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Impact of eutrophication on shallow marine benthic foraminifers over the last 150 years in Osaka Bay, Japan

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Abstract

High-resolution foraminiferal analysis was conducted on a short sediment core from the inner part of Osaka Bay, Japan. Changes in foraminiferal assemblages were associated with eutrophication, bottom water hypoxia, and changes in red tide-causing algae. Before the 1920s, the calcareous species *Ammonia beccarii*, and the agglutinated species *Eggerella advena* and *Trochammina hadai* were rare, but calcareous foraminifers in general were abundant. Between the 1920s and 1940s, calcareous foraminifers decreased abruptly in abundance, while *A. beccarii*, *E. advena* and *T. hadai* increased in abundance. This faunal change corresponded in time to an increase in nutrients flowing in through the Yodo River, and bottom water hypoxia related to eutrophication. In the 1960s and 1970s, *A. beccarii*, *E. advena* and *T. hadai* further increased in abundance to become dominant, and many calcareous foraminifers nearly disappeared, corresponding to increasing bottom water hypoxia related to the rapid increase in discharged nutrients during the high economic growth period from 1953 to 1971. After the 1990s, *A. beccarii* decreased rapidly in abundance and *E. advena* and *Uvigerinella glabra* increased in abundance. The main components of red tide-causing algae changed from dinoflagellates to diatoms in the 1980s through 1990s, thus there was a change in the food supply to the benthos, which may have caused the increase in abundance of *E. advena* and *U. glabra*.

Keywords: benthic foraminifera; pollution; eutrophication; hypoxia; Osaka Bay; Japan

1. Introduction

Enclosed shallow marine environments have been strongly affected by human activities, and the increasing amount of domestic and industrial wastewaters emitted into coastal waters has caused a deterioration in the quality of waters and sediments. The reclamation of coastal areas has led to stagnation, thus accelerated degradation of water quality. As the result of these anthropogenic changes in the environment, coastal marine ecosystems have been strongly damaged (see e.g., reviews by Smith et al., 1999; Jackson, 2001; Islam and Tanaka, 2004).

The reconstruction of the history of the anthropogenic impact on coastal marine ecosystems is important in order

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to learn how the present, anthropogenically stressed ecosystems originated and to evaluate how they might evolve in the future. Studies of short sediment cores allow the reconstruction of the anthropogenic impact on the natural environment (e.g., Valette-Silver, 1993; Cundy et al., 1997). Such studies require the presence of shallow marine organisms such as ostracoda, diatoms, and foraminifera, which have tests which are preserved well in the sediments (e.g., Alve, 2000; Cearreta et al., 2000; Thomas et al., 2000; Elberling et al., 2003; Yasuhara et al., 2003; Hayward et al., 2004a; Ruiz et al., 2004; Platon et al., 2005; Yasuhara and Yamazaki, 2005).

Benthic foraminifers respond not only to the natural environmental variability in such parameters as temperature and salinity (e.g., Alve, 1995b, 1999; Gustafsson and Nordberg, 1999, 2000; Ward et al., 2003; Filipsson and Nordberg, 2004) but also to anthropogenic stresses such as pollution, eutrophication, and hypoxia (see reviews by Alve, 1995a; Yanko et al., 1999; Murray and Alve, 2002, and references therein). Many authors studied the relationship between foraminifers and anthropogenic impact in shallow marine areas around the world using surface sediment samples and short cores (e.g., Geslin et al., 1998; Yanko et al., 1998; Angel et al., 2000; Coccioni, 2000; Samir, 2000; Thomas et al., 2000; Debenay et al., 2001; Samir and El-Din, 2001; Geslin et al., 2002; Platon et al., 2005), and concluded that anthropogenic nutrient overload imposes a major stress (e.g., Smith et al., 1999; Elofson et al., 2003), affecting foraminifers as well as other benthic faunas (e.g., Alve, 1995a; Murray and Alve, 2002).

