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Benthic foraminiferal assemblages in Osaka Bay, southwestern Japan: faunal changes over the last 50 years

AKIRA TSUJIMOTO[1], RITSUO NOMURA[2], MORIAKI YASUHARA[3], AND SHUSAKU YOSHIKAWA[1]

[1]*Division of Biology and Geosciences, Graduate School of Science, Osaka City University, Osaka, 558-8585, Japan (e-mail: tujimoto@sci.osaka-cu.ac.jp)*

[2]*Foraminiferal Laboratory, Faculty of Education, Shimane University, Matsue, Shimane, 690-8504, Japan*

[3]*926A U.S. Geological Survey, Reston, VA 20192, United States/JSPS (the Japan Society for the Promotion of Science) Postdoctoral Fellow for Research Abroad*

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Abstract. Live benthic foraminiferal assemblages from surface sediment in Osaka Bay collected in 1999 were analyzed to characterize the distribution of the modern foraminiferal assemblages. Foraminiferal assemblages were compared with those of previous studies to document environmental changes in Osaka Bay over the past 50 years.

Sixty-one species of foraminifera belonging to 37 genera were recognized from the 1999 surface sediment samples. An agglutinated assemblage containing *Trochammina hadai* and *Eggerella advena* is dominant in the inner part of the bay and is related to eutrophication. The foraminiferal assemblage in areas deeper than about 20 m is composed of *Eggerella advena*, *Ammonia beccarii* forma A, and *Pseudorotalia gaimardii*. This assemblage may be influenced by the large clockwise Okinose Circulation Current which extends throughout the western bay.

Foraminiferal assemblages in Osaka Bay have changed dramatically during the last 50 years. The *Trochammina hadai-Eggerella advena* assemblage became established in the inner part of the bay, reflecting eutrophication that progressed from the 1960s through the 1970s. This assemblage became dominant in 1983, and typically dominated the inner part of the bay. From 1983 to 1999, however, the abundance of taxa belonging to this assemblage decreased greatly following implementation of 1973 Osaka City bylaws that restricted wastewater discharge. Changes in benthic assemblages such as the decrease of *Ammonia beccarii* forma A and increase of *Eggerella advena* have occurred in response to decreased incidence of red tides, and floral change in the species that cause these tides. The results of this study demonstrate that the abundance and distribution of benthic foraminifers in Osaka Bay are intimately related to environmental changes related to the urbanization of coastal areas.

Key words: benthic foraminifera; eutrophication; Japan; Osaka Bay; pollution

Introduction

Coastal areas have suffered environmental damage from pollution associated with industrialization and urbanization over the past few centuries, and foraminiferal assemblages in coastal areas have changed in response. Many studies have been carried out in various areas using foraminifera as bioindicators of marine pollution from sewage, heavy metals, oil, and aquaculture, as summarized by Yanko *et al.* (1994, 1999) and Alve (1995a). The main purpose of these studies was to clarify the relationship between foraminiferal distributions or morphological abnormalities of foraminiferal tests and the various sources of pollution (e.g., Geslin *et al.*, 1998, 2002; Yanko *et al.*, 1998; Angel *et al.*, 2000; Coccioni, 2000; Samir, 2000; Debenay *et al.*, 2001; Samir and El-Din, 2001). Other studies have addressed historical changes of foraminiferal assemblages from the viewpoint of anthropogenic pollution (e.g., Alve, 1991; Thomas *et al.*, 2000; McGann *et al.*, 2003). Elimination of foraminiferal assemblages with increased input of organic materials and chemical pollutants has also been reported from an estuary in Spain (Cearreta *et al.*, 2000).

Pollution has become severe in bays close to large cities such as Tokyo and Osaka due to increasing population, industrialization, and urbanization since the Meiji Restoration of 1867. In Osaka Bay, increased marine pollution has mirrored population increase from around A.D. 1900 onward (Nakatsuji *et al.*, 1998). Pollution peaked during the 1960s to 1970s, when several large-scale land reclamation, industrialization and urbanization projects were undertaken in the coastal zone (Association for New Social Infrastructure of Osaka Bay, 1996). As an example, the occurrence of red tides increased rapidly (Joh, 1986). In addition, anoxia or hypoxia of the bottom layer developed in the inner part of Osaka Bay (Joh, 1986). Benthic ecosystems have been strongly influenced by this bottom water hypoxia (Association for New Social Infrastructure of Osaka Bay, 1996). After about 1970, a national conservation effort placed restrictions on the discharge of substances capable of increasing Chemical Oxygen Demand (COD). However, no actual improvement in water quality (e.g., phosphorus, nitrogen) was reported during the following decade (Association for New Social Infrastructure of Osaka Bay, 1996).

Three studies have addressed the spatial distribution of benthic foraminifera in Osaka Bay (Takayanagi, 1953; Nakaseko, 1953; Konda and Chiji, 1987), using bottom sediment samples collected in 1933, 1952, and 1983, respectively. Takayanagi (1953) only dealt with the southern part of Osaka Bay. The other two reports have greater coverage. Together, they provide useful documentation of the changes in the foraminiferal assemblages in Osaka Bay over the past 50 years.

Environmental setting

Osaka Bay is located at the eastern end of the Seto Inland Sea. The bay is elliptical, with a longer axis of about 60 km and a shorter axis of about 30 km (Figure 1). The bay is about 1500 km^2 in area, and is about 20 m in mean depth. The 20 m isobathymetric line runs approximately north to south in its central part. The seabed at depths shallower than 20 m is relatively flat in comparison with the seabed at depths greater than 20 m. Sediments at depths greater than 20 m consist of sand or gravel, whereas muddy sediment occurs at depths shallower than 20 m. Osaka Bay is almost enclosed, and is connected to Harima-nada Bay and the Kii Channel through the Akashi and Tomogashima Straits, respectively. Two currents occur within Osaka Bay: the Okinose Circulation and East Coast Residual Currents. The Okinose Circulation Current is a large clockwise current in central Osaka Bay. The East Coast Residual Current flows along the bay's eastern margin (Figure 1). The properties of both the water and bottom sediment are influenced by these tidal currents (Fujiwara, 1995).

COD, phosphorus, and nitrogen concentrations are high in the inner part of the bay throughout the year (Figure 2). Productivity of phytoplankton is high in the inner part of the bay, and red tides occur frequently (Association for New Social Infrastructure of Osaka Bay, 1996). These facts result from drainage from households and factories flowing in through the Yodo River, the Yamato River, and other rivers, in addition to stagnant sea water from the inner part to the eastern part of Osaka Bay (Association for New Social Infrastructure of Osaka Bay, 1996). During summer the surface water is saturated in dissolved oxygen due to phytoplanktonic photosynthesis. Stratification occurs in summer, and no oxygen is supplied to the bottom layer from the surface water. In addition, oxygen is consumed by decomposition of descending organic matter. Consequently, the bottom layer reaches a state of anoxia or hypoxia (Association for New Social Infrastructure of Osaka Bay, 1996; Figure 2). Conversely, COD, phosphorous concentration, and nitrogen concentration are comparatively low in the western part of the bay because there are few corrupting inflows in that area, and seawater is actively exchanged (Figure 2).

Samples and methods

Twenty-seven samples (st. 1–8, 10–12, 14, 16–30) were collected by the Marine Ecological Institute Co. on May 26–29 1999, using Ekman-Birge and Smith-McIntyre grab samplers (Figure 1; Hongo and Nakajo, 2003). The basic parameters of sampling sites are shown in Figures 3 and 4. Only the uppermost centimeter of the sediment was used in this study. In the laboratory, samples were washed through a 63 μm sieve. The residues were stained with Rose Bengal solution for 12 h to distinguish live individuals from dead individuals (Walton, 1952). Foraminiferal assemblages were analyzed in the >105 μm fraction and samples containing abundant foraminiferal tests were split for counts of about 200 specimens. We largely followed the taxonomy of Loeblich and Tappan (1988) for the determination of foraminifera. We also examined both live and dead foraminiferal assemblages to establish the difference between them. Although all previous studies in Osaka Bay except that of Konda and Chiji (1987) were based on the total assemblage, we regard the live specimens as representing the modern assemblage. Murray (2000) and Debenay *et al.* (2001) suggested that the total assemblage may be affected by various taphonomic processes (e.g., transport, dissolution of calcareous tests) and represent the average of

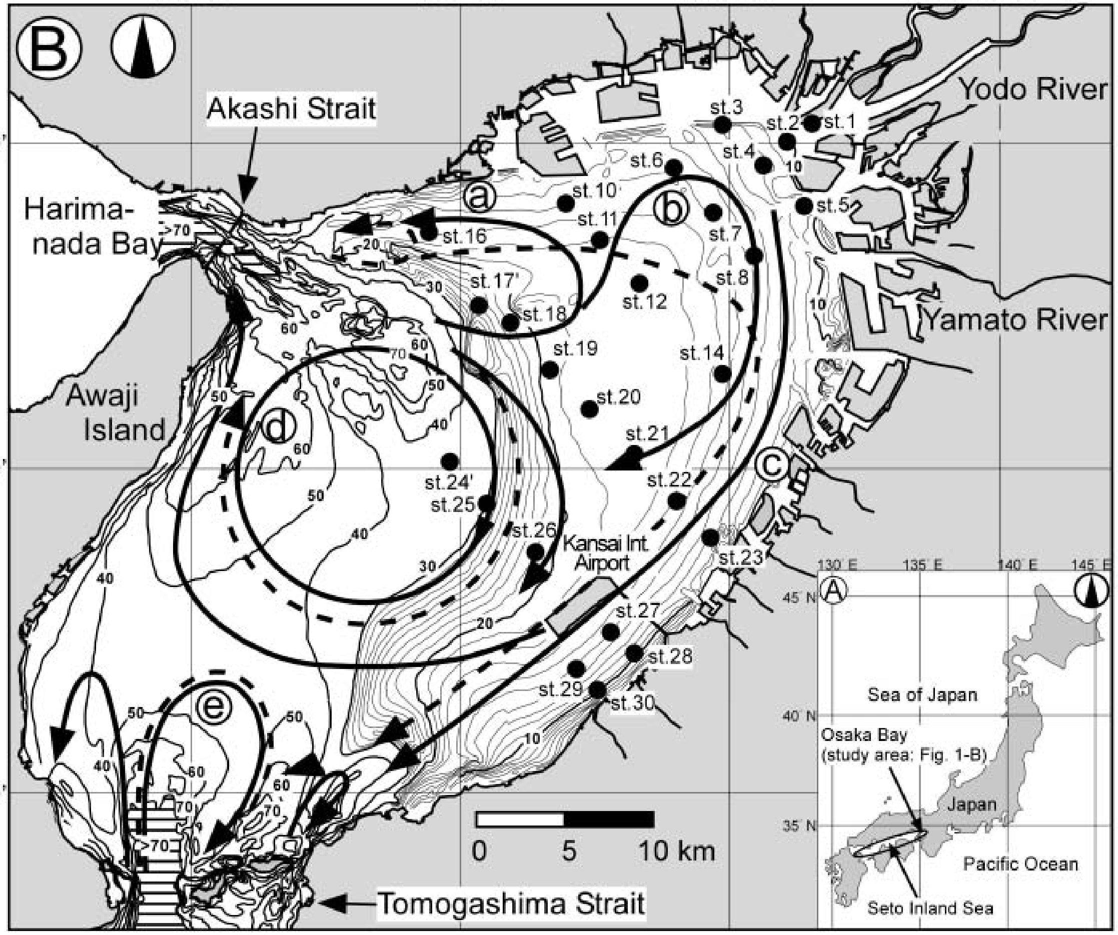

Figure 1. Maps showing location (A) and bathymetry (B) of Osaka Bay, including foraminiferal samples used in this study, and the direction of residual currents (solid line, surface current; dashed line, bottom current). Bathymetric data in meters from Japan Coast Guard (1978, 1995, 1997). Residual currents from Fujiwara *et al.* (1989): a, Suma Counter Current; b, Off Nishinomiya Circulation Current; c, East Coast Residual Current; d, Okinose Circulation Current; e, Tomogashima Counter Current.

previous live assemblages over several years. Consequently, Murray (2000) suggested that ecological studies should be based on the live assemblage. The sedimentation rate in Osaka Bay is quite high, and differs within a range of 0.2–0.8 g/cm^2/year (Hoshika *et al.*, 1994). If we utilize the total assemblage for comparison with previous studies, the total assemblage may lead to inaccurate information about the present environment. However, Debenay *et al.* (2001) also suggested that a sampling bias might be introduced by using seasonal live assemblages due to the foraminiferal life cycle. Therefore, we evaluated differences between live and dead assemblages.

