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Fossil benthic foraminifera in the Nakdong River Delta (southeast Korea) during the early to middle Holocene

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Abstract. We investigated early to middle Holocene benthic foraminifera from four borehole cores in the Nakdong River Delta (southeast Korea) to document faunal associations and the transition of benthic foraminifera in coastal areas along the Tsushima Warm Current. We recognized four varimax factor assemblages. The varimax factor 1 assemblage (characterized by *Pseudoparrella naraensis* with *Eilohedra nipponica*) is common throughout core ND-02, which is seaward in the delta, whereas the varimax factor 2 assemblage (characterized by *Haynesina* sp. A) is dominated by low evenness in core 16ND-C02, which is landward in the delta. The varimax factor 4 assemblage (characterized by *Buccella frigida*) is generally common at the bottom and/or top part of the studied cores, whereas the varimax factor 3 assemblage (characterized by *Elphidium somaense*) tends to be common in the upper part of the three cores in the delta's seaward area. Both the contrasting high diversity and low diversity with low evenness of benthic foraminifera (varimax factor 1 and 2 assemblages, respectively) were present between the seaward and landward portions of the delta during the same period (~7–6 ka), respectively. The combination of these contrasting faunas tended to appear in the delta with the intensification of the Tsushima Warm Current during ~8–6 ka in addition to the sea-level rise. Common taxa in the Nakdong River Delta are largely neritic species of the temperate region in the East Asian margin, whereas some upper bathyal species, such as *Angulogerina ikebei*, *Bolivina decussata*, and *E. nipponica*, were subordinated in the delta's seaward portion. Such faunal features in the Nakdong River Delta are distinguishable from other coastal areas in the Japanese Islands.

Keywords: faunal association, fossil benthic foraminifera, Holocene, Nakdong River Delta, Tsushima Warm Current

Introduction

Information on the sedimentology and paleontology of Holocene shallow-marine sediments has contributed our understanding of the history of sea-level fluctuations, tectonic movement (i.e., subsidence and uplift), and human activities in the East Asian margin (Kawahata *et al.*, 2009; Tanigawa *et al.*, 2013; Song *et al.*, 2018). This information has also been used in paleoceanographic research, such as studies of the evolution of the Tsushima Warm Current (Kitamura *et al.*, 2001; Hsuing and Saito, 2017). The Tsushima Warm Current provides heat to the East Asian margin; therefore, its past behavior is important for understanding terrestrial climate variations in the Korean Peninsula and Japanese Islands. However, sedimentations along the pathway of the Tsushima Warm Current seem complicated, and are sometimes discontinuous (Kang *et al.*, 2006; Kong and Park, 2007; Nishida and Ikehara, 2013).

Takata *et al.* (2016, 2019b) reported on the presence of diverse and nearly continuous benthic foraminifera in Holocene borehole cores from the Nakdong River Delta. Because these sediments contain a variety of microfossils (e.g. Ryu *et al.*, 2005, 2011; Cho *et al.*, 2017), micropaleontological data have the potential to provide useful information for paleoclimatic and paleoceanographic studies in the East Asian margin. Additionally, the Nakdong River Delta is close to the pathway of the Tsushima Warm Current (e.g. Morimoto and Yanagi, 2001). Takata *et al.* (2019b) also reported on occurrence of warm-water planktonic foraminifera in the Nakdong River Delta during ~8–6 ka and possible influence of the precursory enhancement of the Tsushima Warm Current to the benthic foraminiferal fauna during the early Holocene. Hence, the shallow-water benthic foraminiferal fauna from the Nakdong River Delta may provide useful insight into regional variations of the Tsushima Warm Current during the Holocene, compared with those of coastal sediments along the Japanese Islands.

It is also useful for understanding characteristics of neritic benthic foraminiferal fauna in the East Asian margin to document the faunal association in the Nakdong River Delta. Takata *et al.* (2019b) recognized four clusters of benthic foraminifera from the two borehole cores in the Nakdong River Delta. The faunal associations of four clusters consist of common neritic species of modern benthic foraminifera in the temperate to subtropical regions of the Korean and Japanese coasts (Akimoto and Hasegawa, 1989; Inoue, 1989; Lee *et al.*, 2016). Takata *et al.* (2016) noted similarities and differences in the faunal compositions of benthic foraminifera among the Nakdong River Delta, the Izumo Plain in southwestern Japan, and Urauchi Bay of the Kamikoshiki-jima Island in the East China Sea. They suggested that the benthic foraminiferal fauna in the Nakdong River Delta were unique relative to those in the Izumo Plain and Urauchi Bay, based on subordination of some upper bathyal species. However, because Takata *et al.* (2016) studied a single borehole core close to the modern river mouth of the Nakdong River, it is difficult to cover the fauna fully in the past estuarine environments of the Nakdong River Delta (e.g. Khim *et al.*, 2019; Yoo *et al.*, 2020). Recently, a number of borehole cores were collected in the Nakdong River Delta with excellent age constraints by both accelerated mass spectrometry (AMS) ^{14}C dating and optically stimulated luminescence (OSL) dating (Kim *et al.*, 2015; Yoo *et al.*, 2020). These new borehole samples allow us to consider the lateral variation of the faunal association in the past Nakdong River Delta.

In this study, we report on fossil faunas of benthic foraminifera from four borehole cores in the Nakdong River Delta, based on new observations as well as previous studies (Takata *et al.*, 2016, 2019b), and emphasize their utility for paleoclimatic and paleoceanographic studies.

Material and methods

The Nakdong River, the longest river in the southeast Korea (Figure 1), experiences strong seasonal discharges because of monsoonal precipitation patterns (Williams *et al.*, 2013). Borehole cores ND-01, ND-02, and ND-03 were drilled close to the modern river mouth, and these sites are in the lower delta plain of the modern Nakdong River Delta. In addition, borehole core 16ND-C02 was taken from the upper delta plain. Table 1 lists the locations and elevations of these four core drilling sites.

Table 1. Locations and lengths of four cores in the Nakdong River Delta.

Core	Latitude	Longitude	Elevation (m)
ND-01	35° 06′ 03.88” N	128° 54′ 13.67” E	4.8
ND-02	35° 03′ 21.85” N	128° 55′ 48.53” E	0
ND-03	35° 04′ 06.26” N	128° 53′ 04.52” E	0
16ND-C02	35° 11′ 19.10” N	128° 55′ 23.89” E	1.0

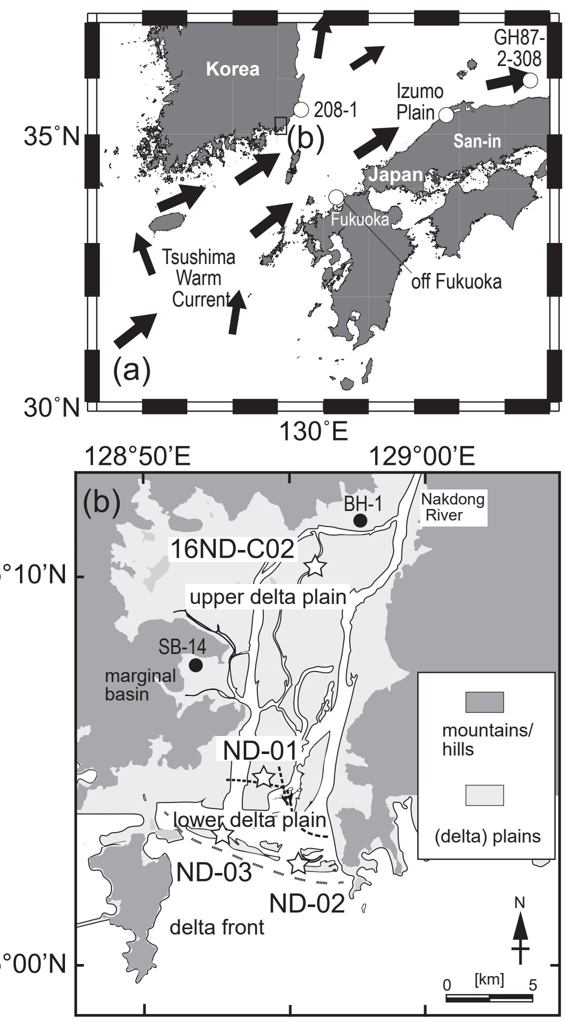

Figure 1. (a) Map of the study area and (b) locations of four borehole cores (ND-01, ND-02, ND-03, and 16ND-C02) and the two published cores (BH-1, SB-14) in the Nakdong River Delta (modified from Cho *et al.*, 2017).

Lithologies mainly consist of massive and bioturbated

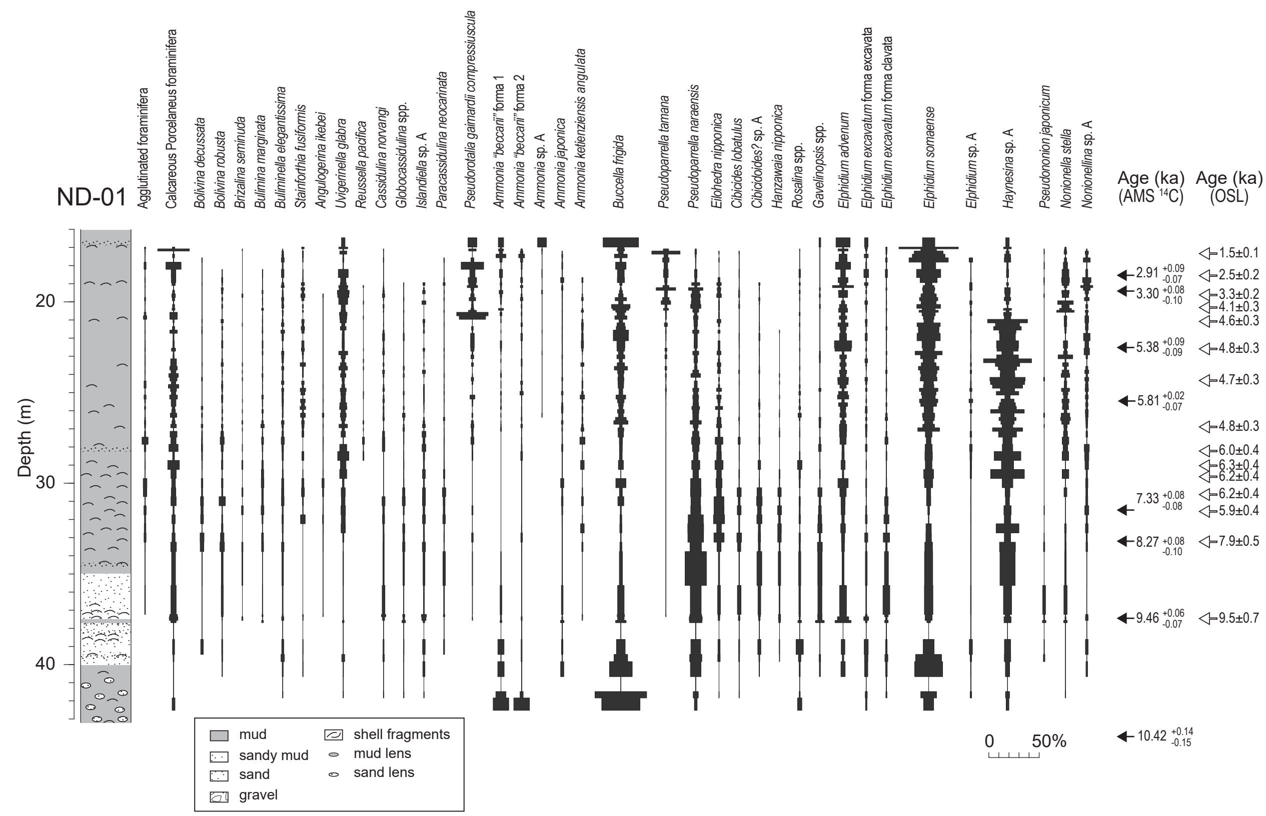

Figure 2. Occurrences of selected benthic foraminifera in core ND-01. Some data were taken from Takata *et al.* (2016, 2019b). Ages (ka) dated by AMS ^{14}C and OSL were originated from Kim *et al.* (2015).

mud, muddy sand, and sand with gravel (e.g. Khim *et al.*, 2019). Sandy sediments are generally dominant in the lowermost, middle, and uppermost parts of the core, whereas muddy sediments containing biogenic grains such as mollusks, echinoids, and foraminifera occupy the middle to upper part of the core. We obtained ages of the core sample materials using AMS ^{14}C and OSL dating. Age data from cores ND-01 (Kim *et al.*, 2015), core ND-02 (Shin, 2016; Khim *et al.*, 2019), core ND-03 (Jeong, 2016; Shin, 2016; Khim *et al.*, 2019), and core 16ND-C02 (Yoo *et al.*, 2020) are shown in Figures 2, 3, 4, and 5, respectively. The AMS ^{14}C age data were converted into the calendar ages (ka) by Khim *et al.* (2019), using CALIB 7.1 software (Stuiver and Reimer, 1993) with curve selections of IntCal13 for plant debris and Marine13 for molluscan shells (Reimer *et al.*, 2013). A ΔR value of –154 (Kong and Lee, 2005) was adopted for the conversion of molluscan shells. Based on this age information, the sediment successions of cores ND-01 and ND-02 cover ~11–3 ka and ~12–1 ka, respectively. Core ND-03 probably contains ~7–1 ka sediments despite fewer age measurements than the other three cores, according to the extrapolation of the age at the core bottom. Core 16ND-C02 has complicated age data; however, this core seems to cover ~11–1 ka (Yoo *et al.*, 2020).