Foraminiferal changes, caused by the increase in human-induced nutrients and seasonal bottom water hypoxia, have been noted in coastal seas around the world. The increase in nutrients led in some places to the development of an agglutinated faunal component (Nagy and Alve, 1987; Alve, 1991a, 1995a) or the increase in abundance of specific species (Nagy and Alve, 1987; Alve, 1991b). Moreover, foraminiferal assemblages in the vicinity of sewage outfalls are characterized by a large number of specimens and low diversity (Alve, 1995b; Thomas et al., 2000). For example, human-induced organic material caused oxygen depletion, and bottom water anoxia has occasionally developed in the Norwegian Skagerrak fjord after the development of sawmills (1550–1870) (Alve, 2000). The anoxic conditions had a negative effect on foraminiferal diversity but a positive one on the population of opportunistic species (e.g., *Stainforthia fusiformis*) (Alve, 2000). Barmawidjaja et al. (1995) studied the changes in foraminiferal assemblages influenced by the supply of human-induced nutrients to the northern Adriatic Sea, and concluded that the increasing nutrient load and consequent stress led to the increase in abundance of stress-tolerant taxa (e.g., *Nonionella turgida*, *Hopkinsina pactjica*, *Bolivina seminuda*). Platon et al. (2005) suggested that the changes in the foraminiferal community were related to the increase in nutrients and bottom water hypoxia in the Louisiana Bight over the last 100 years. In this area, the genus *Quinqueloculina* nearly became extinct from due to hypoxia, whereas several hyaline taxa tolerated the progress of hypoxia in the Louisiana Bight over the last 100 years (Platon et al., 2005).

Few studies investigating the relationship between eutrophication and faunas have been conducted on inner bays, which have more stable natural environmental conditions than estuaries, and have high sedimentation rates that allow high-resolution studies. Tsujimoto et al. (2006) reported that distinct changes related to eutrophication and bottom water hypoxia occurred in the benthic foraminiferal assemblages over the last 50 years in Osaka Bay during three time slices (1952; Nakaseko, 1953; 1983; Konda and Chiji, 1987, 1999; Tsujimoto et al., 2006). However, a detailed reconstruction of anthropogenic impacts on foraminifers was not conducted and the time at which the environmental changes started was not determined.

The aim of this study is to reconstruct historical changes in anthropogenic impact on benthic faunas in Osaka Bay, one of the most polluted marine areas in the world and to ascertain how the present anthropogenic-stressed ecosystems formed, using fossil foraminifers in a short sediment core (Yasuhara and Yamazaki, 2005).

2. Environmental setting

Osaka Bay is located at the eastern end of the Seto Inland Sea, and its bay entrance is semi-closed by Awaji Island (Fig. 1). Monthly changes in water temperature and salinity are shown in Fig. 2. The surface and bottom water temperatures are highest in August and September and lowest in February and March, respectively, in the inner part of the bay (Fig. 2; Osaka Prefectural Fisheries Experimental Station, 1998–2000). The surface-water salinity fluctuates over the year, decreasing to ca. 25 psu in the rainy seasons, but the salinity in the bottom waters is relatively stable over the year in the inner part of the bay (Fig. 2; Osaka Prefectural Fisheries Experimental Station, 1998–2000).

Osaka Bay is close to the cities Osaka and Kobe, from which large amounts of pollutants (household, agricultural, and industrial wastes) are discharged into Osaka Bay. Osaka City, the second largest city in Japan, is the main source of the pollutants, which dominantly flow into