The Shannon-Wiener diversity index (Shannon and Weaver, 1949) was used to evaluate the assemblages. This index incorporates the number of individuals as well as the number of taxa. We calculated diversity using samples containing more than 50 individuals to obtain the foraminiferal diversity distribution. The Shannon-Wiener index is given as:

$$H = -\sum_{i=1}^{S}(P_i)(\ln P_i),$$

where H = index of species diversity; S = number of species observed in a sample; and P_i = proportion of each species.

A Q-mode cluster analysis was also performed using PAST ver. 0.95 (http://folk.uio.no/ohammer/past/) to recognize sample affinities according to species composition. This is a data analysis package intended for paleontology, and includes common statistical, plotting and modeling functions (Hammer *et al.*, 2001). Species with three or more individuals in any samples

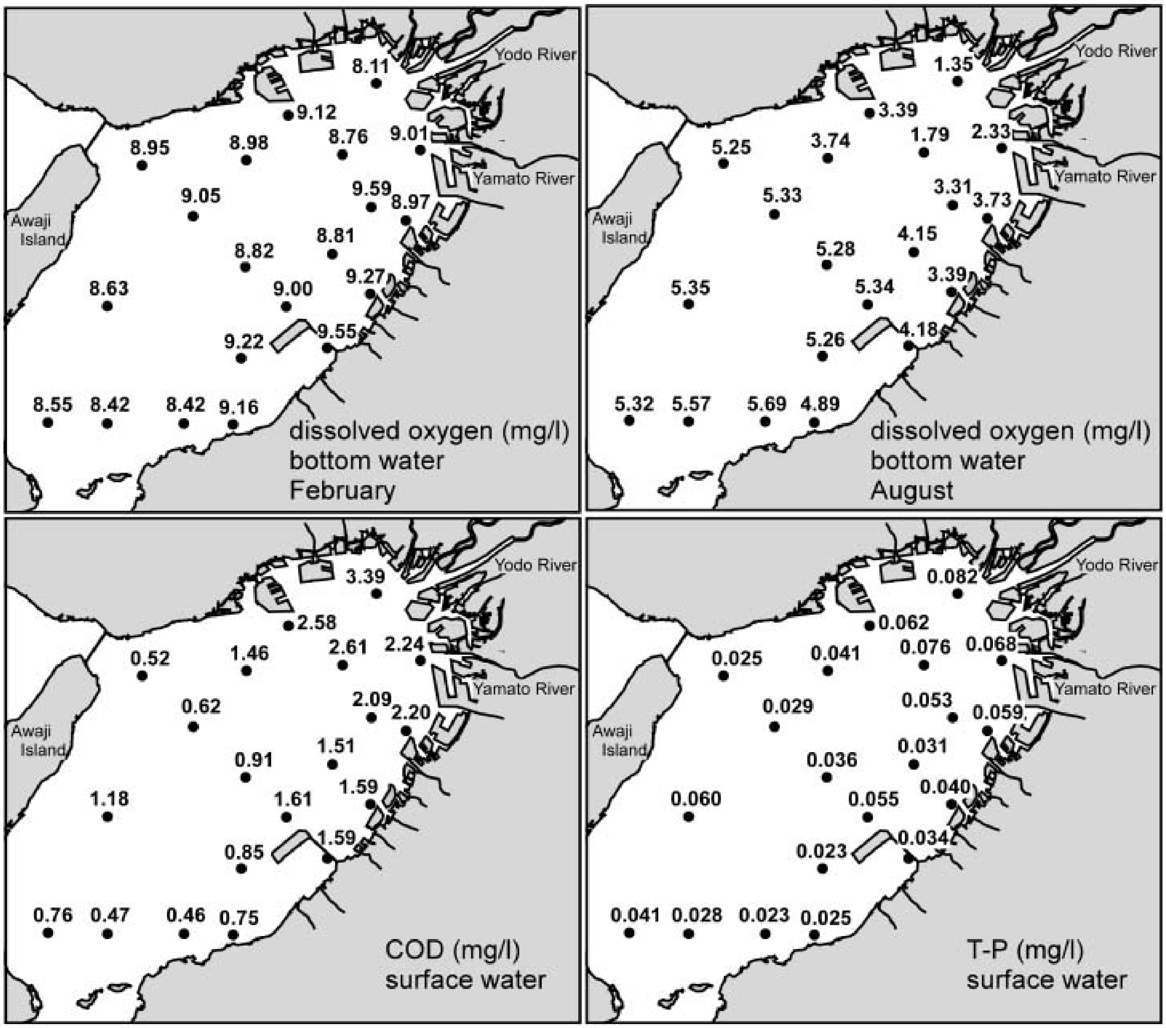

Figure 2. Distribution of dissolved oxygen mg/l in the bottom water (average of observations from 1995 to 1999), and distributions of COD and total phosphorous concentrations mg/l in the surface water (average of 1999). Data from Osaka Prefectural Fisheries Experimental Station (1997 to 2001).

and samples with 50 or more individuals were used in the Q-mode cluster analysis. Similarities used were Horn's overlap indices (Horn, 1966). The UPGMA (unweighted pair-group average) clustering method was used to connect respective clusters. In the UPGMA clustering method, clusters are joined based on the average distance among all members in the two groups (Hammer *et al.*, 2001).

Results

Abundance and diversity

Sixty-one species belonging to 37 genera were identified from 27 samples. No live planktonic foraminifera were recognized in this study. Table 1 lists the foraminifera examined in this study. SEM images of the main foraminiferal species are given in Figures 5 and 6.

Maps of the total number of foraminifera per gram of dry sediment and the distribution of foraminiferal diversity show abundances were greatest at station 17′ (147 individuals per gram) in the central part of the bay (Figure 7). Lower numbers were found at sites such as station 8 (three individuals per gram) and 24′ (six individuals per gram). Generally, lower numbers were found in the inner part of the bay. A small number of live foraminifers were found in the middle of the bay, where the influence of the bottom current is

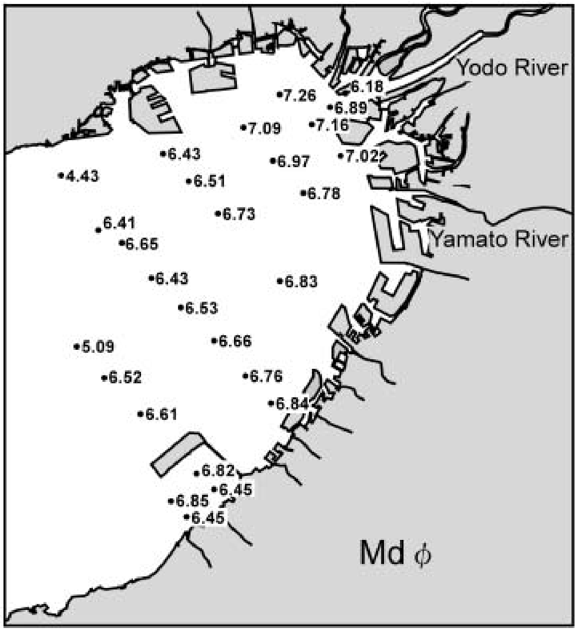

Figure 3. Median diameter (ϕ scale) of bottom sediment in Osaka Bay. Data from Hongo and Nakajo (2003).

strong.

The Shannon-Wiener index indicates that lowest diversity occurs in the inner part of the bay, near the mouth of the Yodo River (Figure 7). Two to six species were found in this area, indicating a diversity index of < 1. In contrast, samples with high diversity occurred in the middle of the bay, with highest diversity (2.22) at station 20. The coastal region in the southern part of the bay near Kansai International Airport also shows high diversity.

Foraminiferal assemblages

Quantitative distribution of the main foraminiferal species per 10 grams of dry sediment (Figure 8) shows *Ammonia beccarii* (Linné) forma A is abundant in the area along the shore, and accounts for 100 or more individuals at sites such as stations 6, 11, 14, 22, and 23. Abundances were greatest at station 23, with 278 individuals. Numbers present generally decrease slightly toward the middle of the bay. *Buccella frigida* (Cushman) mainly occurs in water depths between 15 and 20 m, whereas *Eggerella advena* (Cushman) is abundant throughout the bay. Samples from many sites contained more than 100 individuals; and more than 1000 individuals were found at stations 11 and 17. *Trochammina hadai* Uchio is found throughout Osaka Bay but is most abundant in the inner part of Osaka Bay; a maximum of 241 individuals of this species was recorded at station 2.

Twenty-six samples and twenty-two species were selected for Q-mode cluster analysis based on the above-mentioned rules. A Q-mode cluster analysis grouped the 26 samples into three principal biotopes (A, B, C) (Figures 9, 10C). Biotope A occurred at stations 5 and 23, both of which are situated in the coastal section of the bay (Figure 10C). This biotope is characterized by the dominance of *A. beccarii* forma A (average 56.5%), with minor *B. frigida* (9%) and *E. advena* (6%), *Elphidium subarcticum* Cushman (9%), and *T. hadai* (6%) (Figure 9).

Biotope B comprises 20 samples (stations 6, 7, 10–12, 14, 16–22, 24–30). Two subbiotopes (B_1 and B_2) can be distinguished by the composition of the species. Subbiotope B_1 consists of 12 samples (stations 6, 7, 10–12, 14, 21, 22, 27–30) from water depths of 9.2 to 19.7 m (Figure 10C), and is characterized by the dominance of *E. advena* (44.8%) and *A. beccarii* forma A (26.5%) (Figure 9). Subbiotope B_2 comprises 8 samples (stations 16–20, 24–26) from depths of 17.2–37.2 m (Figure 10C). This subbiotope is characterized by the dominance of *E. advena* (61.1%), with minor *Pseudorotalia gaimardii* (d'Orbigny), *Pseudononion japonicum* Asano and *Pseudoparella tamana* Kuwano (Figure 9).

Biotope C comprises 4 samples (stations 1–4) collected from the mouth of the Yodo River in the inner part of the bay (Figure 10C). This biotope is characterized by the dominance of *E. advena* (47.7%) and *T. hadai* (49.8%) (Figure 9).

