consists of limestone-shale couplet facies and differs from the lower two horizons in containing the *Quadraticephalus* fauna.

The Seokgaejae section is located along a forest road cut, ca. 12 km southeast of Taebaek City (Fig. 1c). It meanders along the road at the elevation of approximately 1,000 m, where about 1,100-m-thick succession of the Taebaek Group is well exposed. The Hwajeol Formation in the section measures ca. 60 m in thickness and is represented by a cyclic succession of shale- and carbonate-dominant facies (Choi et al., 2004). The lowermost part is marked by the nodule-bearing shale bed, which is overlain by thick (ca. 10-m-thick) limestone-shale couplet facies with intercalation of limestone conglomerate beds. The middle part is an alternating succession of limestone nodule-bearing shale and limestone-shale couplet facies with sporadic intercalations of limestone conglomerate beds. The upper part is dominated by nodule-bearing shale and calcareous shale facies. Trilobites from the Hwajeol Formation of the Seokgaejae section are recovered abundantly in three horizons, HCL, HCU, and HF (Fig. 2), and belong to the *Quadraticephalus* fauna. Most of the specimens are silicified and are easily found on weathered surfaces of limestone-shale couplet facies.

4. SYSTEMATIC PALEONTOLOGY

The morphological terms employed in this study generally follow Whittington and Kelly (1997), but the term glabella used herein excludes the occipital ring. Descriptive terms for glabellar furrows and facial sutures follow Henningsmoen (1957). All of the specimens are deposited in the paleontological collections of Seoul National University with registered SNUP numbers. Specimens with PA numbers were originally studied by Kobayashi (1933) and are presently stored at the University Museum, University of Tokyo, Japan.

Order Agnostida Salter, 1864
Family Agnostidae M'Coy, 1849
Subfamily Agnostinae M'Coy, 1849
Genus *Micragnostus* Howell, 1935

Type species: *Agnostus calvus* Lake, 1906 from the Tremadocian of Wales.

Micragnostus sp.
Figures 3(a)-(d)

Material examined: Thirty-six cephala and 16 pygidia; figured specimens: SNUP4019-4022.

Occurrence: CHC of the Sagundari section and HCL, HCU, and HF of the Seokgaejae section; *Quadraticephalus* Zone of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: *Micragnostus* sp., even though poorly preserved, displays morphological features of *Micragnostus*, such as semicircular anteroglabella, transverse F3, and broad pygidial axis with parallel-sided axial furrows. This species may be comparable to *Micragnostus chiushuensis* (Kobayashi, 1931), but differs in having a longer pygidial axis and in lacking posterolateral spines. It is also similar to *Micragnostus hoiformis* (Kobayashi, 1933) in possessing a long pygidial axis, but has a narrower pygidial axis than *M. hoiformis*. Definite assignment to the species level is pending due to poor preservation of the specimens.

Subfamily Pseudagnostinae Whitehouse, 1936
Genus *Pseudagnostus* Jaekel, 1909

Type species: *Agnostus cyclopyge* Tullberg, 1880 from the *Parabolina spinulosa* Zone of Andrarum, Sweden.

Pseudagnostus planulatus (Raymond, 1924)
Figures 3(e)-(h)

Peronopsis planulata Raymond, 1924, p. 395, pl. 12, fig. 9.
Phalacroma parilis (Hall). Raymond, 1924, p. 396, pl. 12, fig. 8.
Phalacroma cyclostigma Raymond, 1924, p. 397, pl. 12, fig. 10.
Rhaptagnostus planulatus (Raymond). Shergold, 1977, p. 99.
Neoagnostus cyclostigma (Raymond). Shergold, 1977, p. 99.
Litagnostus planulatus (Raymond). Ludvigsen et al., 1989, p. 14, pl. 3, figs. 1-17; Westrop, 1995, p. 18, pl. 2, figs. 1-9.

Material examined: Two carapaces, six cephala, and 14 pygidia; figured specimens: SNUP4014, 4023-4025.

Occurrence: CHB1 and CHB2 of the Sagundari section and HCL, HCU, and HF of the Seokgaejae section; *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea; Vermont, USA (Raymond, 1924); *Keithia schucherti* fauna of Newfoundland, Canada (Ludvigsen et al., 1989); and *Naustia papilio* and *Kathleenella subula* zones (upper Sunwaptan) of Mackenzie Mountains, Canada (Westrop, 1995).

Remarks: The specimens on hand are strongly effaced and have a wide and flat pygidial border which is diagnostic

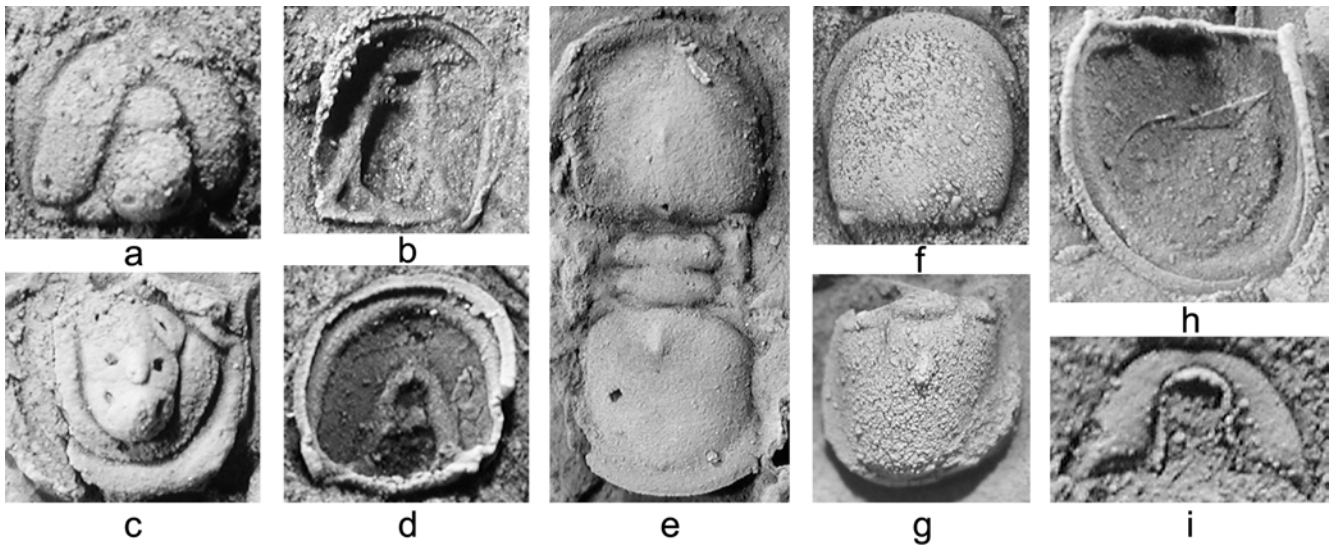

Fig. 3. Trilobite fossils from the Hwajeol Formations, Taebaeksan Basin, Korea. All specimens are silicified. (a–d) *Micragnostus* sp; (a) nearly complete cephalon, dorsal view, SNUP4019, ×17; (b) cephalon, ventral view, SNUP4020, ×12; (c) partly damaged pygidium, dorsal view, SNUP4021, ×12; (d) cephalon, ventral view, SNUP4022, ×14. (e–h) *Pseudagnostus planulatus* (Raymond, 1924); (e) nearly complete carapace, SNUP4023, ×9.1; (f) complete cephalon, SNUP4014, ×8.6; (g) pygidium, dorsal view, SNUP4024, ×9.4; (h) pygidium, ventral view, SNUP4025, ×14. (i) *Koldinioidia* sp., incomplete cranidium, SNUP4026, ×33.

of *Litagnostus planulatus* (Raymond, 1924). Rasetti (1944) established the genus *Litagnostus* to comprise strongly effaced pseudagnostines, which was followed by subsequent studies (Palmer, 1955; Shergold, 1977; Westrop, 1986, 1995; Ludvigsen et al., 1989). Recently, Peng and Robison (2000) treated *Litagnostus* as a junior synonym of *Pseudagnostus*, based on the observation that the effacement is strongly variable among the species of *Pseudagnostus*. Their taxonomic opinion is followed in this study.

Pseudagnostus levisensis (Rasetti, 1944) has a wider cephalon and a more circular pygidium than *P. planulatus*. As Ludvigsen et al. (1989) noted, *Pseudagnostus expansus* (Palmer, 1955) might be a junior synonym of *P. planulatus*, but the fragmentary specimen of *P. expansus* prevents further comparison with other species. *Pseudagnostus orientalis* Kobayashi, 1933 from Liaoning has also highly effaced pygidia, but retains weakly incised accessory furrows extending posterolaterally. Kobayashi (1935) reported *P. orientalis* from the *Chuangia* Zone of the Sesong Formation which is easily distinguished from *P. planulatus* by its clearly defined axial furrows in cephala and pygidia.

