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〈Original article〉

Newly Reported Diatoms (Bacillariophyta) in Korea from Random Collections in the Freshwater and Coastal Areas

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Abstract - To find unrecorded diatom species, random materials were collected from the freshwater, brackish water, and coastal waters. Benthic and periphytic diatoms were sampled from twelve localities. Thirteen species belonging to eight genera are newly added to the national flora of diatom. In the intertidal areas, the five species are new to Korea, *Anaulus minutus* Grunow, *Anaulus simonsenii* Witkowski & Metzeltin, *Eunotogramma laeve* Grunow, *Eunotogramma productum* Grunow, and *Nitzschia subcapitellata* Hustedt. The following two species are new from brackish waters, *Chamaepinnularia krookiformis* (Krammer) Lange-Bertalot & Krammer and *Cymatoneis ovalis* Heiden. The following four species are new from mountain peatlands, *Geissleria ignota* (Krasske) Lange-Bertlaot & Metzeltin, *Chamaepinnularia hassiaca* (Krasske) Cantonati & Lange-Bertalot, *Chamaepinnularia mediocris* (Krasske) Lange-Bertalot and *Pinnularia linearidivergens* Kulikovskiy, Lange-Bertalot & Metzeltin. The following two species are new from river or streams, *Cymbella hustedtii* var. *compacta* Krammer and *Cymbella stigmaphora* Østrup.

Keywords : diatoms, new records, freshwater, brackish water, marine water

INTRODUCTION

Diatoms are more common and widespread in aquatic systems than any other microalgae and show high species diversity. The prevailing concept of diatom biogeography is that most species are widespread, perhaps even cosmopolitan in their spatial distribution (Kristiansen 1996). In order to find unrecorded diatom species in Korea, some localities were selected in mountain peatlands, estuaries and marine intertidal area. Mountain peatlands are a unique place with high acidity and organic richness and is known to have a high diversity of diatom species (Wheeler and Proctor 2000). Although the area of Korea is not wide, mountain wetlands have developed in many places.

Coast and estuaries, the boundary between the sea and continent, are the ecosystem transition areas, which have large geomorphic changes and diverse breeding grounds for living organisms (Elliott and Quintino 2007). Overall, the species diversity of biological organisms is higher in coastal areas than in ocean or inland waters, diatoms are no exception, and recent studies have revealed that diatom community structure and diversity are influenced by geographical factors independent of environmental conditions (Eichbaum *et al*. 1996).

The estuary of the Nakdong River is known as a place where biodiversity is high due to diverse environmental factors and complicated topographical conditions as estuaries, and diatoms are highly diverse in comparison with other regions (Du *et al*. 2009). More than 300 species of benthic diatoms were already reported in the estuarine sediments of the river (Cho 1988). Previous studies on diatoms in the estuary of Nakdong River have been conducted on plankton in estuarine lakes, and on benthic diatoms in sandy sediments. In the intertidal sandflats, the distribution of benthic diatom on the surface (Du *et al*. 2009) and its distribution

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along the depth of the sediment layer (Du *et al*. 2010) were studied. On the other hand, taxonomic studies were carried out recently in diatom species belonging to genus *Navicula* and *Hantzschia* (Joh 2013, 2014).

This study aims to extend the diatom species diversity and to reduce the number of unrecorded species in this country. It was carried out as part of a national task, "The Project on Survey and Excavation of Korean Indigenous Species", supported by the National Institute of Biological Resources (NIBR) and the Nakdonggang National Institute of Biological Resources (NNIBR) under the Ministry of Environment of Korea. The purpose of this study is to find the unrecorded species of diatoms not yet reported in aquatic systems throughout Korean Peninsula.

MATERIALS AND METHODS

Diatoms were collected from eight sites following as below and the sites were shown in Figure 1. In order to find unrecorded species, we selected places where species diversity is high or unrecorded species were discovered until this time. They are two intertidal zones, two brackish waters, one river, two streams, five mountain peatlands, which are summarized into three categories, the eight freshwater, two brackish water and two marine water zones. The time of collection is indicated in parentheses in following paragraphs.

