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Revision of the conodont zonation of the uppermost Hwajeol Formation (Furongian), Taebaeksan Basin, Korea

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ABSTRACT: The uppermost interval of the Hwajeol Formation, Taebaeksan Basin, has been assigned to the *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone. The main species in the zone are *Fryxellodontus inornatus* Miller, *Hirsutodontus hirsutus* Miller, *Monocostodus sevierensis* (Miller), *Semiacontiodus lavadamensis* (Miller), *S. nogamii* Miller, *Utahconus utahensis* (Miller), and *Cordylodus proavus* Müller. These species were re-examined to evaluate the biostratigraphy of the Bangteogol and Maesangol sections. Data were added from eleven sections around the Taebaeksan Basin, which were studied previously by the first author. Conodont occurrences above the *Cambrooistodus minutus* Zone are characterized by a lack of vertical and lateral continuity in sections. Conodont recovery is relatively poor but is sufficient for biostratigraphic assignment. This trend of conodont occurrence seems to be related to sedimentary process, including debris slides and eustatic sea-level fluctuation. Nevertheless, detailed study of the characteristic species of the zone leads to the conclusion that retention of the zone is reasonable. However, it is renamed the *M. sevierensis-S. lavadamensis* Zone because *Fryellodontus inornatus* occurs stratigraphically lower than the other two nominate species. The *M. sevierensis-S. lavadamensis* Zone is correlated with equivalent zones of western USA, Canada, North China, and Australia.

Key words: Furongian, conodonts, Hwajeol Formation, Taebaeksan Basin, Korea

1. INTRODUCTION

Five conodont biozones were erected previously within the Hwajeol Formation, Taebaeksan Basin, mid-eastern Korea: *Proconodontus* Zone, *Eoconodontus notchpeakensis* Zone, *Cambrooistodus minutus* Zone, *Cordylodus proavus* Zone, and *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone, in ascending order (Lee, 1989, 1992). Lee (2014) subdivided the *Proconodontus* Zone into the *Proconodontus tenuiserratus, P. posterocostatus,* and *P. muelleri* Zones for the Makgol section in Jikdong valley, Gangwon Province, Korea.

The *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone was proposed by Lee (1992) as the uppermost conodont zone in the Cheoksan, Teokgol, Maesangol, and Jikdong sections of the Baeksan synclinal area, Taebaeksan Basin. This unit was suggested originally for the next zone above the *Cordylodus proavus* Zone in co-ocurrence with *Cordylodus proavus* Müller.

The main goal of this contribution is to examine the validity of the *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone as an independent biostratigraphic unit and whether the name is appropriate. The analysis includes comparing the recovery, vertical ranges, and lateral distribution of the key species in each section sampled. For this study, one new section (Bangteogol) and one previously studied section (Maesangol) were examined (Figs. 1 and 2). Eleven other sections studied previously were also re-examined, including the Chikdong, Dumugol, Teogol, Iyonnaegol and Dongjeom sections in the southern limb of the Baekunsan syncline, and the Yemi, Machajae, Cheoksan, Cheungsan, Saeumdae and Jeolgol sections in the northern limb of the syncline (Lee, 1989, 1990, 1992; Lee and Lee, 1993, and section locations therein).

2. STRATIGRAPHIC SUMMARY

The Hwajeol Formation (Kobayashi, 1935) is the Furongian lithostratigraphic unit of the Taebaek Group (originally Great Limestone Group of the Duwibong-type Joseon Supergroup) in eastern margin of the North China platform. This unit is well exposed in the Baekunsan synclinal area, Taebaeksan Basin, mid-eastern Korea.

Kobayashi (1935) named the Hwajeol Formation mainly for the limestone beds between the Sesong Slate and Dongjeom Quartzite near the Dongjeom area, Taebaek City. Main lithotypes of the formation are various types of ribbon limestone, bedded limestone, flat-pebble conglomerate, and clastic deposits such as mudstone and sandstone. The upper Cambrian (Furongian) age of the unit is based largely on Kobayashi's (1966) megafossil study. Kobayashi (1935, 1966) established four trilobite zones (*Prochuangia, Chuangia, Kaolishania, Dictyites*) and one brachiopod zone (*Eoorthis*) for the formation and correlated them with megafossils of the Chaumitian Series (Furongian) of North China.