Order Ptychopariida Swinnerton, 1915
Suborder Ptychopariina Swinnerton, 1915
Superfamily Ptychoparioidea Swinnerton, 1915
Family Shumardiidae Lake, 1907
Genus *Koldinioidia* Kobayashi, 1931

Type species: *Koldinioidia typicalis* Kobayashi, 1931 from the Furongian of Liaoning Province, North China.

Remarks: Zhou and Zhang (1985) established *Akoldinioidia* to comprise forms with a well-defined preglabellar furrow that were formerly assigned to *Koldinioidia*. However, Shergold (1991) and Sohn and Choi (2002) considered that the distinctiveness of preglabellar furrow is highly variable and consequently treated *Akoldinioidia* as a junior synonym of *Koldinioidia*. On the other hand, recently Zhu and Peng (2006) attempted to differentiate *Koldinioidia* from *Akoldinioidia* by emphasizing the differences in thoracic and pygidial morphology: they noted that some species of *Akoldinioidia* have macropleural thoracic segments which are absent in *Koldinioidia*. In this study the generic concept of Shergold (1991) is maintained (cf. Sohn and Choi, 2002). Zhu and Peng (2006) also suggested *Eoshumardia* Hupé, 1955 a junior synonym of *Koldinioidia*.

Koldinioidia sp.
Figure 3(i)

Material examined: One incomplete cranidium; figured specimen: SNUP4026.

Occurrence: HCU of the Seokgaejae section; *Quadraticephalus* Zone of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: *Koldinioidia* sp. is represented by a single poorly preserved cranidium. The semicircular outline with a cylindrical glabella and the lack of palpebral lobes is the morphological feature of *Koldinioidia*.

Order Asaphida Salter, 1864
Superfamily Dikelocephaloidea Miller, 1889
Family Dikelocephalidae Miller, 1889
Genus *Hamashania* Kobayashi, 1942a

Type species: *Hamashania pulchera* Kobayashi, 1942a from the Furongian of Liaoning Province, North China.

Other species: *Hamashania busiris* (Walcott, 1905) and *Hamashania funingensis* (Duan and An *in* Duan et al., 2005).

Remarks: The genus *Hamashania* has been comprehensively treated by Sohn and Choi (2005a). Lately, Duan et al. (2005) reported four species of *Mareda* Kobayashi, 1942b including one new species: *Mareda mukazegata* Kobayashi, 1942b, *Mareda sinuata* Guo and Duan, 1978, and *Mareda pulchera* (Kobayashi, 1942a) are however assignable to *Hamashania pulchera*, while *Mareda funingensis* Duan and An in Duan et al., 2005 should be transferred to *Hamashania*. The latter species is distinct from other species of *Hamashania* by a strongly divergent anterior branch of facial suture.

Hamashania pulchera Kobayashi, 1942a
Figures 4(a)-(c)

Hamashania pulchera Kobayashi, 1942a, p. 38, figs. 1-4; Sohn and Choi, 2005a, p. 198, figs. 3A-G.
Platysaukia euryrachis Kobayashi, 1960, p. 407, pl. 19, fig. 12, text-fig. 13b.
Mareda mukazegata Kobayashi, 1960, p. 407, pl. 19, figs. 31-32, text-fig. 14b; Duan et al., 2005, p. 123, pl. 52, figs. 17-18.
Mareda sinuata Guo and Duan, 1978 (*pars*), p. 456, pl. 2, fig. 21; Duan et al., 2005, p. 123, pl. 21, figs. 14-17, text-fig. 7-5.
Mareda busiris (Walcott). Zhang and Jell, 1987 (*pars*), p. 245, pl. 121, fig. 6.
Mareda pulchera (Kobayashi). Duan et al., 2005, p. 124, pl. 21, figs. 10-12, pl. 52, fig. 15.

Material examined: Eight cranidia and 18 pygidia; figured specimens: SNUP4004, 4007, 4009.

Occurrence: CHC of the Sagundari section and HCL, HCU, and HF of the Seokgaejae section; *Quadraticephalus* Zone of the Hwajeol Formation, Korea; and Furongian of Liaoning, Jilin, Hebei, and Shandong provinces, North China (Kobayashi, 1942a; Guo and Duan, 1978; Zhang and Jell, 1987; Duan et al., 2005).

Hamashania sp. cf. H. *busiris* (Walcott, 1905)
Figure 4(d)

cf. *Pterocephalus busiris* Walcott, 1905, p. 68; Walcott, 1913, p. 146, pl. 14, fig. 4; Lu et al., 1965, p. 171, pl. 28, figs. 16-17.
non Pterocephalus busiris, Sun, 1935, p. 66, pl. 4, figs. 19-20 [=*Mareda mukazegata* Kobayashi, 1942b].
cf. *Goumenzia latilimbata* Guo and Duan, 1978, p. 450, pl. 2, fig. 20.
cf. *Mareda sinuata* Guo and Duan, 1978, (*pars*), p. 456, pl. 2, figs. 22-33.
cf. *Mareda busiris* (Walcott). Zhang and Jell, 1987, (*pars*), p. 245, pl. 121, fig. 5.
Hamashania sp. cf. *H. busiris* (Walcott). Sohn and Choi, 2005a, p. 199, figs. 3H-J.

Material examined: Three pygidia; figured specimen: SNUP4013.

Occurrence: HCU of the Seokgaejae section; *Quadraticephalus* Zone of the Hwajeol Formation, Korea.

Family Ptychaspididae Raymond, 1924
Genus *Asioptychaspis* Kobayashi, 1933

Type species: *Ptychaspis ceto* Walcott, 1905 from the Chaumitien Formation of Shandong Province, China.

Other species: *Ptychaspis calyce* Walcott, 1905; *Ptychaspis cacus* Walcott, 1905; *Ptychaspis calchas* Walcott, 1905; *Ptychaspis subglobosa* Sun, 1924; *Ptychaspis brevicus* Sun, 1935; *Ptychaspis shansiensis* Sun, 1935; *Ptychaspis*? *fengshanensis* Sun, 1935; and *Ptychaspis asiatica* Resser and Endo, 1937.

Diagnosis: A genus of the Ptychaspididae with a very short preglabellar area, a parallel-sided to forwardly expanding glabella, and palpebral lobes situated in front of glabellar mid-length.

Remarks: The genus *Asioptychaspis* was originally established by Kobayashi (1933) based on some species of *Ptychaspis* reported from Asia which were thought to be different from *Ptychaspis* from Laurentia in having strongly downsloping posterior margin of pygidia. Later, Shergold (1975) regarded *Asioptychaspis* as a subgenus of *Ptychaspis* and recorded *Ptychaspis* (*Asioptychaspis*) *delta* from western Queensland, Australia. Westrop (1986) claimed *Asioptychaspis* to be an independent genus on the basis of differences in pygidial morphology pointed out by Shergold (1975). However, Zhang and Jell (1987) argued that the difference in the pygidial morphology between the two genera is insufficient for generic separation and suggested that *Asioptychaspis* is a junior synonym of *Ptychaspis*.