1. Sandflats of the Nakdong River estuary in Busan (March in 1991, April in 1997)
2. Coastal area of Wido Island in Buan (May in 2015)
3. Sandflats of Byunsan Coast in Buan (May in 2014)
4. Lagoon Hyungeumho of Geumho District in North Korea (October 1998)
5. Iancheon Stream in Sangju (January 2010) and Jusancheon Stream in Cheonsong (July 2014)
6. The Namhangang River in Danyang (January 2010)
7. Yongneup Peatland of Mountain Daeamsan in Inje (May 2014)
8. Oegogaeneup Peatland of Mountain Jirisan in Sancheong (April 2010)
9. Sinbulsanneup Peatland of Mountain Sinbulsan in Yangsan (May 2016)

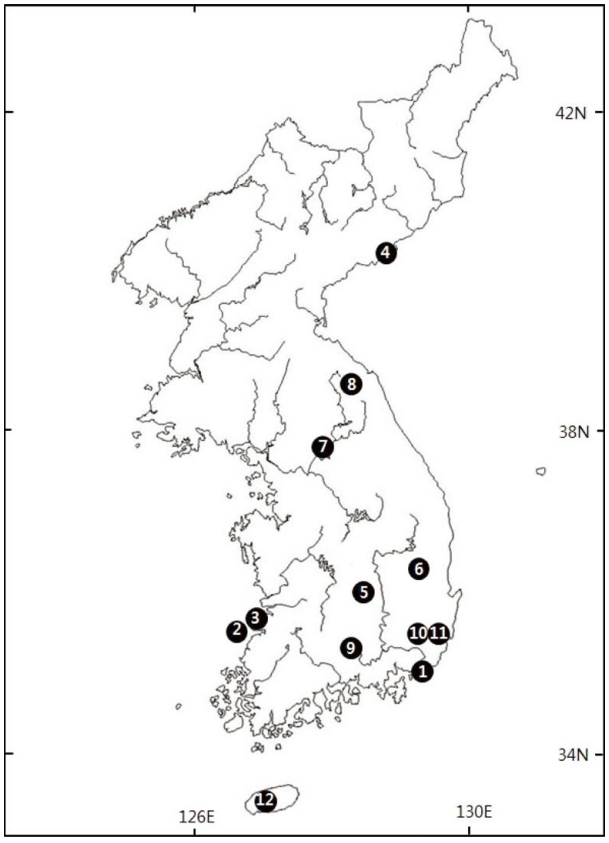

Fig. 1. Map of the sampling localities in the estuary and marine coasts (1. Sandflats of the Nakdong River estuary in Busan. 2. Wido Island in Buan, 3. Sandflats of Byunsan Coast in Buan. 4. A lagoon of Geumho District in North Korea), in river and streams (5. Iancheon Stream in Sangju, 6. Jusancheon Stream in Cheongsong. 7. The Namhangang River in Danyang), and mountain peatlands (8. Yongneup Peatland of Mountain Daeamsan in Inje, 9. Oegogaeneup Peatland of Mountain Jirisan in Sancheong. 10. Sinbulsan Peatland in Yangsan. 11. Mujechineup Peatlands in Yangsan. 12. 1,100 Altitude Peatland of Hallasan in Jeju Island.

10. Mujechineup Peatland of Mountain Jeonjoksan in Ulsan (December 2010)
11. 1,100 Altitude Peatland of Mountain Hallasan in Jeju Island (August 2010)

The materials containing diatoms were oxidized using nitric acid and potassium dichromate in a hot sand bath, followed by repeated washing with distilled water (APHA 1995). Permanent specimens of slide glasses were made using Pleurax medium and diatoms were observed and counted by using two types of light microscopes, including an Olympus microscope (Provis AX2; Olympus, Tokyo, Japan), equipped with differential interference contrast (DIC)