Sohn and Choi (2005) confirmed the record of the *Kaol-*

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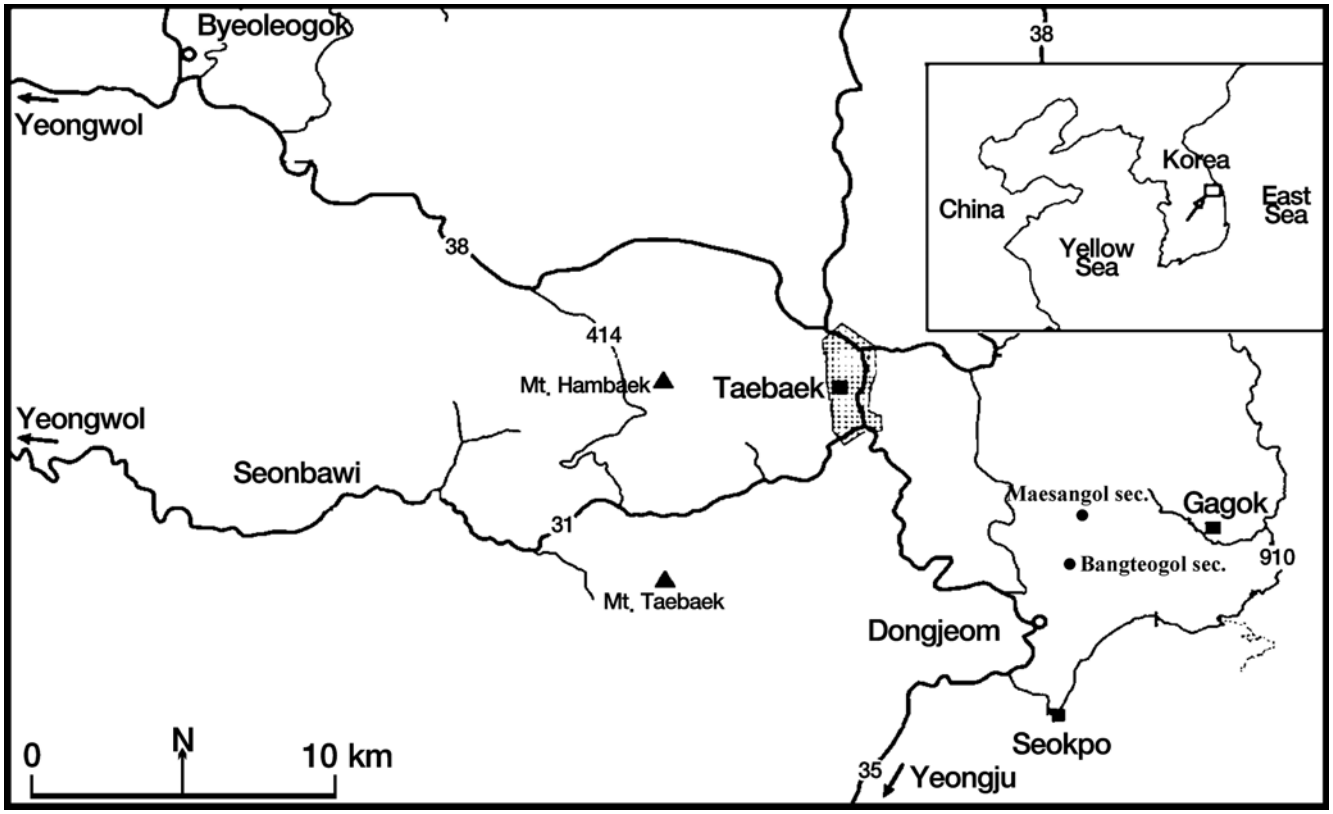

Fig. 1. Road map showing location of the measured sections (modified from Woo et al., 2006).

ishania Zone in the uppermost part of the Sesong Slate, which is lower unit of the Hwajeol Formation, and they correlated the zone with the same zone of North China (Geyer and Shergold, 2000). Sohn and Choi (2005, 2007) also partially revised the trilobite faunas, i.e., *Asioptychaspis, Quadraticephalus*, and *Mictosaukia* faunas, of the Hwajeol Formation.

Many conodont studies were carried out on the Hwajeol Formation in the Taebaeksan Basin (Lee, 1975; Lee and Lee, 1988; Lee, 1989, 1990, 1992; Lee, and Lee, 1993; Lee and Seo, 2008). As a result of these studies, five conodont biozones were identified: *Proconodontus*, *Eoconodontus notchpeakensis*, *Cambrooistodus minutus*, *Cordylodus proavus,* and *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zones (Lee, 1989, 1992). Lee (2014) subdivided the *Proconodontus* Zone into three zones, the *Proconodontus tenuiserratus*, *Proconodontus posterocostatus*, and *Proconodontus muelleri* Zones, based on conodont study of the Makgol section of the Hwajeol Formation in Jikdong valley, Gangwon Province, Korea. Based on their conodont faunas, Lee and Seo (2008) correlated the Hwajeol Formation with the Franconian to Trempealeauan Stages of North America (Miller, 1988) and the Changshanian to Fengshanian Stages of North China (An et al., 1983; Chen, 1986) (Fig. 4).

Choi (2011) interpreted the sedimentary environments of the Hwajeol Formation, based on the sedimentary facies and trilobite faunal contents. He concluded that the Sesong Slate was deposited on the outer part of a clastic shelf, after which the basin became shallower, and the overlying Hwajeol Formation represents a carbonate shelf.

3. MEASURED SECTIONS

Two new measured sections examined herein are the Bangteogol and Measangol sections, which are compared with eleven sections studied previously by Lee (1989, 1992) and Lee and Lee (1993). The Bangteogol section is exposed along the sinuous stream of Bangteogol, which is the valley east of Dongjeom Elementary School, Dongjeom-dong, Taebaek City (Fig. 1). A relatively complete succession of the Hwajeol Formation is well exposed along the valley, even though some parts are covered.

This section consists mainly of ribbon limestone of various types, i.e., shale with limestone nodules or lenses, and planar- or wavy-patterned alternation of shale and limestone beds, as well as flat-pebble conglomerate, bedded limestone, well-bedded siltstone/sandstone and laminated black shale. Nineteen limestone samples were collected only from upper part of the section (68 m thick). Average intervals between samples were ~3.6 m, and average mass of each sample was 2.2 kg.