In this study we consider that *Asioptychaspis* is a valid genus differentiated from *Ptychaspis* based on information from new material from the Hwajeol Formation which provides a sufficient number of cranidia for detailed examination of morphology. Comparison of these specimens with species assigned to *Ptychaspis* by Zhang and Jell (1987) from North China (e.g., *P. ceto*, *P. cacus*, *P. calyce*, and *P. asiatica*) reveals that they share many morphological features such as a strongly convex, long glabella with parallel-sided to forward-expanding axial furrows and relatively

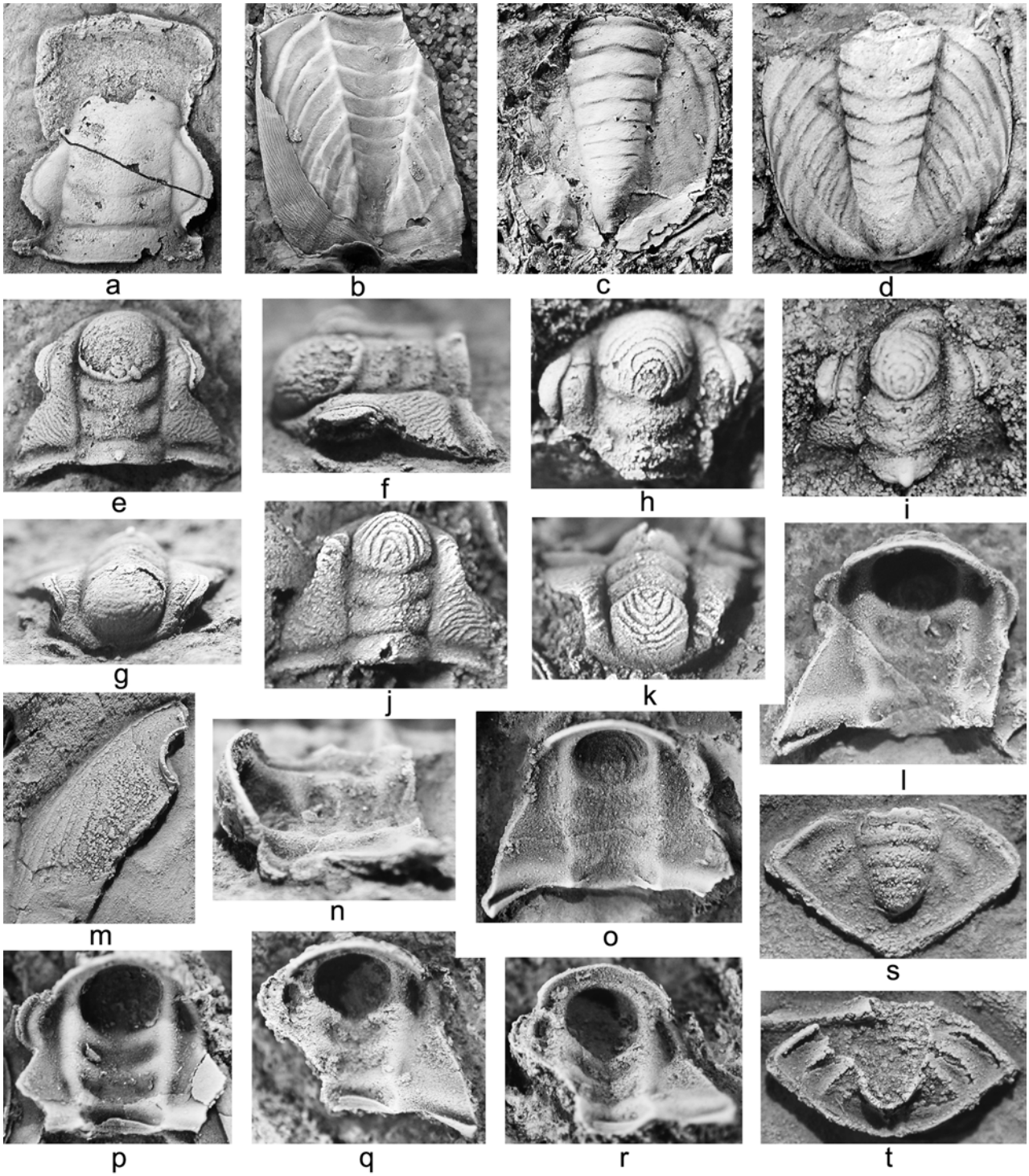

Fig. 4. Polymerid trilobites from the Hwajeol Formation, Taebaeksan Basin, Korea. All specimens are silicified except for (d). (a–c) *Hamashania pulchera* Kobayashi, 1942a; (a) incomplete cranidium, SNUP4004, ×2.3; (b) pygidium, ventral view, SNUP4007, ×2.1; (c) pygidium, dorsal view, SNUP4009, ×2.7. (d) *Hamashania* sp. cf. *busiris* (Walcott, 1905), pygidium, latex cast, SNUP4013, ×5.6. (e–t) *Asioptychaspis subglobosa* (Sun, 1924); (e) cranidium, dorsal view, SNUP4015, ×5.8; (f) lateral view of SNUP4015, ×7.4; (g) anterior view of SNUP4015, ×5.8; (h) incomplete cranidium showing the frontal lobe of glabella, SNUP4027, ×7.2; (i) early holaspid cranidium, SNUP4028, ×9.5; (j) cranidium, dorsal view, SNUP4029, ×11; (k) anterior view of SNUP4029, ×11; (l) cranidium, ventral view, SNUP4030, ×5.5; (m) librigena, SNUP4031, ×2.6; (n) lateral view of SNUP4030, ×6.1; (o) nearly complete cranidium, ventral view, SNUP4032, ×6.4; (p) incomplete cranidium showing glabellar furrows, ventral view, SNUP4033, ×6.6; (q) incomplete cranidium, ventral view, SNUP4034, ×5.7; (r) posterior ventral view of SNUP4034 showing downsloping preglabellar area, ×5.7; (s) pygidium, SNUP4035, ×7.7; (t) incomplete pygidium, SNUP4036, ×7.2.

large palpebral lobes located well in front of glabellar mid-length. *Ptychaspis* from Laurentia can be distinguished from *Asioptychaspis* in having a less convex, generally forwardly-tapering and shorter glabella and smaller palpebral lobes situated at glabellar mid-length (cf. Westrop, 1986).

Ptychaspis (*Asioptychaspis*) *delta* from Australia (Shergold, 1975) is quite different from other species of *Asioptychaspis*. The cranidium (Shergold, 1975, pl. 29, fig. 1) seems to represent a juvenile form and hence is difficult to be evaluated, while the pygidia are also different from other *Asioptychaspis* species in having a relatively long post-axial area. Therefore, *Ptychaspis* (*Asioptychaspis*) *delta* is excluded from *Asioptychaspis*.

Asioptychaspis subglobosa (Sun, 1924)
Figures 4(e)-(t)

Ptychaspis subglobosa Sun, 1924, p. 72, pl. 5, fig. 3a-d; Sun, 1935, p. 28, pl. 4, figs. 10-12; Lu, 1957, p. 286, pl. 148, fig. 9; Zhang and Jell, 1987, p. 227, pl. 112, figs. 6-11.
Asioptychaspis subglobosa (Sun). Kobayashi, 1933, p. 118, pl. 12, figs. 1-7.
Asioptychaspis sphaira Kobayashi, 1933, p. 119, pl. 12, figs. 11-13; Lu et al., 1965, p. 427, pl. 82, figs. 17-19.
Ptychaspis sphaerica Resser and Endo, 1937, p. 273, pl. 55, figs. 10-13; Lu et al., 1965, p. 427, pl. 82, figs. 13-16.
Asioptychaspis chiliensis Resser, 1942, p. 7.

Diagnosis: A species of *Asioptychaspis* characterized by a cylindrical glabella, globose frontal lobe of glabella, relatively narrow palpebral area, and large palpebral lobes.

Description: Cranidium trapezoidal in outline, as wide as long. Glabella long, 80–85% of cranidial length, cylindrical, strongly convex, downsloping anteriorly; S1 and S2 clearly incised, arched backwards and connected across glabella; S3 absent; frontal lobe of glabella globose, strongly convex, and sculptured with concentric ridges and grooves. LO transversely rectangular, ca. one-fifth of cranidial length, slightly wider than glabella, with a small occipital node; SO composite, moderately deep. Preglabellar furrow shallow and narrow; axial furrows moderately deep and parallel-sided. Preglabellar field very short and steeply downsloping anteriorly. Anterior border absent. Preocular area short, strongly downsloping anteriorly. Palpebral area elevated abaxially; palpebral furrow clearly incised; palpebral lobes bean-shaped, ca. one-third of glabellar length, located in front of glabellar mid-length. Eye ridges absent. Posterior field subtriangular, as long as wide, strongly downsloping abaxially. Posterior border transverse, downsloping abaxially; posterior border furrow broad and deep. Facial suture opisthoparian; anterior branch of facial suture convergent convex; posterior branch of facial suture divergent convex. Fixigenal field sculptured with closely-spaced ridges and grooves. Librigena with broad and convex genal field; lateral border not observed in dorsal view.

Pygidium sub-rhomboidal in outline, twice as wide as long. Axis moderately tapering backwards, most anterior axial ring ca. one-third of maximum pygidial width, strongly convex; four axial rings and a semi-circular terminal piece present. Pleural field with three pleurae, weakly convex; interpleural furrows obsolete; pleural furrows directed oblique backwards, broad, and shallow. Border narrow and ridge-like.

Material examined: Nineteen cranidia, three pygidia, and four librigenae; figured specimens: SNUP4015, 4027-4036.