We collected 1-cm thick sediment samples from cores ND-01, ND-02, and ND-03, and 2-cm thick sediment samples from core 16ND-C02 for foraminiferal analysis. After being freeze-dried and weighed, the samples were washed by tapped water using a 63 μm sieve. We then dried the residues at 50°C, and re-weighed and split them into 1/2 to 1/1024 aliquots. More than 200 benthic foraminiferal specimens from the > 63 μm fraction, were identified and counted using a binocular microscope. We also counted the number of planktonic foraminifera from the same sample aliquots. Taxonomic assignments followed Matoba (1970) and Nomura and Seto (1992) and generic classification followed Loeblich and Tappan (1987).

In this study, we obtained 63 new samples from cores ND-03, 29 new samples from core 16ND-C02, 26 new samples from the upper part (26–16 m) of core ND-01, and 68 new samples from the upper part (above 28 m) of core ND-02. We also combined the published faunal data from cores ND-01 and ND-02 (Takata *et al.*, 2016, 2019b). We calculated the abundances of benthic and planktonic foraminifera (> 63 μm) per unit weight of sediment using

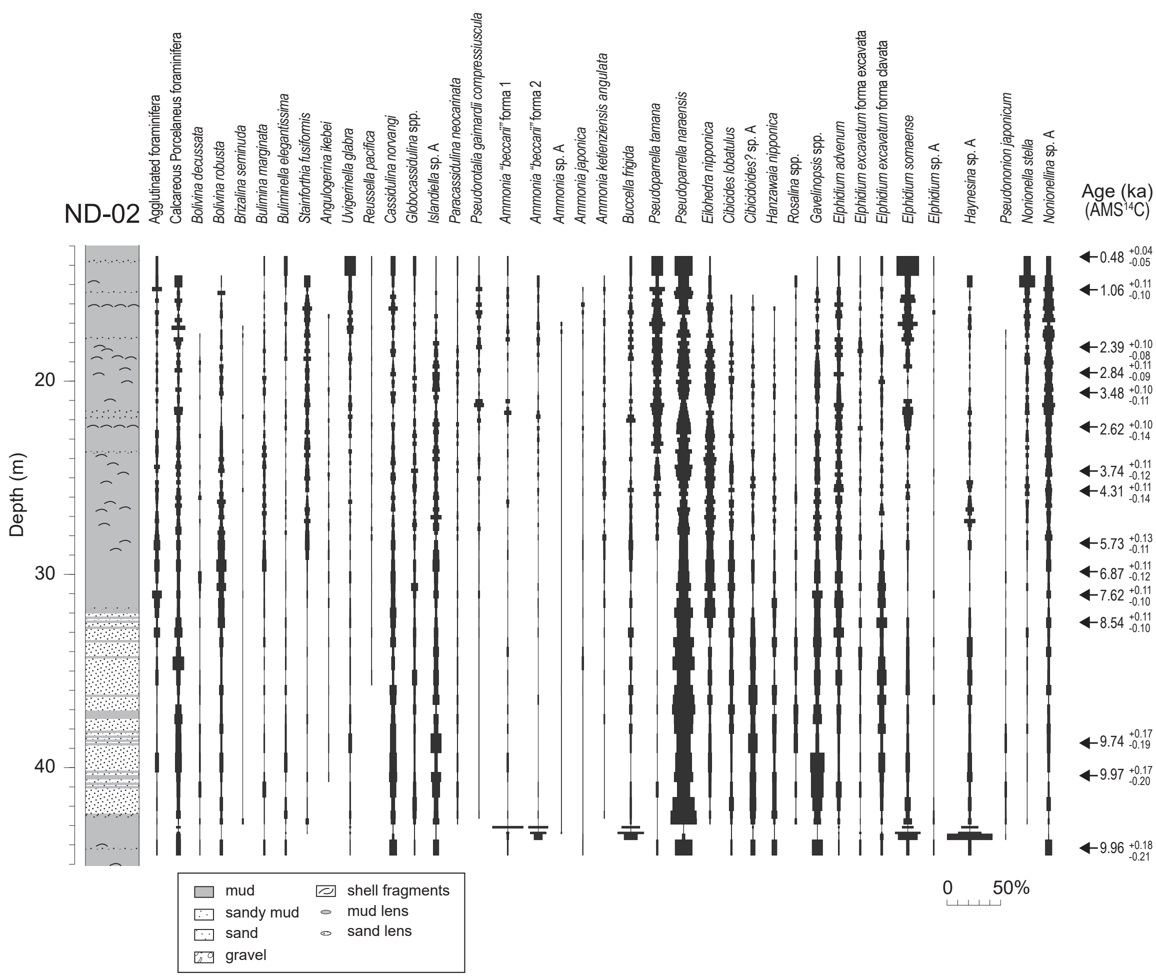

Figure 3. Occurrences of selected benthic foraminifera in core ND-02. Some data were taken from Takata *et al*. (2019b). Ages (ka) dated by AMS ^{14}C were originated from Shin (2016).

the specimen counts, the number of splits, and the weight of each sample. We calculated the planktonic/total (benthic and planktonic) foraminiferal ratio (P/T ratio) based on these abundance data from the > 63 μm fraction. To evaluate the community structure of benthic foraminifera, we calculated the Shannon-Wiener diversity index (H') and rarefaction ($E[S_{50}]$) index for each sample. We also calculated the evenness measure of Buzas and Gibson (1969) for each sample. Calculations of the Shannon-Wiener (H') index and evenness were performed in Microsoft Excel and E(Sn) (the expected number of species in samples rarefied to n individuals; n = 50) for each sample was calculated in the R statistical programming language (R Development Core Team, 2020) using the function from the Vegan community ecology package (Oksanen *et al.*, 2019). For a data matrix consisting of 90 taxa with at least three individuals in each sample and 257 samples with more than 50 counts in each sample, we conducted a Q-mode factor analysis on the data from the four cores using CABFAC (Calgary and Brown Factor Analysis) (Klovan and Imbrie, 1971).

Results

Benthic foraminifera occurred nearly continuously in the studied intervals of all four cores (Appendix 1). Preservation of the foraminiferal tests is generally good without marked destruction or abrasion of the tests (Figures 6 and 7). These features imply that fossil benthic foraminifera were not significantly transported within the study area. *Haynesina* sp. A, *Elphidium somaense*, *Pseudoparrella naraensis*, *Buccella frigida*, *Quinqueloculina* spp., and *Pseudorotalia gaimardii compressiuscula* are common constituents in all four cores (Figures 2–5; Appendix 1). These species have been reported from the coastal areas and shallow-marine strata of the East Asian margin,

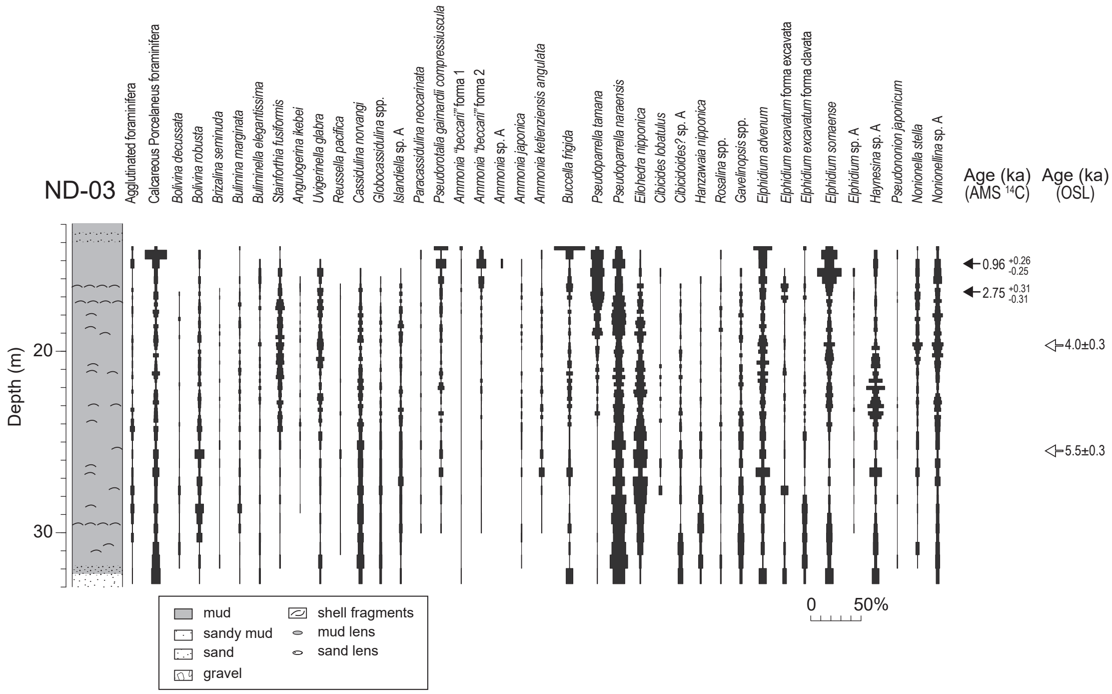

Figure 4. Occurrences of selected benthic foraminifera in core ND-03. Ages (ka) dated by OSL were originated from Jeong (2016).

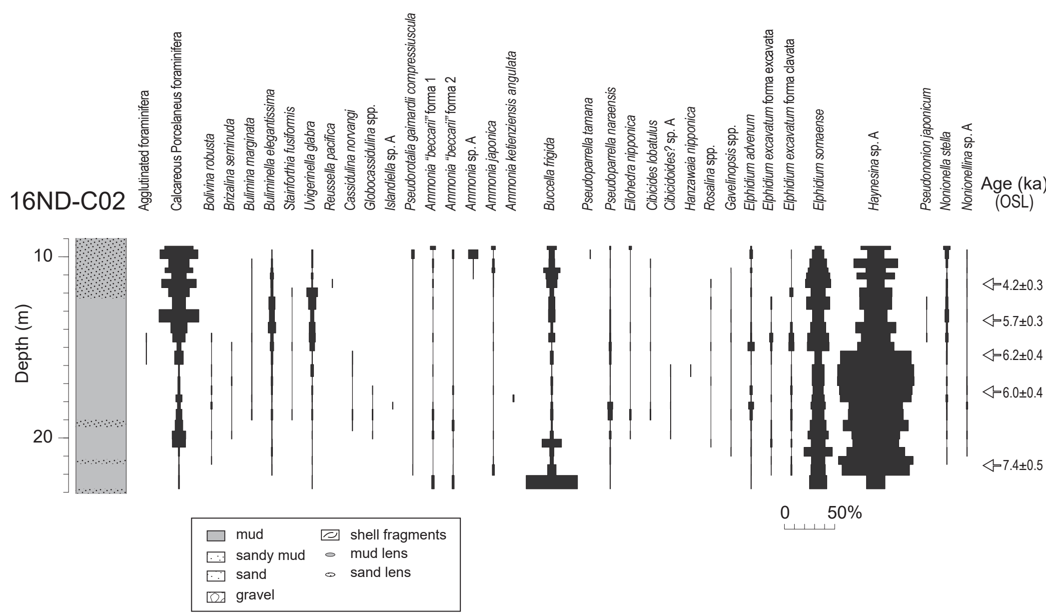

Figure 5. Occurrences of selected benthic foraminifera in core 16NDC-02. Ages dated by OSL were originated from Yoo *et al.* (2020).

including the Japanese Islands (Akimoto and Hasegawa, 1989; Inoue, 1989).