The Maesangol section is located at the valley east of Sangcheolam village, Cheolam-dong, southeast of Taebaek City (Fig. 1). The upper part of the Hwajeol Formation is well

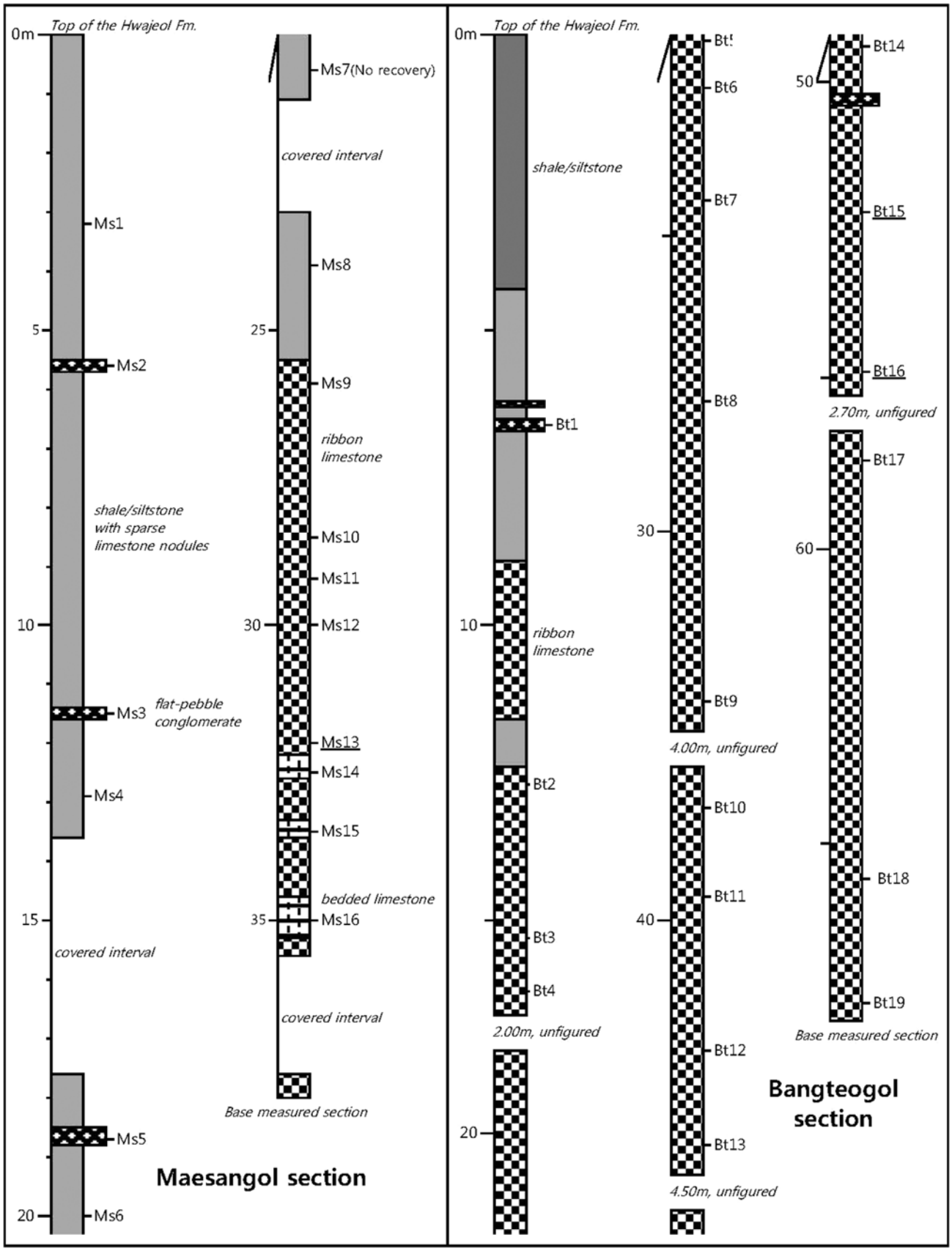

Fig. 2. Lithologies and sample horizons of the upper part of the Hwajeol Formation at Bangteogol and Maesangol sections, Taebaeksan Basin, Korea. Underlined sample numbers indicate no recovery of conodonts.

exposed along the valley floor. The total succession considered herein is 38 m thick, including the top 9.41 m interval that was examined by Lee (1992). Lithotypes of the Maesangol section are almost identical to those of the Bangteogol section mentioned above. Sixteen samples were collected for conodonts from this section. Vertical lithologic change and sampled horizons are shown on Figure 2. Average sample intervals were 5.0 m through the complete section. Average mass of each sample was 1.7 kg, and 1 kg of each sample was dissolved by acetic acid for conodonts.

Refer to Lee (1989, 1992) and Lee and Lee (1993) for locations, lithologies and sample collections of the eleven sections that they studied. These eleven sections are re-examined herein.

4. CONODONT OCCURRENCE

A total of 511 conodont elements were recovered from seventeen samples of the Hwajeol Formation in the Bangteogol (Bt) section, whereas 488 elements were recovered from fourteen samples of the formation in the Maesangol (Ms) section (Tables 1 and 2). The most abundant samples in each section were Bt 9 (83 elements) and Ms 16 (141 elements).