Occurrence: CHB1 and CHB2 of the Sagundari section, *Asioptychaspis* Zone of the Hwajeol Formation, Taebaeksan Basin, Korea; Chaumitien Formation of Hebei and Shandong provinces, North China (Sun, 1924); and *Tsinania* Zone of the Liaoning Province, North China (Kobayashi, 1933; Resser and Endo, 1937; Zhang and Jell, 1987).

Remarks: *Asioptychaspis subglobosa* is most closely similar to *A. ceto*, which however has a less globose frontal lobe of glabella and wider palpebral area. *Asioptychaspis cacus* is characterized by its small palpebral lobes located anteriorly, well-impressed S2 furrow, and long posterior fixigenal area. *Asioptychaspis asiatica* and *A. calyce* differ from *A. subglobosa* in having a forwardly expanding glabella. *Asioptychaspis sphaira* Kobayashi, 1933 was distinguished from *A. subglobosa* by faintly incised glabellar furrows and a smooth frontal lobe of glabella. These features may be attributable to different mode of preservation and therefore *Asioptychaspis sphaira* is regarded as a junior synonym of *A. subglobosa*. *Ptychaspis sphaerica* and *Asioptychaspis chiliensis* were synonymized with *A. subglobosa* by Zhang and Jell (1987).

Genus *Changia* Sun, 1924

Type species: *Changia chinensis* Sun, 1924 from the Chaumitien Formation, Shandong Province, North China.

Other species: *Changia shakuotunensis* Sun, 1935; *Changia chosensis* Kobayashi, 1935; *Coreanocephalus kogenensis* Kobayashi, 1935; *Coreanocephalus cylindricus* Kobayashi, 1935; *Coreanocephalus*? *tenuisulcata* Kobayashi, 1935; *Coreanocephalus planulatus* Kobayashi, 1957; *Wuhuia laevis* An, 1966; *Coreanocephalus longiformis* Yao and Wang, 1978; *Coreanocephalus aplatus* Yao and Wang, 1978; *Coreanocephalus fungosus* Yao and Wang, 1978; *Coreanocephalus anhuiensis* Yao and Wang, 1978; *Coreanocephalus hebeiensis* Zhou *in* Chen et al., 1980; *Coreanocephalus latilimbatus* Zhou *in* Chen et al., 1980; *Changia brevica* Zhou *in* Chen et al., 1980; *Changia acuta* An *in* Duan et al., 1986; *Changia correcta* Shergold, 1991; *Changia curvata* An *in* Duan et al., 2005; *Changia constricta* An *in* Duan et al., 2005; and *Changia distinctus* Duan *in* Duan et al., 2005.

Diagnosis: A genus of the Ptychaspididae characterized by a long and slightly constricted glabella, nearly effaced

lateral glabellar furrows, large palpebral lobes situated close to glabella, moderately long preglabellar area, and short posterior field of fixigena.

Remarks: *Quadraticephalus* and *Coreanocephalus* were synonymized with *Changia* by Zhang and Jell (1987). However *Quadraticephalus* is distinguishable from *Changia* by its smaller and more anteriorly situated palpebral lobes. *Coreanocephalus* Kobayashi (1935) was erected based on poorly preserved specimens. The fragmentary cranidia have a long and constricted glabella, large palpebral lobes located close to glabella, and a long preglabellar area, which are diagnostic features of *Changia*. Hence, *Coreanocephalus* is regarded as a junior synonym of *Changia*, as suggested earlier by Zhang and Jell (1987) and Shergold (1991).

Changia sp.
Figures 5(a)-(e)

Material examined: Six cranidia and five pygidia; figured specimens: SNUP4037-4041.

Occurrence: HF of the Seokgaejae section, *Quadraticephalus* Zone of the Hwajeol Formation, Korea.

Remarks: The cranidia that are preserved ventrally are only available. Therefore this species is difficult to compare with other species of *Changia* and is left under open nomenclature. *Changia* sp. has a long and anteriorly weakly tapering glabella, large palpebral lobes located close to glabella, and a long preglabellar area. It differs from *C. chinensis* Sun, 1924 which has more divergent anterior branches of facial sutures, a constricted glabella, and angulate cranidial anterior margin. *Changia* sp. may also be comparable to *C. planulatus* (Kobayashi, 1957), *C. anhuiensis* (Yao and Wang, 1978), *C. acuta* An *in* Duan et al., 1986, and *C. curvata* An *in* Duan et al., 2005. The associated pygidia are similar to other *Changia* species by having a transversely elliptical outline and faintly impressed pleurae.

Genus *Quadraticephalus* Sun, 1924

Type species: *Quadraticephalus walcotti* Sun, 1924 from the Chaumitien Formation, Shandong Province, North China.

Other species: *Quadraticephalus teres* Kobayashi, 1933; *Quadraticephalus pyrus* Kobayashi, 1933; *Quadraticephalus manchuricus* Kobayashi, 1933; *Ptychaspis*? *fengshanensis* Sun, 1935; *Quadraticephalus quadratus* Kobayashi, 1935; *Quadraticephalus coreanicus* Kobayashi, 1935; *Quadraticephalus elongatus* Kobayashi, 1935; *Quadraticephalus latus* Sun *in* Sun and Xiang, 1979; *Quadraticephalus expansus* Xiang *in* Sun and Xiang, 1979; *Quadraticephalus depressus* Luo, 1983; and *Quadraticephalus latilimbatus* Luo, 1983.

Diagnosis: A genus of the Ptychaspididae having a rectangular glabella, subquadrate preglabellar field, small palpebral lobes located anteriorly and away from glabella, and long triangular posterior area of fixigena.

Remarks: Zhang and Jell (1987) synonymized *Quadraticephalus* with *Changia*. However, Shergold (1991) considered that *Quadraticephalus* can be distinguished from *Changia* by its relatively small palpebral lobes located in front of glabellar mid-point, which is followed in this study.

Quadraticephalus elongatus Kobayashi, 1935
Figures 5(f)-(u)

Quadraticephalus elongatus Kobayashi, 1935, p. 321, pl. 5, figs. 8-9.

Diagnosis: A species of *Quadraticephalus* having a transverse pygidium characterized by a very short axis with short axial rings and extended lateral margins.

Description: Cranidium trapezoidal in outline and moderately convex. Glabella rectangular, weakly tapering forwards, three-fourths of cranidial length, and one-third of posterior cranidial width. Lateral glabellar furrows obsolete; S1 faintly impressed, directed oblique rearwards. LO transversely rectangular, one-eighth of cranidial length, wider than glabella; SO simple, transverse and faintly incised. Axial furrows shallow. Preglabellar furrow shallow. Frontal area weakly convex, one-third of glabellar length, downsloping anteriorly, undifferentiated into preglabellar field and anterior border. Palpebral area upturned abaxially, narrow. Palpebral lobes small, one-fourth of glabellar length, bean-shaped, elevated abaxially, located anteriorly. Posterior field triangular in dorsal view, ca. one-half of glabellar length, as long as wide, downsloping abaxially. Posterior border as long as occipital ring; posterior border furrow shallow, faintly impressed. Facial suture opisthoparian; anterior branches of facial suture parallel-sided; posterior branches of facial suture divergent, straight to weakly convex. Surface sculptured with subparallel ridges and small pits.

Librigena with long and convex genal field and a stout genal spine; genal field downsloping peripherally, sculptured with ridges and pits; anterior and lateral border very narrow, ridge-like, defined by shallow lateral border; doublure very broad and flat.

Pygidium subtrapezoidal in outline, twice as wide as long, with extended lateral margins. Axis weakly tapering backwards, short, strongly convex, with three axial rings and a terminal piece; axial ring short and transverse; interring furrows deep and broad. Pleural field flat, smooth; pleural and interpleural furrows not defined. Border very narrow and elevated. Doublure broad, sculptured with subparallel terrace lines.

Material examined: One hundred and forty-three cranidia, 60 librigenae, and 39 pygidia; figured specimens: SNUP4001, 4042-4053.

