Ocean Sci. J. (2016) 51(1):137–150
http://dx.doi.org/10.1007/s12601-016-0012-1

Article

Available online at http://link.springer.com
SpringerLink

pISSN 1738-5261
eISSN 2005-7172

Implication of Salt Marsh Foraminiferal Assemblages in Suncheon Bay, South Korea

Da Un Jeong[1], Yeon Gyu Lee[1,*], Sora Kang[1], Shin Kim[2], and Jung Sick Lee[3]

[1]*School of Marine Technology, College of Fisheries and Ocean Sciences, Chonnam National University, Yeosu 59626, Korea*
[2]*Nakdong River Environment Research Center, National Institute of Environmental Research, Goryeong 40103, Korea*
[3]*Department of Aqualife Medicine, College of Fisheries and Ocean Science, Chonnam National University, Yeosu 59626, Korea*

Received 21 January 2015; Revised 20 April 2015; Accepted 21 November 2015

Abstract – Analyses of the compositions of benthic foraminifera and sediment, observations of tidal level and salinity, and a geographic survey of the tidal salt marsh in Suncheon Bay were conducted to examine the vertical distribution of foraminifera and evaluate their potential use for sea level studies. The salt marsh is composed mainly of fine-grained silty clay sediment and its salinity is below approximately 11 psu. The tidal current flows in the southwest-to-northeast direction with an average velocity of 26.57 cm/s. A total of 33 species of foraminifera (17 agglutinated and 16 calcareous-hyaline) belonging to 24 genera was identified. The species diversity (1.1 on average) was relatively low. Dominant species were *Ammonia beccarii*, *Miliammina fusca*, *Haplophragmoides wilberti*, and *Jadammina macrescens*. Calcareous foraminifera (29.5%) were dominantly represented by the *Ammonia beccarii* assemblage, which characterized the region between mean tide level and mean low high water (MLHW). Agglutinated species (70.5%) were represented mostly by *Miliammina fusca, Miliammina fusca–Haplophragmoides wilberti,* and *Haplophragmoides wilberti* assemblages, which characterized the MLHW–mean high water (MHW), MHW–mean highest high water (MHHW), and MHHW–Approx. highest high water tide levels, respectively. In particular, the *Haplophragmoides wilberti* assemblage is believed to represent the highest elevation zone of foraminifera in the salt marshes of Suncheon Bay and is considered to be a reliable indicator of sea level as a result of its narrow vertical range.

Key words – salt marsh, benthic foraminifera, Suncheon Bay, sea level change, *Haplophragmoides wilberti*

1. Introduction

Foraminifera, one of the main components of the marine ecosystem, have traditionally been used for several types of geological studies, such as studies of sequence stratigraphy, paleoenvironment, and paleoclimate (Scott et al. 2001). Recently, foraminifera have been used as bioindicators in various marine environmental studies, such as those addressing trace metal pollution, eutrophication, and oil spills (Alve 1995; Scott et al. 2001; Murray 2006). Moreover, salt marsh foraminifera are considered to be the most precise bioindicator for sea level and have been used widely to reconstruct Holocene sea level changes (Gehrels 1994; Varekamp and Thomas 1998; Hayward et al. 1999; Patterson et al. 1999; Southall et al. 2006; Kemp et al. 2009a, 2009b; Leorii et al. 2010; Callard et al. 2011). The foraminifera commonly preserved in salt marsh sediments are well studied using quantitative analysis because they form low-diversity, high-abundance assemblages (Gehrels 2007).

Assemblages of foraminifera are used as indicators of sea level due to their distribution on modern salt marshes, which reflect the frequency and duration of tidal inundation and permit the recognition of elevation-dependent ecological zones (Scott and Medioli 1978; Gehrels 1994; Horton and Edwards 2006). The duration and frequency of tidal exposure are the most important variables controlling the distribution of foraminifera within the intertidal zone, with salinity being the next most significant variable (Hayward et al. 1999; Horton 1999; Horton et al. 1999; Horton and Edwards 2003; Horton and Culver 2008). Characteristic assemblages with different tolerances to inundation period are distinguished among tidal flat, low marsh, high marsh, and highest marsh environments, making foraminifera an ideal proxy for sea level (Scott and Medioli 1978; Jennings and Nelson 1992;

---

*Corresponding author. E-mail: lyg6342@jnu.ac.kr

Patterson et al. 2000; Horton and Culver 2008; Kemp et al. 2009a, 2009b, 2012, 2013; Hawkes et al. 2010; Leorii et al. 2010).

Foraminiferal assemblages from transitional and high salt marsh environments occupy the narrowest elevation range and are the most precise sea-level indicators (Kemp et al. 2009a, 2012). Therefore, the highest intertidal foraminiferal assemblages preserved in the fossil record are of great use to sea-level investigations (Gehrels and van de Plassche 1999).

The aims of this study were to examine the vertical distribution of foraminifera in the salt marsh of Suncheon Bay and to investigate the possibility of application to understand former sea level during the Holocene in Korea. As mentioned above, most studies of salt marsh foraminifera were conducted in Europe and North America. Korean salt marsh foraminifera have not been studied previously.

2. Study Area

Suncheon Bay is composed of arable land, tidal salt marshes, and tidal flats with channels (Fig. 1). The bay receives freshwater inflow from the Dong and Isa streams (Fig. 1), which flow from the northeastern area, at a rate of 2,945.45 m^3/s (average volume for 2007–2008), and the inflow is concentrated mostly in summer and early autumn (K-water 2007, 2008). Another channel that is comparatively smaller in scale flows into the bay from the northwestern area. It has a width of about 5–6 m and a depth of 1–1.5 m. The volume of inflow from this channel is very small compared to those of the Dong and Isa streams.

Tidal salt marshes (area of 5.4 km^2; MOMAF 2001) are distributed mainly on tidal flats, where they contain a number of tidal creeks and abundant marsh grasses. The marsh grasses are incompletely submerged during spring tide floods, and the channels are partly exposed during ebb tides (Lee et al. 2013).

The marsh grasses consist dominantly of *Phragmites australis*, with some *Phacelurus latifolius* at slightly high elevations around levees. *Suaeda japonica* and *Carex scabrifolia* also occur around areas of *Phragmites australis* (Lee et al. 2008). The marsh grass areas exhibit increases in mean breadth from 2.33 ± 0.73 to 3.65 ± 1.64 m/yr and have a round shape. The density and height of the marsh grasses are 119 shoots m^{-2} and 155.4 ± 32.5 cm in newly formed stands and 179 shoots m^{-2} and 89.9 ± 32.5 cm in old stands, respectively.

For the purposes of this study, the tidal salt marsh was separated into two zones (A and B) (Fig. 2). Zone A, located in the northeastern area, is distributed broadly and affected largely by streams. Zone B, located in the northwestern area, is affected only slightly by streams.

Sea level in Korea has increased at a rate of 3.8 mm/yr over the last 10 years. At the south coast of Korea, where Suncheon Bay is located, sea level has increased at a rate of 3.6 mm/yr (KHOA 2012).

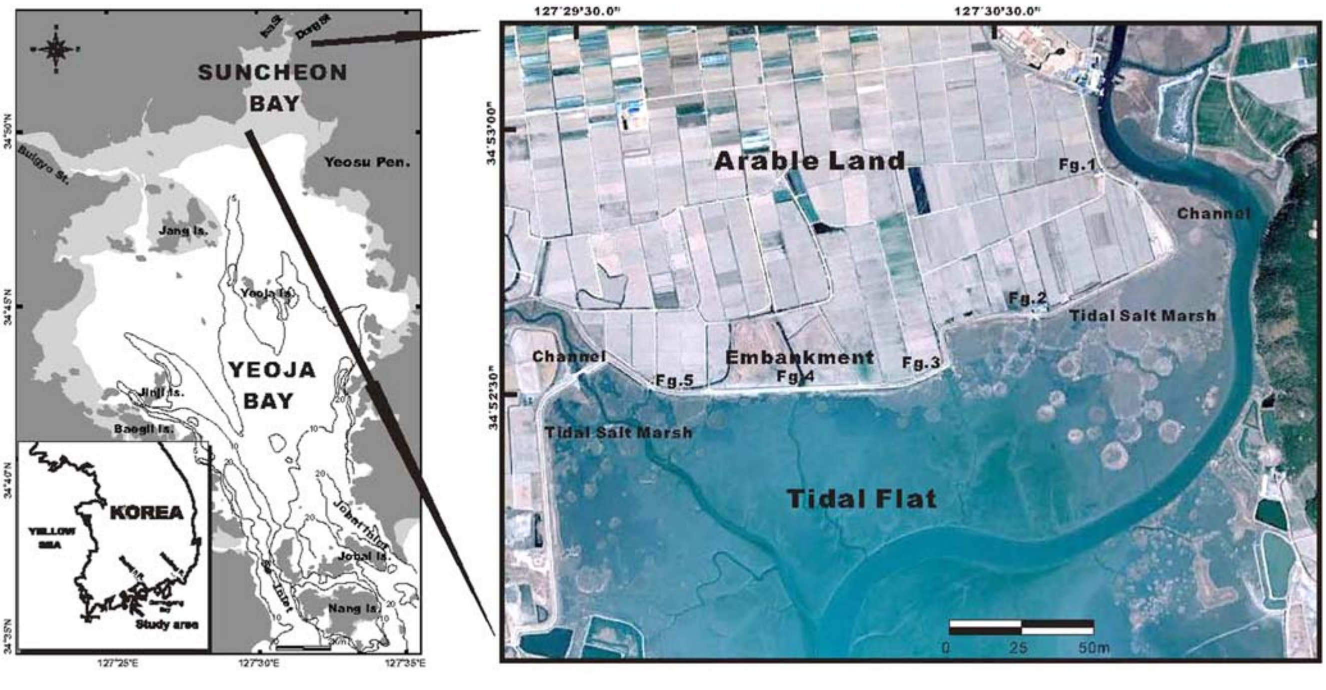

Fig. 1. Locality map showing the geographic characters of the tidal salt marsh in Suncheon Bay, Korea. Fg: floodgate