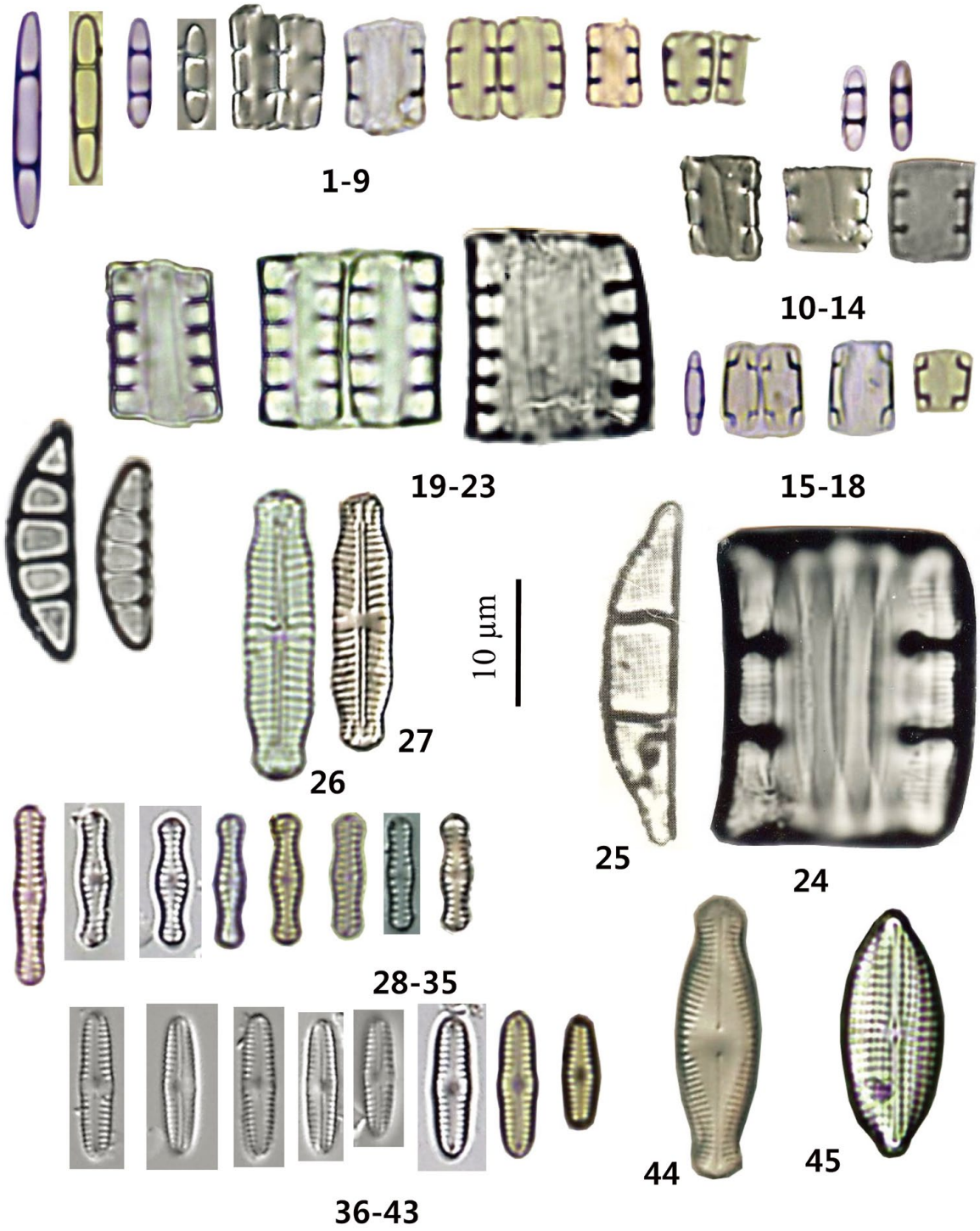

Plate 1. Figs. 1–9. *Anaulus balticus* Simonsen. Figs. 10–14. *Anaulus minutus* Grunow. Figs. 15–18. *Anaulus simonsenii* Witkowski & Metzeltin. Figs. 19–23. *Eunotogramma laeve* Grunow. Figs. 24, 25. *Eunotogramma productum* Grunow. Figs. 26, 27. *Geissleria ignota* (Krasske) Lange-Bertlaot & Metzeltin. Figs. 28–35. *Chamaepinnularia hassiaca* (Krasske) Cantonati & Lange-Bertalot. Figs. 36–43. *Chamaepinnularia mediocris* (Krasske) Lange-Bertalot. Fig. 44. *Chamaepinnularia krookiformis* (Krammer) Lange-Bertalot & Krammer. Fig. 45. *Cymatoneis ovalis* Heiden.

optics and an Axioplan microscope (Carl Zeiss, Oberkochen, Germany). Diatom frustules were counted from 300 to 350 for each sample to determine the frequency and abundance of each species. Many literatures were referred to identify diatoms and to make taxonomic accounts of species, Cleve-Euler (1951), Krammer (2000), Witkowski *et al*. (2000), Krammer (2002) and others.