Table 1. Recovery of conodont species in the samples from the Bangteogol section

Species Samples (Bt)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	17	18	19	Total
Paraconodonts																		
Furnishina asymmetrica																1		1
Furnishina sp. cf. *gladiata*																1		1
Hertzina americana											1							1
Prooneotodus gallatini														1		2		3
Prosagittodontus dahlmani										1								1
Rotundoconus bulbousus																		
tricarinate element																	4	4
tetracarinate element																	6	6
Rotundoconus jingxiensis																		
tricarinate element														3				3
Westergaardodina bicuspidata																1		1
Westergaardodina sp.																1		1
Euconodonts																		
Cambrooistodus minutus					3	1	1	4	7									16
Cambrooistodus cambricus							1	1	4		3							9
Cordylodus proavus																		
rounded element	7	4	12															23
compressed element	1	1	7	1														10
Eoconodontus notchpeakensis																		
rounded element			7	2	6		9	18	37	7	8	2	1					97
compressed element					2	4	2	10	11	3								32
Dasytodus transmutatus																	3	3
Granatodontus ani								1	1		1	1		3		1		8
Granatodontus asymmetrica									1			1		2		1		5
Granatodontus hwajeolensis									1					5		2	5	13
Granatodontus multicorrugata												1		4		3		8
Monocostodus sevierensis	6																	6
Proconodontus muelleri					1	3	3	8	15	1	23	6		24		4	5	93
Proconodontus posterocostatus																1	4	5
Semiacontiodus lavadamensis	1																	1
Teridontus nakamurai	21	2	2		7	6	4	2	6	4	12	16	2	18	1	14	21	138
Teridontus primitivus																	2	2
Chaetognaths (Protoconodonts)																		
Phakelodus elongatus																11	4	15
Phakelodus tenuis														1		4		5
Total	36	7	28	3	19	14	20	44	83	16	48	27	3	61	1	47	54	511

Table 2. Recovery of conodont species in the samples from the Maesangol section

Species Samples (Ms)	1	2	3	4	5	6	8	9	10	11	12	14	15	16	Total
Paraconodonts															
Prooneotodus gallatini						1					1			1	3
Rotundoconus jingxiensis															
tricarinate element						2									2
Euconodonts															
Cambrooistodus minutus						2				6	4	6	2	8	28
Cambrooistodus cambricus						2					3	5	1	7	18
Cordylodus proavus															
rounded element		2			2	8									12
compressed element	3	3	2	2	1	6									17
Eoconodontus notchpeakensis															
rounded element		2	4		1	22		4	1	13	7	21	17	43	135
compressed element		1	3			10	1		3	5	9	23	18	33	106
Dasytodus nodus							1					1	1	2	5
Granatodontus ani						2						3	2	9	16
Granatodontus asymmetrica												1			1
Granatodontus hwajeolensis						1					1	1		4	7
Proconodontus muelleri						10		3	7	1	6	19	6	16	68
Proconodontus serratus						1				2					3
Teridontus nakamurai	2	2	2	2		19		2	3	3	4	4	6	16	65
Chaetognaths (Protoconodonts)															
Phakelodus elongatus														1	1
Phakelodus tenuis														1	1
Total	5	10	11	4	4	86	2	9	14	30	35	84	53	141	488

Average conodont recovery of the Bangteogol section (34.9 elements/sample) was somewhat higher than the Maesangol section (30.0 elements/sample).

The conodonts are relatively well preserved, but some specimens are fragmentary. A few paraconodont elements are exfoliated. Euconodont elements indicate a color alteration index of 5.5, suggesting a burial temperature of greater than 300 °C (Epstein et al., 1977).

Euconodont elements exceed protoconodont and paraconodont elements in number. Protoconodont and paraconodont elements are dominant in lower part of the Bangteogol section, and euconodonts are more common in upper part of each section.

The identifiable conodonts are classified into twenty-eight species referable to seventeen genera. The most dominant euconodont species in both Bangteogol and Masesangol sections are *Eoconodontus notchpeakensis* Miller (370 elements, 37.0% of the total collection) and *Teridontus nakamurai* (Nogami) (203 elements, 20.3%).

5. BIOSTRATIGRAPHIC SUMMARY

Conodont ranges of the measured sections of the Hwajeol Formation in the Taebaeksan Basin permitted recognizing the *Proconodontus posterocostatus, P. muelleri, Eoconodontus notchpeakensis, Cambrooistodus minutus, Cordylodus proavus,* and *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zones in the Bangteogol section, and the *Cambrooistodus minutus* and *Cordylodus proavus* Zones in the Maesangol section, based mainly on taxa of the *Proconodontus* Lineage. The lower parts of each measured section were covered. The *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone is not recognized in the Maesangol section because the nominate species were not recovered.

Six conodont zones of the Hwajeol Formation are defined by the successive lowest occurrence of the zonal species. This zonal scheme is partly equivalent to that of the southern (Lee and Lee, 1988; Lee and Seo, 2008; Lee, 2014) and northern (Lee, 1989, 1990, 1992, 2004; Lee and Lee, 1993) limbs of Paekunsan syncline, Taebaeksan Basin, Korea. International correlation of the zones is shown on Figure 4.