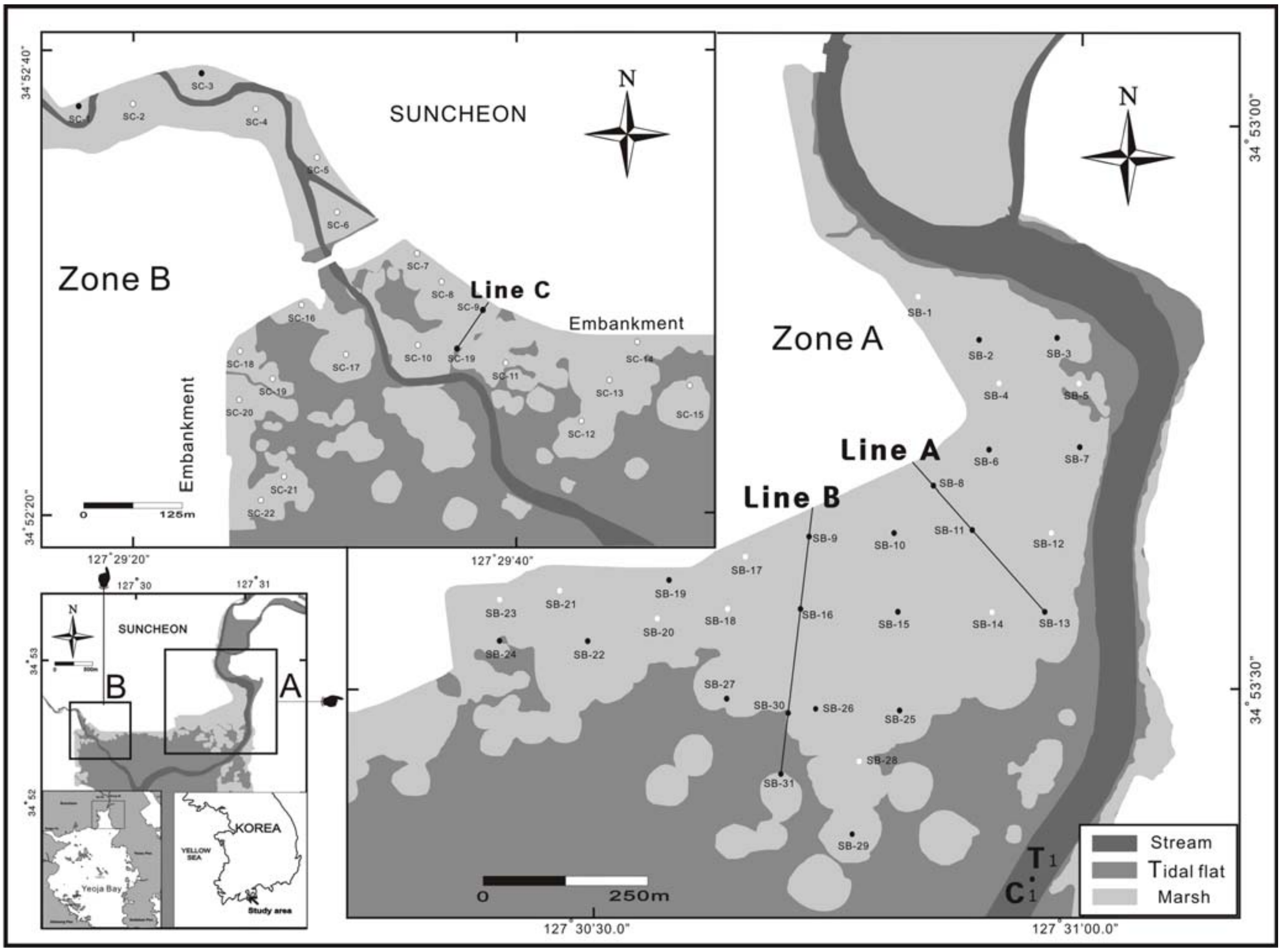

Fig. 2. Map showing the surface sediment sampling locations (Zone A: 31 sites, Zone B: 22 sites), benthic foraminifera sampling sites (black circles; Zone A: 20 sites, Zone B: 4 sites), and three topographic transect lines (Lines a, b, c) for the altitude survey of the tidal salt marsh. C_1: station of tidal current observation, T_1: station of tide observation

3. Methods

Grain size analysis

Surface sediment (top 1 cm) samples were collected for grain size analysis from a total of 53 sites (Zone A: 31 sites; Zone B: 22 sites; all in April 2008) (Fig. 2). Sampling locations were monitored using GPS (GPSV, Garmin Co. LTD, USA; resolution: TFT 160 × 240 pixels).

Grain size and sediment composition were analyzed based on the methods of Ingram (1971). Prior to grain size analysis, organic matter and calcium carbonate were dissolved by sequentially adding 10% hydrogen peroxide (H_2O_2) and 0.1 N hydrochloric acid (HCl), respectively. Subsequently, samples were subjected to a Sedigraph 5100 automatic particle size analyzer and sieve analysis. The weights of each coarse and fine sediment were shown according to weight percentage in each section (Folk 1968). Statistical variables were calculated by the moment method using the weight percentage of each grain size class.

Foraminiferal analysis

Twenty milliliters of surface sediment (top 1 cm) was collected (April 2008) from 24 sites (Zone A: 20 sites; Zone B: 4 sites) for analysis of benthic foraminifera (Fig. 2). The samples were stored in isopropyl alcohol and stained in the field using Rose Bengal stain to differentiate living and dead specimens (Walton 1952). Each sample was washed over a 63 μm sieve and dried at 60°C in the laboratory. The samples were then divided into eight aliquots using a splitter. Foraminifera were counted under a binocular microscope from a known fraction or the full sample. A minimum of 200 specimens was counted, which is sufficient for describing the low diversity assemblages typically formed by salt marsh foraminifera (Fatela and Taborda 2002). The taxonomy of benthic foraminifera used in this study was based on Asano (1950a, 1950b, 1950c, 1950d, 1950e), Matoba (1970), Hayward and Hollis (1994), Gehrels and van de Plassche (1999), Barbosa et al. (2005), and Berkeley et al. (2009). Total (live and dead) foraminiferal assemblages were used for the statistical analysis because the total foraminiferal assemblages most accurately represent the modern environment and are most suitable for paleoenvironmental reconstructions (Scott and Medioli 1980; Scott et al. 2001).

A scanning electron microscope (model S-3000N, Hitachi, Japan) was used to observe the surface ornamentation and state of preservation of test margins and to aid the identification of some smaller species by using surface ultrastructural characteristics. Cluster analysis was conducted to understand the similarities between the component species at each site and to determine the foraminiferal assemblage. Statistical analysis of benthic foraminifera was carried out for number of benthic foraminifera (BF) individuals/20 ml, species diversity, and evenness. Species diversity (H') and evenness (J) were calculated using the formulae of Shannon and Weaver (1963) and Pielou (1966). Planktic foraminifera were not identified due to their very low abundance.

Salinity and tide

Salinity measurement of the tidal flat was conducted from a fast boat at flooding time for about two hours (08:30–10:40) on 27 October 2007. Salinity was estimated at 36 sites (see Fig. 4) using an YSI 600XL sonde with an accuracy of ± 0.1 psu (practical salinity unit).

Tide data were acquired from the mooring (location T1 in Fig. 2) at a water depth of 2 m over 1 month (21 August–20 September 2008) with a tide gauge (TGR-2050, RBR, Canada). Tidal current data were obtained at 30 min intervals (also at a depth of 2 m) from the mooring (location C1 in Fig. 2) over a period of 15 days (11–26 September 2008) using a tidal current gauge (RCM-9, Aanderaa, Norway).