RESULTS AND DISCUSSION

Benthic and periphytic diatoms were collected from sediments in twelve sampling localities. The selected diatoms are examined on the basis of light microscopy observation and important characters, valve outlines, the shapes of valve ends, a number of striae and areola density, and the shape of axial and central area. The morphological characteristics that can be obtained from light microscopy are used to confirm the diatoms to species level. In this taxonomic works, 13 species are identified as unrecorded ones that have never been reported in Korea, however, and one already reported species is presented. The basic morphological characters are included in each description. In this report, eight genera, *Anaulus*, *Eunotogramma*, *Geissleria*, *Chamaepinnularia*, *Cymatoneis*, *Pinnualria*, *Cymbella* and *Nitzschia* are described in the floristic survey of diatoms.

In this study, 13 diatom species representing eight genera are new to Korea. Four species was found in mountain peatlands, two species was in river and streams, three species was in brackish waters, and four species was from intertidal areas. Of the 13 species, four are araphid diatoms, nine biraphid diatoms. Some of these species have been rarely reported in freshwater or coastal areas in other areas since their new publication in the past. Four species, *Anaulus minutus*, *A. simonsenii*, *Chamaepinnularia krookiformis* and *Nitzschia subcapitellata*, correspond to this category.

Genus *Anaulus* Ehrenberg 1844

1. *Anaulus balticus* Simonsen 1959 (Pl. 1, Figs. 1–9) (Witkowski *et al*. 2000, p. 23, Pl. 10, Figs. 5, 6, 36)

Frustules in girdle view rectangular with rounded corners. Valves narrowly linear, the ends of valve rounded. Two pseudosepta deeply penetrating in girdle view, slightly bent towards the ends. Striae very fine, not resolvable in light microscopy. Valves occurring in local areas 6–17.1 μm in length, 1.6–2 μm in breadth.

As marine diatoms, this species is widespread on sediments and substrates of coastal areas over the world (Witkowski *et al*. 2000), and type locality of the species, Kiel Bay of Baltic Sea in Germany. In Korea, the species occurred rarely on the sandflats of the Nakdong River Estuary in Busan, and of coastal area in Buan. This species is not an unrecorded species in Korea, but it is presented in order to compare it to the forms of other species belonging to genus *Anaulus*.

2. *Anaulus minutus* Grunow in Van Heurck 1882 (Pl. 1, Figs. 10–14) (Witkowski *et al*. 2000, p. 23, Pl. 10, Figs. 33–35)

Frustules in girdle view rectangular to square with acutely rounded corners. Valves narrowly linear, the ends of valve rounded. Two pseudosepta straightly and deeply penetrating in girdle view. Striae very fine, not resolvable in light microscopy. Valves occurring in local areas 5.5–8 μm in length, 1.5 μm in breadth. This species is similar in valve forms with *Anaulus balticus*, but different in the rectangular to square girdle view and acutely rounded corners in girdle, and straight pseudosepta in girdle view.

As marine diatoms, this species is infrequent over the world, and occurred in the Mediterranean, Seychelles Islands and Qurum Beach of Oman (Witkowski *et al*. 2000). In Korea, this is found only in the sandflats of coastal area in Buan, May in 2014, is newly reported.

3. *Anaulus simonsenii* Witkowski & Metzeltin in Witkowski *et al*. 2000 (Pl. 1, Figs. 15–18) (Witkowski *et al*. 2000, p. 23, Pl. 10, Figs. 7–12)

Frustules in girdle view rectangular with rounded corners. Valves narrowly linear, the ends of valve protracted and subcapitate. Two pseudosepta penetrating in girdle view, sharply bent towards the ends. Striae very fine, not resolvable in light microscopy. Valves 4.5–7.5 μm in length, 1.4 μm in breadth.

As marine diatoms, this species occurred in the sediments of the undesignated type locality, and in western Baltic Sea and the Qurum Beach in Oman (Witkowski *et al*. 2000), but is rarely reported in other places. In Korea, this is found

only in the sandflats of coastal area in Buan, May in 2014, and is newly reported.

Genus *Eunotogramma* Weisse 1855

4. *Eunotogramma laeve* Grunow in Cleve and Möller 1879 (Pl. 1, Figs. 19–23)

Synonym: *Eunotogramma laevis* Grunow in Van Heurck 1883 (Witkowski *et al*. 2000, p. 32, Pl. 10, Fig. 4)

Valves semi-elliptical to semi-circular, the ventral margin of valve more or less straight, slightly convex or concave, the ends of valve obtusely rounded. Pseudosepta deeply in the girdle view, 1–8 of valve. Striae unresolvable in light microscopy. Valves of the local area 13–19 μm in length, 4–5 μm in breadth.