Occurrence: CHC of the Sagundari section and HCL, HCU, and HF of the Seokgaejae section; *Quadraticephalus*

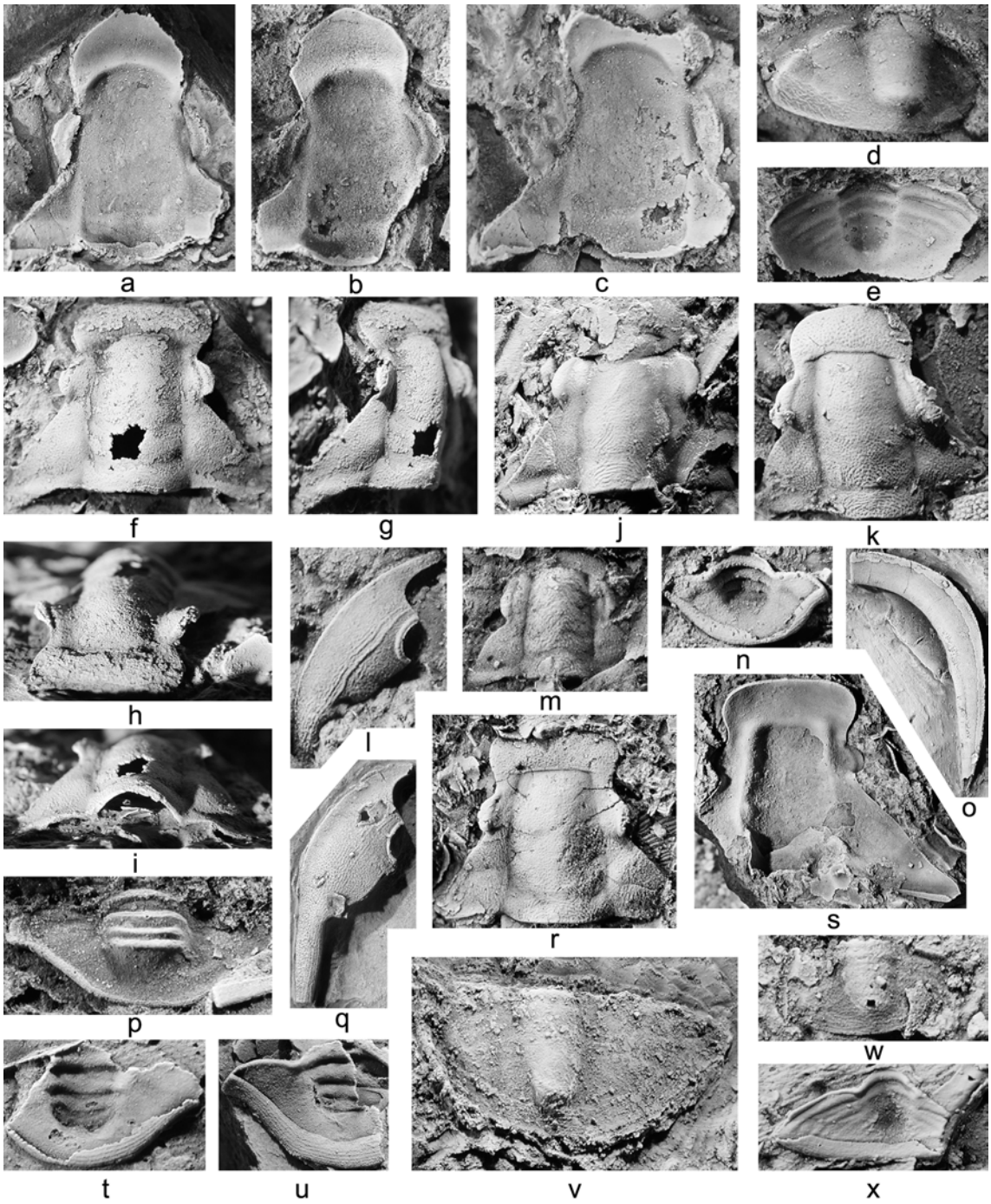

Fig. 5. Polymerid trilobites from the Hwajeol Formation, Taebaeksan Basin, Korea. All specimens are silicified. (a–e) *Changia* sp.; (a) cranidium, ventral view, SNUP4037, ×3.1; (b) incomplete cranidium showing angulated anterior margin, ventral view, SNUP4038, ×5.1; (c) complete cranidium, ventral view, SNUP4039, ×5.1; (d) pygidium showing faintly indicated border, dorsal view, SNUP4040, ×6.8; (e) pygidium showing ventral structure of pygidial furrows, ventral view, SNUP4041, ×2.3. (f–u) *Quadraticephalus elongatus* Kobayashi, 1935; (f) nearly complete cranidium, dorsal view, SNUP4042, ×3.1; (g) oblique lateral view of SNUP4042 showing downsloping preglabellar field, ×3.1; (h) anterior view of SNUP4042 showing elevated palpebral lobes, ×3.5; (i) posterior view of SNUP4042, ×2.8; (j) incomplete cranidium, SNUP4043, ×4.5; (k) oblique dorsal view of cranidium showing preglabellar area, SNUP4044, ×5.7; (l) incomplete librigena, SNUP4045, ×7.9; (m) early holaspid cranidium showing relatively large palpebral lobes, SNUP4046, ×5.6; (n) pygidium, ventral view, SNUP4047, ×5.8; (o) librigena, ventral view, SNUP4048, ×1.5; (p) pygidium, dorsal view, SNUP4049, ×7.3; (q) nearly complete librigena, SNUP4050, ×3.0; (r) dorso-ventrally flattened cranidium, SNUP4001, ×4.3; (s) cranidium, ventral view, SNUP4051, ×1.8; (t) incomplete pygidium, ventral view, SNUP4052, ×6.7; (u) incomplete pygidium, ventral view, SNUP4053, ×3.9. (v-x) ptychaspidid genus and species indeterminate; (v) pygidium, dorsal view, SNUP4054, ×4.2; (w) incomplete pygidium, dorsal view, SNU4055, ×6.3; (x) pygidium, ventral view, SNUP4056, ×5.2.

Zone of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: This species is fully described based on well-preserved specimens obtained in this study. Kobayashi (1935) emphasized that the very long, cylindrical glabella and transverse pygidium with short axis are important morphological features of *Q. elongatus*. In general, cranidia referred to the species of *Quadraticephalus* by Kobayashi (1935) are closely similar to each other and therefore it is difficult to differentiate species of *Quadraticephalus* based solely on cranidia. The present specimens are assigned to *Q. elongatus*, because the associated pygidia are identical to those illustrated by Kobayashi (1935) in having a very short axis with short axial rings and flat pleural regions.

Ptychaspidid genus and species indeterminate
Figures 5(v)-(x)

Description: Pygidium semi-elliptical in outline, wider than long. Axis strongly convex, narrow, one-fourth to one-fifth of pygidial width, tapering rearwards, reaching to posterior border; axial rings faintly defined; axial furrow shallow, indicated by abrupt change in slope. Pleural field flat; pleural furrows and interpleural furrows faintly incised. Border broad and sculptured with terrace lines; border furrow obsolete. Doublure flat, as broad as border, occupying ca. one-fifth of pygidial length.

Material examined: Thirty-three pygidia; figured specimens: SNUP4054-4056.

Occurrence: CHB1 of the Sagundari section and HCL and HCU of the Seokgaejae section; *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: The present pygidia are difficult to compare with other ptychaspidid trilobites due to their poor preservation and hence are described under open nomenclature.

Family Saukiidae Ulrich and Resser, 1930
Genus *Lophosaukia* Shergold, 1972

Type species: *Lophosaukia torquata* Shergold, 1972 from the Gola Beds (upper Furongian), Queensland, Australia

Other species: Shergold (1972) listed the following species to be members of *Lophosaukia*: *Prosaukia*(?) *orientalis* Kobayashi, 1933; *Saukia*(?) *orientalis* Resser and Endo, 1937; *Prosaukia ulrichi* Kobayashi, 1933; *Sinosaukia pustulosa* Sun, 1935 (in part); *Ptychaspis angulata* Mansuy, 1916 (in part); and *Ptychaspis angulata* var. *chinensis* Sun, 1924 (=*Lophosaukia chinensis*). Later Shergold (1975) and Shergold et al. (1988) added more species to the genus including "*Eosaukia*" *baruvasi* Kobayashi, 1957 (in part); *Ptychaspis cadmus* Walcott, 1905; *Lophosaukia acuta* Shergold, 1975; *Lophosaukia baoshanensis* Xiang *in* Sun and Xiang, 1979; *L. rectangulata* Ergaliev, 1980; *L. arpaozenensis* Ergaliev, 1983; and *L. jiangnanensis* Lu and Lin, 1983.

Remarks: Shergold (1972) erected *Lophosaukia* to accommodate the saukiid trilobites with a long, parallel-sided to anteriorly somewhat expanded glabella, relatively large palpebral lobes located close to but not attached to axial furrows, and narrow preglabellar area that is not differentiated into the preglabellar field and cranidial border. Shergold et al. (1988) emphasized the triangular preglabellar area as the diagnostic feature of the genus.