Faunal composition of benthic foraminifera in core ND-01 matches the result of Takata *et al.* (2016): a rapid transition of common species in the lower part and a gradual faunal shift toward the upper part of the core (Figure 2). We also observed an equivalent succession in this study, with common occurrence from *B. frigida* and *E. somaense* to *P. naraensis* from the lower to the middle part and more common occurrence of *Haynesina* sp. A,

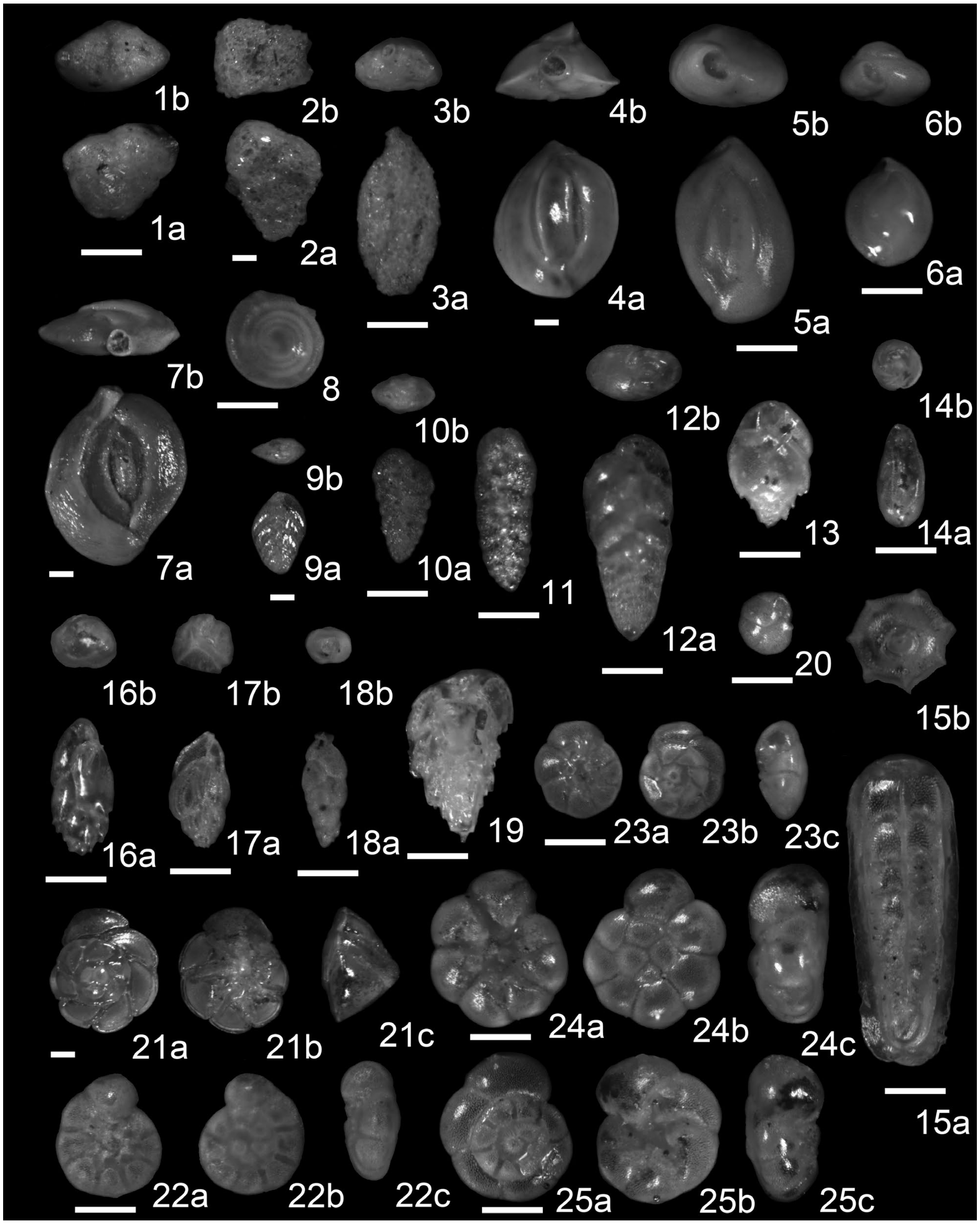

Figure 6. Light micrographs of selected benthic foraminifera in the Nakdong River Delta. Scale bar is 100 µm. **1a, b,** *Textlaria kerimbaensis* from 2560 cm of core ND-03; **2a, b,** *Gaudryina* sp. from 2860 cm of core ND-03; **3a, b,** *Siphonaperta* sp. A from 1450 cm of core 16ND-C02; **4a, b,** *Quinqueloculina akneriana* from 1080 cm of core 16ND-C02; **5a, b,** *Quinqueloculina seminulum* from 980 cm of core 16ND-C02; **6a, b,** *Quinqueloculina* cf. *seminulum* from 1150 cm of core 16ND-C02; **7a, b,** *Massilina secans* from 3230 cm of core ND-03; **8,** *Cyclogyra planorbis* from 1190 cm of core 16ND-C02; **9a, b,** *Bolivina robusta* from 2560 cm of core ND-03; **10a, b,** *Bolivina decussata* from 2720 cm of core ND-03; **11,** *Bolivina pseudoplicata* from 2620 cm of core ND-03; **12a, b,** *Brizalina striatula* from 1390 cm of core 16ND-C02; **13,** *Bulimina marginata* from 2860 cm of core ND-03; **14a, b,** *Buliminella elegantissima* from 1960 cm of core ND-03; **15a, b,** *Rectobolivina raphana* from 1840 cm of core ND-03; **16a, b,** *Stainforthis fusiformis* from 1860 cm of core ND-03; **17a, b,** *Angulogerina ikebei* from 1880 cm of core ND-03; **18a, b,** *Uvigerinella glabra* from 1190 cm of core 16ND-C02; **19,** *Reussella pacifica* from 2560 cm of core ND-03; **20,** *Cassidulina norvangi* from 2300 cm of core ND-03; **21a-c,** *Pseudorotalia gaimardii compressiuscula* from 2200 cm of core ND-03; **22a–c,** *Ammonia "beccarii"* forma 1 from 940 cm of core 16ND-C02; **23a–c,** *Ammonia "beccarii"* forma 2 from 2361 cm of core ND-03; **24a–c, 25a–c,** *Ammonia japonica* from 980 cm and 2460 cm of core ND-03, respectively.

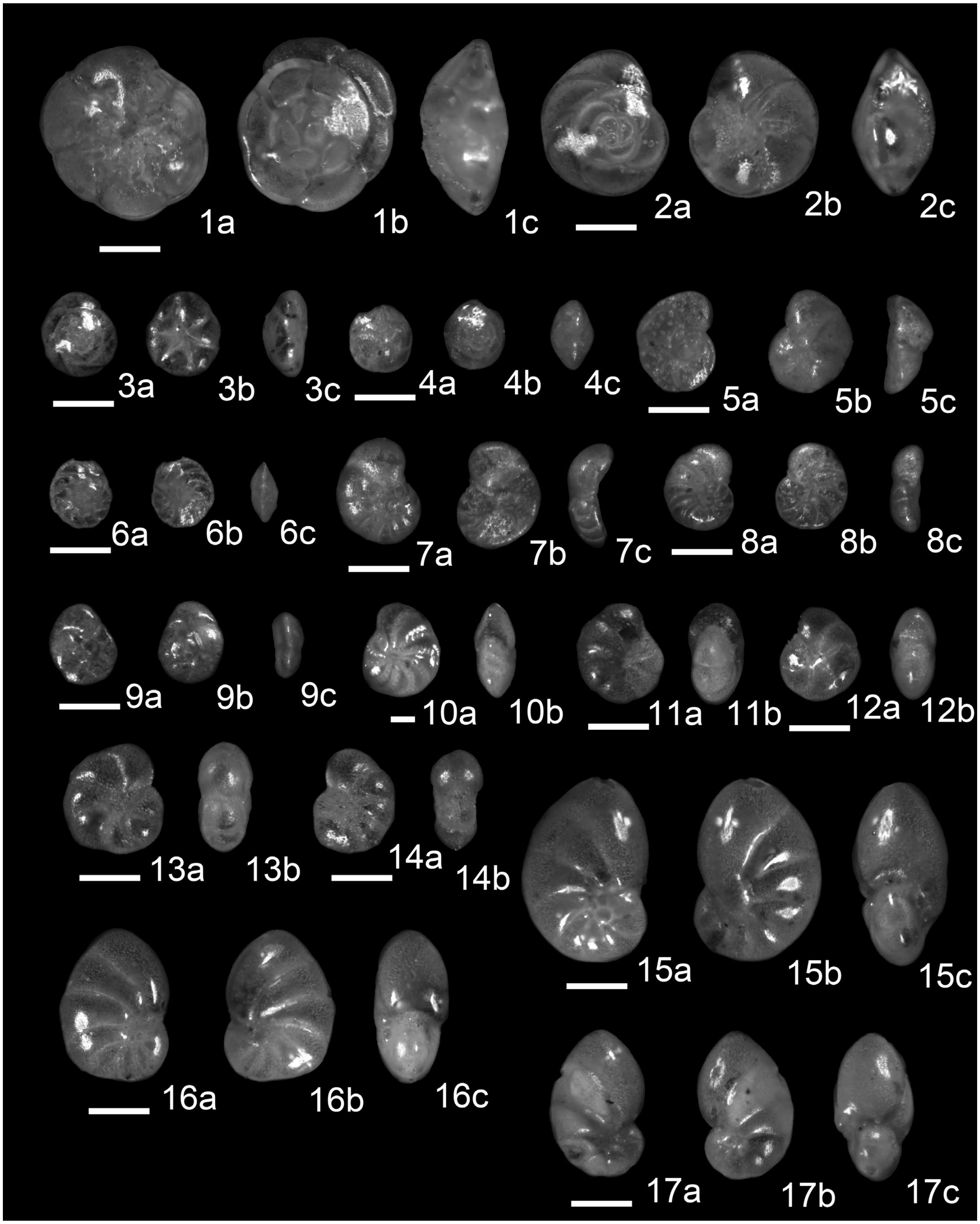

Figure 7. Light micrographs of selected benthic foraminifera in the Nakdong River Delta. Scale bar is 100 µm. **1a–c,** *Ammonia ketienziensis angulata* from 2560 cm of core ND-03; **2a–c,** *Buccella frigida* from 1080 cm of core 16ND-C02; **3a–c,** *Pseudoparrella naraensis* from 2920 cm of core ND-03; **4a–c,** *Eilohedra nipponica* from 2720 cm of core ND-03; **5a–c,** *Cibicides lobatulus* from 2620 cm of core ND-03; **6a–c,** *Cibicidoides*? sp. A from 3080 cm of core ND-03; **7a–c, 8a–c,** *Hanzawaia nipponica* from 2920 cm of core ND-03; **9a–c,** *Rosalina* sp. A from 3160 cm of core ND-03; **10a, b,** *Elphidium advenum* from 2660 cm of core ND-03; **11a, b, 12a, b,** *Elphidium somaense* from 1095 cm of core 16ND-C02; **13a, b. 14a, b,** *Haynesina* sp. A from 1680 cm of core 16ND-C02; **15a–c,** *Nonionella stella* from 1960 cm of core ND-03; **16a–c, 17a–c,** *Nonionellina* sp. A from 1960 cm of core ND-03.