As marine diatoms, this species is widesread in the coasts in the world, especially in the warmer regions (Witkowski *et al*. 2000). In Korea, the species was found rarely in two places, the sediments of coasts in Buan, the estuary of the Nakdong River in Busan, and is newly reported.

5. *Eunotogramma productum (producta)* Grunow in Van Heurck 1883 (Pl. 1, Figs. 24, 25) (Cleve-Euler 1951, p. 161, Fig. 284; Oreshkina and Radionova 2014, pl. 6, Fig. 12)

Valves semi-elliptical, the ventral margin of valve more or less straight, the ends of valve protracted and obtusely rounded. Pseudosepta deeply in the girdle view, usually two in a valve. Striae unresolvable in light microscopy. Valves of the local area 25–27.5 μm in length, 5.5 μm in breadth.

The species has been found in the fossil sediments (Oreshkina and Radionova 2014). In Korea, the species was found only in the sandflats of the Nakdong River estuary, and is newly reported.

Genus *Geissleria* Lange-Bertalot & Metzeltin 1996

6. *Geissleria ignota* (Krasske) Lange-Bertlaot & Metzeltin 1996 (Pl. 1, Figs. 26, 27) (Lange-Bertalot 2001, p. 125, Pl. 97, Figs. 25–30, Pl. 98, Figs. 1, 2; Lowe 2011 in Diatoms of North America)

Basionym: *Navicula ignota* Krasske 1932.

Synonym: *Navicula lagerstedtii* Cleve (non O'Meara 1975) sensu Hustedt in Schmidt *et al*. 1934 (Schmidt *et al*. 1934, Pl. 400, Figs. 33–37).

Valves linear in outline, the margins of valve triundulate, the ends of valve broadly rostrate to subcapitate. Raphe straight, but missing in the ends by the annula structures. Axial area narrow, linear, and central area transapically rectangular with a few shortened median stria. Striae radiate throughout, 14–15 rows in 10 μm, shortened in the end parts of valve by the 'annulae' (circular or semi-circular hyaline area on the valve face). The annula structures distinct at the ends of valve with two pairs of shortened striae. Valves 20–20.8 μm in length, 4.5–5 μm in breadth.

The speceis prefers wet habitats such as bryophytes and moist soil in freshwater, and cosmopolitan in the world, but infrequent (Lange-Bertalot 2001). In Korea, this species occurred in two mountain peatlands, Yongneup of Mountain Daeam in Inje and Mujechinep of Mountain Jeongjok in Ulsan, and is newly reported.

Genus *Chamaepinnularia* Lange-Bertalot & Krammer in Lange-Bertalot and Metzeltin 1996

7. *Chamaepinnularia hassiaca* (Krasske) Cantonati & Lange-Bertalot 2009 (Pl. 1, Figs. 28–35) (Tyree 2018 in Diatoms of North America)

Basionym: *Navicula hassiaca* Krasske 1925.

Synonym: *Navicula soehrensis* var. *hassiaca* (Krasske) Lange-Bertalot in Krammer and Lange-Bertalot 1985 (Krammer and Lange-Bertalot 1985, p. 94, Pl. 78, Figs. 10–13)

Valves linear in outline, the middle margin of valve expanded, the ends of valve subcapitate to capitate. Raphe filiform, the central ends of raphe distant each other. Axial area narrow linear, slightly expanding in the center of the valve, and central area not developed. Striae slightly radiate at the center of valve, parallel to slightly convergent at the ends, 16–18.8 rows in 10 μm. Valves 8.8–14 μm in length, 2.1–2.7 μm in breadth.

As freshwater diatoms, this species was reported as periphytic or aerophytic diatoms in streams and lakes (Morales *et al*. 2007; Tyree 2018), and peatlands or bogs in Europe and America (Vidaković *et al*. 2016). In Korea, this species occurred in a peatland, 1,100 Altitude Wetland, in Mountain Hallasan of Jeju Island, and is newly reported.