Discussion

Relationship between foraminiferal assemblages and marine environments in Osaka Bay

The main species of biotopes A–C are common in coastal areas and bays around Japan and around the world (Nomura, 1982, 1983, 1997; Alve, 1995a). The genus *Ammonia* mainly occurs in shallow marine or slightly brackish intertidal environments (Hayward *et al.*, 2004). This genus has high morphologic variability (e.g., *beccarii*, *parkinsoniana*, *tepida*), and also has great molecular variability (Holzmann *et al.*, 1998; Hayward *et al.*, 2004). *A. beccarii* forma A is a morphologic type of *Ammonia beccarii* in Japan, and is ubiquitous in brackish lakes influenced by fresh water and in the areas around river mouths (e.g., Takayanagi, 1955; Matoba, 1970; Ikeya, 1970; Inoue, 1986; Kosugi *et al.*, 1991; Nomura and Seto, 2002). Both *B. frigida* and *E. advena* are common in the waters around the islands of Japan and in inland seas (e.g., Ishiwada, 1964; Matoba, 1970; Kato, 1986; Oki, 1989;

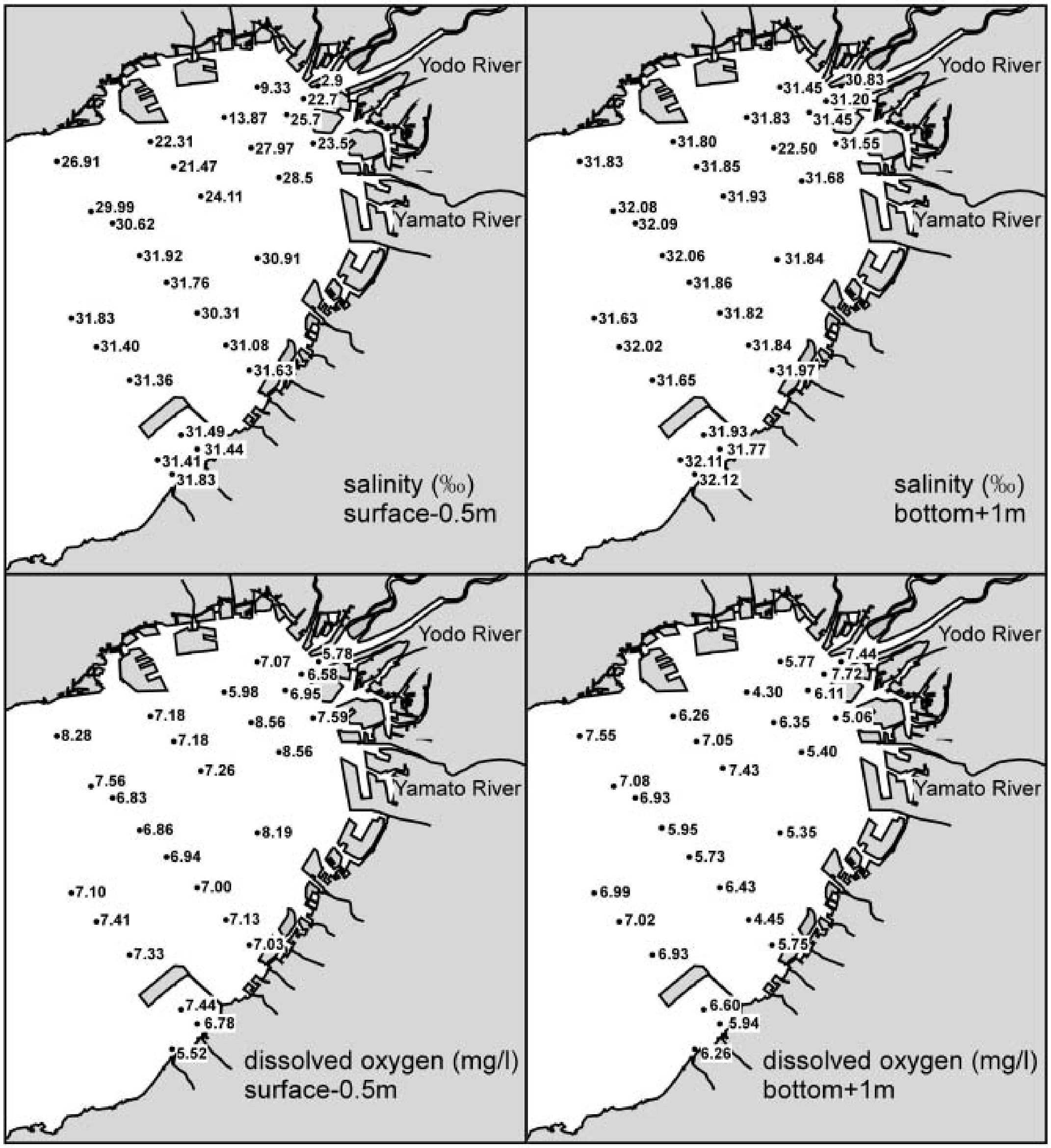

Figure 4. Salinity and dissolved oxygen at sampling sites (May, 1999). Data for salinity from Hongo and Nakajo (2003). Data for dissolved oxygen from Yasuhara and Irizuki (2001).

Kosugi *et al.*, 1991), whereas *T. hadai* is abundant in organic-rich sediments deposited in brackish waters (Uchio, 1962; Matoba, 1970; Kosugi *et al.*, 1991; Nomura and Seto, 1992, 2002).

Biotope B is divided into two subbiotopes, B_1 and B_2, and its boundary is recognized at a water depth of about 20 m. Faunal change at 20 m water depth in Osaka Bay has also been recognized in ostracodes (Yasuhara and Irizuki, 2001), and other benthic faunal changes also occur at this water depth (Association for New Social Infrastructure of Osaka Bay, 1996). Within Osaka Bay, the properties of waters (e.g., dissolved oxygen content, salinity of surface waters, and COD) are divided into a western part and an eastern part by the large clockwise Okinose Circulation Current on the boundary of the 20 m isobathymetric line (Fujiwara, 1995; Figure 2). The western waters are mixed from the surface layer to the bottom layer strongly and homogeneously (Fujiwara, 1995). There is a tidal front around 20–30 m water depth, and the suspended organic matter and the sinking organic matter are different from across the tidal frontal area (Montani *et al.*, 1991). In the tidal frontal area, the relative abundance of terrestrial organic matter is low

Table 1. List of living foraminifera from Osaka Bay

	st. 1	st. 2	st. 3	st. 4	st. 5	st. 6	st. 7	st. 8	st. 10	st. 11	st. 12	st. 14	st. 16	st. 17′	st. 18	st. 19	st. 20	st. 21	st. 22	st. 23	st. 24′	st. 25	st. 26	st. 27	st. 28	st. 29	st. 30
Ammoscalaria tenuimargo																	1										
Ammomarginulina sp.				1																							
Ammonia angulata																				1							
A. beccarii forma A					63	85	86	2	36	49	52	80	8	1	11	11	20	23	79	163	9	5	17	84	44	32	30
A. beccarii forma B									1		2													1			
A. japonica									1					2		7							3				
A. tepida									1							1								1			
Astrononion gallowayi														1													
Buccella frigida					15	19	9		44	16	25		1		2	13	9	93	29	17	1	5	9	70	19	30	13
Bulimina gibba					1					1							1								2		
B. marginata					2												1					1					1
Bulimina sp.					1																						
Buliminella elegantissima					3				2	4			1	3	4	15	14	15	3	3	1	2	13	5	12	8	1
Brizalina striatula													2		2		2				1	3					
B. seminula																	1				1	1					
Cancris auriculus														2													
Cibicidoides pseudoungerianus														1							1	1					
Cibicidoides sp.																					2						
Dentalina communis															1												
Deuterammina sp.														1													
Discorbis sp.															1												
Eggerella advena	38	102	106	126	9	205	29	23	94	278	206	130	204	173	126	99	73	85	70	13	59	113	224	65	49	42	91
E. scabra												4		35									7				
Elphidium advenum					1					1			2				1						1	1			2
E. clavatum					3				1	1			4	3	3	5		5		6		3	1	3	3		1
E. excavatum						1													1								
E. kusiroense																									2		
E. somaense					1				3		3		2			1	1	4		1		1	2	9	33	7	16
E. subarcticum					5				1	4			5	3	6	12	4	16	2	33		39	7	19	14		18
E. subincertum									3																		
E. reticulosum					10								1														
Fissurina annectens					4					1					2	2	4	2		2		2		3			1
Gavelinopsis praegeri													4	2	3						6	3					
Gavelinopsis cf. *praegeri*														1													
Gavelinopsis sp.														1													
Haplophragmoides canariensis	1																										
Karreriella cf. *apicularis*						1																		1			

Karreriella sp.													2				1										
Lagena sulcata spicata													1														
Miliolinella sp.																											1
Nonionella stella																					2						
Pacinonion novozealandicum																						2					
Pseudorotalia gaimardii													5		2		1				8	1					
Pseudononion japonicum					2									1	4		5				3	2					
Pseudoparrella tamana													2	1	1	3	3					3	2				
Pulsiphonia sp.															1												
Quinqueloculina tubilocula																											1
Q. seminula																						1					
Quinqueloculina sp.																						1					
Reophax catelia																5	7	2				1	2				
Rosalina globularis													1														
R. vilardeboana													1									2					
Rotaliammina chitinosa					1					1				1	2		7					5			3		2
Textularia earlandi	3					1			1						1	1	1				2			1		1	
Textularia cf. *andenensis*	1					1							1				2	1									
Trochammina hadai	174	160	41	110	13	4	11	9	5	3		2	12	5	3	2	7	4	10	5	4	7	3	23	11	16	3
T. pacifica																	1										
Trochammina sp.								1																			
Paratrochammina pacifica	1		1												1							1					
Uvigerinella glabra					2					7					4	42	43	12			1	4	7	4	6	2	2
Valvulineria hamanakoensis																								1			
Gen et sp. indet.																	1				1			2	1		
Total number of specimens	218	262	148	237	136	317	135	35	193	366	288	216	259	237	180	219	211	262	194	244	102	209	298	293	199	138	183
Number of specimens per 1 g	21	40	8	15	20	56	10	3	13	139	35	34	47	148	47	38	36	26	41	42	6	45	91	21	27	7	74

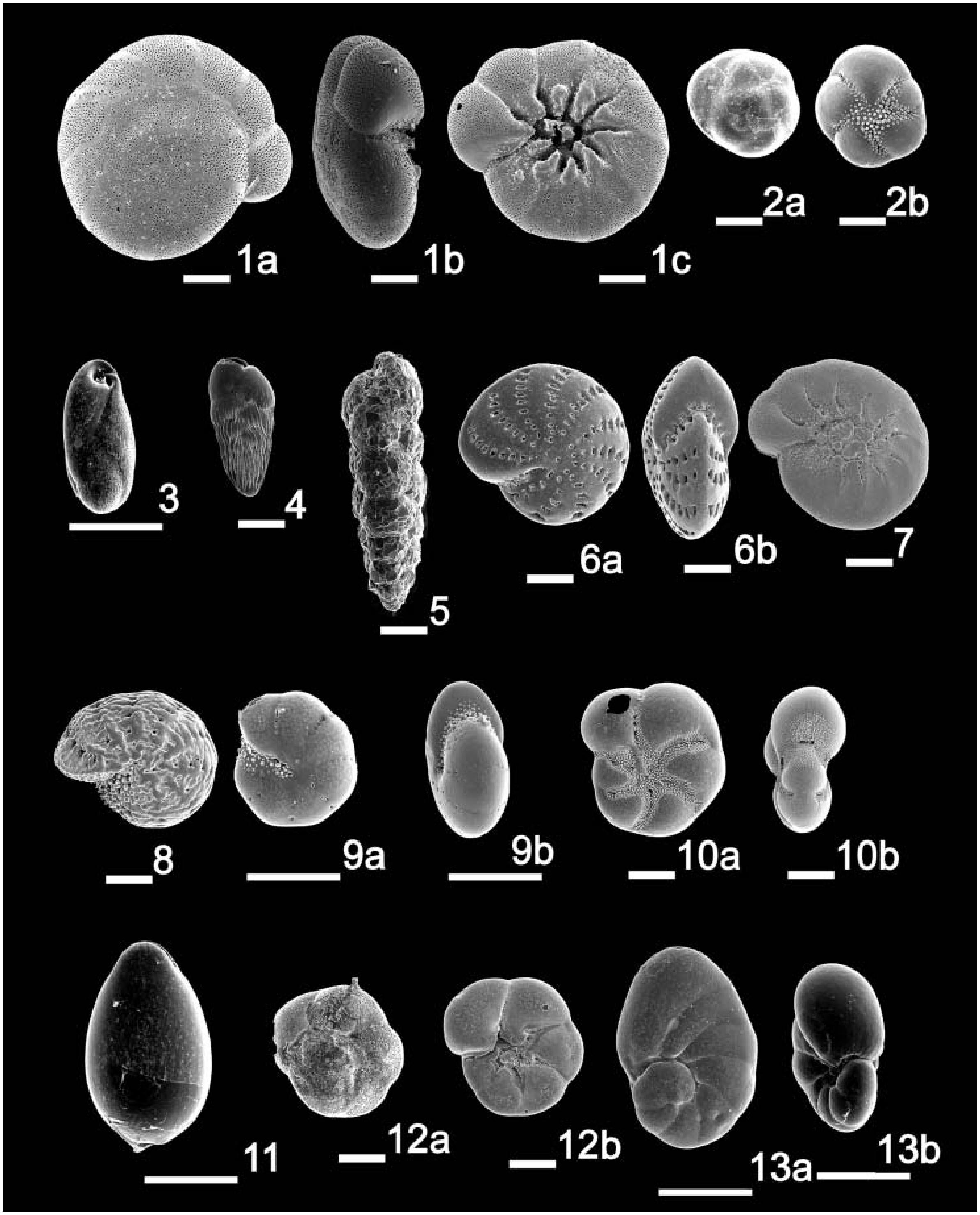

Figure 5. Scanning electron micrographs of the foraminifera from Osaka Bay (scale bars = 100 μm). **1a–1c.** *Ammonia beccarii* (Linné) forma A. **2a, 2b.** *Buccella frigida* (Cushman). **3.** *Buliminella elegantissima* (d'Orbigny). **4.** *Brizalina striatula* (Cushman). **5.** *Eggerella advena* (Cushman). **6a, 6b.** *Elphidium advenum* (Cushman). **7.** *Elphidium clavatum* Cushman. **8.** *Elphidium reticulosum* Cushman. **9a, 9b.** *Elphidium somaense* Takayanagi. **10a, 10b.** *Elphidium subarcticum* Cushman. **11.** *Fissurina annectens* (Burrows and Holland). **12a, 12b.** *Gavelinopsis praegeri* (Heron-Allen and Earland). **13a, 13b.** *Pseudononion japonicum* Asano.