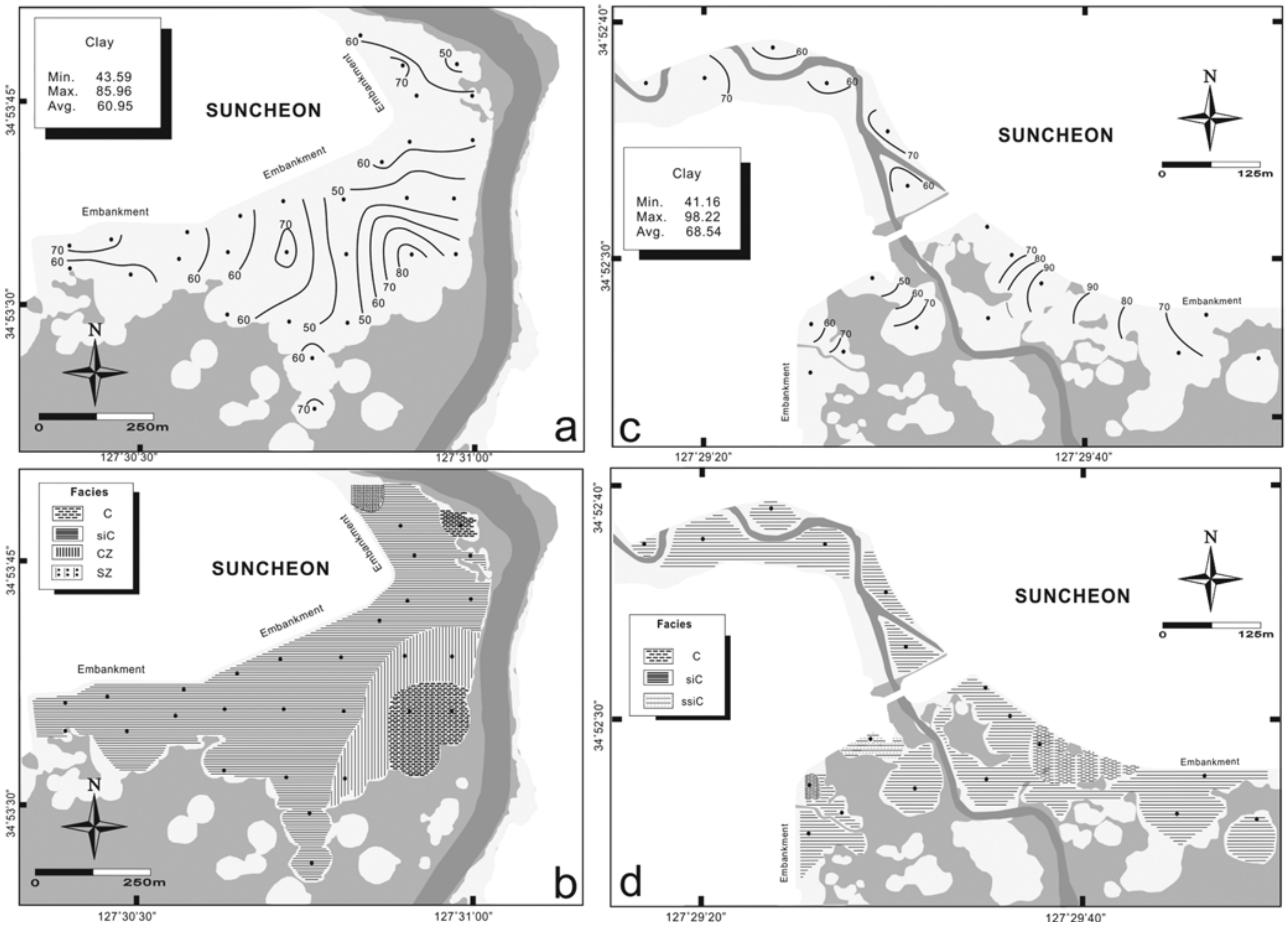

Fig. 3. Map of surface sediment composition of the tidal salt marsh in Suncheon Bay. C: clay; siC: silty clay; cZ: clayey silt; sZ: sandy silt; ssiC: sandy silty clay

Surveys of tidal range and topography were conducted along three transect lines (Lines a, b, and c in Fig. 2) to investigate their possible role in benthic foraminifera distribution. The surface elevation of the tidal salt marsh along the transect lines (see Fig. 6 for sites) was surveyed using a total station (POWERSET Series 100, Sokkia, Ltd., Japan). The benchmark was based on the sea-level control point set up by the National Geographic Information Institute.

4. Results

Sediment composition of marsh substrate

The tidal salt marsh sediments are dominantly fine grained. Sediments of Zone B, consisting of 28.81% silt and 68.54% clay, are slightly finer on average than sediments of Zone A, which consist of 36.84% silt and 59.99% clay.

The sediment compositions of Zone A and Zone B were broadly divided into five grain-size categories: clay, silty clay, clayey silt, sandy silt, and silty clayey sand (Fig. 3). Silty clay is the predominant grain-size category in both Zone A and Zone B. The fine-grained clay material appears to be an essential component in the surface sediment composition of the Suncheon tidal salt marsh.

Salinity of tidal flat

The distribution of salinity in the tidal flat (average of 20.2 psu; range of 26.4–5.0 psu) distinguished three areas with respect to the channel (Fig. 4). Salinity ranged from 22–26 psu, 9–22 psu, and 5–21 psu in the east, west, and north areas of the channel, respectively.

Tidal level and elevation

The tidal flat of Suncheon Bay is a mesotidal flat with a mean tidal range of 217.8 cm (neap, 117.9 cm; spring, 317.7 cm). The tide measures 396.7 cm at approximately highest high water (Approx. HHW), 357.2 cm at mean highest high water

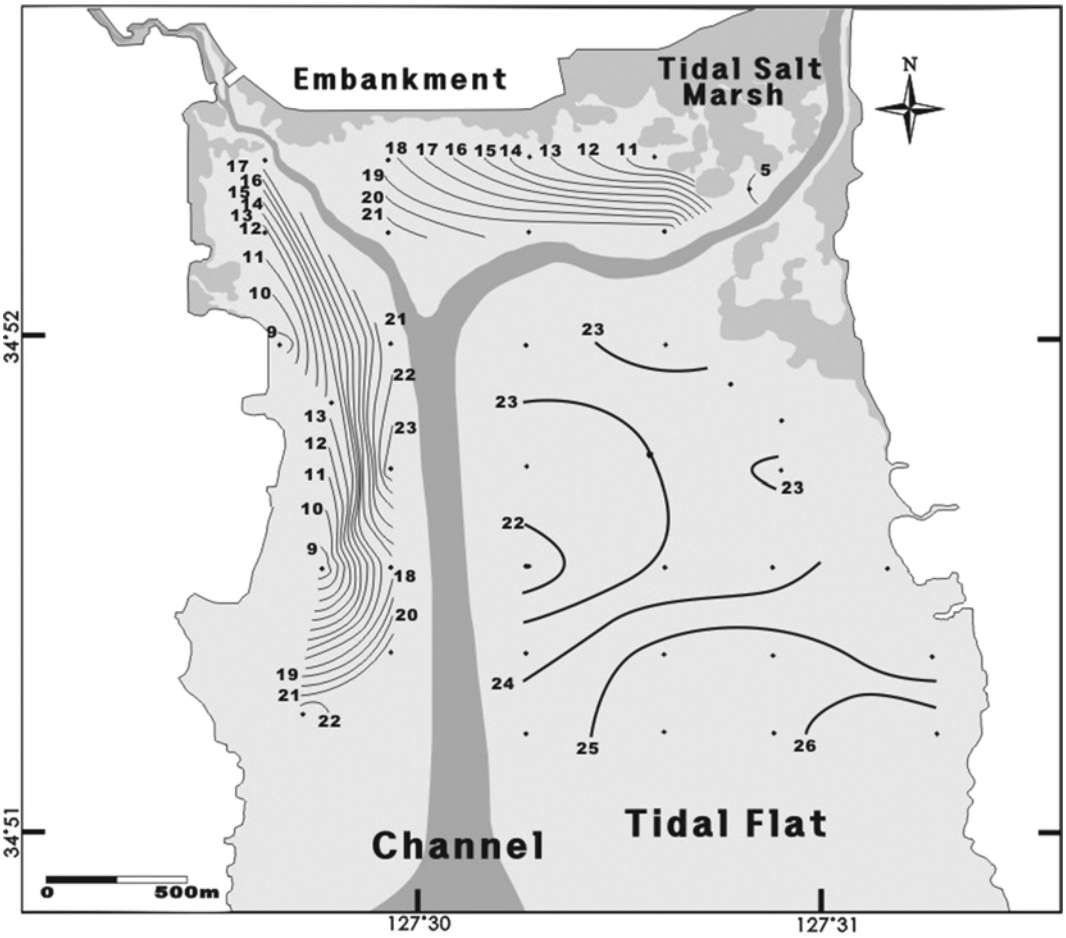

Fig. 4. Map showing the salinity distribution of the tidal flat in Suncheon Bay, Korea. Black circles show the 36 sites of salinity observation