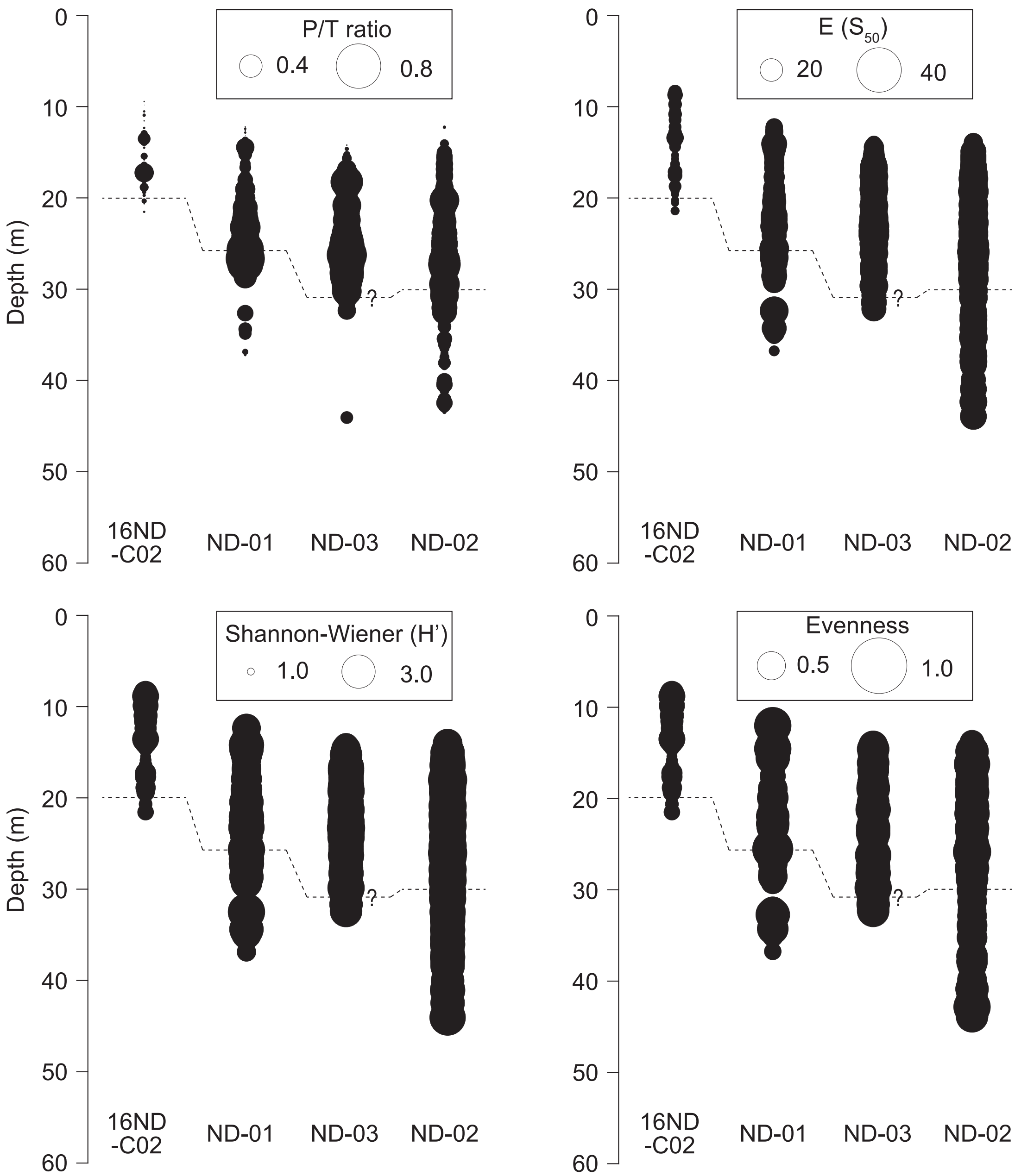

Figure 8. Spatiotemporal variations of planktonic/total (benthic and planktonic) foraminiferal ratio (P/T ratio), rarefaction E[S_{50}], Shannon-Wiener (H'), and evenness of Buzas and Gibson (1969) among four cores in the Nakdong River Delta. The depth level of each core was adjusted to present day sea level, based on elevation (Table 1). The dashed line represents ~7 ka time slice.

E. somaense, and *P. gaimardii compressiuscula* in the middle to upper parts of the core. In contrast, the relative abundance of *Haynesina* sp. A decreased markedly at ~21 m, whereas *P. gaimardii compressiuscula* is intermittently common above this horizon (Figure 2).

The faunal composition of benthic foraminifera in core ND-02 is also similar to that of Takata *et al.* (2019b), with *P. naraensis* being common throughout almost the entire core except for the lowermost part (Figure 3). *Eilohedra nipponica* also occurs nearly throughout the core. In contrast, *Pseudoparrella tamana* and *E. somaense* increase above ~24 m in the upper part of the core which Takata *et al.* (2019b) did not investigate. *Cibicides* spp., *Rosalina* spp., and *Gavelinopsis* spp. are slightly common in the middle part including the sandy sediments (~42–32 m) of core ND-02 (Figure 3). The faunal composition of benthic foraminifera in core ND-03 is generally similar to that of core ND-01. *Pseudoparrella naraensis* and *E. nipponica* are common nearly throughout the core, and *P. tamana* and *E. somaense* increase toward the upper part (Figure 4).

The faunal composition of benthic foraminifera in core 16ND-C02 is characterized by the predominance of *Haynesina* sp. A in association with *E. somaense*, *Quinqueloculina* spp., and *B. frigida* (Figure 5). *Pseudoparrella naraensis* and *E. nipponica* also occur, but these relative abundances are considerably lower than those of other three cores. *Haynesina* sp. A decreases slightly above ~15 m. These faunal associations differ from those of the other three cores, which were collected farther seaward in the lower delta plain. The faunal associations of core 16ND-C02 seem similar to those from cores BH-1 and SB-14 by Ryu *et al.* (2005, 2011) from the upper delta plain and marginal basin (Figure 1).

The P/T ratio (> 63 μm) in core ND-01 increases from the bottom to ~38 m (Figure 8) and decreases gradually upward within the middle to upper parts, as reported by Takata *et al*. (2016). A similar variation pattern is also noted in cores ND-02 and ND-03. As in similar faunal associations, the foraminiferal P/T ratio in core 16ND-C02 is generally lower than those of other three cores.

Rarefaction ($E[S_{50}]$) and Shannon-Wiener (H') in core 16ND-C02 are also low compared with those in the other three cores (Figure 8). Both indices are relatively stable throughout each core. The evenness of Buzas and Gibson (1969) shows a similar lateral variation to that of the rarefaction and Shannon-Wiener (H'); however, evenness is specifically low in the lower part of core 16ND-C02 (Figure 8), an interval in which *Haynesina* sp. A is predominant (Figure 5). Thus, the species richness and species diversity decrease toward the inner portion of the delta, particularly in the lower part of core 16ND-C02.

A factor analysis of eight varimax factors revealed that four varimax factors account for 82% of the total variance in the combined foraminiferal dataset from the four cores. The contributions of varimax factors 1, 2, 3, and 4 were 37.7%, 23.0%, 15.9%, and 5.8%, respectively. The varimax factor 1 assemblage is characterized mainly by *P. naraensis* with *E. nipponica* (scores: 0.62 and 0.43, respectively) (Appendix 2). The varimax factor 2 assemblage is characterized largely by *Haynesina* sp. A (score: −0.95) (Appendix 2). The varimax factor 3 assemblage is characterized largely by *P. tamana* and *E. somaense* (scores: 0.61 and 0.51, respectively) (Appendix 2). The varimax factor 4 assemblage is characterized largely by *B. frigida* (score: −0.81) (Appendix 2).

The varimax factor loading of varimax factor 1 is highly positive for most samples from core ND-02 (Figure 9), whereas the varimax factor loading of varimax factor 2 is highly negative in samples from core 16ND-C02 and the middle to upper parts of core ND-01 (Figure 9). The varimax factor loading of varimax factor 3 is high in the upper part of the cores ND-01, ND-02, and ND-03 (Figure 9). The similar stratigraphic distributions of varimax factor loading were observed in core 16ND-C02 despite the relatively lower loading. The varimax factor loading of the varimax factor 4 is highly negative in the top part of core ND-01, the bottom part of core 16ND-C02, the bottom part of core ND-02, and the top part of core ND-03 (Figure 9).

Discussion

The characteristic species of these four varimax factor assemblages are generally similar to those of cluster analysis by Takata *et al.* (2019b) for cores ND-01 and ND-02. *Pseudoparrella naraensis* with *Eilohedra nipponica* are characteristic species of both the varimax factor 1 assemblage and cluster D in Takata *et al.* (2019b). Similarly, *Buccella frigida* is the characteristic species of both the varimax factor 4 assemblage and cluster C in Takata *et al.* (2019b). In contrast, *Haynesina* sp. A and *Elphidium somaense* are characteristic species of cluster B, whereas *Haynesina* sp. A and *E. somaense* are characteristic species of the varimax factor 2 and 3 assemblages, respectively. Thus, despite minor differences in combination of characteristic species between the two multivariate analyses, the characteristic species of the four varimax factor assemblages in this study are generally similar to those of the four clusters in Takata *et al.* (2019b). Hence, we consider the ecological characteristics of these varimax factor assemblages, referring to the arguments of Takata *et al*. (2019b) and the references of modern benthic foraminifera therein (Matoba, 1970; Matoba and Honma, 1986; Akimoto and Hasegawa, 1989; Inoue, 1989; Oki, 1989; Kosugi *et al.*, 1991; Nomura and Seto, 1992; Takata *et al.*, 2006b).

The varimax factor 1 assemblage is common almost throughout core ND-02, but it becomes rare toward the landward portion (core 16ND-C02) of the Nakdong River Delta (Figure 9). Conversely, the varimax factor 2 assemblage is common in core 16ND-C02 in the upper delta plain. Thus, the varimax factor 1 and 2 assemblages show contrasting lateral variations within the Nakdong River Delta. In addition, the varimax factor 1 assemblage is common in the lower part of core ND-01, whereas the varimax factor 2 assemblage is common in its middle and upper parts of core ND-01. Thus, alternation of these two varimax factor assemblages across the middle part of core ND-01 also shows contrasting stratigraphic variations of cores ND-02 and 16ND-C02. These lateral and stratigraphic variations imply that the varimax factor 1

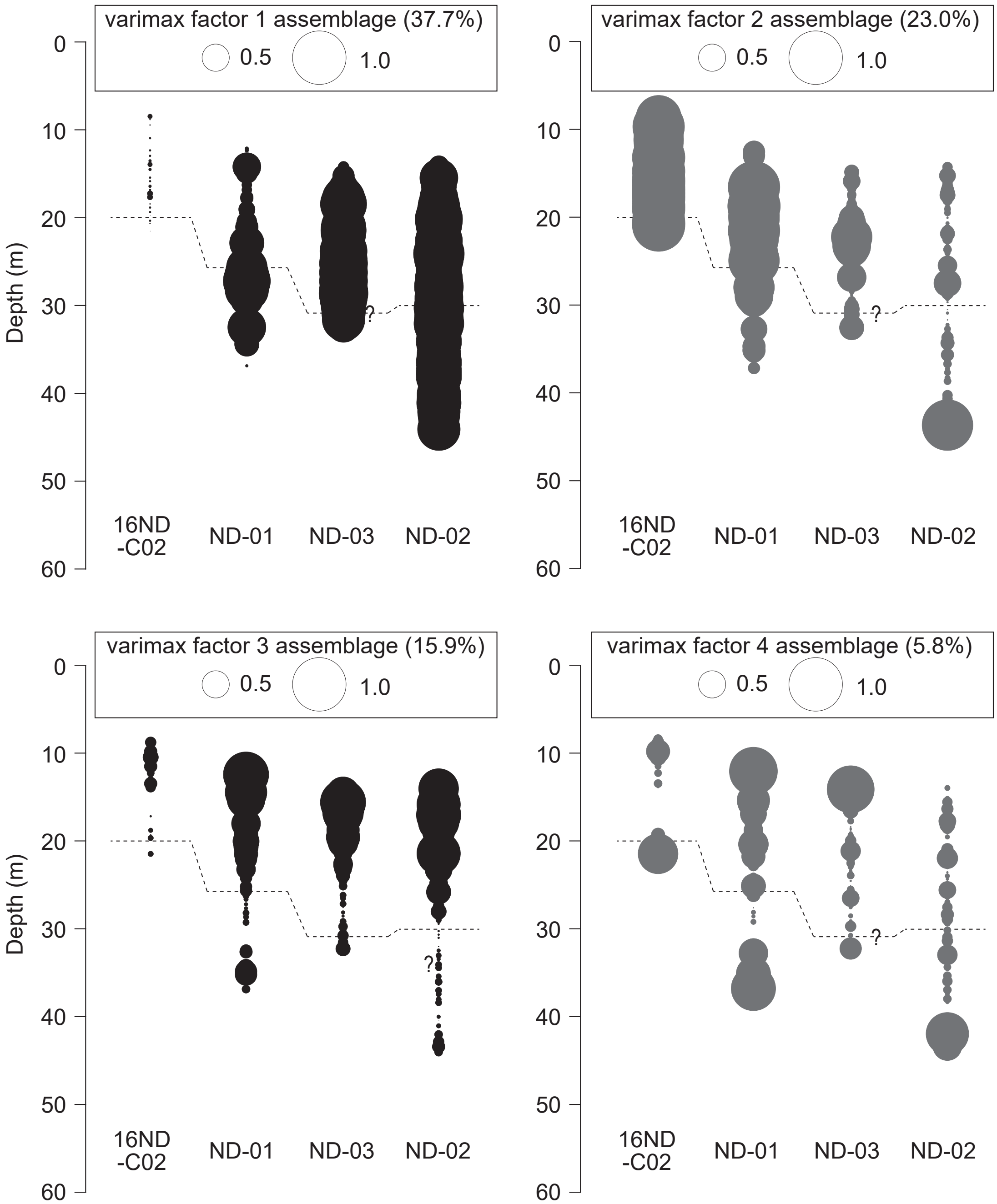

Figure 9. Spatiotemporal variations of the varimax factor loading of varimax factor 1–4 assemblages among four cores in the Nakdong River Delta. Values in parenthesis represent contribution of each varimax factor. The varimax factor loadings of the varimax factor 2 and 4 assemblages shown by gray shading are scaled negatively. The depth level of each core was adjusted to present day sea level, based on elevation (Table 1). The dashed line represents ~7 ka time slice.