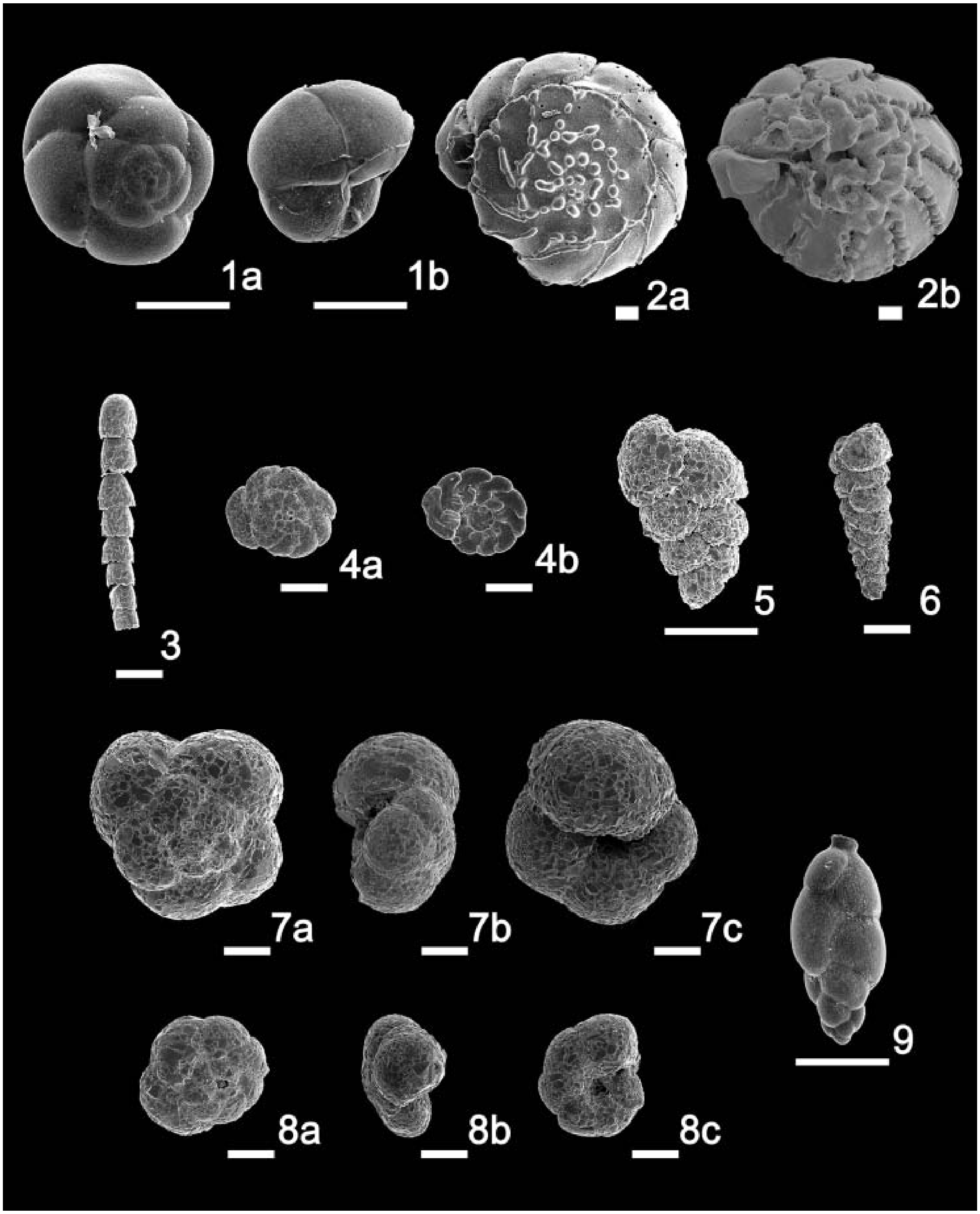

Figure 6. Scanning electron micrographs of the foraminifera from Osaka Bay (scale bars = 100 μm). **1a, 1b.** *Pseudoparella tamana* Kuwano. **2a, 2b.** *Pseudorotalia gaimardii* (d'Orbigny). **3.** *Reophax catella* (Höglund). **4a, 4b.** *Rotaliammina chitinosa* (Cushman). **5.** *Textularia* cf. *andenensis* Asano. **6.** *Textularia earlandi* Parker. **7a–7c, 8a–8c.** *Trochammina hadai* Uchio. **9.** *Uvigerinella glabra* (Millett).

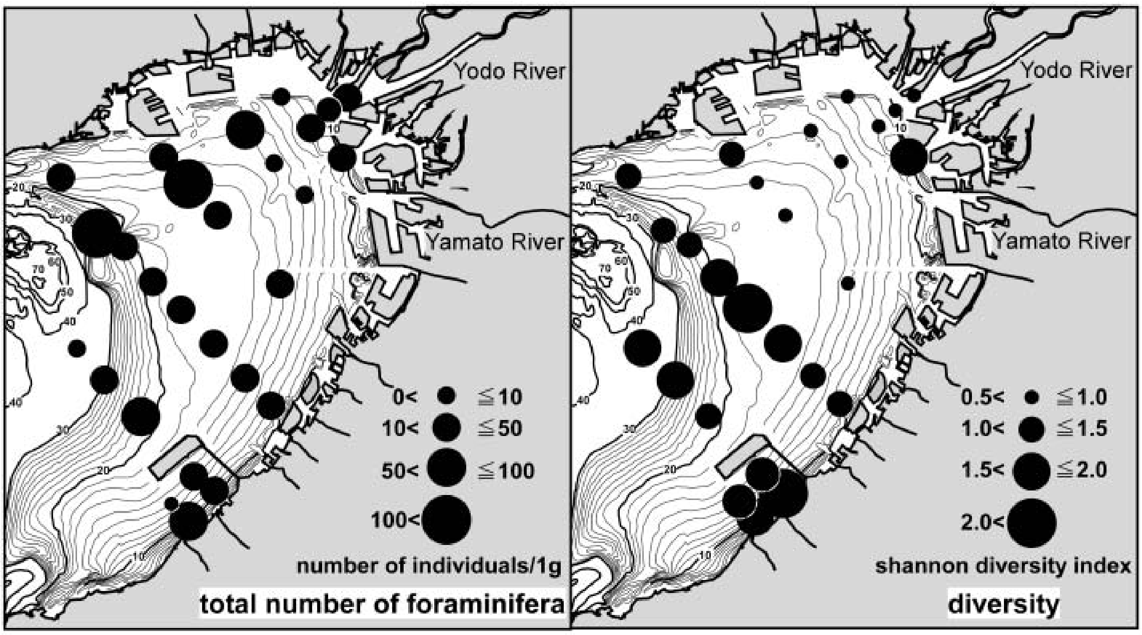

Figure 7. Distribution of foraminiferal abundance and diversity in Osaka Bay.

(Mishima *et al.*, 1999). A small amount of fresh organic matter sinks in the eastern part of the tidal front, whereas a large quantity of decomposed labile fraction sinks in the tidal frontal area and western part of the tidal front (Montani *et al.*, 1991). Benthic foraminifers respond to hydrographic variations, dissolved oxygen content in bottom waters and variations in food supply (Alve, 1995b, 1999; Gustafsson and Nordberg, 1999, 2000; Ward *et al.*, 2003). Thus, the faunal change of biotope B may be primarily influenced by the changes of properties of water masses and sinking organic matter controlled by the Okinose Circulation Current.

Agglutinated species such as *E. advena* and *T. hadai* are dominant species in biotope C, which is also characterized by the lowest diversity among all the biotopes (0.62–0.72). Agglutinated foraminifers have the potential to assess polluted environments (Nagy and Alve, 1987; Alve, 1991, 1995a), as increased organic pollution leads to development of an agglutinated assemblage (Alve, 1991, 1995a). Conversely, foraminiferal assemblages distributed close to sewage outfalls are characterized by high number of specimens and low diversity (Alve, 1995b; Thomas *et al.*, 2000). Based on these features, the agglutinated *E. advena*–*T. hadai* assemblage distributed in the inner part of Osaka Bay may be related to eutrophication of coastal waters in that area. *T. hadai* is abundant in many Japanese and American brackish waters, together with *A. beccarii* (Matoba, 1970; Matsushita and Kitazato, 1990; McGann and Sloan, 1997). Uchio (1962) suggested that the increase in organic matter carried by rivers influences *T. hadai* abundances more than water temperature and the salinity of the bottom waters. Konda and Chiji (1987, 1989) pointed out the relationship between increased relative frequency of *T. hadai* and bottom water hypoxia in polluted bays. *E. advena* is another taxon that is common in waste discharge regions (Watkins, 1961; Clark, 1971; Schafer and Cole, 1974; Bates and Spencer, 1979; Alve and Nagy, 1986; McGann *et al.*, 2003). The salinity of the bottom layer was almost the same at each sampling site in our present study (Figure 4), and therefore the presence of *T. hadai* and *E. advena* is intimately related to the environmental parameters of organic matter load and dissolved oxygen content in the habitat. In the inner part of Osaka Bay, COD and phosphorus concentrations are high throughout the year, and the bottom layer usually becomes anoxic or hypoxic in summer (Association for New Social Infrastructure of Osaka Bay, 1996; Figure 2). Yasuhara and Irizuki (2001) suggested that modern ostracodes are rare in surface sediments in inner Osaka Bay, and attributed this low abundance to bottom water hypoxia. Tsujino and Tamai (1996) suggested that the distribution of meiobenthos is strongly affected by the eutrophic water and the hypoxic water in the inner part of Osaka Bay. Thus, Biotope C is formed by the eutrophic