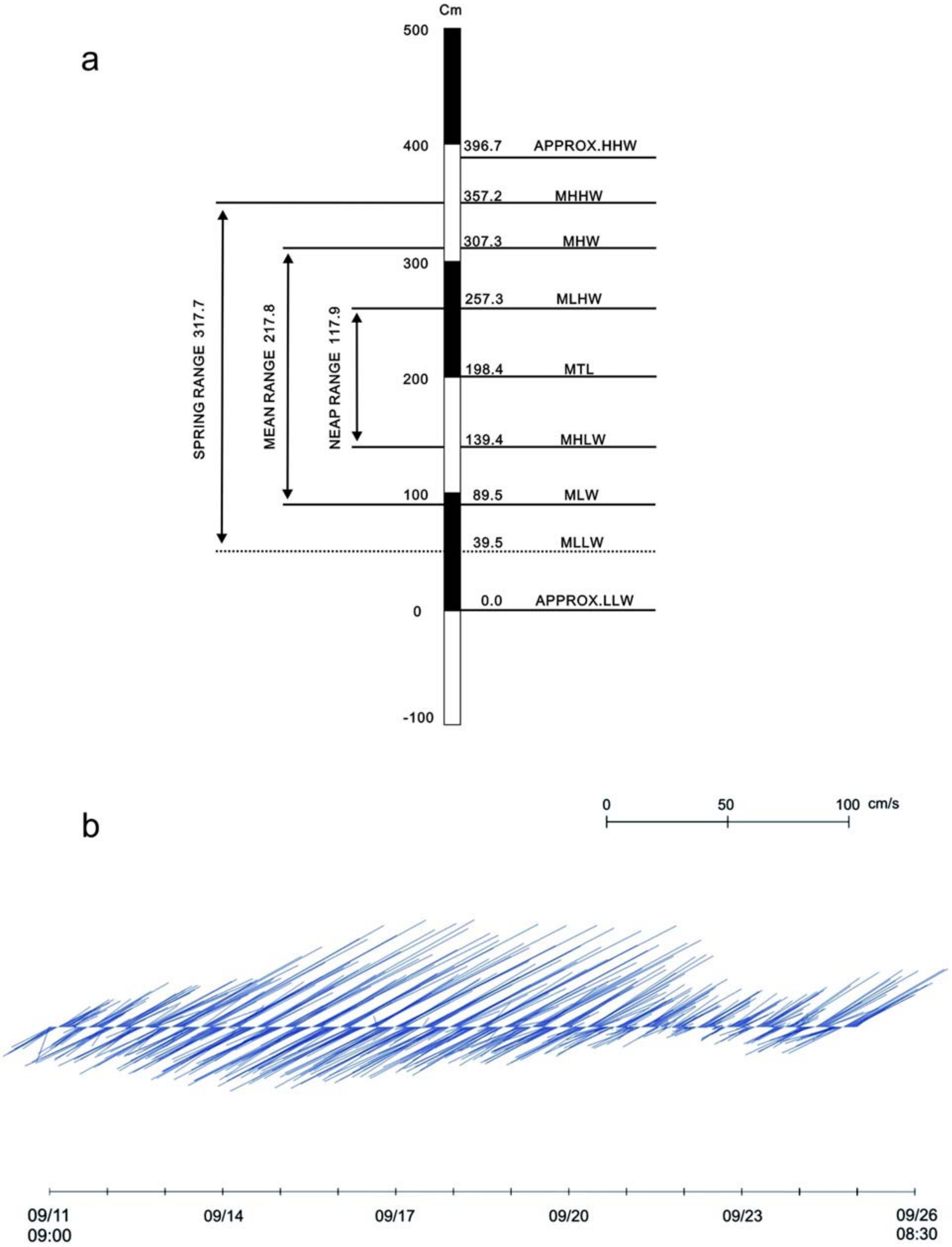

Fig. 5. a: Tidal level of Suncheon Bay. Approx. HHW: approximate highest high water; MHHW: mean highest high water; MHW: mean high water; MLHW: mean low high water; MTL: mean tide level; MHLW: mean highest low water; MLW: mean low water; MLLW: mean lowest low water; and Approx. LLW: approximate lowest low water. b: Stick diagram of tidal current in Suncheon Bay. The average velocity of the tidal current is 26.57 cm/s, and the current flows in the southwest–northeast direction

(MHHW), 307.3 cm at mean high water (MHW), 257.3 cm at mean low high water (MLHW), and 198.4 cm at mean tide level (MTL) relative to the lower low water datum (Fig. 5a). The direction of the tidal current, which has an average velocity of 26.57 cm/s (maximum velocity of 92.68 cm/s), is southwest to northeast (Fig. 5b).

The topographic cross-section of transect Line A (total distance of 320 m), located in the northern area of Zone A, was distributed between MLHW and MHHW (Fig. 6a). Sites SB-8, 11, and 13 were located at distances of 40 m (elevation: 3.4 m), 150 m (elevation: 3.1 m), and 320 m (elevation: 2.7 m) from the benchmark, respectively. The topographic cross section

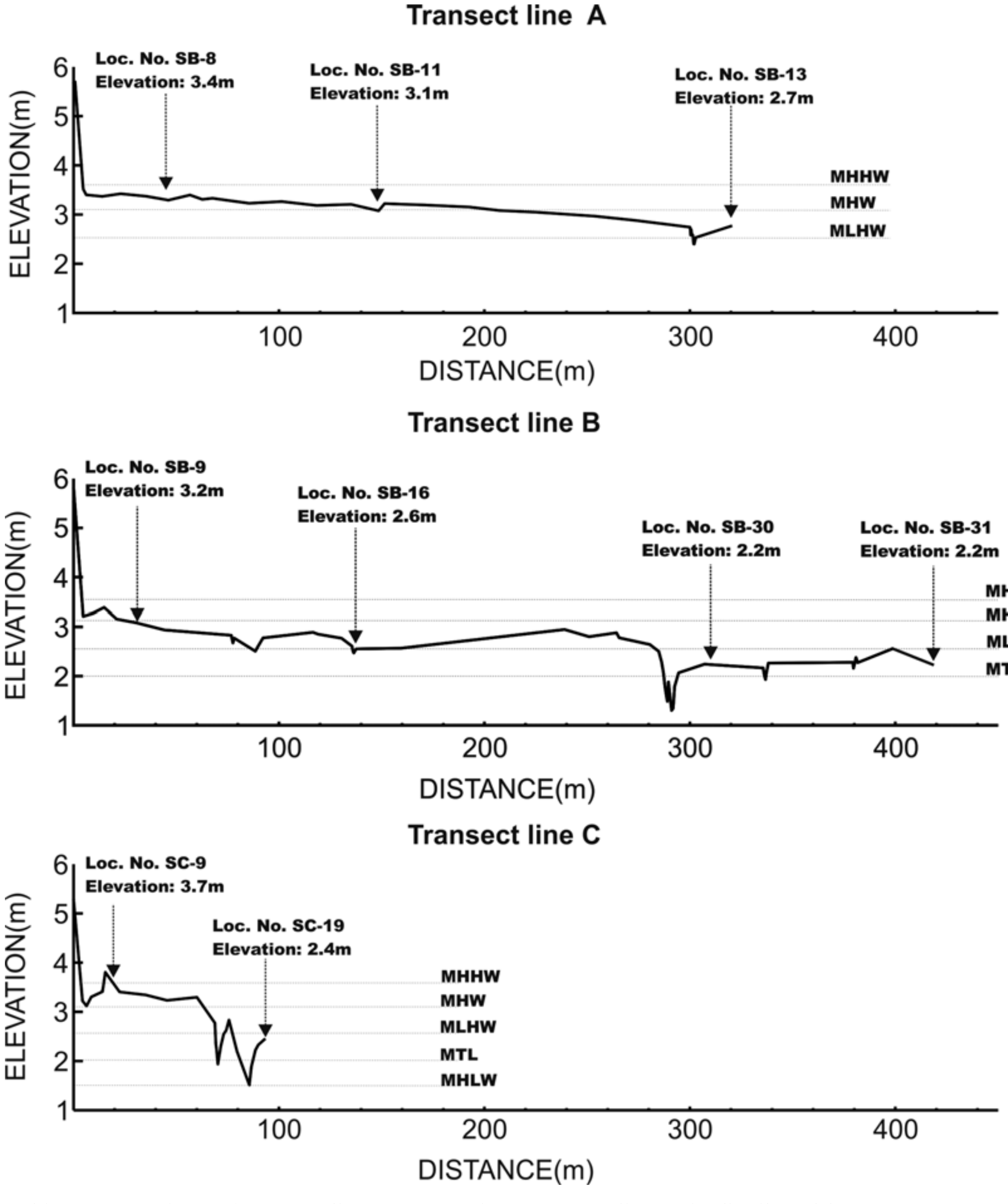

Fig. 6. Topographic cross sections of transect lines A, B, and C. Transect line A is distributed between MLHW and MHHW, and transect lines B and C are distributed between MTL and MHHW and MTL and Approx. HHW, respectively. Approx. HHW: approximate highest high water; MHHW: mean highest high water; MLHW: mean low high water; and MTL: mean tide level See Fig. 2 for sites. Site SB-8 is located at a distance of 40 m (elevation: 3.4 m) from the benchmark and is between MHW and MHHW. Sites SB-11 and 13 are located at distances of 150 m (elevation: 3.3 m) and 320 m (elevation: 2.9 m) from the benchmark and are between MLHW and MHW. Site SB-9 is 20 m (elevation: 3.2 m) from the benchmark and between MLHW and MHW. Sites SB-16, 30, and 31 are 140 m (elevation: 2.6 m), 310 m (elevation 2.2 m), and 420 m (elevation 2.2 m) from the benchmark, respectively, and are between MTL and MLHW. Site SC-9 is 20 m (elevation: 3.7 m) from the benchmark and between MHHW and Approx. HHW, and site SC-19 is 95 m (elevation: 2.4 m) from the benchmark and between MTL and MLHW

of Line B (total distance of 420 m) was distributed between MTL and MHHW and included some tidal salt marsh creeks (Fig. 6b). Site SB-9 was located at a distance of 20 m (elevation: 3.2 m) from the benchmark and between MLHW and MHW. Site SB-16 was located at a distance of 140 m (elevation: 2.6 m) from the benchmark and between MTL and MLHW. Sites SB-30 and 31 were located at a distance of 310 m (elevation: 2.2 m) and 420 m (elevation 2.2 m) from the benchmark, respectively, and between MTL and MLHW. The topographic cross section of Line C (total distance of 90 m), located in Zone B, was distributed between MTL and Approx. HHW (Fig. 6c), was geographically even in the central area, and included some tidal salt marsh creeks and a channel. Site SC-9 was located at a distance of 20 m (elevation: 3.7 m) from the benchmark and between Approx. HHW and MHHW, and site SC-19 was located at a distance of 95 m (elevation: 2.4 m) from the benchmark and between MTL and MLHW.