8. *Chamaepinnularia krookiformis* (Krammer) Lange-Bertalot & Krammer in Lange-Bertalot and Genkal 1999 (Pl. 1, Fig. 44) (Lange-Bertalot and Genkal 1999, p. 37, Pl. 45, Figs. 6–10; Witkowski *et al*. 2000, p. 170, Pl. 69, Figs. 24, 25)

Valves elliptical in outline, and the ends of valve broadly capitate. Raphe straight, the central ends of raphe expanded and relatively distant each other. Axial area gradually wider towards central area, and central area large rhombic-elliptical, but not reaching up to the margin of valve. Striae radiate at the center of valve, parallel to slightly convergent at the ends, 19 rows in 10 μm. Valves 21.7 μm in length, 6.5 μm in breadth.

The species showed high morphological variability (Żelazna-wieczorek and Olszyński 2016). The habitats are diverse from temperate to Antarctic or Arctic regions, from lowland freshwaters to mountain peatlands. This has been reported in freshwater area (Potapova 2014), in Antarctic and Arctic regions (Van de Vijver *et al*. 2010) and in peatlands as non-marine diatoms (Neplyukhina *et al*. 2018), and in marine water (Witkowski *et al*. 2000). In Korea, this species occurred in a lagoon in Geumho District of North Korea in 1998, and is newly reported.

9. *Chamaepinnularia mediocris* (Krasske) Lange-Bertalot in Lange-Bertalot and Metzeltin 1996 (Pl. 1, Figs. 36–43) (Lange-Bertalot and Metzeltin 1996, p. 35, no fig.; Otu and Spaulding 2011 in Diatoms of North America)

Basionym: *Navicula mediocris* Krasske 1932.

Synonym: *Pinnularia mediocris* (Krasske) Mills 1935.

Valves linear to slightly oval, the margins of valve gibbous in the middle, the ends of valve rounded. Raphe filiform and slightly curved and the central ends of raphe distant each other. Axial area more or less narrow, central area extends to the valve margins, occasionally irregular striae at the margins. Striae parallel throughout the valve, 20–20.5 rows in 10 μm. Valves 9–11.4 μm in length, 2.3–2.5 μm in breadth.

The species prefers oligotrophic water and are uncommon in streams and rivers (Otu and Spaulding 1996), but inhabits various freshwater areas, in river (Krizmanic *et al*. 2015), moors (Kihara *et al*. 2009), spring fens (Fránková *et al*. 2009), in bryophytes as epiphytons (Buczkó 2006), In Korea, this species occurred in two mountain peatlands, 1,100 Altitude Wetland of Mountain Hallasan in Jeju Island and Oegogaeneup of Mountain Jirisan in Sancheong, and is newly reported.

Genus *Cymatoneis* Cleve 1894

10. *Cymatoneis ovalis* Heiden in Heiden and Kolbe 1928 (Pl. 1, Fig. 45) (Witkowski *et al*. 2000, p. 179, Pl. 109, Figs. 4–7)

Valves elliptical, the ends of valve rounded to weakly produced. Raphe slightly bent, the central ends of raphe slightly expanded, the terminal ends of raphe curved in opposite side. Striae radiate, 14 rows in 10 μm, longitudinal furrows at both sides of the raphe. Valves of local areas 19.7 μm in length, 8 μm in breadth.

The species was reported in the type locality, Porte Grande of Cape Verde Islands, in Atlantic Ocean near Africa (Witkowski *et al*. 2000), but infrequent in the other places. In Korea, this species occurred rarely as periphytons in the coastal areas of Wido Island in Buan, and is newly reported.

Genus *Pinnularia* Ehrenberg 1843, nom. et typ. cons.

11. *Pinnularia linearidivergens* Kulikovskiy, Lange-Bertalot & Metzeltin 2010 (Pl. 2, Fig. 62) (Kulikovskiy *et al*. 2010, p. 360)

Replaced synonym: *Pinnularia divergens* var. *linearis* Østrup 1910. (Krammer 2000, p. 61, Pl. 32, Fig. 1, Pl. 34, Fig. 6, Pl. 41, Fig. 5)

Synonym: *Pinnularia parallela* var. *crassa* Østrup 1910; *Pinnularia divergens* var. *parallela* Cleve-Euler 1934.