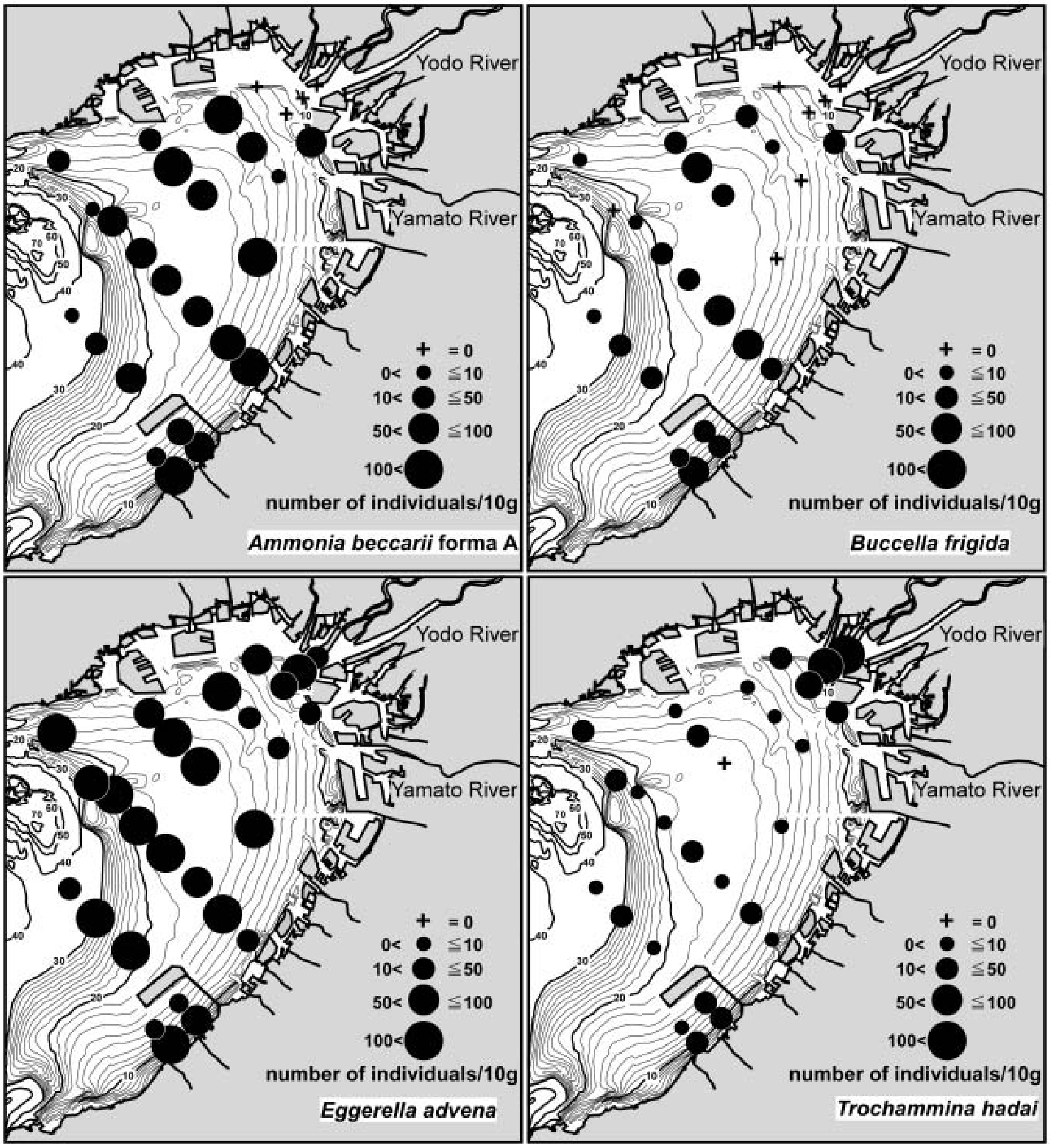

Figure 8. Distribution and abundance of main and characteristic species in Osaka Bay (number of individuals/10 g dry sediment).

waters and the bottom water hypoxia. *T. hadai* and *E. advena* can therefore be used as an index of eutrophication in Osaka Bay.

As noted above, foraminiferal assemblages classified by Q-mode cluster analysis suggest that both natural variability and human activity are significant factors in determining change in the character of modern sediments in Osaka Bay. However, human-induced change is more significant in causing eutrophication in the inner part of the bay. Recent foraminiferal assemblages of Osaka Bay have changed distinctly by the influence of this human-induced eutrophication as follows.

Changes of benthic foraminiferal assemblage and implications for environmental changes in Osaka Bay from the 1950s to the 1990s

In addition to the live assemblages, we examined the difference between live and dead assemblages to demonstrate that the live assemblages are not represented by temporal variations (Figure 11). Biotope A is mainly composed of *A. beccarii*. Little difference is seen between the proportions of the dead and live assemblages at station 23, whereas there are minor

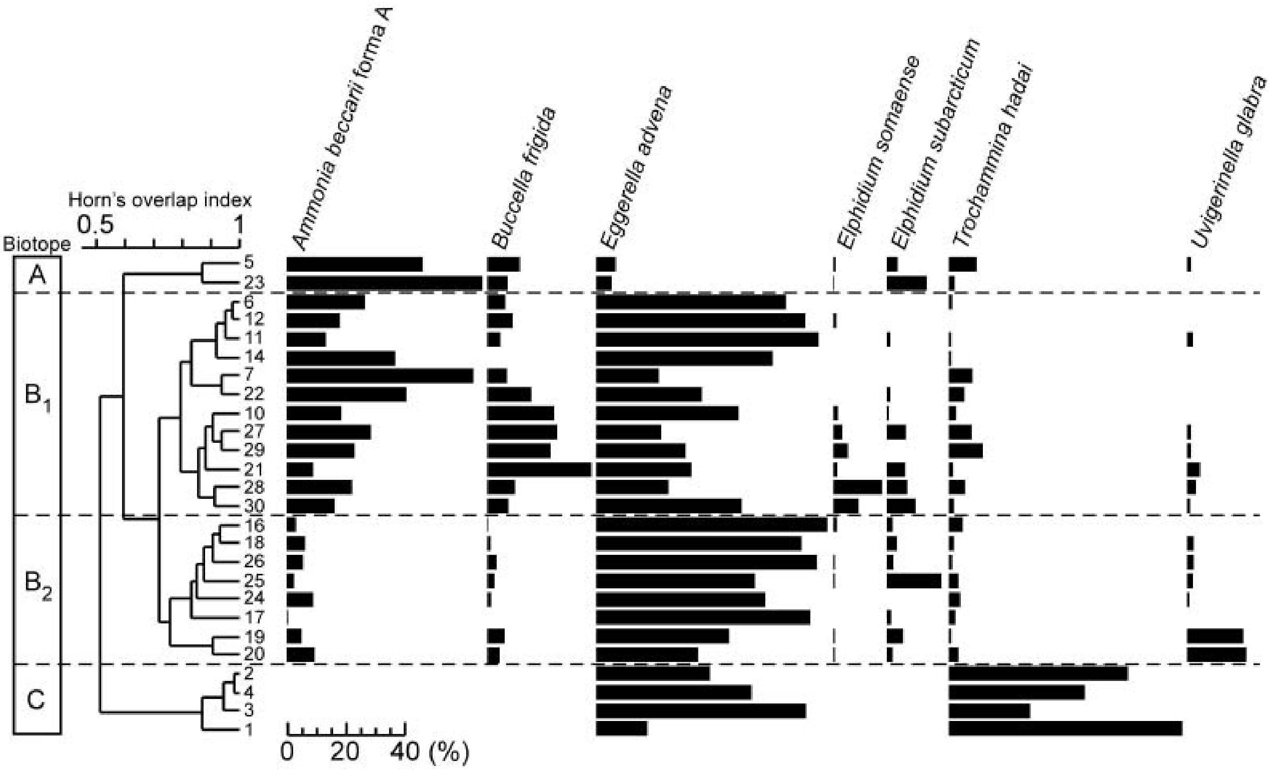

Figure 9. Dendrogram of Q-mode cluster analysis and relative frequency of characteristic species.

differences between the proportions of live and dead specimens of *A. beccarii* and *T. hadai* at station 5. Biotope B_1 is mainly composed of *A. beccarii*, *E. advena* and *T. hadai*. For *A. beccarii* little difference is seen between the proportions of the dead and live assemblages, whereas for *E. advena* the proportion of living specimens is higher. The reverse is seen for *T. hadai*, with a high proportion of dead specimens. High proportions of dead *T. hadai* are found on the inner side of the bay in biotope B_1 (stations 6, 7, 10, 11, 12, 14). Therefore, these dead *T. hadai* may be transported from biotope C. Biotope C is mainly composed of *E. advena* and *T. hadai*. Little difference is seen between the proportions of the dead and live specimens at stations 1 and 2, whereas there are minor differences between the proportions of live and dead specimens of *E. advena* and *T. hadai* at stations 3 and 4. However, in this study, we do not discuss the proportions of *E. advena* and *T. hadai* in the *T. hadai–E. advena* assemblage. As mentioned above, there are some stations that have differences between the proportions of the dead and live assemblages, but no critical differences in main species composition could be found between them in biotopes A, B_1, and C. However, biotope B_2 contains various dead species and is characterized by diversified thanatocoenoses. The sediment of this biotope contains sand grains which have been transported from shallower to deeper parts of Osaka Bay by the active influence of the Okinose Circulation Current (Fujiwara, 1995). The dead assemblage of this biotope is characterized by *Gavelinopsis praegeri* (Heron-Allen and Earland), *Pseudorotalia gaimardii*, *Cibicides* spp., and *Cancris auriculus* (Fichtel and Moll). These species favor coarse-grained sediments with low concentrations of organic carbon or fresh organic matter (Konda and Chiji, 1987; Altenbach *et al.*, 2003), and are found in the mouth of Osaka Bay abundantly (Konda and Chiji, 1987). On the other hand, *E. advena*, which is both the live and dead dominant species in biotope B_2, favors high organic content. Many species of the dead assemblage have different habitats from *E. advena*, and therefore it is assessed that the dead assemblage contains various allochthonous specimens. Although the live assemblage of biotope B_2 differs from the dead assemblage, no critical difference in main species composition could be found between them. Therefore, the occurrence of the live assemblages confirms the environmental conditions of the present Osaka Bay.

Recent studies of benthic foraminifera in Osaka

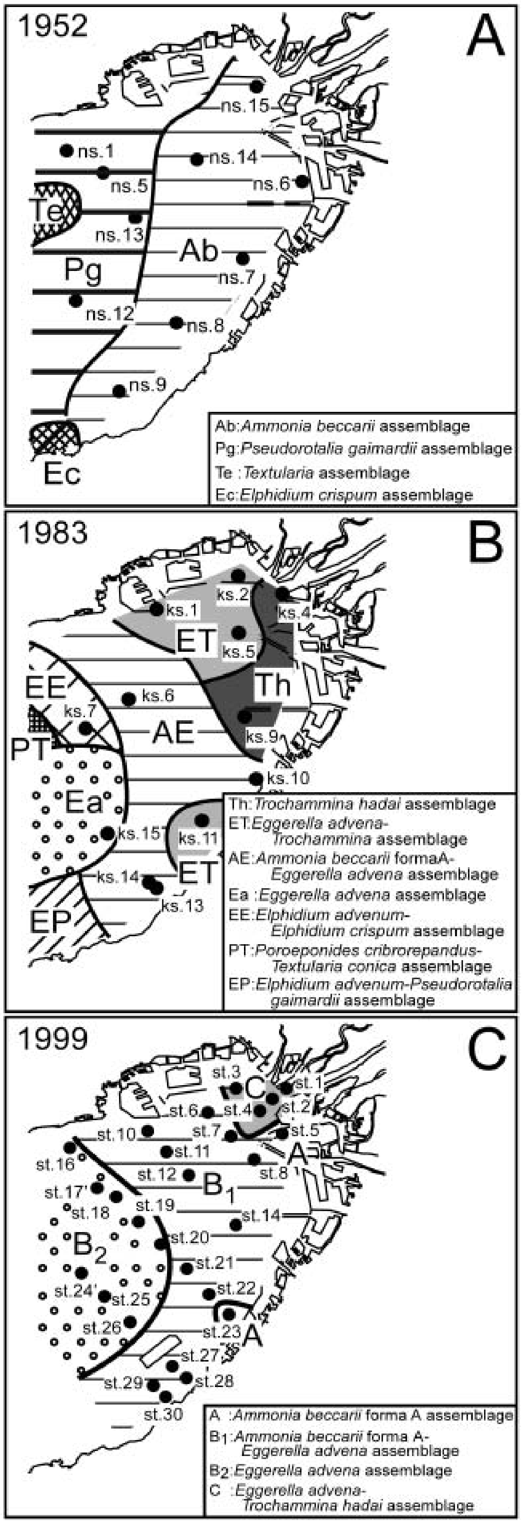

Figure 10. Time series of foraminiferal distributions in Osaka Bay. **A.** Data for surface samples collected in 1952 (after Nakaseko, 1953). **B.** Data for surface samples collected in 1983 (after Konda and Chiji, 1987). **C.** Data for surface samples collected in 1999 (this study).