Monocostodus sevierensis Miller and *Semiacontiodus lavadamensis* Miller, two nominate species of the *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone, were recovered from only sample Bt 1, which is 6.7 m below the top of the Hwajeol Formation in the Bangteogol section (Table 1). This level marks the base

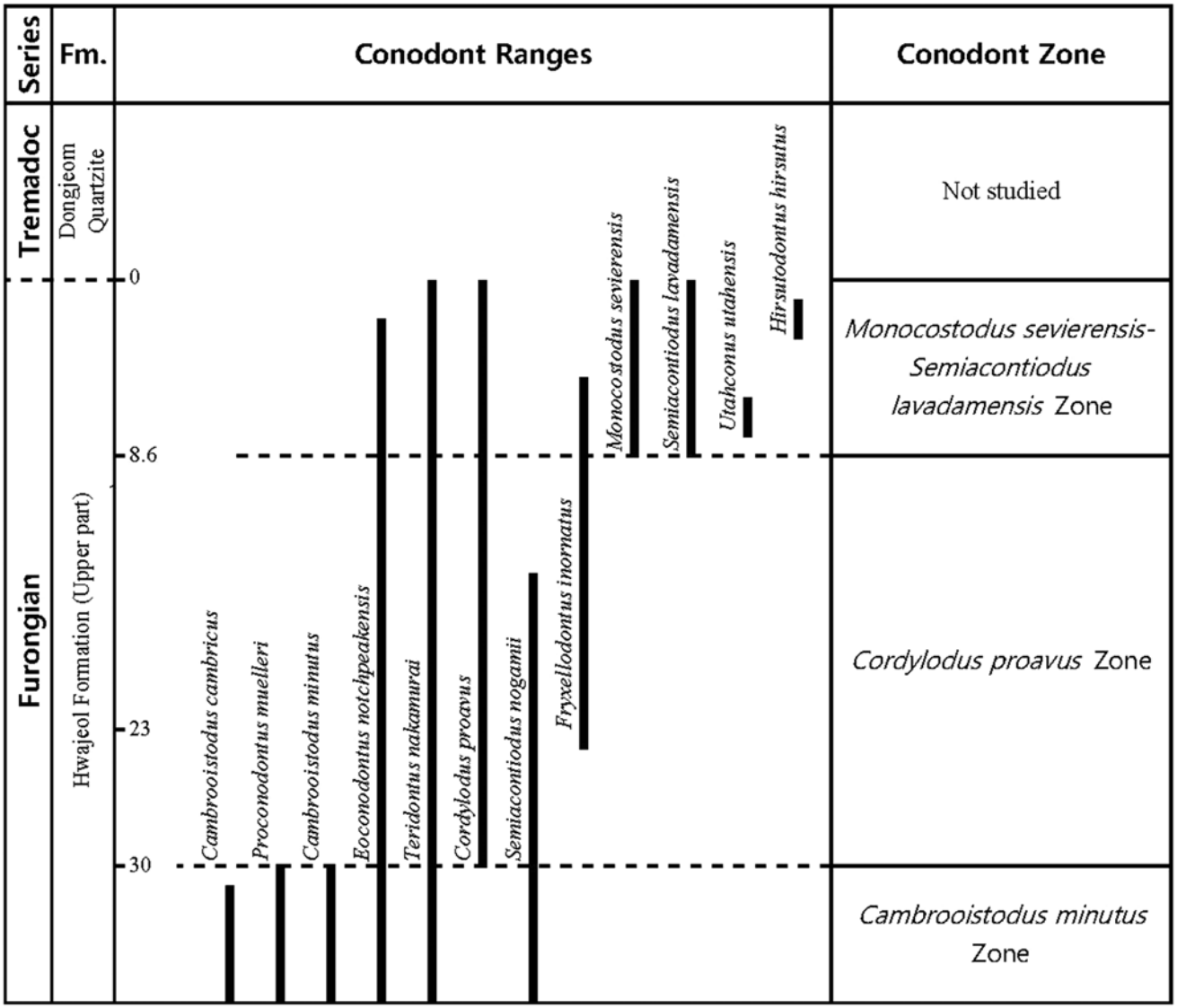

Fig. 3. Composite range chart of selected conodont species above the *Eoconodontus notchpeakensis* Zone in the thirteen sections considered in this study.

of the zone. The conodont fauna from this zone is much less diverse than underlying zones (Fig. 3). Besides the nominate species, *Cordylodus proavus* Müller and *Teridontus nakamurai* (Nogami) are common species.

Previously, *Monocostodus sevierensis* was discovered from the following levels below the top of the named sections of the Hwajeol Formation: 8.4–8.6 m at the Chikdong section (Lee, 1992), 8.6 m at the Jeolgol section, and 3.1 m at the Dongjeom section (Lee and Lee, 1993). *Semiacontiodus lavadamensis* appeared 8.6 m below the top of the Jeolgol section, 3.9 m below the top of the Cheoksan section (Lee, 1992), and 7.5 m below the top of the Yemi section (Lee and Lee, 1993).

Fryxellodontus inornatus Miller, which is also a nominate species of the *Fryxellodontus inornatus-Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone, was not present in the two sections discussed in this study. Based on previous occurrences in other sections around the Taebaeksan Basin, *F. inornatus* occurred stratigraphically lower than the two other nominate species. A total of seven planar elements and one intermediate element were recovered from 23.4 m below the top of the Hwajeol Formation in northern Taebaek City (Lee, 1989), from 19.5 m below the formation top at the Machajae section, and 7.3 m below the top at the Dongjeom section (Lee and Lee, 1993). As a whole, *F. inornatus* was hitherto recovered from three beds ranging from 23.4–7.3 m below the top of the Hwajeol Formation at three separate sections in Taebaeksan Basin.