and 2 assemblages correspond to the influences of more pelagic and coastal waters in the past Nakdong River Delta, respectively. In particular, correlation between the foraminiferal P/T ratio and varimax factor loading of the varimax factor 1 is strong (r = 0.76), but its correlation with other three varimax factors is very weak (Figure 10), suggesting that the varimax factor 1 assemblage is closely related to the influence of more pelagic water into the past Nakdong River Delta. In contrast, *Haynesina* sp. A, the characteristic species of the varimax fac-

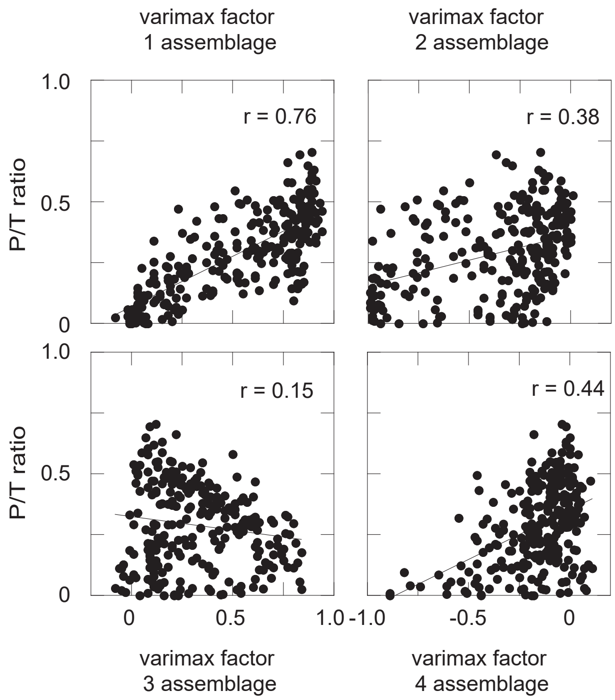

Figure 10. Crossplots of the varimax factor loading of the varimax factor 1–4 assemblages and planktonic/total (benthic and planktonic) foraminiferal ratio (foraminiferal P/T ratio) among four cores in the Nakdong River Delta.

tor 2 assemblage, may be an opportunistic species in the coastal environment in the East Asian margin. Takata *et al.* (2019b) noted that the dispersal potential of this species seems to be high, referring to the modern instance in Lake Saroma in northern Japan (Takata *et al.*, 2006b). *Haynesina* sp. A or probable equivalent species, *Elphidium subarcticum*, has been also reported from the inner bay environment (e.g. Matoba, 1970; Kosugi *et al.*, 1991; Lee *et al.*, 2016). The common occurrence of *Haynesina* sp. A in core 16ND-C02 may be explained by the influence of low salinity water due to the landward position of this core, whereas the low abundance of brackish-water species such as *Ammonia "beccarii"* forma 1 is unlikely to support this explanation. Species diversity is high in cores ND-01, ND-02, and ND-03 from the lower delta plain during ~8–6 ka, whereas evenness is low in core 16ND-C02 from the upper delta plain during a similar period (~7–6 ka, according to Yoo *et al.*, 2020) (Figure 8). Thus, the common varimax factor 2 assemblage in the upper delta plain of the Nakdong River Delta may be explained by the dispersal of this species. This varimax factor assemblage also occasionally appears in the lowermost part of core ND-02. Several variations of this varimax factor assemblage may be also explained by opportunistic characteristics of *Haynesina* sp. A.

The varimax factor 4 assemblage tends to occupy either the bottom or top part of the four cores. Based on the ecological information on *B. frigida*, which is the characteristic species of this varimax factor assemblage, such a specific stratigraphic variation may be interpreted by the shallower paleo-depth of the study sites during the early transgression and subsequent regression with sediment burial, as Takata *et al.* (2016) argued. The varimax factor 3 assemblage is generally rare in the middle part of cores ND-01, ND-02, and ND-03, whereas it becomes more common toward the upper parts of these cores. This varimax factor assemblage is also present in the lower parts of cores ND-01, ND-02, and ND-03 despite the smaller loading. Such vertical distributions are probably related to the rapid transgression and subsequent gradual regression. The varimax factor 2 assemblage decreases markedly in the uppermost parts of cores ND-01 and ND-03, whereas the varimax factor 3 assemblage increases above these horizons. Takata *et al.* (2019c) reported, based on plankton tow studies, that *P. tamana* shows a passive dispersal potential in Maizuru Bay in central Japan. In addition, based on the ephemeral settlements in the Lake Nakaumi in southwestern Japan, *E. somaense* might also have dispersal potential from the further seaward area by seasonally winter winds (Takata *et al.*, 2019a). The alternating varimax factor 2 and 3 assemblages in these cores might be related to a certain climatic event, as well as the shoaling of paleo-depths at the study sites.

Takata *et al.* (2016) noted similarities and differences in the fauna compositions of benthic foraminifera among core ND-01, the Izumo Plain in southwestern Japan, and Urauchi Bay, the Kamikoshiki-jima Island in the East China Sea. In this study, we also compared the faunal associations of Holocene benthic foraminifera between the Nakdong River Delta and off Fukuoka in southwestern Japan (Takata *et al.*, 2018b), in addition to the early Holocene fauna of the Izumo Plain (Takata *et al.*, 2016). Both of the Nakdong River Delta and off Fukuoka are along the pathways of the second and first branches of the Tsushima Warm Current, respectively (Morimoto and Yanagi, 2001). Overall, we found 43 common taxa between the Nakdong River Delta, off Fukuoka, and the Izumo Plain, whereas we found 51 taxa only in the Nakdong River Delta (Appendix 3). Common occurrences of *Cibicides* spp., *Hazawaia nipponica, Rosalina* spp., and *Gavelinopsis* spp. off Fukuoka (Takata *et al.*, 2018b) are markedly different from those of the Nakdong River Delta. Such difference is distinguishable between the two study areas. This can be explained by the different depositional settings of the two areas. *Cibicides* spp., *H. nipponica*, probably *Rosalina* spp., and *Gavelinopsis* spp. commonly attach to hard substrates or calcareous algae (Kitazato, 1988). These taxa are the important diag-

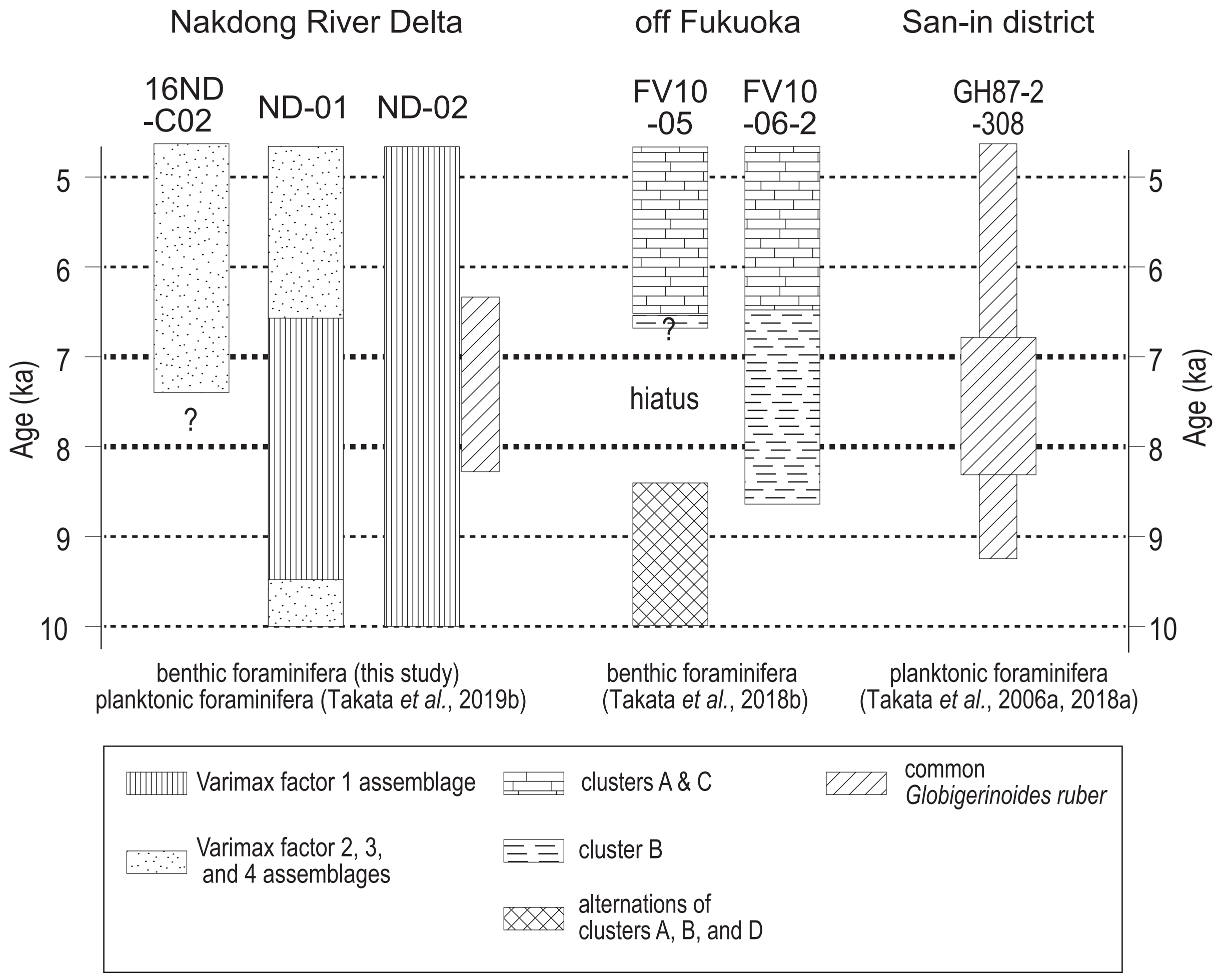

Figure 11. Spatiotemporal variations of benthic foraminiferal fauna and planktonic foraminifera (modified from Takata *et al.*, 2018b) among the Nakdong River Delta (cores 16ND-C02, ND-01, and ND-03), off Fukuoka (cores FV10-05 and FV10-06-2), and in the San-in District (core GH87-2-308). Information of core ND-03 was not shown due to the fewer age constraints. The hiatus interval of core FV10-05 is based on Nishida and Ikehara (2013).

nosis to discriminate sample clusters off Fukuoka. These species are generally not common in the Nakdong River Delta (Figures 2, 3, 4, and 5). It is reasonable to suppose that a paucity of these attached taxa on hard substrates or calcareous algae in the Nakdong River Delta can be attributed to an abundant supply of fine-grained terrigenous materials. Exceptionally, these attached taxa are slightly common in ~42–28 m of core ND-02 (Figure 3) that warm-water planktonic foraminifera are also present in ~32–28 m (Takata *et al.*, 2019b). Nishida and Ikehara (2013) suggested that the enhancement of the Tsushima Warm Current during 8.4–6.6 ka was related to the hiatus off Fukuoka. The precise reason for exceptionally common attached taxa at the more offshore site in the Nakdong River Delta particularly during ~8–7 ka should be solved by more sedimentological data in future.

The common occurrence of *E. nipponica* with *Angulogerina ikebei* and *Bolivina decussata* in the Nakdong River Delta is also obviously different from the result off Fukuoka. *Eilohedra nipponica* has been reported from the upper bathyal zone along the northern margin of southwestern Japan (Akimoto and Hasegawa, 1989; Inoue, 1989). An abundance of this species has been also reported in bathyal depth cores IMAGES MD01-2407 (932 m water depth; Usami *et al.*, 2013) and GH87-2-308 (308 m water depth; Takata *et al.*, 2018a) off southwestern Japan. A possible explanation for the unusual occurrences of these upper bathyal species in our study area is intrusion of subsurface cold water toward the Nakdong River Delta. A relatively low temperature (<10°C) has been commonly recorded at a water depth of 50 m at station KODC 208-1 (approximately 70 m water depth;

35°28.5′N, 129°27.3′E; Figure 1) off the east coast of Korea in summer (data from Korea Ocean Data Center, 2020: http://www.nifs.go.kr/kodc/eng/index.kodc). Intrusion of subsurface cold water might stimulate dispersal of these upper bathyal species from the eastern coast of the Korean Peninsula into the Nakdong River Delta. Thus, the influence of cold subsurface water might be an important insight for precise paleoceanographic interpretation in this area that is also close to the pathway of the second branch of the Tsushima Warm Current, based on benthic foraminiferal fauna.