Bay were undertaken by Takayanagi (1953), Nakaseko (1953) and Konda and Chiji (1987). Takayanagi (1953) studied 11 samples collected from the middle to the mouth of the bay in 1933, and reported that the main species included *Bolivina robusta* Brady, *E. advena*, and *Textularia* spp. His study is not used for comparison here, however, because the two study areas do not overlap.

Nakaseko (1953) analyzed 40 samples collected from the entire bay in 1952, and Konda and Chiji (1987) analyzed 28 samples in 1983. Nakaseko (1953) analyzed the >73 μm fraction, and there is no mention of the analyzed size fraction in Konda and Chiji (1987). Nakaseko (1953) recognized four foraminiferal assemblages, the *Rotalia beccarii* (= *Ammonia beccarii*) assemblage, *Rotalia papillosa* (= *Pseudorotalia gaimardii*) assemblage, *Textularia* assemblage, and *Elphidium crispum* assemblage. Among them, the *Textularia* assemblage and *Elphidium crispum* assemblage are not discussed, because the distribution areas of these assemblages do not overlap with areas of this study. The *Ammonia beccarii* assemblage contained *A. beccarii* ($>30\%$) as well as *B. frigida*, *Elphidium advenum* (Cushman), and *Nonion pacificum* (Cushman), and occurred in the eastern part of the bay. The *Pseudorotalia gaimardii* assemblage, which contained *P. gaimardii* ($>30\%$) along with *A. beccarii* and *E. advenum*, was distributed in the western part, as shown in Figure 10A.

Konda and Chiji (1987) studied both live and dead faunas. They recognized eight total assemblages at that time. In this study, we judged that their *Eggerella scabra* was within the range of variation of *Eggerella advena* based on close examination of their photographs of this species. We identified *Trochammina hadai* (Figure 6–8) with *Trochammina* cf. *japonica* of Konda and Chiji (1987). Matsushita and Kitazato (1990) suggested that microspheric agamont generations of *Trochammina hadai* disperse under the influence of summer hypoxic bottom water, whereas megalospheric generations disoerse in water of high dissolved oxygen content. Consequently, we determined that our *Trochammina* (Figure 6–8) and *Trochammina* cf. *japonica* of Konda and Chiji (1987) fall within the range of variation of *Trochammina hadai* (microspheric generation of Matsushita and Kitazato (1990)). The change in these species names does not affect the following discussion, because we recognize the same specimens as Konda and Chiji (1987) based on close examination of their photographs. The *E. advena–T. hadai* assemblage is dominated by *E. advena* ($>51\%$) with subordinate *T. hadai* (24–46%). The *T. hadai* assemblage is mostly dominated by *T.*

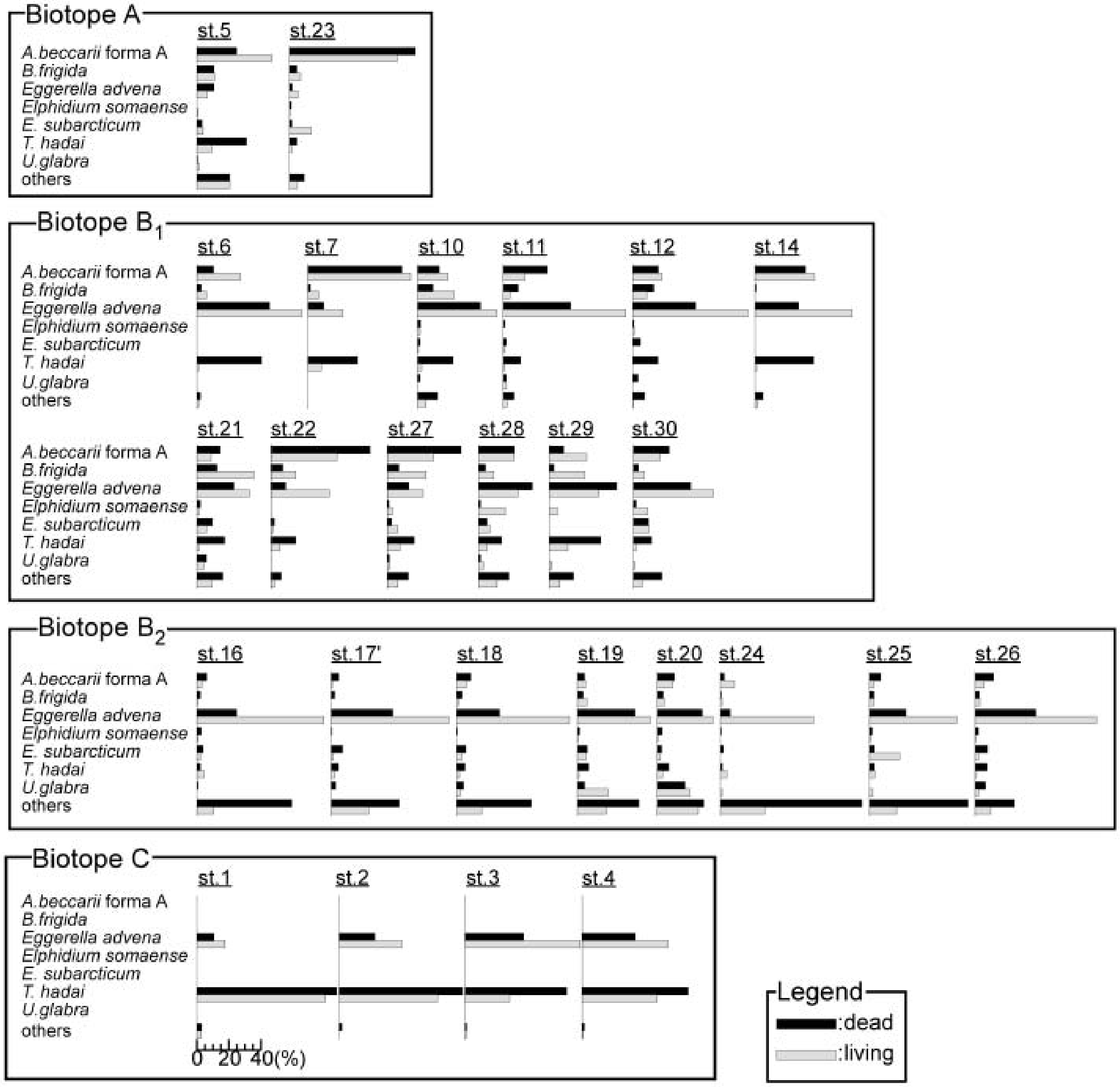

Figure 11. Comparison of relative frequency of dead and living specimens of the most abundant species.

hadai (>58%) with lesser *E. advena* (5–39%). These two assemblages were widely distributed in the inner and southeastern parts of the bay. The *A. beccarii* forma A–*E. advena* assemblage, in which *A. beccarii* forma A accounts for >25% of the assemblage which also includes *E. advena* and *T. hadai*, is widely distributed in the middle part of the bay (Figure 10B). As mentioned above, analyzed size fractions differ between Nakaseko (1953) (>73 μm), Konda and Chiji (1987) (no description about the analyzed size fraction), and this study (>105 μm). However, we judged that different size fractions do not affect the comparison of main foraminiferal composition described as follows.

The foraminiferal assemblages recognized in this study clearly suggest that the main foraminiferal composition changed distinctly during the 50-year interval from the 1950s through the 1990s (Figure 10). An understanding of the environmental changes in Osaka Bay that are attributable to human activity can be developed by examining the main species, as follows. Although *A. beccarii* was the dominant species in the inner part of the bay in 1952, the agglutinated species *E. advena* and *T. hadai* had overtaken this region in 1983. These species remained abundant in 1999 (Figures 10, 12). This distinct change dose not occur due to differences of analyzed size fractions.

The volume of organic material and nutrients such

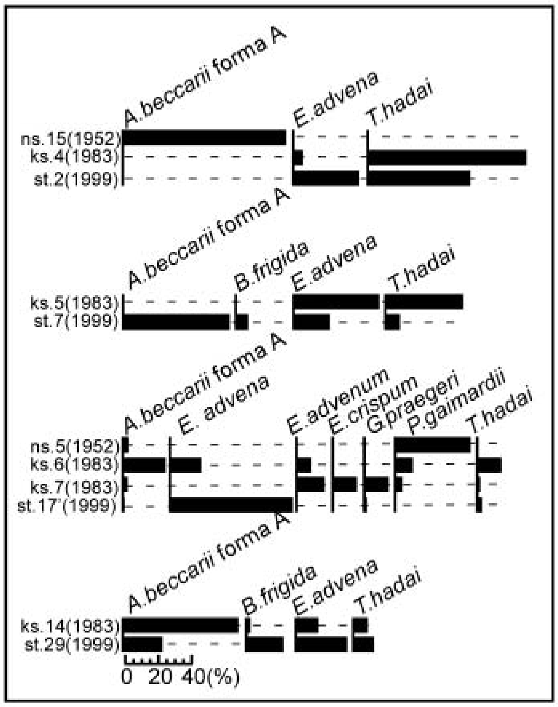

Figure 12. Comparison of relative frequency of the most abundant species. Sample numbers (ns, ks, st) correspond to the sampling site numbers in Figure 10. Data of surface samples collected in 1952, 1983, 1999 from Nakaseko (1953), Konda and Chiji (1987), this study, respectively.

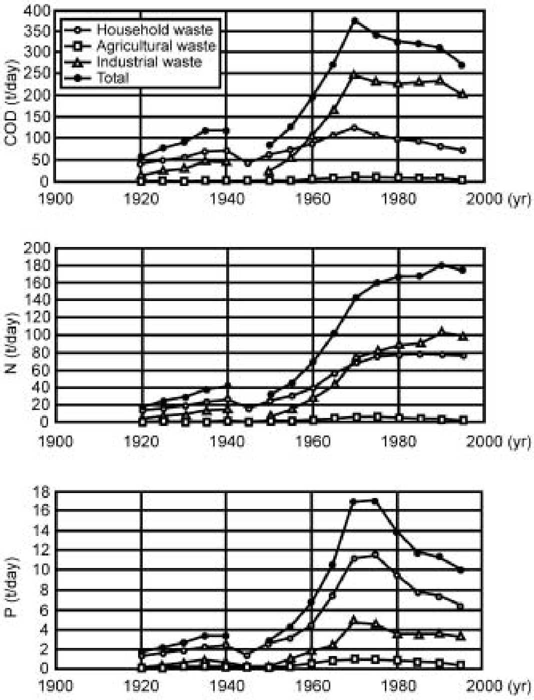

Figure 13. Secular change of inflow loads from the Osaka Bay region. Data for nitrogen, phosphorus, and COD from Nakatsuji *et al.* (1998).

as phosphorus and nitrogen discharged into Osaka Bay increased with the rapid economic growth which occurred from the middle 1950s to the middle 1970s, and pollution of Osaka Bay's waters progressed simultaneously (Figure 13). Consequently, from the latter half of the 1960s, outbreaks of red tide occurred in spring and summer (Joh, 1986). In addition, anoxia or hypoxia of bottom water commonly occurred in the inner part of Osaka Bay (Joh, 1986).

Our surface study suggested that two dominant species, *E. advena* and *T. hadai*, are good indicators of eutrophication in Osaka Bay. Increased organic pollution accelerates the dominance of agglutinated assemblages (Alve, 1991, 1995a). Murray (1991) described *E. advena* as a detritivore, and Thomas *et al.* (2000) suggests that the change in abundance of *E. advena* is related to change in the composition of the food supply. Thus, the remarkable change from the *A. beccarii* assemblage to an agglutinated assemblage (*E. advena–T. hadai* assemblage) between 1952 and 1999 was caused by eutrophication of the bottom water, and change in the food supply due to red tides. The latter have frequently occurred in the inner part of the bay since the 1960s (Joh, 1986). In comparison with Konda and Chiji's (1987) report, however, the area characterized by the *T. hadai–E. advena* assemblage had decreased by 1999 (Figure 10). Governmental restriction of nutrient discharge from around 1980 has led to some improvement in water quality in terms of COD (Figure 13; Association for New Social Infrastructure of Osaka Bay, 1996). Therefore, the reduced distribution of the *T. hadai–E. advena* assemblage may indicate alleviation of eutrophy due to the restrictions imposed on the discharge of wastewater.