Lophosaukia orientalis (Kobayashi, 1933)
Figures 6(a)-(h)

Prosaukia(?) *orientalis* Kobayashi, 1933, p. 126, pl. 13, fig. 10; Lu et al., 1965, p. 449, pl. 88, fig. 4.
Lophosaukia orientalis (Kobayashi). Shergold, 1972, p. 62.

Diagnosis: A species of *Lophosaukia* with less angulate preglabellar area and densely-spaced pustules.

Description: Cranidium trapezoidal in outline, sculptured with densely-spaced small and large pustules. Glabella rectangular, four-fifths of cranidial length, slightly wider than one-half of palpebral cranidial width, convex, strongly downsloping forwards; three pairs of lateral glabellar furrows merging with axial furrows; S1 arched backwards, connected across glabella, deep and wide; S2 transverse and slit-like; S3 pit-like. LO subrectangular, one-fifth of glabellar length, as wide as glabella, with a small median node; SO composite, deep and wide. Axial furrows nearly parallel-sided, deep and wide. Preglabellar furrow deep and clearly incised. Frontal area very short with angulate frontal margin, not differentiated into frontal field and anterior border. Palpebral area flat, semi-elliptical, elevated; palpebral furrow narrow, clearly incised; palpebral lobes ca. one-half of glabellar length, bean-shaped, flat, slightly narrower than palpebral area, located behind glabellar mid-point; palpebral ledge sharply incised, divided palpebral lobe into subequal width. Eye ridges absent. Posterior field very short and ca. one-half of glabellar width, downsloping abaxially and posteriorly. Posterior border short, less than one-half of length of occipital ring, downsloping abaxially; posterior border furrow shallow and broad. Facial suture opisthoparian; anterior branches of facial suture parallel to weakly divergent, straight; posterior branches of facial suture strongly divergent, straight.

Librigena with broad and convex genal field and convex lateral border; genal field sculptured with small pits, downsloping marginally; lateral border broad, ornamented with subparallel terrace lines, separated from librigenal field by broad and shallow border furrow.

Pygidium transversely elliptical in outline. Axis strongly tapering backwards, with two axial rings and a terminal piece, sculptured with closely-spaced granules. Pleural field divided by deep pleural furrows, ornamented with transversely aligned granules; interpleural furrows indistinct.

Border narrow, sculptured with subparallel terrace ridges. Doublure as wide as border.

Material examined: Sixty-four cranidia, 22 librigenae, and six pygidia; figured specimens: SNUP4057-4062.

Occurrence: CHC of the Sagundari section and HCL and HCU of the Seokgaejae section; *Quadraticephalus* Zone of the Hwajeol Formation, Taebaeksan Basin, Korea; and *Tsinania* Zone of Liaoning Province, North China (Kobayashi, 1933).

Remarks: The specimens on hand agree with *Prosaukia*(?) *orientalis* Kobayashi, 1933 in having a short preglabellar area, forwardly-downsloping frontal lobe of glabella, and comparable size of palpebral lobes. Kobayashi (1933) commented that this species is distinct from *Prosaukia* and other described genera of the Saukiidae in lacking anterior border. Shergold (1972, 1975) transferred *Prosaukia*(?) *orientalis* to *Lophosaukia*, which is herein accepted. Zhang and Jell (1987) considered *Prosaukia*(?) *orientalis* to be synonymous with *L. cadmus* (Walcott, 1905), which however bears coarser and less densely-distributed pustules.

Lophosaukia? sp.
Figures 6(i)-(j)

Material examined: Six cranidia and one pygidium; figured specimens: SNUP4063-4064.

Occurrence: HF of the Seokgaejae section; *Quadraticephalus* Zone of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: *Lophosaukia*? sp. from the Hwajeol Formation has a very short (sag.) preglabellar area and angulate anterior margin, which are characteristic features of *Lophosaukia*, but has a pair of divergent preocular furrows emerging from anterolateral corners of axial furrows. As no cranidia showing dorsal view are available, this species is included in *Lophosaukia* with some reservation. The pygidium assigned to this species differs from *Lophosaukia orientalis* by its longer axis and semicircular outline.

Superfamily Illaenoidea Hawle and Corda, 1847
Family Tsinaniidae Kobayashi, 1933
Genus *Tsinania* Walcott, 1914

Type species: *Illaenurus canens* Walcott, 1905 from the Chaumitien Formation, Shandong Province, North China.

Tsinania canens (Walcott, 1905)
Figures 6(k)-(n)

Illaenurus canens Walcott, 1905, p. 96; Walcott, 1913, p. 222, pl. 23, figs. 3, 3a-c.
Illaenurus ceres Walcott, 1905, p. 97; Walcott, 1913, p. 223, pl. 23, figs. 4, 4a.
Illaenurus sp. Walcott, 1905, p. 222, pl. 23, fig. 6.
Illaenurus dictys Walcott, 1913, p. 224, pl. 23, figs. 5, 5a.
Gen. and sp. indeterminate. Walcott, 1913, p. 224, pl. 23, fig. 8.
Illaenurus pagoda Sun, 1924, p. 82, pl. 5, figs. 10a-c.
Tsinania canens (Walcott). Kobayashi, 1931, p. 186, pl. 20, figs. 7-9; Kobayashi, 1935, p. 306, pl. 5, fig. 20; pl. 6, figs. 13, 14; Endo, 1944, p. 95; Kobayashi, 1952, p. 150, pl. 13, figs. 1-8, text-fig. 2; Lu, 1957, p. 269, pl. 147, figs. 9, 10; Lu et al., 1965, p. 341, pl. 63, figs. 18-25; Zhang and Jell, 1987, p. 195, pl. 86, figs. 12-16; pl. 87, figs. 1-14; pl. 88, figs. 1-13; pl. 89, fig. 5.
Tsinania canens pagoda (Sun). Kobayashi, 1931, p. 186, pl. 20, fig. 10.
Tsinania canens shansiensis Sun, 1935, p. 53, pl. 5, figs. 20, 21.
Tsinania vulgaris Resser and Endo, 1937, p. 295, pl. 56, figs. 13-18.
Tsinania convexa Resser and Endo, 1937, p. 296, pl. 56, figs. 19, 20.
Tsinania longicephala Resser and Endo, 1937, p. 296, pl. 55, figs. 22-27.

Material examined: Twelve cephala, 33 pygidia, and two librigenae; figured specimens: SNUP4003, 4065-4067.

Occurrence: CHB1, CHB2, and CHC of the Sagundari section and HCL, HCU, and HF of the Seokgaejae section; *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea; *Tsinania-Ptychaspis* Zone of the Chaumitien Formation, Shandong and Liaoning provinces, North China (Walcott, 1913; Sun, 1924, 1935; Resser and Endo, 1937; Zhang and Jell, 1987); *Tsinania* Zone of North Korea (Kobayashi, 1933).

Remarks: *Tsinania canens* (Walcott, 1905) is characterized by a rectangular cranidium with effaced axial and glabellar furrows and a semicircular pygidium with effaced axial and pleural furrows. Zhang and Jell (1987) allowed a wide range of intraspecific morphological variations for both cranidia and pygidia: cranidia have slightly incised to completely effaced axial furrows and glabellar furrows, relatively short to long frontal area, and rounded to slightly angulate anterior margin; and pygidia are flat to convex, with semi-circular to semi-elliptical outline and nearly effaced to faintly indicated axial furrows. The cranidia on hand are generally characterized by completely effaced lateral glabellar furrows and axial furrows, and undifferentiated frontal area, but also display broadly rounded to slightly angulate anterior margin. Associated pygidia are flat to moderately convex and show semi-elliptical to semicircular outline, faintly defined axis, and smooth pleural field.

Tsinania sp.
Figure 6(o)

Material examined: Three pygidia; figured specimen: SNUP4068.