Because of the stratigraphic position of *F. inornatus* relative to *M. sevierensis* and *S. lavadamensis*, this study establishes the *Monocostodus sevierensis-Semiacontiodus lavadamensis*

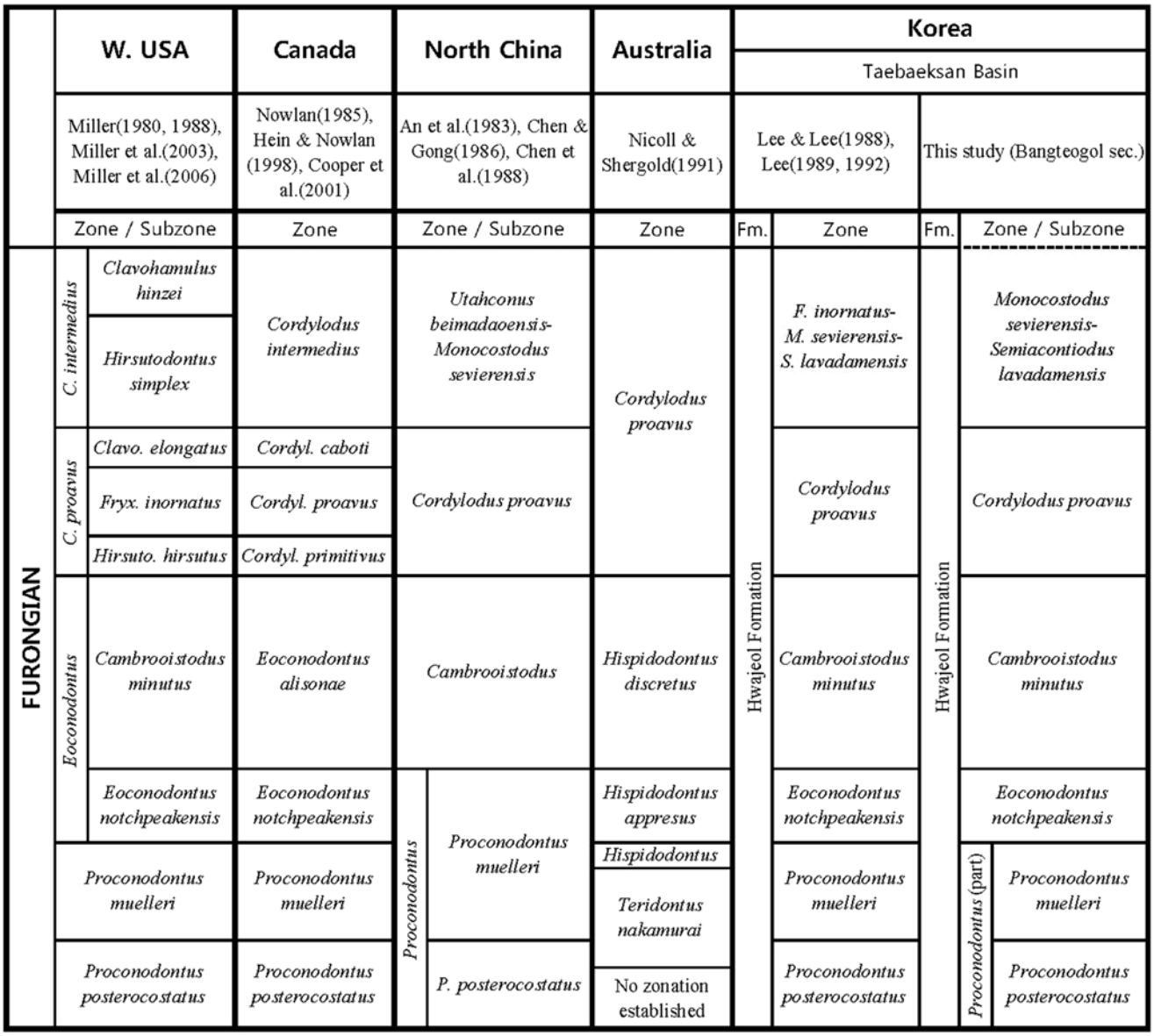

Fig. 4. The Furongian (Upper Cambrian) conodont zones of the Hwajeol Formation, Korea and their international correlation.

Zone, which is the next zone above the *Cordylodus proavus* Zone, for the narrow, uppermost stratigraphic interval of the Hwajeol Formation (Figs. 3 and 4). This shorter name replaces the longer zone name, and the lower stratigraphic interval that is characterized by *F. inornatus* is assigned to the *Cordylodus proavus* Zone. This new upper zone is correlated to the *Cordylodus intermedius* Zone of western United States (Miller, 1980, 1988; Miller et al., 2003; Miller et al., 2006), coeval zones of Canada (Nowlan, 1985; Hein and Nowlan, 1998; Cooper et al., 2001), of North China (An et al., 1983; Chen and Gong, 1986; Chen et al., 1988) and of Australia (Nicoll and Shergold, 1991) (Fig. 4).

Some conodont taxa disappeared abruptly toward the top of the Hwajeol Formation. Taxa of the upper four zones, i.e., the *Eoconodontus notchpeakensis, Cambrooistodus minutus, Cordylodus proavus,* and *Monocostodus sevierensis-Semiacontiodus lavadamensis* Zones, are much less diverse than the underlying zones, which contain several other euconodont and paraconodont taxa. As an extreme example, only *Cordylodus proavus* and *Teridontus nakamurai* and the two nominate species are common in the *M. sevierensis-S. lavadamensis* Zone in the Bangteogol section. As Miller et al. (2003, 2006) discussed earlier, the reduced divertsity appears to be related to sea level changes.