P. gaimardii was the dominant species in the middle part of the bay in 1952. However, the relative abundance of this species subsequently decreased, accounting for 10% or less in 1983. Abundance of this species decreased further (several percent or less) in 1999. *P. gaimardii* is a large-sized species (Figure 6-2). Therefore, this change in abundance of *P. gaimardii* cannot be due to differences of analyzed size fractions. The decline of this species is intimately related to the progressive eutrophication of the bay waters, which became too severe for *P. gaimardii* to live. Consequently, *P. gaimardii* decreased continuously from the 1950s onward.

A. beccarii forma A decreased, whereas *E. advena* increased throughout Osaka Bay in comparison with the distribution reported by Konda and Chiji (1987) (Figure 12). *E. advena* was not reported from any sites in the 1950s (Nakaseko, 1953), and it thus is clear that a distinct increase of *E. advena* has occurred over the past 50 years. According to the Association for New Social Infrastructure of Osaka Bay (1996), no conspicuous change in water quality has occurred in Osaka Bay in the last decade. Thus, the increase of this species is a matter for discussion with respect to environmental change.

McGann *et al.* (2003) reported reciprocal occurrence of two species over the past 40 years in Santa Monica Bay in relation to sewage discharge and remediation. *Trochammina pacifica* prefers organic wastes, and decreased in abundance after initiation of sewage treatment programs, whereas *E. advena* increased in abundance. As a consequence, however, the different response of the two species suggests substantial degradation in the sediment quality, and the competitive advantage of *E. advena*. The same ecological response is suggested by two species in Osaka Bay. Occurrence of *T. hadai* decreased, and *E. advena* increased in abundance after wastewater discharge restrictions were imposed in 1973. However, even after regulation, red tides still occur frequently in the innermost part of Osaka Bay (Association for New Social Infrastructure of Osaka Bay, 1996; see Figure 14). Moreover, the main species of the red tide-causing organisms changed after the environmental regulations were instituted (Figure 15). The number of red tides caused by *Skeletonema costatum* decreased after 1975. Although dinoflagellates (e.g., *Ceratium furca*, *Gymnodium lacustre*, *Olisthodiscus* sp. and *Peridinium* sp.) caused red tides frequently during the 1970s, this type of red tide decreased after the 1980s. Red tides caused by diatoms (e.g., *Chaetoceros* spp., *Nitzschia pungens*, and *Rhizosolenia fragilissima*) and *Heterosigma akashiwo* (zooxanthella) then increased. It is well known that food supply substantially influences benthic foraminifer populations (Alve, 1995b, 1999; Gustafsson and Nordberg, 1999, 2000; Thomas *et al.*, 2000; Ward *et al.*, 2003; Topping *et al.*, 2006). Red tides cause the accumulation of a large amount of detritus at the bottom of the sea, which then becomes food for detritivores. The changes of composition of red tide-causing organisms cause changes in the organic supply to the bottom of the sea. Consequently, changes in the food supply may have triggered the changes in the benthic foraminiferal assemblages from the 1980s onward. Although the number of red tides has decreased gradually under the impact of environmental regulations, and the makeup of the red tide-causing organisms has changed, sediment quality has not been remediated to the degree that the foraminiferal assemblage has rebounded to the assemblage present in the early 1950s. Further study is necessary to fully understand the relationship between changes in the benthic foraminiferal assemblages and changes in the food supply.

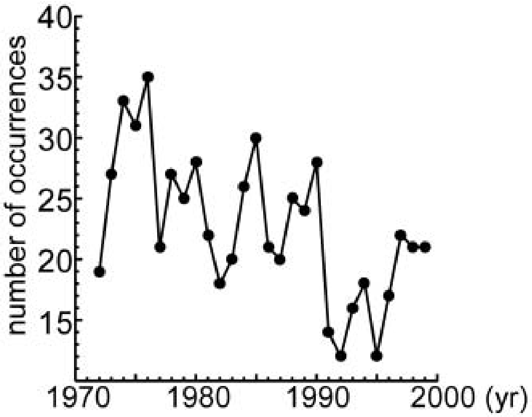

Figure 14. Temporal change in the occurrences of red tides. Data from Osaka Prefectural Fisheries Experimental Station (1973 to 2001).

Conclusions

Sixty-one species of foraminifera belonging to 37 genera were found in Osaka Bay. Foraminiferal diversity is lower toward the inner part of the bay due to water pollution. Three assemblages are identified by Q-mode cluster analysis. Among these, the *E. advena* and the *A. beccarii* forma A–*E. advena* assemblages are strongly influenced by natural environmental factors related to the residual current. The *T. hadai–E. advena* assemblage is strongly influenced by bottom water anoxia or hypoxia. These assemblages are thus important when considering the influence of human activity which can induce such conditions.

Foraminiferal assemblages in Osaka Bay have changed greatly in the past 50 years. Eutrophication accelerated in the 1970s, and the *T. hadai–E. advena* assemblage occupied extensive areas of the inner bay. The areal extent of the *T. hadai–E. advena* assemblage decreased greatly between 1983 and 1999. However, *E. advena* has increased throughout Osaka Bay over the past 50 years. The number of occurrences of red tides has decreased gradually following improved environmental regulations instituted in 1973, and the composition of the red tide-causing organisms has also changed. These changes may have caused the

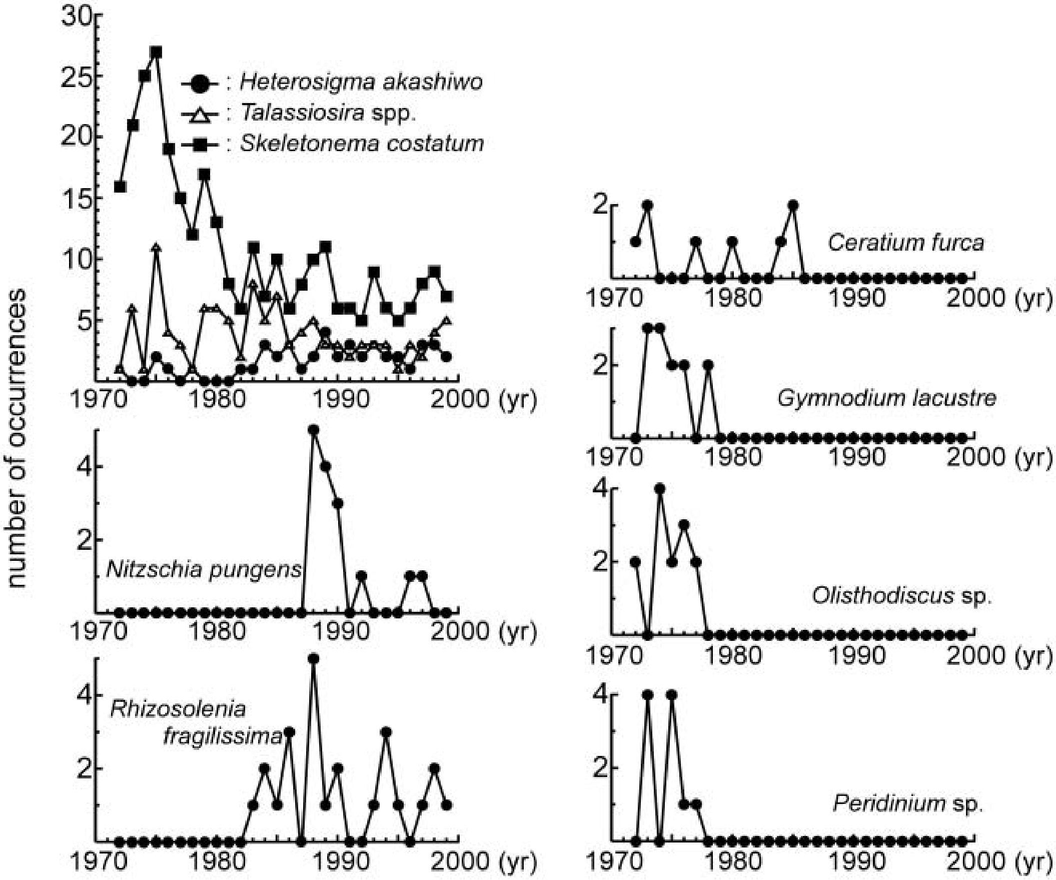

Figure 15. Temporal changes in the number of occurrences of red tide-causing organisms. Data from Osaka Prefectural Fisheries Experimental Station (1973 to 2001).

substantial changes in the foraminiferal assemblages. However, sediment quality has not been remediated sufficiently to permit the foraminiferal assemblages to recover to those seen in the early 1950s, prior to the phase of rapid economic development and the pollution that ensued. Further study is necessary to fully understand the relationship between changes in the benthic foraminiferal assemblages and changes in the food supply.

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References

Altenbach, A. V., Lutze, G. F., Schiebel, R., Schönfeld, J., 2003: Impact of interrelated and interdependent ecological controls on benthic foraminifera: An example from the Gulf of Guinea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 197, p. 213–238.

Alve, E., 1991: Benthic foraminifera in sediment cores reflecting heavy metal pollution in Sørfjord, western Norway. *Journal of Foraminiferal Research*, vol. 21, p. 1–19.

Alve, E., 1995a: Benthic foraminiferal responses to estuarine pollution: A review. *Journal of Foraminiferal Research*, vol. 25, p. 190–203.

Alve, E., 1995b: Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Drammensfjord, southern Norway. *Marine Micropaleontology*, vol. 25, p. 169–186.

Alve, E., 1999: Colonization of new habitats by benthic foraminifera: A review. *Earth-Science Reviews*, vol. 46, p. 167–185.

Alve, E. and Nagy, J., 1986: Estuarine foraminiferal distribution in Sandebukta, a branch of the Oslo Fjord. *Journal of Foraminiferal Research*, vol. 16, p. 261–284.

Angel, D. L., Verghese, S., Lee, J. J., Saleh, A. M., Zuber, D., Lindell, D. and Symons, A., 2000: Impact of a net cage fish farm on the distribution of benthic foraminifera in the northern gulf of Eilat (Aqaba, Red Sea). *Journal of Foraminiferal Research*, vol. 30, p. 54–65.

Association for New Social Infrastructure of Osaka Bay, *ed*., 1996: *Communication Tool for Sustainable Development*, 268 p. Institute of Coastal Environment Inc., Osaka. (*in Japanese*)

Bates, J. M. and Spencer, R. S., 1979: Modification of foraminiferal trends by the Chesapeake-Elisabeth sewage outfall, Virginia Beach, Virginia. *Journal of Foraminiferal Research*, vol. 9, p. 125–140.

Cearreta, A., Irabien, M. J., Leorri, E., Yusta, I., Croudace, I. W. and Cundy, A. B., 2000: Recent anthropogenic impacts on the Bilbao Estuary, northern Spain: Geochemical and microfaunal evidence. *Estuarine, Coastal and Shelf Science*, vol. 50, p. 571–592.

Clark, D. F., 1971: Effects of aquaculture outfall on benthonic foraminifera in Clam Bay, Nova Scotia. *Maritime Sediments*, vol. 7, p. 76–84.

Coccioni, R., 2000: Benthic foraminifera as bioindicators of heavy metal pollution. *In*, Martin, R. E., *ed*., *Environmental Micropaleontology: The Application of Microfossils to Environmental Geology*, p. 71–103. Kluwer Academic/Plenum Publishers, New York.

Debenay, J. P., Tsakiridis, E., Soulard, R. and Grossel, H., 2001: Factors determining the distribution of foraminiferal assemblages in Port Joinville Harbor (Ile d'Yeu, France): The influence of pollution. *Marine Micropaleontology*, vol. 43, p. 75–118.

Fujiwara, T., 1995: Structure of the flow which governs the ecosystem of Osaka Bay. *Scientific Forum of the Seto Inland Sea*, vol. 2–3, p. 85–93. (*in Japanese*)

Fujiwara, T., Higo, T. and Takasugi, Y., 1989: Residual current, tidal current and eddy. *Proceedings of Coastal Engineering*, vol. 36, p. 209–213. (*in Japanese*)

Geslin, E., Debenay, J. P. and Lesourd, M., 1998: Abnormal wall textures and test deformation in *Ammonia beccarii* (hyaline foraminifer). *Journal of Foraminiferal Research*, vol. 28, p. 148–156.