Takata *et al.* (2016, 2018b, 2019b) demonstrated, mainly based on warm-water planktonic foraminifera, that the intensification of the Tsushima Warm Current during ~8–7 ka affected sedimentation and biota of the coastal regions along the pathway of the Tsushima Warm Current and open ocean off San-in District (Figure 11). In addition, Takata *et al.* (2019b) noted the maximum landward expansion of benthic foraminifera in the Nakdong River Delta with common *Globigerinoides ruber*, a subtropical species of planktonic foraminifera, of core ND-02 during ~8–7 ka. They suggested that the enhanced Tsushima Warm Current during ~8–7 ka resulted in the landward expansion of benthic foraminifera within the delta along with sea-level rise in the early Holocene.

Our results show that the diverse faunas of benthic foraminifera with upper bathyal species were present in the lower delta plain (cores ND-01, ND-02, and ND-03) of the Nakdong River Delta in ~8–6 ka, whereas extremely low diversity fauna appeared in the upper delta plain (core 16ND-C02) in ~7–6 ka because of the predominance of *Haynesina* sp. A, a possible opportunistic species. Thus, both the contrasting high diversity and low diversity with low evenness faunas likely appeared in the Nakdong River Delta during the similar period, possibly in tandem with the enhanced Tsushima Warm Current in addition to the early Holocene sea-level rise. Better understanding the co-occurrence of these contrasting faunas will be important for precisely interpreting development in the Nakdong River Delta during the Holocene. Because of important potential for the continuous micropaleontological record during the Holocene in the Nakdong River Delta, detailed studies based on more core sites are highly preferable to determine the impact of the Tsushima Warm Current to the paleoclimatic and paleoceanographic variations along the pathway of the Tsushima Warm Current.

Conclusions

We studied fossil benthic foraminifera in four borehole cores from the Nakdong River Delta and led to the following conclusions:

(1) We recognized four varimax factor assemblages. The varimax factor 1 assemblage (characterized by *Pseudoparrella naraensis* with *Eilohedra nipponica*) is common throughout core ND-02, which is seaward in the delta. The varimax factor 2 assemblage characterized by *Haynesina* sp. A. is dominated by low evenness in core 16ND-C02, which is landward in the delta. The varimax factor 3 assemblage (characterized by *Elphidium somaense*) tends to be common in the upper part of three cores in the seaward area whereas the varimax factor 4 assemblage (characterized by *Buccella frigida*) is generally common at the bottom and/or top part of the studied cores.

(2) Both the contrasting high diversity and low diversity with low evenness of benthic foraminifera were present between the seaward and landward portions of the delta during ~7–6 ka, respectively. The combination of these contrasting faunas tended to appear in the delta with the intensification of the Tsushima Warm Current during ~8–6 ka with the early Holocene sea-level rise.

(3) Common taxa in the Nakdong River Delta are largely neritic species of the temperate region in the East Asian margin, whereas some upper bathyal species were subordinated in the delta's seaward portion. Such faunal features in the Nakdong River Delta are distinguishable from other coastal areas in the Japanese Islands.

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Faunal references

Ammobaculites exiguus Cushman and Brönnimann, 1948, p. 38, pl. 7, figs. 7, 8.

Ammonia "beccarii" (Linné) forma 1 Matoba, 1970, p. 48, pl. 5, figs. 8, 9.

Ammonia "beccarii" (Linné) forma 2 Matoba, 1970, p. 48, pl. 5, figs. 10–12.

Ammonia japonica (Hada) = *Rotalia japonica* Hada, 1931, p. 137, text-figs. 93.

Ammonia ketienziensis angulata (Kuwano) = *Rotalia ketienziensis angulata* Kuwano, 1950, p. 312, text-fig. 1.

Angulogerina ikebei Husezima and Maruhashi, 1944, p. 396, pl. 34, figs. 8a–c.

Bolivina decussata Brady, 1881, p. 28; Brady, 1884, pl. 53, figs. 12–13.

Bolivina humilis Cushman and McCulloch = *Bolivina seminuda* Cushman var. *humilis* Cushman and McCulloch, 1942, p. 211, pl. 26, figs. 1–6.
Bolivina pseudoplicata Heron-Allen and Earland, 1930, p. 81, pl. 3, figs. 36–40.
Bolivina robusta (Brady) = *Bulimina (Bolivina) robusta* Brady, 1881; Brady, 1884, p. 421, pl. 53, figs. 7–9.
Bolivina subspinescens Cushman, 1911, p. 46–47, figs. 76a–b.
Brizalina convallaria (Millett) = *Bolivina convallaria* Millett, 1900, p. 544, pl. 4, figs. 6a, b.
Brizalina pacifica (Cushman and McCulloch) = *Bolivina acerosa* Cushman var. *pacifica* Cushman and McCulloch, 1942, p. 185, pl. 21, figs. 2, 3.
Brizalina seminuda (Cushman) = *Bolivina seminuda* Cushman, 1911, p. 34, text-fig. 55.
Brizalina striatula (Cushman) = *Bolivina striatula* Cushman, 1922b, p. 27, pl. 3, fig. 10.
Buccella frigida (Cushman) = *Pulvinulina frigida* Cushman, 1922a, p. 12.
Buccella makiyamai Chiji, 1961, p. 234, text-figs. 2a–c, pl. 1, figs. 13a–14b.
Bulimina marginata d'Orbigny, 1826, p. 269, pl. 12, figs. 10–12.
Buliminella elegantissima (d'Orbigny) = *Bulimina elegantissima* d'Orbigny, 1839b, p. 51, pl. 7, figs. 13, 14.
Cancris auriculus (Fichtel and Moll) = *Nautilus auriculus* var. α Fichtel and Moll, 1798, p. 108, pl. 20, figs. a–c.
Cassidulina norvangi Thalmann = *Cassidulina islandica* Nørvang var. *norvangi* Thalmann in Phleger, 1952, p. 83, footnote 1.
Cassidulinoides akitaensis Nomura, 1999, p. 46, figs. 33–3a–c, 33–4a–c, 33–5a–c, 34, 36–7, 36–8, 36–9.
Cibicides lobatulus (Walker and Jacob) = *Nautilus lobatulus* Walker and Jacob in Kanmacher, 1798, p. 642, pl. 14, fig. 36.
Cibicides cf. *refulgens* Montfort = Cf. *Cibicides refulgens* Montfort, 1808, p. 122.
Cyclogyra planorbis (Schultze) = *Cornuspira planorbis* Schultze, 1854, p. 40, pl. 2, fig. 21.
Discorbinella convexa (Takayanagi) = *Planulina convexa* Takayanagi, 1953, p. 34, pl. 4, figs. 14a–c.
Eilohedra nipponica (Kuwano) = *Epistominella nipponica* Kuwano in Matoba, 1967, p. 254, figs. 8a–f, pl. 26, figs. 13a–c.
Elphidium advenum (Cushman) = *Polystomella advena* Cushman, 1922b, p. 56, pl. 9, figs. 11, 12.
Elphidium crispum (Linné) = *Nautilus crispus* Linné, 1758, p. 709.
Elphidium excavatum (Terquem) forma clavata = *Elphidium clavatum* Cushman, emend, Loeblich and Tappan, 1953, p. 98, 101, 102, pl. 19, figs. 8a, b, 9, 10.
Elphidium excavatum (Terquem) forma excavata = *Polystomella excavata* Terquem, 1875, p. 20, pl. 2, figs. 2a, b.
Elphidium jenseni (Cushman) = *Polystomella jenseni* Cushman, 1924, p. 49, pl. 16, figs. 4, 6.
Elphidium kusiroense Asano, 1938, p. 590, pl. 14, fig. 2.
Elphidium reticulosum Cushman, 1933a, p. 51, pl. 12, figs. 5a, b.
Elphidium somaense Takayanagi, 1955, p. 43, 52, text-figs. 28a, b.
Elphidium subincertum Asano, 1950, p. 10, text-figs. 56, 57.
Geminospira simaensis Makiyama and Nakagawa, 1941, p. 241, figs. 3–5.
Hanzawaia nipponica Asano 1944, p. 99, pl. 4, figs. 1a, b, 2a, b.
Haynesina sp. A = *Haynesina* sp., Kosugi *et al.*, 1991, p. 53, figs. 5, 10–11.
Hyalinea balthica (Schröter in Gmelin) = *Nautilus balthicus* Schröter in Gmelin 1791:WoRMS, 2020 [online]. [Cited 2020-12-04] Available from: http://www.marinespecies.org/aphia.php?p=taxdetails&id=955359.
Islandiella algida (Cushman) = *Cassidulina algida* Cushman, 1944, p. 35, pl. 4, figs. 24a–c.
Islandiella japonica (Asano and Nakamura) = *Cassidulina japonica* Asano and Nakamura, 1937, p. 144, text-figs. 2a, b.
Massilina secans (d'Orbigny) = *Quinqueloculina secans* d'Orbigny, 1826, p. 303.
Miliammina fusca (Brady) = *Quinqueloculina fusca* Brady, 1870, p. 286, pl. 11, figs. 2a–c, 3a, b.
Murrayinella globosa (Millett) = *Discorbina imperatoria* (d'Orbigny) var. *globosa* Millett, 1903, p. 701, pl. 7, figs. 6a–c.
Murrayinella minuta (Takayanagi) = *Rotalia*? *minuta* Takayanagi, 1955, p. 45, 52, text-figs. 29a–c.
Nonion manpukuziensis Otuka, 1932, p. 654, fig. 1.
Nonionella stella Cushman and Moyer = *Nonionella miocenica* Cushman var. *stella* Cushman and Moyer, 1930, p. 56, pl. 7, fig. 17.
Oolina hexagona (Williamson) = *Entosolenia squamosa* (Montagu) var. *hexagona* Williamson, 1848, p. 20, pl. 2, fig. 23.
Oolina melo d'Orbigny, 1839b, p. 20, pl. 5, fig. 9.
Paracassidulina neocarinata (Thalmann) = *Cassidulina neocarinata* Thalmann, 1950, p. 44.
Pararotalia nipponica (Asano) = *Rotalia nipponica* Asano, 1936a, p. 614, pl. 31, figs. 2a–c.
Planocassidulina norcrossi (Cushman) = *Cassidulina norcrossi* Cushman, 1933b, p. 7, pl. 2, figs. 7a–c.
Planocassidulina sublimbata (Asano and Nakamura) = *Cassidulina sublimbata* Asano and Nakamura, 1937, p. 146, pl. 14, figs. 3–4.
Planoglabratella opercularis (d'Orbigny) = *Rosalina opercularis* d'Orbigny, 1839a, p. 93 pl. 3 fig. 24–25, pl. 4, fig. 1.
Planoglabratella subopercularis (Asano) = *Discorbis subopercularis* Asano, 1951, p. 3, text-figs. 17–19.
Pseudononion japonicum Asano, 1936a, p. 347, text-figs. a–c.
Pseudoparrella naraensis Kuwano, 1950, p. 317, text-fig. 6.
Pseudoparrella tamana Kuwano, 1950, p. 317, text-figs. 5a–c.
Pseudorotalia gaimardii compressiuscula (Brady) = *Rotalia papillosa* Brady *compressiuscula* Brady, 1884, p. 708, pl. 107, fig. 1; p. 108, fig. 1.
Pullenia apertura Cushman, 1927, p. 171, pl. 6, fig. 10.
Quinqueloculina akneriana d'Orbigny, 1846, p. 290, pl. 18, figs. 16–21.
Quinqueloculina costata d'Orbigny, 1826, p. 301.
Quinqueloculina elongata Natland, 1938, p. 141, pl. 4, fig. 5.
Quinqueloculina seminulum (Linné) = *Serpula seminulum* Linné, 1758, p. 786.
Rectobolivina raphana (Parker and Jones) = *Uvigerina (Sagrina) raphanus* Parker and Jones, 1865, p. 364, pl. 18, figs. 16a–b, 17.
Reussella pacifica Cushman and McCulloch, 1948, p. 251, pl. 31, figs. 6a, b.
Rosalina austlaris (Parr) = *Discorbis australis* Parr, 1932, p. 227, pl. 22, figs. 31a–c.
Rosalina bradyi (Cushman) = *Discorbis globularis* var. *bradyi* Cushman, 1915, p. 12, pl. 8, figs. 1a–c.
Sagrinella convallaria (Millett) = *Bolivina convallaria* Millett, 1900, p. 544, pl. 4, fig. 7a, b.
Seabrookia pellucida Brady, 1890, p. 568–569, tf. 60, 1a–c, 2.
Spirillina vivipara Ehrenberg, 1843, p. 442, pl. 3, fig. 41.
Spirosigmoillina pusilla (Earland) = *Spiroloculina pusilla* Earland, 1934, p. 47, pl. 1, figs. 3–4.
Stainforthia fusiformis (Williamson) = *Bulimina pupoides* d'Orbigny var. *fusiformis* Williamson, 1858, p. 63, pl. 5, figs. 129, 130.
Textularia kerimbaensis Said, 1949, p. 5, pl. 1, fig. 8.
Trochammina cf. *japonica* Ishiwada = Cf. *Trochammina japonica* Ishiwada, 1950, p. 190, pl., figs. 2a–c.
Uvigerinella glabra (Millett) = *Uvigerina auberiana* d'Orbigny var.

glabra Millett, 1903, p. 268, pl. 5, figs. 8a, b.