Valves linear, the margins of valve parallel, the ends of valve obtusely rounded. Raphe lateral, the outer fissure of the raphe curved, the central ends of raphe bent in one side, the terminal ends of the raphe bayonet-shaped. Axial area narrows linear or linear-lanceolate, central area rhombic expanding to valve margins, and thickenings at the margins of the central area. Striae radiate in the middle and convergent towards the ends, and 8 rows in 10 μm, longitudinal lines absent across the striae. Valves 67 μm in length, 16.2 μm in breadth.

As freshwater diatoms, the species was reported from the

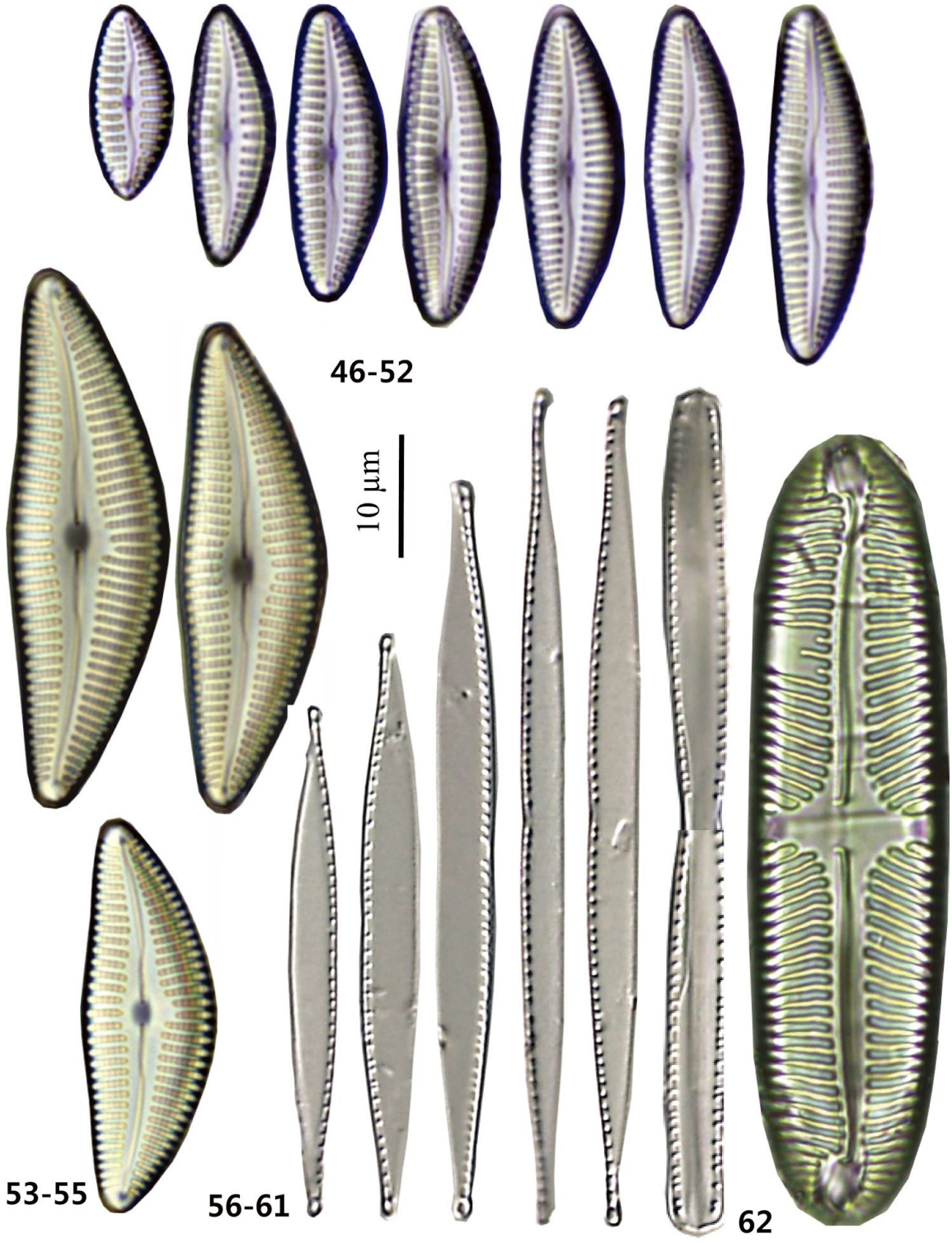

Plate 2. Figs. 46–52. *Cymbella hustedtii* var. *compacta* Krammer. Figs. 53–55. *Cymbella stigmaphora* Østrup. Figs. 56–61. *Nitzschia subcapitellata* Hustedt. Fig. 62. *Pinnularia linearidivergens* Kulikovskiy, Lange-Bertalot & Metzeltin.

type locality, North-East Greenland, but not other places. In Korea, this species occurred rarely in a peatland, Sinbulsanneup, of Mountain Sinbulsan in Yangsan, and is newly reported.