Benthic foraminifera of tidal salt marsh

A total of 33 species (live and dead) (17 agglutinated and 16 calcareous-hyaline) belonging to 24 genera were identified (Appendix 1). A total of 3,510 benthic foraminiferal individuals per 20 ml of sediment, which was below 1% of the total numbers at six localities (sites SB-8, 9, 10, 13, 22, and 24), was found. The proportions of agglutinated and calcareous-hyaline foraminifera were 70.5% and 29.5%, respectively. Species diversity was relatively low with an average of 1.1 (max.: 1.9 at site SB-2; min.: 0.2 at site BC-3).

Dominant species with more than 5% abundance frequency were *Ammonia beccarii* (36.6%), *Miliammina fusca* (31.2%), *Haplophragmoides wilberti* (17.3%), and *Jadammina macrescens* (5.5%). *Ammonia beccarii* occurred with very high abundance frequency (64.7%) at only site SB-31, whereas *Miliammina fusca* and *Haplophragmoides wilberti* were distributed broadly in the tidal salt marsh.

Cluster analysis using the Bray–Curtis similarity index (SI) was conducted to understand the similarity between the component species at each site using only the benthic foraminifera comprising > 1% in any one sample (Fig. 7). Twenty-two samples were categorized into three groups with SI ≈ 0.62. Cluster I, represented by *A. beccarii*, was composed of three smaller clusters (I-A, B, and C) distinguished by differences between the co-occurring species. In I-A and I-B, *A. beccarii* co-occurred with *J. macrescenes* (29.5%) and *M. fusca* (more than 31%), respectively. Sites SB-31, 27, and 26 of I-C were characterized by high abundance frequencies (more than 64%) of *A. beccarii*. Site SB-29 of I-C was characterized by the co-occurrence of *Elphidium subincertum* (34.9%). Cluster II, represented by *M. fusca,* was composed of two smaller clusters (II-A and II-B). II-A was composed of sites SB-9, 11, 24, 25, and SC-3 and was characterized by high abundance frequencies (more than 77%) of *M. fusca*.

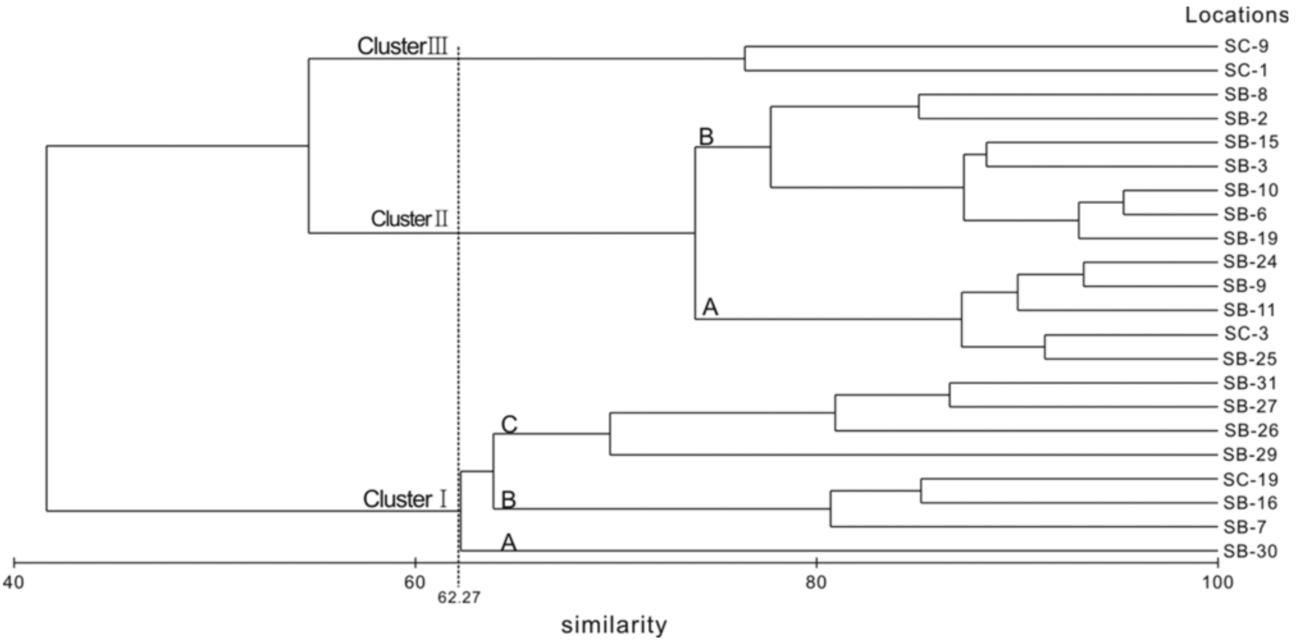

Fig. 7. Dendrogram resulting from cluster analysis on the basis of the Bray–Curtis similarity index (SI) between benthic foraminifera species and sites in the tidal salt marsh of Suncheon Bay, Korea

II-B, which was composed of sites SB-2, 3, 6, 8, 10, 15, and 19, was characterized by co-occurrence with *H. wilberti*. Cluster III, composed of sites SC-1 and SC-9, was characterized by high abundance frequency (more than 64%) of *H. wilberti*.

5. Discussion

Elevation-dependent ecological zones of benthic foraminifera

The use of salt marsh foraminifera to reconstruct relative sea level (RSL) requires that the elevation of modern assemblages be expressed relative to a tidal (e.g. MHW) rather than an orthometric (e.g. NAVD88) datum (van de Plassche 1986). The result of the topographic cross sections of transect lines A, B, and C demonstrates that the elevation of the tidal salt marsh in Suncheon Bay is distributed in four tidal levels (MTL–MLHW, MLHW–MHW, MHW–MHHW, and MHHW–Approx. HHW) (Fig. 6).

The elevation-dependent ecological zones defined using cluster analysis and tidal level are shown in Fig. 8. Sites SB-16, 19, 30, and 31 of cluster I are located between MLHW and MTL (Fig. 6). The benthic foraminifera of site SB-30 are composed mainly of *A. beccarii* with 62.8% abundance frequency and *J. macrescens* with 29.5%, and those of site SB-31 are composed mainly of *A. beccarii* with 83% abundance frequency, *H. wilberti* with 8.6%, and *J. macrescens* with 1.6%. Site SC-19 is comprised mainly of *A. beccarii* with 50.0% abundance frequency, *M. fusca* with 31.6%, and *H. wilberti* with 10.5%, and site SB-16 has *M. fusca* with 37.7% abundant frequency, *A. beccarii* with 34.7%, and *H. wilberti* with 14.3%. The benthic foraminiferal assemblage of cluster I belonging to MTL–HLHW was represented by *A. beccarii* co-occurring with *M. fusca* and/or *H. wilberti* and *J. macrescens* (Fig. 8).

A. beccarii has been considered a dominant species in nearshore, subtidal environments. The *A. beccarii* assemblage has been reported in temperate localities in the UK (Gehrels et al. 2001; Horton and Edwards 2006; Massey et al. 2006), New Zealand (Hayward and Hollis 1994; Hayward et al. 1999), and North America (Buzas et al. 2002; Horton and Culver 2008; Kemp et al. 2009a).