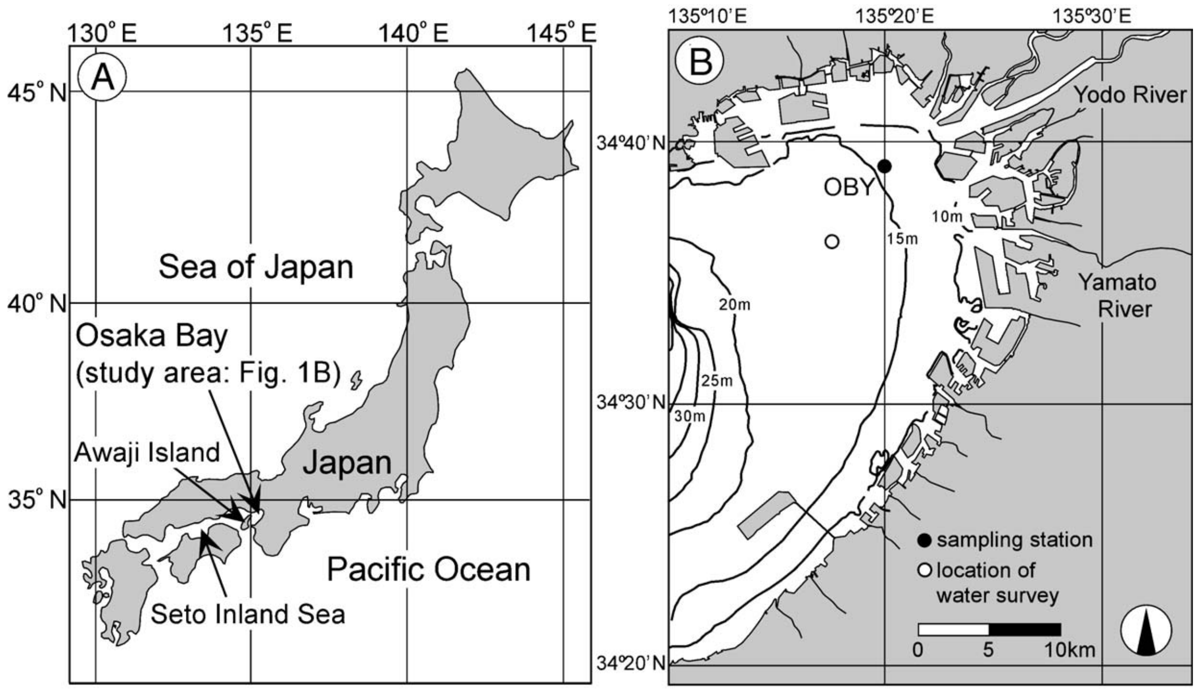

Fig. 1. Index and location maps: (A) showing the location of Osaka Bay; (B) the location of core OBY.

the bay through the Yodo River (Association for New Social Infrastructure of Osaka Bay, 1996). Marine pollution has increased since around the 1920s, associated with the increase in the population of Osaka City (Yamane et al., 1997; Nakatsuji et al., 1998; Osaka City, 2004; Fig. 3). The marine environment became severely polluted as the result of industrialization and urbanization during the high economic growth period from 1953 to 1971 (Association for New Social Infrastructure of Osaka Bay, 1996).

Anthropogenic nutrient loading occurred since the 1920s, especially during the 1950s–1970s. Consequently, the frequency of occurrence of hypoxic bottom waters in the innermost part of the bay increased during the 1950s (Joh, 1986). Outbreaks of red tide in spring to summer increased rapidly in the latter half of the 1960s, and bottom waters were anoxic to hypoxic in one-third of the bay (Joh, 1986). The spatial distribution patterns of the meiobenthic community have been strongly influenced by this seasonal hypoxia (Tsujino and Tamai, 1996; Yasuhara and Irizuki, 2001; Tsujimoto et al., 2006). In an effort to improve environmental conditions within the bay, a sewage treatment began in 1973, imposing

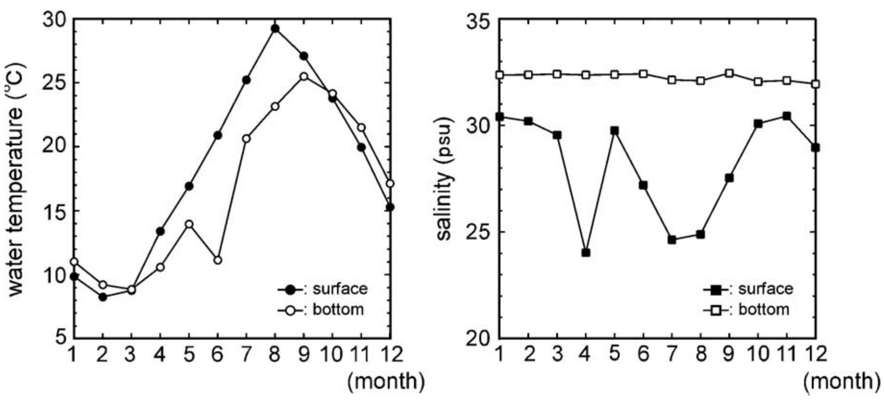

Fig. 2. Monthly changes in the temperature and the salinity (average of observations from 1996 to 1998; Osaka Prefectural Fisheries Experimental Station, 1998–2000). Location of water survey is shown in Fig. 1B.