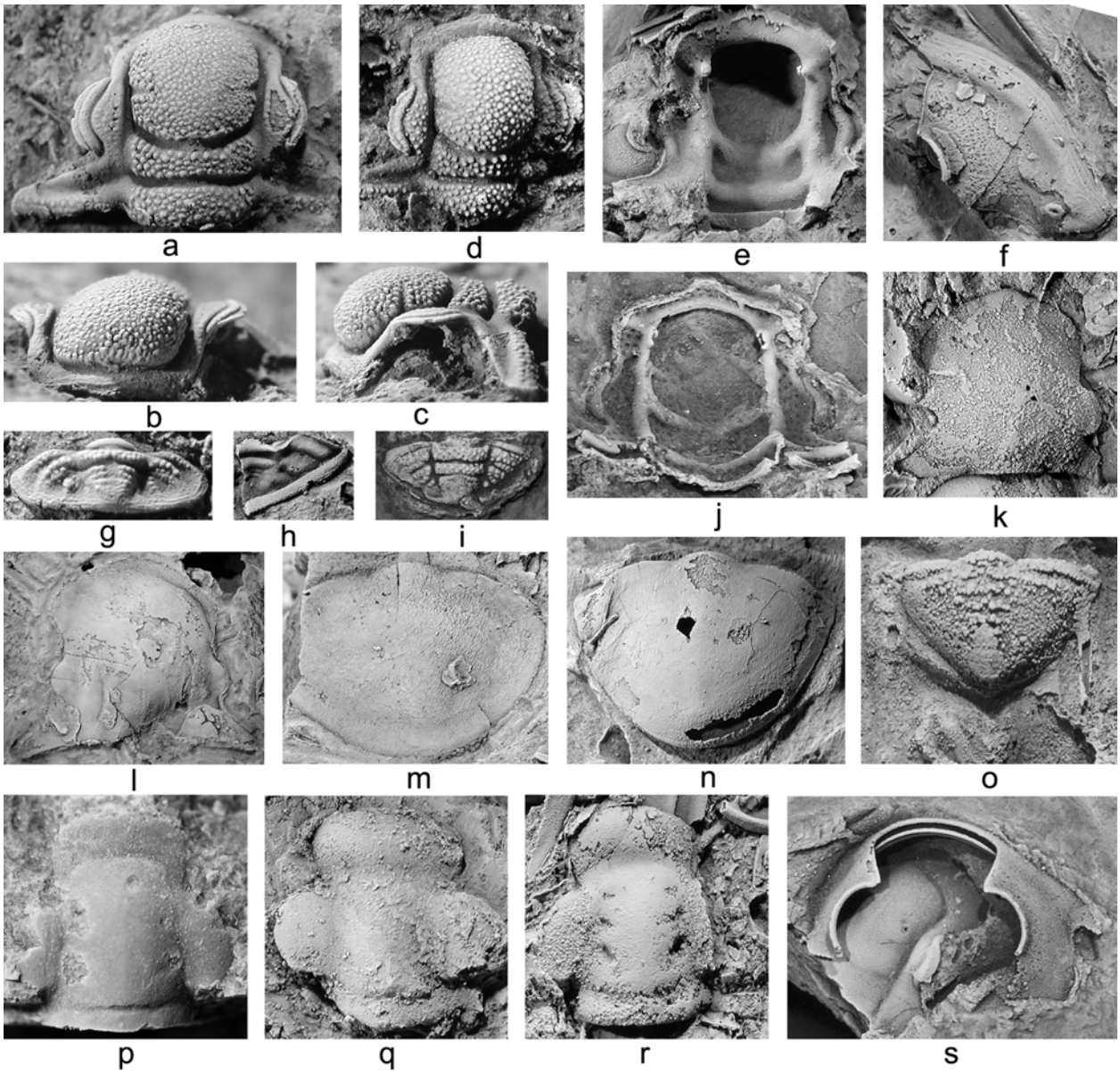

Fig. 6. Polymerid trilobites from the Hwajeol Formation, Taebaeksan Basin. All specimens are silicified. (a–h) *Lophosaukia orientalis* (Kobayashi, 1933); (a) nearly complete cranidium, dorsal view, SNUP4057, ×5.4; (b) anterior view of SNUP4057, ×5.5; (c) lateral view of SNUP4057, ×5.5; (d) cranidium, dorsal view, SNUP4058, ×7.2; (e) incomplete cranidium, ventral view, SNUP4059, ×3.6; (f) librigena, SNUP4060, ×2.8; (g) pygidium, dorsal view, SNUP4061, ×7.4; (h) incomplete pygidium, ventral view, SNUP4062, ×4.4. (i–j) *Lophosaukia*? sp.; (i) pygidium, dorsal view, SNUP4063, ×2.2; (j) cranidium, ventral view, SNUP4064, ×3.5. (k–n) *Tsinania canens* (Walcott, 1905); (k) cranidium, dorsal view, SNUP4065, ×4.3; (l) cranidium, dorsal view, SNUP4003, ×1.2; (m) pygidium, dorsal view, SNUP4066, ×3.5; (n) pygidium, dorsal view, SNUP4067, ×2.7. (o) *Tsinania* sp., pygidium, dorsal view, SNUP4068, ×6.5. (p–s) *Haniwa sosanensis* Kobayashi, 1933; (p) holotype of *Haniwa sosanensis* from Chosan area, northern Korea, PA0421, ×5.1; (q) nearly complete cranidium, dorsal view, SNUP4069, ×5.1; (r) cranidium, dorsal view, SNUP4070, ×4.2; (s) yoked librigenae, SNUP4071, ×3.9.

Occurrence: CHB1 and CHB2 of the Sagundari section; *Asioptychaspis* Zone of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: *Tsinania* sp. is characterized by a pair of long marginal spines in pygidia. *Tsinania humilis* Kobayashi, 1933 has been described to have a pair of short spines (cf. Kobayashi, 1952), while Zhang and Jell (1987) illustrated two juvenile specimens of *Tsinania canens* (Walcott, 1905) with pygidial spines. The present pygidia differ from both *T. humilis* and the putative juvenile specimens of *T. canens* reported by Zhang and Jell (1987) in having a subtriangular outline and a pair of rearward-directed stout spines.

Superfamily Remopleuridioidea Hawle and Corda, 1847
Family Richardsonellidae Raymond, 1924
Genus *Haniwa* Kobayashi, 1933

Type species: *Haniwa sosanensis* Kobayashi, 1933, from the *Tsinania* Zone of Chosan area, Korea.

Remarks: Kobayashi (1933) originally made no attempt to allocate the suprageneric position of the genus *Haniwa*, but later Kobayashi (1935) assigned *Haniwa* to the subfamily Anomocarinae of the family Ptychopariidae. Shergold (1975) regarded *Haniwa* as a member of family Incertae Sedis under the superfamily Remopleuridacea, while Guo and Duan (1978), Qiu et al. (1983) and Chen et al., (1985) placed the genus under the family Anomocaridae. Lately Zhu and Wei (1991) suggested that *Haniwa* belongs to the family Richardsonellidae Raymond, 1924 on the basis of well-preserved specimens of *Haniwa longa* Yao and Wang, 1978, which is followed in this study.

Haniwa sosanensis Kobayashi, 1933
Figures 6(p)-(s)

Haniwa sosanensis Kobayashi, 1933, p. 148, pl. 15, figs. 2-5.

Diagnosis: A species of *Haniwa* characterized by weakly convex frontal area, slightly divergent anterior branch of facial suture, and large palpebral lobes.

Description: Cranidium subrectangular in outline, as long as wide, with smooth surface. Glabella rectangular to subtrapezoidal, two-thirds of cranidial length, weakly convex; S1, S2, and S3 short, slit-like, where impressed. LO transversely rectangular, as wide as glabella, one-fifth of glabellar length; SO shallow, simple, transverse. Axial furrows very shallow; preglabellar furrow broadly rounded and shallow. Frontal area weakly convex, not differentiated into frontal field and anterior cranidial border. Palpebral lobes large, semicircular, slightly shorter than glabella, attached to glabella, and weakly convex; palpebral furrows not impressed. Facial suture presumably opisthoparian; anterior branches of facial suture divergent straight; posterior branches of facial suture not observed.

Librigenae yoked together along narrow anterior border and doublure, strongly downsloping peripherally; genal field weakly convex differentiated from narrow lateral border by shallow border furrow; eye socle elevated, clearly separated from genal field by shallow eye socle furrow. Doublure as broad as lateral border.

Material examined: Thirty-three cephala, and 15 librigenae; figured specimens: PA0421, SNUP4069-4071.

Occurrence: CHB1, CHB2, and CHC of the Sagundari section and HCL and HCU of the Seokgaejae section; *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea.

Remarks: The present specimens are nearly identical to *Haniwa sosanensis* in having an undifferentiated frontal area, obsolete palpebral furrows, and a nearly effaced glabella. *Haniwa sosanensis* was established by Kobayashi, 1933 based on poorly-preserved specimens recovered from the *Tsinania* Zone of Chosan area, northern Korea (holotype specimen refigured here in Fig. 6p). It is easily distinguished from other species of *Haniwa* (*H. ambolti* Troedsson, 1937; *H. mucronata* Shergold, 1975; *H. dactyloides* Guo and Duan, 1978; *H. longa* Yao and Wang, 1978; and *H. dactylofera* Zhang *in* Qiu et al., 1983) by its obsolete palpebral furrows and undifferentiated frontal area. *Haniwa elongata* Qian *in* Chen et al., 1985 also has obsolete palpebral furrows and an undifferentiated frontal area, but differs from *H. sosanensis* in having a relatively longer glabella and concave frontal area. No pygidia assignable to this species have been found.