The sites of cluster I are located mostly at the marsh edges of the southwestern area in Zone A, which is strongly affected by flood tide, progressing in the northeastern direction from the tidal flat with relatively high salinity (about 11 psu; see Fig. 4). These areas are thought to maintain relatively higher salinity than other areas, such as the inner area, because of the characteristic of longer duration of inundation of MTL–HLHW compared with other tidal levels. In cluster I-A, *A. beccarii* co-occurs with *J. macrescens*, which is known to occur in the highest elevation zone (located at the transition between salt marsh and upland environments) of foraminifera in salt marshes (Kemp et al. 2009b). However, this cluster seems to provide very poor habitat for *J. macrescens* because the tidal current is unable to progress to the transition between salt marsh and upland environments. Thus, these *J. macrescens* co-occurring with *A. beccarii* are believed to be transported by small tidal creeks of the salt marsh during ebb tide. Cluster I-B has co-occurrence with *M. fusca,* which is a representative assemblage of MLHW–MHW. Site 16 of cluster I-B is located at the boundary line of MLHW in the inner area of

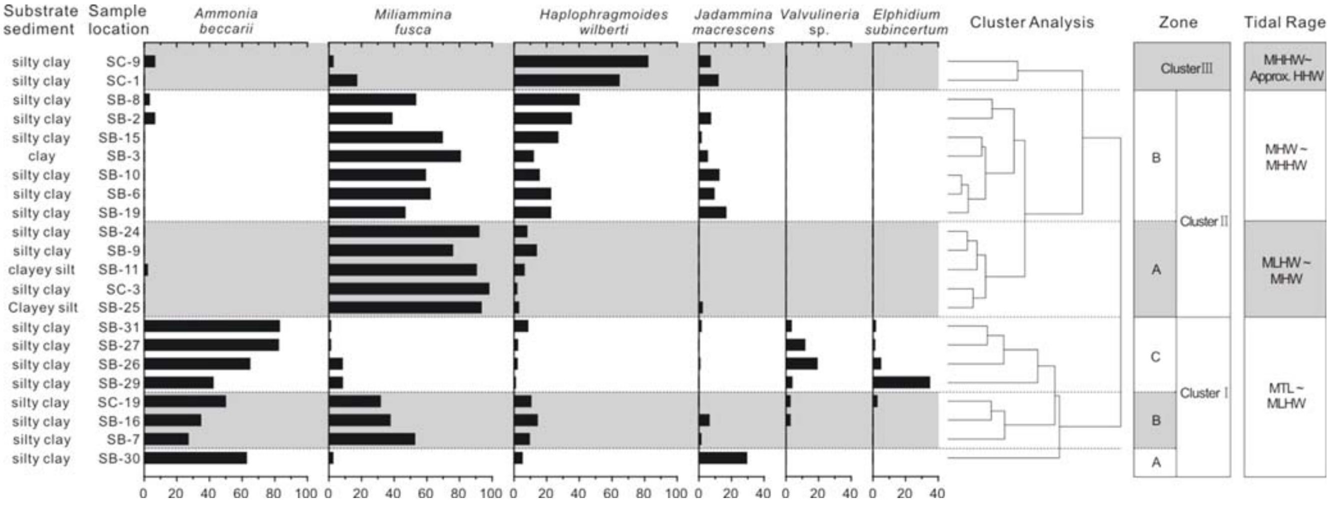

Fig. 8. Elevation-dependent ecological zones defined by cluster analysis of benthic foraminifera and tidal level, and sediment composition of substrate at tidal salt marsh of Suncheon Bay, Korea

the marsh and is affected by small tidal creeks. Murray (1991) stated that shallow estuaries and lagoons in eastern North America are only dominated by calcareous foraminifera in environments where salinity is greater than 18 psu for *Ammonia* spp. and 22 psu for *Elphidium* spp. The appearance of *M. fusca* and *A. beccarii* in cluster I-B may be due to the effect of elevation and the effect of small tidal creeks that carry relatively high-salinity water from the tidal flat during flood tide, respectively. According to Murray (1991), cluster I-C, with co-occurrence with *E. subincertum,* which is representative of foraminifera of the inner tidal flat, may be affected by the highest salinity in cluster I.

Sites SB-9 and SB-11 in cluster II-A are located between MLHW and MHW (Fig. 6). Site SB-9 is composed of 75.9% *M. fusca* and 13.8% *H. wilberti*, and site SB-11 is composed of 90.4% *M. fusca*. Although site SB-13 is located between MLHW and MHW (Fig. 6), it was not measured because of extremely low abundant frequency. Sites SB-9, 11, 24, 25, and SC-3 of cluster II-A are all located between MLHW and MHW and are characterized by *M. fusca* assemblages (Fig. 8).

The *M. fusca* assemblage has also been identified in North America by de Rijk and Troelstra (1997), Spencer (2000), Edwards et al. (2004), Patterson et al. (2000, 2005), and Kemp et al. (2009a, 2009b, 2012, 2013). Its presence was noted in the UK by Horton (1999) and Horton and Edwards (2006) and in New Zealand by Hayward and Hollis (1994) and Hayward et al. (2004). The *M. fusca* assemblage is known as a typical assemblage of areas inundated by tides on a daily basis (de Rijk 1995) and is distributed through a wide range of salinities (Murray 1991).

Site SB-8 in cluster II-B is located between MHW and MHHW (Fig. 6). It has abundances frequencies of 53.3% *M. fusca* and 40.0 % *H. wilberti*. Sites SB-2, 3, 10, 15, and 19 of cluster II-B are also located between MHW and MHHW and are characterized by *M. fusca–H. wilberti* assemblages (Fig. 8). The presence of *M. fusca* and *Haplophragmoides* spp. is usually associated with lower salinities (Hayward et al. 2004). Hayward et al. (1996, 1999) stated that the *Miliammina* assemblage occurs below MHW, whereas the *Haplophragmoides* assemblage occurs predominantly above MHW, although *H. wilberti* and *M. fusca* are well documented as obligate brackish water inhabitants around New Zealand (Hayward and Hollis 1994). However, the *M. fusca–H. wilberti* assemblage of the present study occurs above MHW.

Site SC-9, which has abundance frequencies of 82.2% *H. wilberti* and 7.0% *J. macrescens*, and site SC-1 of cluster III are both located between the tidal levels of MHHW and Approx. HHW (Fig. 6) and characterized by the *H. wilberti* assemblage (Fig. 8). The *H. wilberti* assemblage is considered to be a dominant assemblage in high marsh environments (Horton and Edwards 2005; Massey et al. 2006; Horton and Culver 2008; Kemp et al. 2009a).

The foraminiferal assemblages of the tidal salt marsh in Suncheon Bay seem to be linked with tidal level. Horton and Culver (2008) and Kemp et al. (2009a) stated that the distribution of modern salt-marsh foraminifera is controlled by the elevation of the tidal flat. In particular, the *Haplophragmoides* assemblage has been considered to represent the highest elevation zone of foraminifera on the salt marshes in Suncheon Bay and is thought to be a precise sea-level indicator because of its narrow vertical range.

Kemp et al. (2009b) stated that salt marsh foraminifera in the Albemarle-Pamlico estuarine system of North Carolina have distinctive spatial distributions reflecting the pattern of salinity regimes. High-salinity marshes are dominated by *M. fusca* in low marshes and *H. wilberti* in high marshes. In contrast, lower-salinity marshes have *Ammobaculities* spp. In subtidal settings, *M. fusca*-dominated low marsh and high marsh are also characterized by *J. macrescens*. The distribution pattern of elevation-dependent ecological zones in the salt marsh of Suncheon Bay shows the characteristics of high-salinity marsh.

It is known that an absence of calcareous taxa occurs in areas that have elevation higher elevation than MLHW and that these areas are dominated by agglutinated species such as *M. fusca*, *H. wilberti*, and *J. macrescens* (Kemp et al. 2012). The percentages of agglutinated and calcareous-hyaline foraminifera in the present study were 70.5% and 29.5%, respectively. Calcareous foraminifera, which were composed mainly of *A. beccarii,* were distributed between MTL and MLHW. These results concur well with those of Kemp et al. (2012).

Marsh foraminiferal habitat of Suncheon Bay

The environmental parameters controlling the distribution patterns of marsh foraminifera include flooding frequency, salinity, substrate, vegetation, and food source (de Rejk and Troelstra 1997).

The substrate of the tidal salt marsh in which foraminifera live in Suncheon Bay consists mostly of silty clay. This fine-grained sediment is supplied by flood tidal currents with high concentrations of suspended sediments acquired from the muddy tidal flat and generated by waves within the bay caused by strong winds or storms (Lee et al. 2013). It is generally known that the foraminifera inhabiting the substrate use mainly a clayey or silty grain size to build their agglutinated tests (de Rijk and Troelstra 1997). The present study does not show an interrelationship between sediment composition of substrate, foraminiferal distribution, and tidal level (Fig. 8), although the foraminifera inhabiting the substrate consist mainly of a fine-grained silty clay material.

Foraminifera live as epifauna or as infauna between the roots of salt marsh vegetation (Lee and Anderson 1991), and the composition or density of marsh grasses can influence foraminiferal occurrence. The marsh grasses in Suncheon Bay are dominantly *Phragmites australis* with some *Phacelurus latifolius* at slightly high elevations around levees. *Suaeda japonica* and *Carex scabrifolia* are also found around *Phragmites australis* areas. The density and height of the marsh grasses are 119 shoots m^{-2} and 155.4 ± 32.5 cm, respectively (Lee et al. 2008). These marsh grass conditions are thought to offer good habitat for foraminiferal growth and reproduction. The cause of the extremely low abundance frequency at sites SB-13 and SB-22 may be related to the incomplete development of the marsh grasses.

Salinity is also a major factor controlling the distribution of foraminifera (de Rejk 1995), although the distribution of marsh foraminifera is strongly affected by their tidal-level elevation (Hayward et al. 2004; Kemp et al. 2009a), and local physiography, storms, hydrology, and plant productivity have effects. Salinity is determined by the relative influence of marine water and fresh water. Salt marshes are subjected to daily and seasonal variations in salinity and other parameters linked to tidal inundation. Flooding of the salt marsh surface is the primary factor controlling salinity and is described according to the frequency and duration of inundation as well as the salinity of the inundating water. The flooding characteristics of a salt marsh are complex and highly variable at even local scales as a result of topography and drainage channels (Van der Molen 1997).