Valvulineria hamanakoensis (Ishiwada) = *Anomalina hamanakoensis* Ishiwada, 1958, p. 18, text-figs. 3a–c, pl. 1, figs. 24–27.

Wiesnerella auriculata (Egger) = *Planispirina auriculata* Egger, 1893, p. 371, pl. 13, figs. 19–21.

References

Akimoto, K. and Hasegawa, S., 1989: Bathymetric distribution of the Recent benthic foraminifers around Japan—As a contribution to the new paleobathymetric scale. *Memoirs of the Geological Society of Japan*, vol. 32, p. 229–240. (*in Japanese with English abstract*)

Asano, K., 1936a: *Pseudononion*, a new genus of foraminifera found in Muraoka-mura, Kamakura-gori, Kanagawa Prefecture. *Journal of the Geological Society of Japan*, vol. 43, p. 347–348.

Asano, K., 1936b: Foraminifera from Muraoka-mura, Kamakura-gori, Kanagawa Prefecture. (Studies on the fossil foraminifera from the Neogene od Japan. Part I.) *Journal of the Geological Society of Japan*, vol. 43, p. 603–614.

Asano, K., 1938: On the Japanese species of *Bolivina* and its allied genera. *Journal of Geological Society of Japan*, vol. 45, p. 600–609.

Asano, K., 1944: *Hanzawaia*, a new genus of Foraminifera from the Pliocene of Japan. *Journal of the Geological Society of Japan*, vol. 51, p. 97–98.

Asano, K., 1950: *Illustrated Catalogue of Japanese Tertiary Smaller Foraminifera, Part 1, Nonionidae*, p. 1–12. Hosokawa Printing Company, Tokyo.

Asano, K., 1951: *Illustrated Catalogue of Japanese Tertiary Smaller Foraminifera*, *Part 14*, *Rotaliidae*, p. 1–21. Hosokawa Printing Company, Tokyo.

Asano, K. and Nakamura, M., 1937: On the Japanese species of *Cassidulina*. *Japanese Journal of Geology and Geography*, vol. 14, p. 143–153.

Brady, H. B., 1870: Analysis and descriptions of the foraminifera. *Annals and Magazine of Natural History*, ser. 4, vol. 6, p. 273–309.

Brady, H. B., 1881: Notes on some of the Reticularian Rhizopoda of the Challenger Expedition. Part III, 1. Classification. 2. Further notes on new species. 3. Note on *Biloculina* mud. *Quaternary Journal of Microscopical Science*, *new ser.*, vol. 21, p. 31–71.

Brady, H. B., 1884: Report on the foraminifera dredged by H. M. S. Challenger, during the years 1873–1876. *Report on the Scientific Results of the Voyage of the H. M. S. Challenger during the years 1873–1876, Zoology*, vol. 9, p. 1–814.

Brady, H. B., 1890: Note on a new type of foraminifera of the family Chilostomellidae. *Journal of the Royal Microscopical Society*, *London*, vol. 1890, p. 567–571.

Buzas, M. A. and Gibson, T. G., 1969: Species diversity: benthonic foraminifera in western North Atlantic. *Science*, vol. 163, p. 72–75.

Chiji, M., 1961: Foraminifera from the Asahiyama shell bed, Himi City, Toyama Prefecture. *In*, Matsushita, S. *et al. eds.*, *Prof. Jiro Makiyama Memorial Volume*, p. 229–238. Makiyama Kyouju Taikan-Kinen-Jigyokai, Kyoto.

Cho, A., Cheong, D., Kim, J. C., Shin, S., Park, Y.-H. and Katsuki, K., 2017: Delta formation in the Nakdong River, Korea, during the Holocene as inferred from the diatom assemblage. *Journal of Coastal Research*, vol. 33, p. 67–77.

Cushman, J. A., 1911: A monograph of the foraminifera of the North Pacific Ocean. Pt. 2. Textulariidae. *Bulletin of the United States National Museum*, vol. 71, p. 1–108.

Cushman, J. A., 1915: A monograph of the foraminifera of the North Pacific Ocean. Pt. 5. Rotaliidae. *Bulletin United States National Museum*, vol. 71, p. 1–81.

Cushman, J. A., 1922a: Results of the Hudson Bay Expedition. I. The Foraminifera. *Contributions to Canadian Biology*, vol. 1921, p. 133–147.

Cushman, J. A., 1922b: Shallow-water foraminifera of the Tortugas Region. *Carnegie Institution of Washington*, *no. 311*, *Department of Marine Biology*, vol. 17, p. 1–85.

Cushman, J. A., 1924: Samoan foraminifera. *Carnegie Institution of Washington*, *no. 342*, *Department of Marine Biology*, no. 21, p. 1–75.

Cushman, J. A., 1927: Recent foraminifera from off the West coast of America. *Bulletin of Scripps Institution of Oceanography*, *Technical Series*, vol. 1, p. 119–188.

Cushman, J. A., 1933a: The foraminifera of the tropical Pacific collections of the "Albatross," 1899–1900. Pt. 2. Lagenidae to Alveolinellidae. *Bulletin of the United States National Museum*, vol. 161, p. i-vi, 1–79.

Cushman, J. A., 1933b: New Arctic foraminifera collected by Capt. R. A. Bartlett from Fox Basin and off the northeast coast of Greenland. *Smithsonian Miscellaneous Collections*, vol. 89, p. 1–8.

Cushman, J. A., 1944: Foraminifera from the shallow water of the New England coast, *Special Publications Cushman Laboratory for Foraminiferal Research*, vol. 12, p. 1–37.

Cushman, J. A. and Brönnimann, P., 1948: Some new genera and species of foraminifera from brackish water of Trinidad. *Contribution from the Cushman Laboratory for Foraminiferal Research*, vol. 24, p. 15–21.

Cushman, J. A. and McCulloch, I., 1942: Some Virgulininae in the collections of the Allan Hancock Foundation. *Allan Hancock Pacific Expeditions*, vol. 6, p. 179–230.

Cushman, J. A. and McCulloch, I., 1948: The species of *Bulimina* and related genera in the Collections of the Allan Hancock Foundation. *Allan Hancock Pacific Expeditions*, vol. 6, p 231–294.

Cushman, J. A. and Moyer, D. A., 1930: Some recent foraminifera from off Sun Pedro, California. *Contribution from the Cushman Laboratory for Foraminiferal Research*, vol. 6, p. 49–62.

Earland, A., 1934: Foraminifra. Part III. The Falklands sector of the Antarctic (excluding South Georgia). *Discovery Reports*, vol. 10, p. 1–208.

Egger, J. G., 1893: Foraminiferen aus Meeresgrundproben, gelothet von 1874 bis 1876 von S. M. Sch. Gazelle. *Abhandlungen der Mathematisch-Physikalischen Classe der Königlich Bayerischen Akademie der Wissenschaften*, vol. 18, p. 193–458.

Ehrenberg, C. G., 1843: Über Verbreitung und Einfluss des mikroskopischen Lebens in Süd- und Nordamerika. *Bericht über die zu Bekanntmachung geeigneten Verhandlungen der Königlichen Pressischen Akanemie der Wissenschaften zu berlin*, vol. 1841, p. 139–145.

Fichtel, L. von and Moll, J. P. C. von, 1798: *Testacea microscopica, aliaque minuta ex generibus Argonauta et Nautilus, ad naturam picta et descripta (Microscopische und andere klein Schalthiere aus den geschlechtern Argonaute und Schiffer)*, 123 p., In der Camesinaischen Buchhandlung, Vienna.

Hada, Y., 1931: Report of the biological survey of Mutsu Bay. 19, Notes on the recent foraminifera from Mutsu Bay. *Science Reports of the Tohoku Imperial University*, *4th series, Biology*, vol. 6, p. 45–148.

Heron-Allen, E. and Earland, A., 1930: The Foraminifera of the Plymouth district. I. *Journal of the Royal Microscopical Society*, vol. 50, p. 46–84.

Hsuing, K.-H. and Saito, Y., 2017: Sediment trapping in deltas of small mountainous rivers of southwestern Taiwan and its influence on East China Sea sedimentation. *Quaternary International*, vol. 455, p. 30–44.

Husezima, R. and Maruhashi, 1944: A new genus and thirteen new species of foraminifera from the core-sample of Kasiwazaki oil field, Niigata-ken. *Journal Sigenkagaku Kenkyusyo*, vol. 1, p. 391–400.

Inoue, Y., 1989: Northwest Pacific foraminifera as paleoenvironmental indicators. *Science Report of the Institute of Geoscience*, *University of Tsukuba*, *Section B*, vol. 10, p. 57–162.

Ishiwada, Y., 1950: Foraminiferal death assemblages from the mouth of Toyama Bay (Studies on Recent marine sediments–No. 1). *Bulletin of the Geological Survey of Japan*, vol. 1, p. 182–194. (*in Japanese and English abstract*)

Ishiwada, Y., 1958: Studies on brackish water. III. Recent foraminifera from the brackish lake Hamana-ko. *Reports*, *Geological Survey of Japan*, no. 180, p. 19. (*in Japanese and English abstract*)

Jeong, U., 2016: *Evolution study of sedimentary environments of Late Pleistocene caused by sea-level changes in the Nakdong River estuary, Korea*, 58 p. Master Thesis, Kangwon National University, Chuncheon. (*in Korean with English abstract*)

Kang, S., Lim, D. I., Rho, K. C., Jung, H. S., Choi, J. Y. and Yoo, H. S., 2006: Planktic foraminiferal assemblages of core sediments from Korea Strait and paleoceanographic changes. *Journal of Korean Earth Science Society*, vol. 27, p. 464–474. (*in Korean with English abstract*)

Kawahata, H., Yamamoto, H., Ohkushi, K., Yokoyama, Y., Kimoto, K., Ohshima, H. and Matsuzaki, H., 2009: Changes of environments and human activity at the Sannai-Maruyama ruins in Japan during the mid-Holocene Hypsithermal climatic interval. *Quaternary Science Reviews*, vol. 28, p. 964–974.

Khim, B.-K., Shin, S., Kim, J.-C., Takata, H., Hyun, S. and Cheong, D., 2019: Sediment properties of lithologic units and their correlation within the lower delta plain of the Nakdong River Delta, southeast Korea. *Quaternary International*, vol. 519, p. 170–182.

Kim, J. C., Cheong, D., Shin, S., Park, Y. and Hong, S. S., 2015: OSL chronology and accumulation rate of the Nakdong deltaic sediments, southeastern Korean Peninsula. *Quaternary Geochronology*, vol. 30, Part B, p. 245–250.

Kitamura, A., Takano, O., Takata, H. and Omote, H., 2001: Late Pliocene–early Pleistocene paleoceanographic evolution of the Sea of Japan. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, vol. 172, p. 81–98.

Kitazato, H., 1988: Ecology of benthic foraminifera in the tidal zone of a rocky shore. *Revue de Paleobiologie*, *Special Volume 2*, p. 815–825.

Klovan, J. E. and Imbrie, J., 1971: An algorithm and FORTRAN IV program for large-scale Q-mode factor analysis and calculation of factor scores. *Journal of the International Association for Mathematical Geology*, vol. 3, p. 61–77.

Kong, G. S. and Lee, C. W., 2005: Marine reservoir corrections (ΔR) for southern coastal waters of Korea. *Journal of the Korean Society of Oceanography*, vol. 10, p. 124–128. (*in Korean with English abstract*)

Kong, G. S. and Park, S. C., 2007: Paleoenvironmental changes and depositional history of the Korea (Tsushima) Strait since the LGM. *Journal of Asian Earth Sciences*, vol. 29, p. 84–104.

Korean Ocean Data Center, 2020: Coastal Oceanographic Observation [online]. [Cited 9 September 2020]. Available from: http://www.nifs.go.kr/kodc/eng/index.kodc.

Kosugi, M., Kataoka, H. and Hasegawa, S., 1991: Classification of foraminifer communities as indicators of environments in an inner bay and its application to reconstruction paleoenvironment. *Fossils (Palaeontological Society of Japan)*, no. 50, p. 37–55. (*in Japanese with English abstract*)

Kuwano, Y., 1950: New species of foraminifera from the Pliocene of Tama Hills in the vicinity of Tokyo. *Journal of the Geological Society of Japan*, vol. 56, p. 311–321.