5. BIOSTRATIGRAPHY AND CORRELATION

This study formally proposes two Upper Cambrian trilobite biozones, *Asioptychaspis* and *Quadraticephalus* zones, within the Hwajeol Formation of the Taebaek Group (cf. Sohn and Choi, 2005b). Kobayashi (1935, 1966) originally reported five Upper Cambrian biozones within the Hwajeol Formation: from the oldest to the youngest *Prochuangia*, *Chuangia*, *Kaolishania*, *Dictyites*, and *Eoorthis* zones. As stated earlier, Sohn and Choi (2005b) suggested quite different stratigraphic scheme for the Sesong and Hwajeol formations from that of Kobayashi (1966) (Fig. 7): i.e., the *Prochuangia*, *Chuangia*, and *Kaolishania* zones are allocated to the Sesong Formation, while the *Asioptychaspis* and *Quadraticephalus* zones and the saukiid-dominated fauna are included in the Hwajeol Formation and may be collectively comparable to the *Dictyites* and *Eoorthis* zones of Kobayashi (1966). The saukiid-dominated fauna is extended upwards into the Dongjeom Formation in the Seokgaejae section and hence will be treated in a separate paper.

5.1. *Asioptychaspis* Zone

Composition: The *Asioptychaspis* Zone is recognized by the occurrence of *Asioptychaspis subglobosa*, *Tsinania* sp., *Haniwa sosanensis*, ptychaspidid genus and species indeterminate, *Pseudagnostus planulatus*, and *Tsinania canens*. This zone is composed predominantly of *A. subglobosa*, comprising ca. 60% of polymerid trilobites. *Asioptychaspis subglobosa* and *Tsinania* sp. occur exclusively in this zone. *Pseudagnostus planulatus*, *T. canens*, *H. sosanensis*, and ptychaspidid genus and species indeterminate are relatively rare and extend their stratigraphic ranges into the overlying *Quadraticephalus* Zone.

Stratigraphic occurrence: The *Asioptychaspis* Zone occurs in a relatively narrow interval (ca. 1-m-thick) represented by two horizons (CHB1, CHB2) from the lowermost part of the Hwajeol Formation in the Sagundari section (Fig. 2).

Correlation: *Asioptychaspis subglobosa* was previously

Age	TAEBAEK		NORTH CHINA		AUSTRALIA	
	Formation	biozone	Stage	biozone	Stage	biozone
Ordovician						
Furongian	Dongjeom	*Richardsonella*	Xinchangian	*Yosimuraspis*	Datsonian	*Cordylodus prolindstromi* *Hirsotodontus simplex*
		Pseudokoldinioidia		*Richardsonella/* *Platypeltoides*		*Cordylodus proavus*
				'Missisquoia' perpetis		
	Hwajeol	saukiid-dominated	Fengshanian	*Mictosaukia*	Payntonian	*Mictosaukia perplexa*
		Quadraticephalus		*Changia* *(Quadraticephalus)*		*Neoagnostus quasibilobus/* *Shergoldia nomas*
						Sinosaukia impages
		Asioptychaspis		*Ptychaspis-Tsinania*	Iverian	*Rhaptagnostus clarki maximus/* *Rhaptagnostus papilio*
						Rhaptagnostus bifax/ *Neoagnostus denticulatus*
	Sesong	*Kaolishania*	Changshanian	*Kaolishania*		*Rhaptagnostus clarki prolatus/* *Caznaia sectatrix*
						Rhaptagnostus clarki patulus *Caznaia squarnosa* *Hapsidocare lilyensis*
						Peichiashania tertia/ *Peichiashania quarta*
						Peichiashania secunda/ *Prochuangia glabella*
		Chuangia		*Changshania*		*Wentsuia iota/* *Rhaptagnostus apsis*
						Irvingella tropica
				Chuangia	Idamean	*Stigmatoa diloma*
		Prochuangia				*Erixanium sentum*
						Proceratopyge cryptica
						Glyptagnostus reticulatus

Fig 7. Correlation of the trilobite zones of the Taebaek Group with those of North China and Australia. Modified from Geyer and Shergold (2000), Duan et al. (2005), and Sohn and Choi (2005b).

documented from the *Dictyites* Zone of the Hwajeol Formation by Kobayashi (1935) and was also known to occur in the middle Furongian *Tsinania canens* Zone of Liaoning Province (Kobayashi, 1933) and *Ptychaspis-Tsinania* Zone of Shandong Province (Zhang and Jell, 1987), North China. *Tsinania canens* and *H. sosanensis* were reported from the *Ptychaspis-Tsinania* Zone of North China (Zhang and Jell, 1987) and the *Tsinania* Zone of North Korea (Kobayashi, 1933), respectively. Consequently, the *Asioptychaspis* Zone of the Hwajeol Formation can be correlated with the *Ptychaspis-Tsinania* Zone of North China with confidence (Fig. 7).

5.2. *Quadraticephalus* Zone

Composition: The *Quadraticephalus* Zone yields *Haniwa sosanensis*, ptychaspidid genus and species indeterminate, *Pseudagnostus planulatus*, *Tsinania canens*, *Lophosaukia orientalis*, *Quadraticephalus elongatus*, *Micragnostus* sp., *Hamashania pulchera*, *Hamashania* sp. cf. *H. busiris*, *Koldinioidia* sp., *Lophosaukia* sp., and *Changia* sp. The base of the zone is defined by the first appearance of *Lophosaukia orientalis*, *Quadraticephalus elongatus*, and *Hamashania pulchera*. More than 500 specimens were collected from the Seokgaejae section, whereas a few specimens were available from the Sagundari section. *Quadraticephalus elongatus* is the predominant taxon in the *Quadraticephalus* fauna (ca. 44% in relative abundance). *Lophosaukia orientalis* (Kobayashi, 1933), *Haniwa sosanensis*, and *Micragnostus* sp. constitute 32% of the fauna. *Koldinioidia* sp. and *Lophosaukia* sp. are relatively rare.

Stratigraphic occurrence: The *Quadraticephalus* Zone occupies most of the lower part of the Hwajeol Formation in the Seokgaejae section. It is also recovered in a horizon (CHC) of 5 m above the base of the Hwajeol formations in the Sagundari section (Fig. 2).

Correlation: *Quadraticephalus elongates* and *T. canens* were reported from the *Dictyites* Zone of the Hwajeol Formation by Kobayashi (1935). The most dominant genus of this zone, *Quadraticephalus*, has been known from the *Ptychaspis-Tsinania* and *Changia* zones of North China (Kobayashi, 1933; Zhang and Jell, 1987; Duan et al., 2005) and the Late Cambrian Assemblage 1 of Amadeus Basin, Australia (Shergold, 1991). *Hamashania* was restricted to the *Changia* (or *Quadraticephalus*) Zone of North China (Guo and Duan, 1978; Zhang and Jell, 1987). Specimens assignable to *Lophosaukia* have been reported from Australia, China, Vietnam, Thailand, and Kazakhstan: *Lophosaukia* from Australia is the oldest in occurrence from the *Rhaptagnostus bifax–Neoagnostus denticulatus* Zone; in North China it has been documented from the *Tsinania* Zone or simply Fengshanian strata (Sun, 1924; Kobayashi, 1933;

Qiu et al., 1983; Zhang and Jell, 1987; Duan et al., 2005); *Lophosaukia jiangnanensis* from South China was known from the *Lotagnostus punctatus* Zone (Lu and Lin, 1984) and slightly older *Probilacunaspis nasalis-Peichiashania hunanensis* Zone (Peng, 1992); and in Kazakhstan three species of *Lophosaukia* were described from the *Micragnostus mutabilis* Zone (Ergaliev, 1980, 1983) (cf. Geyer and Shergold, 2000).

In summary, the *Asioptychaspis* and *Quadraticephalus* zones from the Hwajeol Formation of the Taebaek Group are most closely comparable to the contemporaneous biozones of North China. The *Asioptychaspis* Zone is well correlated with the *Ptychaspis-Tsinania* Zone of North China, while the *Quadraticephalus* Zone should be equated with the *Changia* (or *Quadraticephalus*) Zone of North China (Fig. 7). Recognition of these two trilobite assemblages of the Hwajeol Formation supports a strong paleogeographical link between the Taebaeksan Basin and North China Platform during the late Furongian.

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