Suncheon Bay receives most of its fresh water as inflow from the Dong and Isa streams in the northeastern area, which contribute fresh water at a rate of 2,945.45 m^3/s (average volume of 2007 to 2008; K-water 2007, 2008). The streams flow into the tidal flat during ebb tide via the channel, but remain at midstream levels during flood tide (Lee et al. 2013). The tidal current mixed with fresh water at flood tide reduces the salinity of seawater and inflows mostly into the northeastern area where there is a broadly distributed tidal salt marsh. It is currently assumed that the salinity of the tidal salt marsh in Suncheon Bay may be between about 5 and 11 psu (see Fig. 4). The interrelationship between the distribution of benthic foraminifera, tidal level, and salinity in the tidal salt marsh of Suncheon Bay may be described as follows.

The southwestern area of the salt marsh, initially affected by the tidal current, formed at the tidal level of MTL–MLHW and is characterized by the *A. beccarii* assemblage. With the progression of the tidal current toward the inner area of the salt marsh, the *M. fusca* assemblage and the *M. fusca–H. wilberti* assemblage characterize the areas belonging to the MLHW–MHW and MHW–MHHW tide levels, respectively (Fig. 9). On the other hand, the *H. wilberti* assemblage occurs in the landward margins of the salt marsh belonging to the MHHW–Approx. HHW tide level, which is less affected by tidal current and salinity.

6. Conclusion

The identification of elevation-dependent ecological zones at individual localities implies that the salt marsh foraminifera in Suncheon Bay are appropriate for use as indicators to reconstruct Holocene RSL. The *Ammonia beccarii* assemblage indicates the MTL–MLHW tidal level, and the *M. fusca, M. fusca–H. wilberti*, and *H. wilberti* assemblages reflect the MLHW–MHW, MHW–MHHW, and MHHW–Approx. HHW levels, respectively. Of particular significance is the *H. wilberti* assemblage that is considered to be the highest elevation zone of foraminifera on the salt marshes in Suncheon Bay and can be used as a precise indicator of sea level as a result of its narrow vertical range.

Our research provides the first results from benthic foraminifera of salt marshes in South Korea. Additionally, studies conducted in the Pacific Rim represent a small minority of such studies; therefore, the present study helps compensate for the skewed spatial distribution of reliable Holocene sea level reconstructions.

Acknowledgements

We appreciate Dr. Kim from Chonnam National University and Dr. Woo from Korea Institute of Ocean Science and Technology for their valuable discussion. We also thank the two anonymous referees for this paper for their thorough reviews and constructive remarks. This study was supported financially by Chonnam National University, 2014. This research was supported by Golden Seed Project, Ministry of Agriculture, Food and Rural Affairs (MAFRA), Ministry of Oceans and Fisheries (MOF), Rural Development Administration (RDA) and Korea Forest Service (KFS).

References

Alve E (1995) Benthic foraminiferal responses to estuarine pollution: a review. J Foramin Res **25**:190–203

Asano K (1950a) Illustrated catalogue of Japanese Tertiary smaller Foraminifera. Part 1: Nonionionidae. Hosokawa Printing Co, Tokyo

Asano K (1950b) Illustrated catalogue of Japanese Tertiary smaller Foraminifera. Part 2: Buliminidae. Hosokawa Printing Co, Tokyo

Asano K (1950c) Illustrated catalogue of Japanese Tertiary smaller Foraminifera. Part 3: Textulariidae. Hosokawa Printing Co, Tokyo

Asano K (1950d) Illustrated catalogue of Japanese Tertiary smaller Foraminifera. Part 4: Valvulinidae. Hosokawa Printing Co, Tokyo

Asano K (1950e) Illustrated catalogue of Japanese Tertiary smaller Foraminifera. Part 5: Verneuilinidae. Hosokawa Printing Co, Tokyo

Barbosa CF, Scott DB, Seoane JCS, Turcq BJ (2005) Foraminiferal zonations as base lines for quaternary sea-level fluctuations in souths-southeast Brazilian mangroves. J Foramin Res **35**: 22–43

Berkeley A, Perry CT, Smithers SG (2009) Taphonomic signatures and patterns of test degradation on tropical, intertidal benthic foraminifera. Mar Micropaleontol **73**:148–163

Buzas MA, Hayek LC, Reed SA, Jett JA (2002) Foraminiferal densities over five years in the Indian River Lagoon, Florida: a model of pulsating pateches. J Foramin Res **32**:68–93

Callard SL, Gehrels WR, Morrison BV, Grenfell HR (2011) Suitability of salt–marsh foraminifera as proxy indicators of sea level in Tasmania. Mar Micropaleontol **79**:121–131

de Rijk S (1995) Salinity control on the distribution of salt marsh foraminifera (Great Marshes, Massachusetts). J Foramin Res **25**:156–166

de Rijk S, Troelstra SR (1997) Salt marsh foraminifera from the Great Marshes. Massachusetts: environmental controls. Palaeogeogr Palaeocl **30**:81–112

Edwards RJ, Wright AJ, van de Plassche O (2004) Surface distributions of salt-marsh foraminifera from Connecticut. USA: modern analogues for high resolution sea level studies. Mar Micropaleontol **51**:1–21

Fatela F, Taborda R (2002) Confidence limits of species proportions in microfossil assemblages. Mar Micropaleontol **45**:169–174

Folk RL (1968) Petrology of sedimentary rocks. Hemphill Publishing, Texas, 170 p

Gehrels WR (1994) Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, U.S.A. J Coastal Res **10**:990–1009

Gehrels WR (2007) Sea level studies: microfossil reconstructions. In: Elias SA (ed) Encyclopedia of quaternary science. Elsevier, Oxford, pp 3015–3024

Gehrels WR, Roe HM, Charman DJ (2001) Foraminifera, testate amoebae and diatoms as sea-level indicators in UK salt marshes: a quantitative, multiproxy approach. J Quaternary Sci **16**:201–220

Gehrels WR, van de Plassche O (1999) The use of *Jadammina macrescens* (Brady) and *Balticammina pseudomacrescens* Brönnimann, Lutze and Whittaker (Protozoa: Foraminiferida) as sea-level indicators. Palaeogeogr Palaeocl **149**:89–101

Hawkes AD, Horton BP, Nelson AR, Hill DF (2010) The application of intertidal foraminifera to reconstruct coastal subsidence during the giant Cascadia earthquake of AD 1700 in Oregon, USA. Quatern Int **221**:116–140

Hayward BW, Hollis CJ (1994) Brackish foraminifera in New Zealand: a taxonomic and ecological review. Micropaleontology **40**:185–222

Hayward BW, Grenfell HR, Cairns G, Smith A (1996) Environmental controls on benthic foraminiferal and thecamoebian associations in a tidal New Zealand inlet. J Foramin Res **26**:150–171

Hayward BW, Reid CM, Scott DB (1999) Tidal range of marsh foraminifera for determining former sea-level height in New Zealand. New Zeal J Geol Geop **42**:395–413

Hayward BW, Scott GC, Grenfell HR, Carter R, Lipps JH (2004) Techniques for estimation of tidal elevation and confinement (~salinity) histories of sheltered harbours and estuaries using benthic foraminifera: examples from New Zealand. The Holocene **14**:218–232

Horton BP (1999) The distribution of contemporary intertidal foraminifera at Cowpen Marsh, Tees Estuary, UK: implications for studies of Holocene sea-level changes. Palaeogeogr Palaeocl **149**:127–149

Horton BP, Culver SJ (2008) Modern intertidal foraminifera of the Outer Banks, North Carolina, U.S.A., and their applicability for sea-level studies. J Coastal Res **24**:1110–1125

Horton BP, Edwards RJ (2003) Seasonal distributions of foraminifera and their implications for sea-level studies, Cowpen Marsh, U.K. In: Olson HC, Leckie RM (eds) Micropaleontologic proxies for sea-level change and stratigraphic discontinuities. SEPM Special Publication 75, pp 21–30

Horton BP, Edwards RJ (2005) The application of local and regional transfer functions to the reconstruction of Holocene sea levels, north Norfolk, England. Holocene **15**:216–228

Horton BP, Edwards RJ (2006) Quantifying Holocene sea level change using intertidal foraminifera: lessons from the British Isles. Cushman Foundation for Foraminiferal Research, Special Publication 40, 97 p

Horton BP, Edwards RJ, Lloyd JM (1999) A foraminiferal-based transfer function: implications for sea-level studies. J Foramin Res **29**:117–129

Ingram RL (1971) Sieve analysis. In: Carver RE (ed) Procedures in sedimentary petrology. Willey, New York, pp 49–67

Jennings AE, Nelson AR (1992) Foraminiferal assemblage zones in Oregon tidal marshes; relation to marsh floral zones and sea level. J Foramin Res **22**:13–29

K-water (2007) Juam Regulating Dam annual administration report. K-water, 376 p (in Korean)

K-water (2008) Juam Regulating Dam annual administration report. K-water, 362 p (in Korean)