Lee, Y. G., Jeong, D. U., Lee, J. S., Choi, Y. H. and Lee, M. O., 2016: Effects of hypoxia caused by mussel farming on benthic foraminifera in semi-closed Gamak Bay, South Korea. *Marine Pollution Bulletin*, vol. 109, p. 566–581.

Linné, C., 1758: *Systema Naturae, per Regna Tria Naturae, Secundum Classes, Ordines, Genera, Species, cum Characteribus, Diferentiis, Synonymis, Locis. Editio decima, reformata.* Tomus, I, iv + 824 p., Impensis Laurentii Salvii, Holmiae (Stockholm).

Loeblich, A. R. Jr. and Tappan, H., 1953: Studies of Arctic Foraminifera. *Smithsonian Miscellaneous Collections*, vol. 121, p. 1–150.

Loeblich, A. R. Jr. and Tappan, H., 1987: *Foraminiferal Genera and their Classification*, 970 p. Van Nostrand Reinhold, New York.

Makiyama, J. and Nakagawa, T., 1941: Pleistocene foraminifera from Simi, Mie Prefecture. *Journal of the Geological Society of Japan*, vol. 48, p. 239–243. (*in Japanese with English abstract*)

Matoba, Y., 1967: Younger Cenozoic foraminiferal assemblages from the Choshi district, Chiba Prefecture. *Science Reports of Tohoku University*, *2nd series (Geology)*, vol. 38, p. 221–263.

Matoba, Y., 1970: Distribution of recent shallow water foraminifera of Matsushima Bay, Miyagi Prefecture, Northeast Japan. *Science Reports of Tohoku University*, *2nd series (Geology)*, vol. 42, p. 4–85.

Matoba, Y. and Honma, N., 1986: Depth distribution of recent benthic foraminifera off Nishitsugaru, eastern Sea of Japan. *In*, Matoba, Y. and Kato, M. *eds.*, *Studies on Cenozoic Benthic Foraminifera in Japan*, p. 53–78. Akita University, Akita. (*in Japanese with English abstract*)

Millett, E. W., 1900: Report on the Recent foraminifera of the Malay Archipelago collected by Mr. A. Durrand, E. R. M. S. Part VIII. *Journal of the Royal Microscopical Society*, vol. 1900, p. 273–281.

Millett, E. W., 1903: Report on the Recent foraminifera of the Malay Archipelago collected by Mr. A. Durrand, E. R. M. S. Part XIV. *Journal of the Royal Microscopical Society*, vol. 1903, p. 253–275.

Montfort P. [Denys de], 1808: *Conchyliologie systématique et classification méthodique des coquilles*, vol. 1, p. lxxxvii + 409. Schoell, Paris.

Morimoto, A. and Yanagi, T., 2001: Variability of sea surface circulation in the Japan Sea. *Journal of Oceanography*, vol. 57, p. 1–13.

Natland, M. L., 1938: New species of Foraminifera from off the west coast of North America and from the later Tertiary of the Los Angeles basin. *Bulletin of the Scripps Institution of Oceanography of the University of California*, *Technical Series*, no. 4, p. 137–163.

Nishida, N. and Ikehara, K., 2013: Holocene evolution of depositional processes off southwest Japan: Response to the Tsushima Warm Current and sea-level rise. *Sedimentary Geology*, vol. 290, p. 138–148.

Nomura, R., 1999: Miocene Cassidulinid Foraminifera from Japan. *Paleontological Society of Japan*, *Special Papers*, no. 38, p. 1–69.

Nomura, R. and Seto, K., 1992: Benthic foraminifera from brackish Lake Nakaumi, San-in district, southwestern Hoshu, Japan. *In*, Ishizaki, K. and Saito, T. *eds.*, *Centenary of Japanese Micropaleontology*, p. 227–240. Terra Scientific Publishing Company, Tokyo.

Oki, K., 1989: Ecological analysis of benthonic foraminifera in Kagoshima Bay, south Kyushu, Japan. *South Pacific Study*, vol. 10, p. 1–191.

Oksanen, J., Blanchet, G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymons, P., Stevens, M. H. H., Szoecs, E. and Wagner, H., 2019: Vegan: community ecology package. R package version v. 2. 5-6 [online]. [Cited 1 September 2019]. Available from: http://cran.r-project.org/web/packages/vegan/index.html.

Orbigny, A. D. d', 1826: Tableau méthodique de la classe des Céphalopodes. *Annales des Sciences Naturelles*, vol. 7, p. 96–169 and p. 245–314.

Orbigny, A. D. d', 1839a: Foraminifères, in de la Sagra R., *Histoire physique, politique et naturelle de l'ile de Cuba*, p. 1–224. Arthus Bertrand, Paris.

Orbigny, A. D. d', 1839b: *Voyage dans l'Amérique méridionale–Foraminifères*, tome 5, pt. 5. p. 1–86, P. Bertrand, Paris and Strasbourg.

Orbigny, A. d', 1846: *Foraminifères fossiles du Bassin Tertiaire de Vienne (Autriche)*, vol. I--XXXVII, p. 1–312. Gide et Comp., Paris.

Otuka, Y., 1932: Geology of Tama Hill (part 1). *Journal of the Geological Society Tokyo*, vol. 39, p. 641–655 (*in Japanese*)

Parker, W. K. and Jones, T. R., 1865: On some foraminifera from the North Atlantic Oceans, including Davis Straits and Baffin's Bay. *Philosophical Transactions of the Royal Society*, vol. 155, p. 325–441.

Parr, W. J., 1932: Victorian and South Australian shallow-water foraminifera. Part II. *Proceedings of the Royal Society of Victoria*, vol. 44, p. 218–234.

Phleger, F. B., 1952: Foraminifera distribution in some sediment samples from the Canadian and Greenland Arctic. *Contributions from the Cushman Foundation for Foraminiferal Research*, vol. 3, p. 80–89.

R Development Core Team, 2020: R: a language and environments for statistical computing [online]. [Cited 22 June 2020]. Available from: http://www.R-project.org.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffman, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M. and van der Plicht, J., 2013: IntCal13 and Marine13 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon*, vol. 55, p. 1869–1887.

Ryu, C. K., Kang, S. and Chung, S. G., 2005: Late Quaternary paleoenvironmental changes in the western Nakdong River delta. *Journal of Korean Earth Science Society*, vol. 26, p. 443–458. (*in Korean with English abstract*)

Ryu, C. K., Kang, S., Chung, S. G. and Jeon, Y. M., 2011: Late Quaternary depositional environmental change in the northern marginal area of the Nakdong River delta, Korea. *Journal of the Geological Society of Korea*, vol. 47, p. 213–233. (*in Korean with English abstract*)

Said, R., 1949: Foraminifera of the northern Red Sea. *Special Publications Cushman Laboratory for Foraminiferal Research*, vol. 26, p. 1–44.

Schultze, M. S., 1854: *Über den Organismus der Polythalamien (Foraminiferen), nebst Bermerkungen über die Rhizopoden im Allgemeinen*, 68 p. Wilhelm Emgelmann, Leipzig.

Shin, S., 2016: *Sedimentary environment evolution analysis through core sediments in Lake Hovsgol of the Northern Mongolia and Nakdong Estuary, Korea*, 115 p. Ph. D. Dissertation, Kangwon National University, Chuncheon. (*in Korean with English abstract*)

Song, B., Yi, S., Yu, S.-Y., Nahm, W.-H., Lee, J.-Y., Lim, J., Kim, J.-C., Yang, Z., Han, M., Jo, K. and Saito, Y., 2018: Holocene relative sea-level changes inferred from multiple proxies on the west coast of South Korea. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, vol. 496, p. 268–281.

Stuiver, M. S. and Reimer, P. J., 1993: Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon*, vol. 35, p. 215–230.

Takata, H., Irizuki, T., Seto, K. and Nomura, R., 2019a: Response of benthic foraminifera (Rhizaria) to anthropogenic environmental changes in the Honjo area of Lake Nakaumi (southwestern Japan): dispersal potential of neritic benthic foraminifera. *LAGUN*A, vol. 26, p. 19–30.

Takata, H., Itaki, T., Ikehara, K. and Khim, B.-K., 2018a: Correlation between faunal transitions of benthic foraminifera and ballasting of particulate organic carbon by siliceous plankton during the Holocene off San-in district, southwestern Japan. *The Holocene*, vol. 28, p. 444–454.

Takata, H., Itaki, T., Ikehara, K., Yamada, K. and Takayasu, K., 2006a: Significant Tsushima Warm Current during the Early–Middle Holocene along the San-in District Coast inferred from foraminiferal profiles. *The Quaternary Research*, vol. 45, p. 249–256. (*in Japanese with English abstract*)

Takata, H., Khim, B.-K., Cheong, D., Shin, S., Takayasu, K., Park, Y. and Lim, H. S., 2016: Holocene benthic foraminiferal faunas in the coastal deposits of Nakdong River delta (Korea) and Izumo plain (Japan). *Quaternary International*, vol. 392, p. 13–24.

Takata, H., Khim, B.-K., Shin, S., Lee, J.-W., Kim, J.-C., Katsuki, K. and Cheong, D., 2019b: Early to middle Holocene development of the Tsushima Warm Current based on benthic and planktonic foraminifera in the Nakdong River delta (southeast Korea). *Quaternary International*, vol. 519, p. 183–191.

Takata, H., Nishida, N., Ikehara, K., Katsuki, K. and Khim, B.-K., 2018b: Mid-Holocene forcing of the Tsushima Warm Current to the coastal environments in southwestern Japan with a view to foraminiferal faunas. *Quaternary International*, vol. 482, p. 56–66.

Takata, H., Nomura, R., Sampei, Y., Tanaka, S. and Khim, B.-K., 2019c: Dispersal potential of neritic benthic foraminifera in the coastal areas of the Japanese Islands and its application to paleoenvironmental studies. *Estuarine, Coastal and Shelf Science*, vol. 227, 106288.

Takata, H., Takayasu, K. and Hasegawa, S., 2006b: Foraminifera in an organic-rich, brackish-water lagoon, Lake Saroma, Hokkaido, Japan. *Journal of Foraminiferal Research*, vol. 36, p. 44–60.

Takayanagi, Y., 1953: New genus and species of foraminifera found in the Tonohama Group, Kochi Prefecture, Shikoku, Japan. *Short Papers from the Institute of Geology and Paleontology*, *Tohoku University*, vol. 5, p. 25–36.

Takayanagi, Y., 1955: Recent foraminifera from Matsukawa-Ura and its vicinity. *Contributions from the Institute of Geology and Paleontology*, *Tohoku University*, no. 45, p. 18–52. (*in Japanese with English abstract*)

Tanigawa, K., Hyodo, M. and Sato, H., 2013: Holocene relative sea-level change and rate of sea-level rise from coastal deposits in the Toyooka Basin, western Japan. *Holocene*, vol. 23, p. 1038–1051.

Terquem, O., 1875: *Essai sur le classement des animaux qui vivent sur la plage et dans les environs de Dunqerque*. Fasc. 2, p. 55–100, Paris.

Thalmann, H. E., 1950: New names and homonyms in foraminifera. *Contributions from the Cushman Foundation for Foraminiferal Research*, vol. 1, p. 41–45.

Usami, K., Ohi, T., Hasegawa, S. and Ikehara, K., 2013: Foraminiferal records of bottom-water oxygenation and surface-water productivity in the southern Japan Sea during 160–15 ka: Associations with insolation changes. *Marine Micropaleontology*, vol. 101, p. 10–27.

Walker, G. and Jacob, E., 1798: Adam's Essay on the Microscope. *In*, Kanmmacher, F. *ed*., *The Second Edition*, *with Considerable Additions and Improvements*, Chapter 11, p. 629–645. Dillon and Keating, London.

Williams, J. R., Dellapenna, T. M. and Lee, G., 2013: Shifts in depositional environments as a natural response to anthropogenic alterations: Nakdong Estuary, South Korea. *Marine Geology*, vol. 343, p. 47–61.

Williamson, W. C., 1848: On the Recent British species of the genus *Lagena*. *Annals and Magazine of Natural History, series 2*, vol. 1, p. 1–20.

Williamson, W. C., 1858: *On the Recent foraminifera of Great Britain*. 107 p., Ray Society, London.

Yoo, D. G., Hong, S. H., Lee, G. S., Kim, J. C., Yoon, H. H. and Cheong, D., 2020: Stratigraphic evolution of the Nakdong River valley in response to late Quaternary sea-level changes. *Marine Geology*, vol. 427, 106243.

Author contributions

HT was responsible for faunal data and paleontological discussion about benthic foraminifera. SHH and DGY conducted stratigraphic framework and sedimentological studies for core 16ND-C02. JCK contributed chronological data of the study cores. DC was a project leader for cores ND-01, ND-02 and ND-03. BKK designed the study and led to paleoenvironmental discussion with financial support. HT and BKK wrote the manuscript.