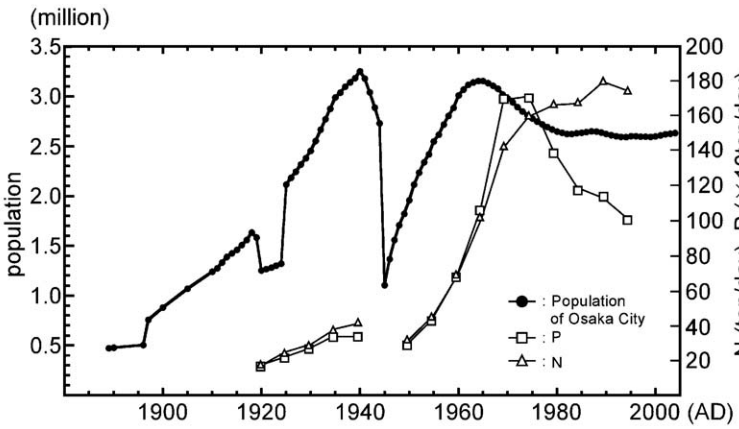

Fig. 3. Secular change in the influx of nitrogen and phosphorus (Nakatsuji et al., 1998), and the population size of Osaka City (Osaka City, 2004).

restrictions on discharge. As a result, the chemical oxygen demand (COD), and the concentration of phosphorus and nitrogen decreased, but there have been no major further changes over the last 10 years (Association for New Social Infrastructure of Osaka Bay, 1996).

3. Materials and methods

An 84-cm-long sediment core (core OBY) was obtained by scuba divers using an acrylic corer (10 cm in diameter) on September 1, 2001 (Fig. 1; 34°39′00″ N, 135°819′ 50″ E, 14 m water depth). The sediments consist of homogenous clay throughout the core. The core was sliced in 2-cm-thick samples. For the foraminiferal analysis, samples were washed through a 75 μm sieve, after which the residues were dried and sieved. Foraminiferal assemblages were analyzed in the >105 μm fraction, and samples containing abundant foraminiferal tests were split into fractions containing approximately 200 specimens. Dry weights, which were used to calculate the number of foraminiferal specimens per gram of sediment, were calculated from the wet weights and water content. The Shannon–Wiener index (*H*) (Shannon and Weaver, 1949) and the Buzas and Gibson's evenness (*E*) were used to assess the temporal trend in species diversity (Buzas and Gibson, 1969). Horn's overlap index (Horn, 1966) was used to evaluate similarities. Clustering was performed using the unweighted pair-group arithmetic

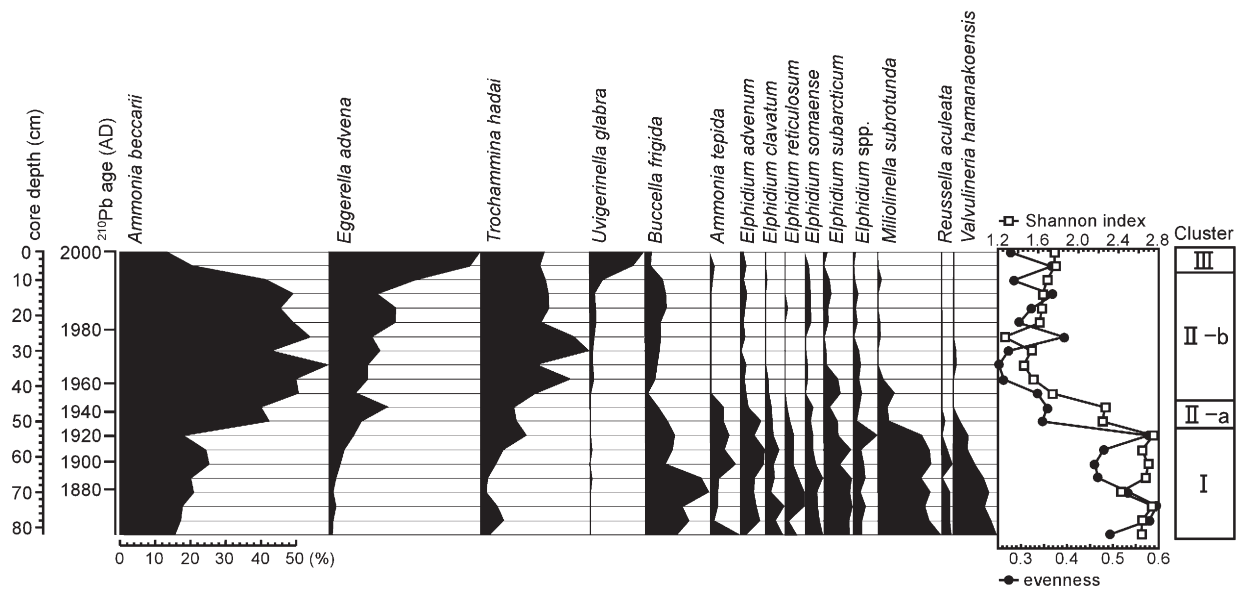

Fig. 4. Relative abundance of the dominant species, Shannon–Wiener diversity index, Buzas and Gibson's evenness, and Q-mode cluster grouping, plotted with depth in core OBY.