6. CONCLUSIONS

The uppermost conodont zone of the Hwajeol Formation was reassessed in the Bangteogol and Maesangol sections discussed herein and in eleven sections discussed in previous

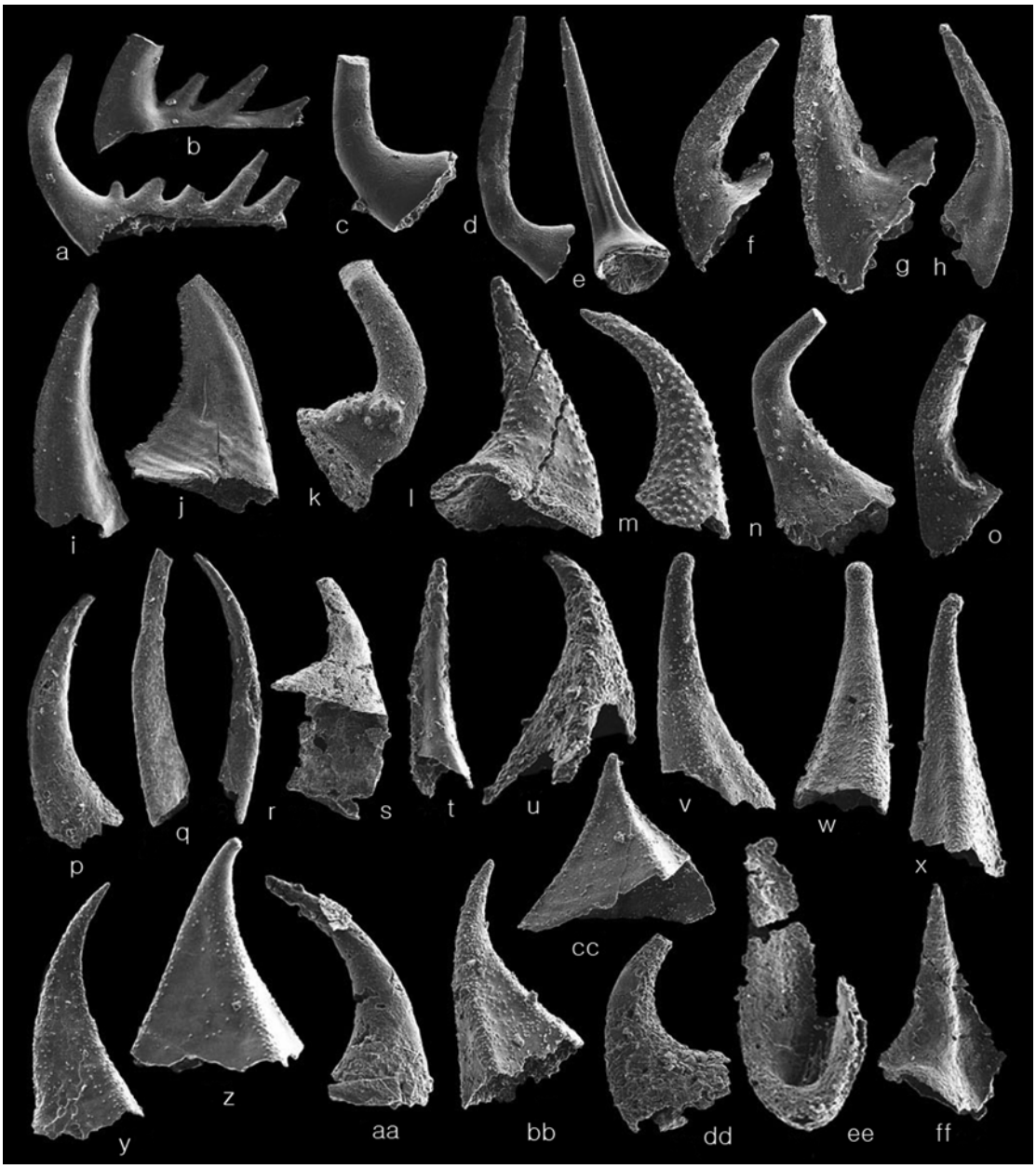

Fig. 5. Scanning electron photomicrographs of conodonts from the Hwajeol Formation, Taebaeksan Basin, Korea. All images are lateral views except as noted below. (a, b) *Cordylodus proavus* Müller, Bt 01, Ms 03 (JBNUCC 14-01 and 14-02), ×45, ×55; (c) *Teridontus nakamurai* (Nogami), Bt 01 (JBNUCC 14-03), ×40; (d) *Monocostodus sevierensis* Miller, Bt 01 (JBNUCC 14-04), ×60; (e) *Semiacontiodus lavadamensis* Miller, posterior view, Bt 01 (JBNUCC 14-05), ×55; (f) *Cambrooistodus minutus* (Miller), Ms 11 (JBNUCC 14-06), ×65; (g) *Cambrooistodus cambricus* (Miller), Ms 14 (JBNUCC 14-07), ×48; (h, o) *Eoconodontus notchpeakensis* (Miller), rounded and compressed elements, Ms 14, Ms 14 (JBNUCC 14-08 and 14-09), ×50, ×45; (i) *Proconodontus muelleri* (Miller), Bt 14 (JBNUCC 14-10), ×25; (j) *Proconodontus serratus* (Miller), Ms 06 (JBNUCC 14-11), ×30; (k) *Dasytodus nodus* (Zhang and Xiang), Ms 14 (JBNUCC 14-12), ×50; (l) *Granatodontus asymmetrica* Lee, posterolateral view, Ms 14 (JBNUCC 14-13), ×65; (m) *Granatodontus ani* Wang, Ms 16 (JBNUCC 14-14), ×55; (n) *Dasytodus transmutatus* (Xu and Xiang), Bt 19, posterolateral view, (JBNUCC 14-15), ×45; (p) *Proconodontus posterocostatus* Miller, Bt 18 (JBNUCC 14-16), ×45; (q) *Phakelodus elongatus* (An), Bt 18 (JBNUCC 14-17), ×44; (r) *Phakelodus tenuis* (Müller), Ms 16 (JBNUCC 14-18), 50; (s) *Furnishina asymmetrica* Müller, Bt 18 (JBNUCC 14-19), ×40; (t) *Furnishina* sp. cf. *gladiata*, Bt 18 (JBNUCC 14-20), oblique posterior view, ×40; (u) *Prosagittodontus dahlmani* Müller, Bt 10 (JBNUCC 14-21), 35; (v–x) *Rotundoconus bulbousus* Lee, tricarinate (v, x) and tetracarinate elements, lateral, lateral and posterior views, all Bt 19 (JBNUCC 14-22~24), all ×45; (y) *Hertzina americana* Müller, Bt 11 (JBNUCC 14-25), ×40; (z) *Granatodontus hwajeolensis* (Lee), posterior view, Ms 06 (JBNUCC 14-26), ×35: (aa) *Teridontus primitivus* Lee, Bt 19 (JBNUCC 14-27), ×60; (bb) *Granatodontus multicorrugata* Lee, Bt 14 (JBNUCC 14-28), ×60; (cc) *Rotundoconus jingxiensis* (An et al.), tricarinate element, Bt 14 (JBNUCC 14-29), ×45; (dd) *Prooneotodus gallatini* Müller, Bt 01, (JBNUCC 14-30), 65; (ee) *Westergaardodina bicuspidata* Müller, posterior view, Bt 18 (JBNUCC 14-31), ×65; (ff) *Westergaardodina* sp., posterior view, Bt 18 (JBNUCC 14-32), ×55.