Geslin, E., Debenay, J. P., Duleba, W. and Bonetti, C., 2002: Morphological abnormalities of foraminiferal tests in Brazilian environments: comparison between polluted and non-polluted areas. *Marine Micropaleontology*, vol. 45, p. 151–168.

Gustafsson, M. and Nordberg, K., 1999: Benthic foraminifera and their response to hydrography, periodic hypoxic conditions and primary production in the Koljo fjord on the Swedish west coast. *Journal of Sea Research*, vol. 41, p. 163–178.

Gustafsson, M. and Nordberg, K., 2000: Living (stained) benthic foraminifera and their response to the seasonal hydrographic cycle, periodic hypoxia and to primary production in Havstens fjord on the Swedish west coast. *Estuarine, Coastal and Shelf Science*, vol. 51, p. 743–761.

Hammer, Ø., Harper, D. A. T. and Ryan, P. D., 2001: PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica 4*, 9 p. (http://palaeo-electronica.org/2001_1/past/issue1_01.htm)

Hayward, B. W., Holzmann, M., Grenfell, H. R., Pawlowski, J. and Triggs, C. M., 2004: Morphological distinction of molecular types in *Ammonia* towards a taxonomic revision of the world's most commonly misidentified foraminifera. *Marine Micropaleontology*, vol. 50, p. 237–272.

Holzmann, M., Piller, W., Zaninetti, L., Fenner, R., Martini, R., Serandrei-Barbero, R. and Pawlowski, J., 1998: Molecular versus morphologic variability in *Ammonia* spp. (Foraminifera, Protozoa) from the Lagoon of Venice, Italy. *Revue de Micropaléontologie*, vol. 41, p. 59–69.

Hongo, M. and Nakajo, T., 2003: Fine-grained sediments dispersion in the eastern part of Osaka Bay, based on distribution of remains of *Pediastrum biwae* (fresh water green alga) from the Yodo River. *Journal of the Sedimentological Society of Japan*, no. 56, p. 17–26.

Horn, H. S., 1966: Measure of "overlap" in comparative ecological studies. *American Naturalist*, vol. 100, p. 419–424.

Hoshika, A., Tanimoto, T. and Mishima, Y., 1994: Sedimentation processes of particulate matter in the Osaka Bay. *Umi no Kenkyu* (*Oceanography in Japan*), vol. 3, no. 6, p. 419–425. (*in Japanese with English abstract*)

Ikeya, N., 1970: Population ecology of benthic foraminifera in Ishikari Bay, Hokkaido, Japan. *Records of Oceanographic Works in Japan, New series*, vol. 10, p. 173–191.

Inoue, Y., 1986: Foraminiferal assemblages from the surface deposits of Suruga Bay. *Kaiyo Monthly*, no. 18, p. 564–569. (*in Japanese*)

Ishiwada, Y., 1964: Benthonic foraminifera off the Pacific coast of Japan referred to biostratigraphy of the Kazusa Group. *Report, Geological Survey of Japan*, no. 205, p. 1–45.

Japan Coast Guard, 1978: *Tomogashima Suido*. 1:50,000 Basic Maps for the Sea in Coastal Waters no. 6383-4.

Japan Coast Guard, 1995: *Eastern Part of Osaka Wan*. 1:50,000 Basic Maps for the Sea in Coastal Waters no. 6383-1.

Japan Coast Guard, 1997: *Akashi Kaikyo*. 1:50,000 Basic Maps for the Sea in Coastal Waters no. 6383-3.

Joh, H., 1986: Studies on the mechanism of eutrophication and the effect of it on fisheries production in Osaka Bay. *Bulletin of the Osaka Prefectural Fisheries Experimental Station*, vol. 7, p. 1–174. (*in Japanese*)

Kato, M., 1986: Recent shallow water foraminifera in Hiroshima Bay, Seto Inland Sea, Japan. *In*, Matoba, Y. and Kato, M., *eds*., *Studies on Cenozoic Benthic Foraminifera in Japan*, p. 27–42. Akita University. (*in Japanese*)

Konda, I. and Chiji, M., 1987: Change of foraminiferal thanatocoenoses of the Osaka Bay during the last fifty years. *Bulletin of Kansai Organization for Nature Conservation*, no. 14, p. 11–22. (*in Japanese*)

Konda, I. and Chiji, M., 1989: Change of foraminiferal thanatocoenoses in Tanabe Bay, Kii Peninsula, during the last thirty years. *In*, Takayanagi, Y. and Ishizaki, K., *eds*., *Col-*

lected papers on foraminifera from the Japanese Islands, p. 105–110. Toko Press, Sendai. (*in Japanese*)

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 of paleoenvironments. *Fossils* (*Palaeontological Society of Japan*), vol. 50, p. 37–55. (*in Japanese with English abstract*)

Loeblich, A. R., Jr. and Tappan, H., 1988: *Foraminiferal genera and their classification*. 2 vols., 970 p. 847 plates. Van Nostrand and Reinhold Company, New York.

Matoba, Y., 1970: Distribution of recent shallow water foraminifera of Matsushima Bay, Miyagi Prefecture, Northeast Japan. *Tohoku University, Science Reports, 2nd Series* (*Geology*), vol. 42, p. 1–85.

Matsushita, S. and Kitazato, H., 1990: Seasonality in the benthic foraminiferal community and the life history of *Trochammina hadai* Uchio in Hamana Lake, Japan. *In*, Hemleben, C., Kaminski, M. A., Kuhnt, W., and Scott, D., *eds*., *Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera*, p. 695–715. Kluwer Academic Publishers, Dordrecht.

McGann, M., Alexander, C. R. and Bay, S. M., 2003: Response of benthic foraminifers to sewage discharge and remediation in Santa Monica Bay, California. *Marine Environmental Research*, vol. 56, p. 299–342.

McGann, M. and Sloan, D., 1999: Benthic foraminifers in the regional monitoring program's San Francisco estuary samples. *San Francisco Estuary Regional Monitoring Program for trace substances, 1997 Annual Report*, p. 249–258.

Mishima, Y., Hoshika, A. and Tanimoto, T., 1999: Deposition rates of terrestrial and marine organic carbon in the Osaka Bay, Seto Inland Sea, Japan, determined using carbon and nitrogen stable isotope ratios in the sediment. *Journal of Oceanography*, vol. 55, p. 1–11.

Montani, S., Mishima, Y., and Okaichi, T., 1991: Scavenging processes of marine particles in Osaka Bay. *Marine Pollution Bulletin*, vol. 23, p. 107–111.

Murray, J. W., 1991: *Ecology and paleoecology of benthic foraminifera*, 451 p. Longman Scientific and Technical Publishers, Essex.

Murray, J. W., 2000: The enigma of the continued use of total assemblages in ecological studies of benthic foraminifera. *Journal of Foraminiferal Research*, vol. 30, p. 244–245.

Nagy, J. and Alve, E., 1987: Temporal changes in foraminiferal faunas and impact of pollution in Sandebukta, Oslo fjord. *Marine Micropaleontology*, vol. 12, p. 109–128.

Nakaseko, K., 1953: Foraminiferal thanatocoenoses of Osaka Bay (part 1). *Science Report South College, North College, Osaka University*, vol. 2, p. 101–105. (*in Japanese with English abstract*)

Nakatsuji, K., Teraguchi, T. and Yamane, N., 1998: Time change of water qualities in Osaka Bay during past 70 years and numerical experiments. *Proceedings of Coastal Engineering*, vol. 45, p. 1011–1015. (*in Japanese*)

Nomura, R., 1982: List and bibliography of the recent benthonic foraminifera. *Memoirs of the Faculty of Education, Shimane University* (*Natural Science*), vol. 15, p. 31–69.

Nomura, R., 1983: List and bibliography of the recent benthonic foraminifera. *Memoirs of the Faculty of Education, Shimane University* (*Natural Science*), vol. 16, p. 21–54.

Nomura, R., 1997: List of the recent benthic foraminifera. *Memories of the Faculty of Education, Shimane University* (*Natural Science*), vol. 31, p. 1–25.

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

Nomura, R. and Seto, K., 2002: Influence of man-made construction on environmental conditions in brackish Lake Nakaumi, southwest Japan: foraminiferal evidence. *The Journal of the Geological Society of Japan*, vol. 108, p. 394–409.

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

Osaka Prefectural Fisheries Experimental Station, 1973–2001: *Business Report of Osaka Prefectural Fisheries Experimental Station, 1972–1999*. (*in Japanese*)

Samir, A. M., 2000: The response of benthic foraminifera and ostracods to various pollution sources: A study from two lagoons in Egypt. *Journal of Foraminiferal Research*, vol. 30, p. 83–98.

Samir, A. M. and El-Din, A. B., 2001: Benthic foraminiferal assemblages and morphological abnormalities as pollution proxies in two Egyptian bays. *Marine Micropaleontology*, vol. 41, p. 193–227.

Schafer, C. T. and Cole, F. E., 1974. Distribution of benthic foraminifera: Their use in delimiting local nearshore environments. *Offshore Geology of Canada, Eastern Canada, Geological Survey of Canada*, vol. 1, p. 103–108.

Shannon, C. E. and Weaver, W., 1949. *The Mathematical Theory of Communication*, 117 p. University of Illinois Press, Urbana.

Takayanagi, Y., 1953: Distribution of the recent foraminifera from adjacent seas of Japan. *Records of oceanographic works in Japan, New Series*, vol. 1, p. 78–85.

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*)

Thomas, E., Gapotchenko, T., Varekamp, J. C., Mecray, E. L. and Buchholz ten Brink, M. R., 2000: Benthic foraminifera and environmental changes in Long Island Sound. *Journal of Coastal Research*, vol. 16, p. 641–655.

Topping, J. N., Murray, J. W. and Pond, D. W., 2006: Sewage effects on the food sources and diet of benthic foraminifera living in oxic sediment: A microcosm experiment. *Journal of Experimental Marine Biology and Ecology*, vol. 329, p. 239–250.

Tsujino, M. and Tamai, K., 1996: Sediment conditions and meiobenthic community in Osaka Bay, Japan. *Bulletin of the Nansei Regional Fisheries Research Laboratory*, no. 29, p. 87–100. (*in Japanese with English abstract*)

Uchio, T., 1962: Influence of the River Shinano on foraminifera and sediment grain size distribution. *Seto Marine Biological Laboratory Publications*, vol. 10, p. 363–393.

Walton, W. R., 1952: Techniques for recognition of living foraminifera. *Contributions from the Cushman Foundation for Foraminiferal Research*, vol. 3, p. 56–60.

Ward, N. J., David, W. P. and Murray, J. W., 2003: Feeding of benthic foraminifera on diatoms and sewage-derived organic matter: an experimental application of lipid biomarker techniques. *Marine Environmental Research*, vol. 56, p. 515–530.

Watkins, J. G., 1961: Foraminiferal ecology around the Orange

County, California, ocean sewer outfall. *Micropaleontology*, vol. 7, p. 199–206.

Yanko, V., Ahmad, M. and Kaminski, M., 1998: Morphological deformities of benthic foraminiferal tests in response to pollution by heavy metals: implications for pollution monitoring. *Journal of Foraminiferal Research*, vol. 28, p. 177–200.

Yanko, V., Arnold, A. J. and Parker, W. C., 1999. Effect of marine pollution on benthic foraminifera. *In*, Sen Gupta, B. K., *ed.*, *Modern Foraminifera*, p. 201–216. Kluwer Academic Publishers, Dordrecht.

Yanko, V., Kronfield, J. and Flexer, A., 1994: Response of benthic foraminifera to various pollution sources: implications for pollution monitoring. *Journal of Foraminiferal Research*, vol. 24, p. 1–17.

Yasuhara, M. and Irizuki, T., 2001: Recent Ostracoda from the northeastern part of Osaka Bay, southwestern Japan. *Journal of Geoscience, Osaka City University*, vol. 44, p. 57–95.