Kemp AC, Engelhart SE, Culver SJ, Nelson A, Briggs RW, Haeussler PJ (2013) Modern salt-marsh and tidal flat foraminifera from Sitkinak and Simeonof Islands, southwestern Alaska. J Foramin Res **43**:88–98

Kemp AC, Horton BP, Corbett DR, Culver SJ, Edwards RJ, van de Plassche O (2009a) The relative utility of foraminifera and diatoms for reconstructing late Holocene sea-level change in North Carolina, USA. Quaternary Res **71**:9–21

Kemp AC, Horton BP, Culver SJ (2009b) Distribution of modern salt-marsh foraminifera in the Albemarle-Pamlico estuarine system of North Carolina, USA: implications for sea-level research. Mar Micropaleontol **72**:222–238

Kemp AC, Horton BP, Vann DR, Engelhart SE, Grand Pre CA, Vane CH, Nikitina D, Anisfeld SC (2012) Quantitative vertical zonation of salt-marsh foraminifera for reconstructing former sea level: an example from New Jersey, USA. Quaternary Sci Rev **54**:26–39

KHOA (2012) Subject map of marine science in Korea. Korea Hydrographic and Oceanographic Administration, 115 p

Lee JJ, Anderson OR (1991) Biology of foraminifera. Academic Press, London, 368 p

Lee YG, Kim S, Jeong DU, Kim JK, Woo HJ (2013) Effects of heavy rain fall on sedimentation in the tidal salt marsh of Suncheon Bay, South Korea. J Coastal Res **29**:566–578

Lee YG, Kim S, Lee HW, Min BM (2008) Chemical properties of sediment and increase of reed (*Phragmites australis*) stands at Suncheon Bay. J Wetlands Res **10**:9–26

Leorii E, Gehrels WR, Horton BP, Fatela F, Cearreta A (2010) Distribution of foraminifera in salt marshes along the Atlantic coast of SW Europe: tools to reconstruct past sea-level variations. Quatern Int **221**:104–115

Massey AC, Gehrels WR, Charman DJ, White SV (2006) An intertidal foraminifera based transfer function for reconstructing Holocene sea-level changes in southwest England. J Foramin Res **36**:215–232

Matoba Y (1970) Distribution of recent shallow water foraminifera of Matsushima Bay, Miyagi Prefecture, northeast Japan. Sci Rep Tohoku Univ **42**:1–85

MOMAF (2001) Studies on inventories and a sustainable use of tidal flats in Korea. Ministry of Maritime Affairs & Fisheries, 1214 p

Murray JW (1991) Ecology and palaeoecology of benthic foraminifera. Longman Scientific and Technical, Harlow, 408 p

Murray JW (2006) Ecology and applications of benthic foraminifera. Cambridge University Press, New York, 426 p

Patterson RT, Guilbault JP, Clague JJ (1999) Taphonomy of tidal marsh foraminifera: implications of surface sample thickness for high-resolution sea-level studies. Palaeogeogr Palaeocl **149**:199–211.

Patterson RT, Huchinson I, Guilbault JP, Clague JJ (2000) A comparison of the vertical zonation of diatom, foraminifera and macrophyte assemblages in a coastal marsh: implications for great paleo-sea level resolution. Micropaleontology **46**:229–244

Patterson RT, Dalby AP, Roe HM, Guilbault JP, Huchinson I, Clague JJ (2005) Relative utility of foraminifera, diatoms and macrophytes as high resolution indicators of paleo-sea level in coastal British Columbia, Canada. Quaternary Sci Rev **24**:2002–2014

Pielou EC (1966) The measurement of diversity in different types of biological collection. J Theor Biol **13**:131–144

Scott DB, Medioli FS (1978) Vertical zonation of marsh foraminifera as accurate indicators of former sea-levels. Nature **272**:528–531

Scott DB, Medioli FS (1980) Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. Cushman Foundation for Foraminiferal Research, Special Publication 17, 58 p

Scott DB, Medioli FS, Schafer CT (2001) Monitoring in coastal environments using foraminifera and thecamoebian indicators. Cambridge University Press, Cambridge, 192 p

Shannon CE, Weaver W (1963) The mathematical theory of communication. University Illinois Press, Urbana, 125 p

Southall KE, Gehrels WR, Hayward BW (2006) Foraminifera in a New Zealand salt marsh and their suitability as sea-level indicators. Mar Micropaleontol **60**:167–179

Spencer RS (2000) Foraminiferal assemblages from a Virginia salt marsh, Philips Creek, Virginia. J Foramin Res **30**:143–155

Van der Molen J (1997) Tides in a salt-marsh (Great Marshes, Barnstable, Cape Cod, USA). Ph.D. Thesis, University of Amsterdam, 104 p

Van de Plassche O (1986) Sea-level research: a manual for the collection and evaluation of Data. Geobooks, Norwich, 618 p

Varekamp JC, Thomas E (1998) Climate change and the rise and fall of sea level over the millennium. Eos Trans Amer Geophys Union **79**:69–75

Walton WR (1952) Techniques for recognition of living foraminifera. Contr Cushman Found Foraminif Res **3**:56–60

Appendix 1. Species list and statistical analysis of benthic foraminifers in tidal salt marsh of Suncheon Bay, Korea

SITE	SB-2	SB-3	SB-6	SB-7	SB-8	SB-9	SB-10	SB-11	SB-13	SB-15	SB-16	SB-19	SB-22	SB-24	SB-25	SB-26	SB-27	SB-29	SB-30	SB-31	SC-1	SC-3	SC-9	SC-19
Agglutinated Foram																								
Arenoparella mexicana												9.2												
Ammobaculites sp.				1.4																				
Balticammina pseudomacrescens		0.7				6.9				1.6	1.1	1.4			1.5								1.1	
Centropyxis sp.	3.7																	0.9						
Diffugia sp.	0.9	0.7					6.3		33.3			0.2												
Discorbis sp.																		0.9						
Haplophragmoides wilberti	35.2	11.9	22.6	9.5	40.0	13.8	15.6	6.4		27.0	14.3	22.6		8.0	2.9	2.1	2.4	0.9	5.1	8.6	64.5	1.9	82.2	10.5
Jadammina macrescens	7.4	5.3	9.4	1.4			12.5			1.6	6.4	16.8			2.2	0.7			29.5	1.6	11.8		7.0	
Miliammina fusca	38.9	80.8	62.3	52.7	53.3	75.9	59.4	90.4	33.3	69.7	37.7	46.8	0.0	92.0	93.4	8.3	1.2	8.5	2.6	1.2	17.2	98.1	2.7	31.6
Pseudothurammina sp.	1.9		3.8	1.4	3.3		3.1				0.5	0.9								0.1				
Saccammina sp.		0.7		4.1				1.1			0.8	0.2					1.2			0.4	4.3			2.6
Spiroplectammina sp.																					1.1			
Trochammina inflata											0.5	0.2												
Trochammina macrescens												1.6												
Trochammina sp.	1.9			1.4			3.1																	
Calcareous-Hyaline Foram																								
Ammonia beccarii	6.5			27.0	3.3			2.1	33.3		34.7		66.7			64.8	82.4	42.5	62.8	83.0			6.5	50.0
Elphidium advenum	0.9																							
Elphidium clavatum																		0.9						
Elphidium subincertum											0.3					4.8	1.2	34.9		1.7				2.6
Elphidium sp.											0.5													
Fissurina sp.											0.3													
Gyroidinoides nipponicus																					1.1			
Helenina anderseni											0.3													
Hyalinea sp.																		0.9						
Pseudoparella naraensis	0.9																	1.9						
Pseudoparella tamana																		0.9						
Pseudorotalia gaimardii			1.9																					
Rosalina sp.	1.9																							
Uvigerinella glabra																		1.9						
Valvulineria sp.											2.7		33.3			19.3	11.8	3.8		3.4			0.5	2.6
Valvulineria japonica																		0.9						
Miscellaneous				1.4		3.4																		
No of B. Foram	108	151	53	74	30	29	32	94	3	122	377	434	3	25	136	145	85	106	78	1001	93	108	185	38
No. of P. Foram	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
R. of Agglutinated Foram (%)	89.8	100	98.1	71.6	96.7	96.6	100	97.9	66.7	100	61.3	100	0	100	100	11.0	4.7	11.3	37.2	11.9	98.9	100	93.0	44.7
R. of Cal.-Hyaline Foram (%)	10.2	0	1.9	28.4	3.3	3.4	0	2.1	33.3	0	38.7	0	100	0	0	89.0	95.3	88.7	62.8	88.1	1.1	0	7.0	55.3
Species Number S	11	6	5	8	4	3	6	4	3	4	13	10	2	2	4	6	6	13	4	8	6	2	6	6
Species Diversity H(s)	2.1	1.0	1.0	1.6	0.9	0.6	1.4	0.7	1.8	0.6	2.0	1.5	0.9	0.3	0.6	1.0	1.1	2.6	0.7	1.0	1.1	0.2	1.0	1.4
Evenness J	0.7	0.4	0.7	0.6	0.7	0.6	0.7	0.3	1.0	0.5	0.6	0.6	0.9	0.4	0.2	0.6	0.4	0.6	0.6	0.3	0.6	0.1	0.4	0.7