publications of the first author. *Monocostodus sevierensis* and *Semiacontiodus lavadamensis*, two nominate species of this highest zone, were recovered from 8.6–3.1 m below the top of the Hwajeol Formation in various sections. These taxa comprise the fauna of the *M. sevierensis-S. lavadamensis* Zone, the base of which is at the lowest occurrence of either species. The two species occur together with *Cordylodus proavus* and *Teridontus nakamurai*. We propose the shorter name *Monocostodus sevierensis-Semiacontiodus lavadamensis* Zone for the uppermost zone of the Hwajeol Formation as an alternative to the former zone. This zone is correlated to coeval zones in the western United States (Miller, 1980, 1988; Miller et al., 2003; Miller et al., 2006), of Canada (Nowlan, 1985; Hein and Nowlan, 1998; Cooper et al., 2001), of North China (An et al., 1983; Chen and Gong, 1986; Chen et al., 1988) and of Australia (Nicoll and Shergold, 1991), respectively.

The name of the zone previously included *Fryxellodontus inornatus*, but it was not present in the two sections studied in this paper. It was recovered at a lower stratigraphic level than *Monocostodus sevierensis* and *Semiacontiodus lavadamensis* in sections around Taebaeksan Basin, from 23.4–7.3 m below the top of the Hwajeol Formation. Strata containing *Fryxellodontus inornatus* is reassigned to the underlying *Cordylodus proavus* Zone.

There is a drop in diversity in conodont faunas in the upper part of the Hwajeol Formation. This drop in diversity appears to be related to sea level changes that were discussed by Miller et al. (2003, 2006).

7. SYSTEMATIC PALEONTOLOGY

Most of the conodonts from the Bangteogol and Maesangol sections in this report are fully described elsewhere, so only two taxa that are placed in open nomenclature are discussed below. All figured specimens are deposited in the collections of the Department of Earth Science Education, Chonbuk National University, Jeonju, and have collection numbers JNUCC 14: 01-32.

Genus *Furnishina* Müller, 1959
Type species: *Furnishina furnishi* Müller, 1959
Furnishina sp. cf. *F. gladiata*
Fig. 5t

Remarks – One specimen recovered in this study is very similar in its general outline to *Furnishina gladiata* Müller and Hinz. It also has a tunnel-like median structure on the posterior face like *F. gladiata*. However, it differs from that of Müller and Hinz (1991) in the degree of lateral expansion and the detail of median structure; therefore, it is only tentatively referred to the species.

Occurrence – Sample Bt 18 in the Bangteogol section (*Proconodontus muelleri* Zone).

Material – One specimen.

Genus *Westergaardodina* Müller, 1959
Type species: *Westergaardodina bicuspidata* Müller, 1959
Westergaardodina sp.
Fig. 5ff

Remarks – One specimen appears to be an element of the genus *Westergaardodina* Müller, but only one lateral denticle is preserved; therefore it is only tentatively referred to the genus.

Occurrence – Sample Bt 18 in the Bangteogol section (*Proconodontus muelleri* Zone).

Material – One specimen

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