Genus *Cymbella* Agardh 1830

12. *Cymbella hustedtii* var. *compacta* Krammer 2002 (Pl. 2, Figs. 46–52) (Krammer 2002, p. 138, Pl. 160, Figs. 19, 20)

Valves dorsiventral and lanceolate, the ends of valve rounded and not produced. Raphe filiform, lateral, the central ends of raphe reverse-lateral and ventrally deflected, the terminal ends of raphe deflected dorsally. Axial area narrow, central area not developed, but wider from the ends to the middle. A stigma absents in the central area. Striae radiate, strongly radiate towards the ends of valve, 10–11 rows in 10 μm, the punctas of stria distinct, 20–22 in 10 μm. Valves 15.5–28.7 μm in length, 6.6–8.5 μm in breadth.

Krammer (2002) remarked the nominate species as probably cosmopolitan in low electrolyte waters of the temperate zones, but, in North America, the species was found in a prairie stream in Montana (Bahl 2016a). In Korea, this species occurred as epilithons in the Jusancheon Stream in Cheongsong, and the Iancheon Stream in Sangju, and is newly reported.

Cymbella hustedtii and its varieties are distinguished from *Cymbella neoleptoceros* Østrup by the smaller valve and finer striae (Krammer 2002). This variety is wider in the breadth of valve and coarser in the strial punctas than the nominate variety (Krammer 2002).

13. *Cymbella stigmaphora* Østrup 1910 (Pl. 2, Figs. 53–55) (Krammer 2002, p. 135, Pl. 154, Figs. 18–23, Pl. 158, Figs. 1–5, Pl. 161, Figs. 1–6; Bahl 2016b in Diatoms of North America)

Valves dorsiventral and rhombic-lanceolate, the ends of valve acutely rounded. The dorsal margin of valve strongly arched, the ventral margin weakly convex with a tumid center. Raphe filiform, lateral, the central ends of raphe reverse-lateral and ventrally deflected, the terminal ends of raphe deflected dorsally. Axial area narrow, central area not developed, but wider from the ends to the middle. A stigma absents in the central area. Striae radiate, more radiate towards the ends of valve, 9–10 rows in 10 μm, the punctas of stria distinct, 21 in 10 μm. Valves 31.5–43.5 μm in length, 11.5–13 μm in breadth.

This species was found from mesotrophic lakes in the lower Alps (Krammer 2002), and mountain streams and lakes in North America (Bahl 2016b). In Korea, the species occurred as epilithons in the Namhangang River in Danyang, and is newly reported.

This species is distinguished from the others of the *Cymbella leptoceros* complex by the wide breadth of valves, and from *Cymbella neoleptoceros* by the more or less denser striae (Krammer 2002).

Genus *Nitzschia* Hassal 1845

14. *Nitzschia subcapitellata* Hustedt 1939 (Pl. 2, Figs. 56–61) (Simonsen 1987, p. 262, Pl. 385, Figs. 1–9)

Valves linear to lanceolate, the margins of valve slightly constricted in the middle, but not distinct in small forms, the ends of valve acute and capitate. Raphe eccentric, fibulae eccentric and distant in the central parts of valve, 9–10 in 10 μm. Striae very fine, not resolvable in light microscopy. Valves 42–69.5 μm in length, 3.7–4.5 μm in breadth.

This species has rarely occurred outside the type locality, the coasts of Ems River in Germany, and is presumed to be a species favoring the brackish water. In Korea, this is found in the sandflats of the Nakdong River estuary in Busan, and is newly reported.

Krammer and Lange-Bertalot (1988) incorporated this species into *Nitzschia capitellata* Hustdet, but the latter is a collection of heterogeneous forms in the valve morphology. No definitive revision has yet been made. We followed *Nitzschia subcapitellata* as shown by Simonsen (1987), apart from *N. capitellata*. The local specimens are different from *Nitzschia capitellata* by the capitately acute ends and the constricted, not concave, middle margins of valve.

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