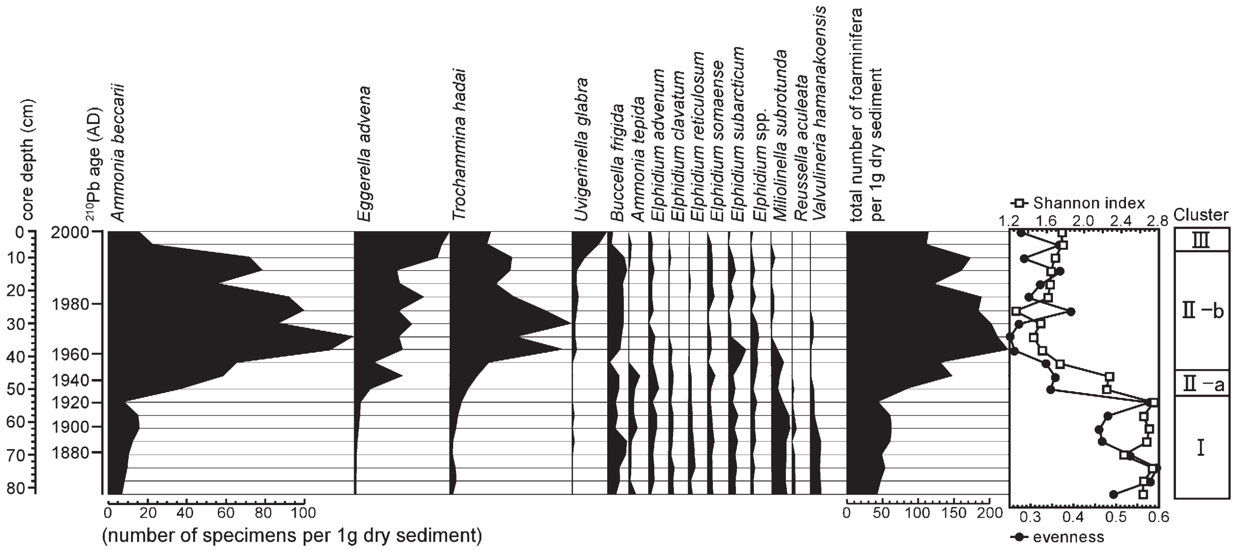

Fig. 5. Absolute number of specimens per gram dry sediment of dominant foraminiferal species and total foraminifera, and Q-mode cluster grouping, plotted with depth in core OBY.

average method by the software “PAST” (http://folk.uio.no/ohammer/past/) (Hammer et al., 2001).

The chronology of the core OBY was based on ^{210}Pb and ^{137}Cs information, as published in Yasuhara and Yamazaki (2005).

4. Results and discussion

Seventy-six species belonging to 40 genera were identified (Appendix A.1 and A.2). Figs. 4 and 5 show the vertical changes in relative abundance, the absolute number of specimens, the Shannon–Wiener index, and Buzas and Gibson’s evenness. Q-mode cluster analysis was applied to species of which three or more individuals were present in at least one sample. Three major clusters (I, II, III) and two sub-clusters (II-a, II-b) were distinguished (Fig. 6). Table 1 shows the faunal characteristics of each cluster. The vertical changes in relative abundance and absolute number of specimens showed a similar trend, and the following discussion is based on the absolute abundance data.

4.1. Responses of three dominant species to anthropogenic stresses

The foraminiferal assemblage was dominated by three species [*Ammonia beccarii* (Linné), *Eggerella advena* (Cushman), and *Trochammina hadai* Uchio; Fig. 7]. *A. beccarii* of Osaka Bay (Fig. 7, (1A–1C)) is a species widely distributed in Japanese inner bays and coastal areas, but is morphologically different from *A. beccarii* of the type locality in the Adriatic Sea, as described in Hayward et al. (2003) and Hayward et al. (2004b).

These three species occurred throughout the core, constituting up to 59% of the total assemblage. The genus *Ammonia* dominates in shallow marine or slightly brackish intertidal environments (Hayward et al., 2004b).

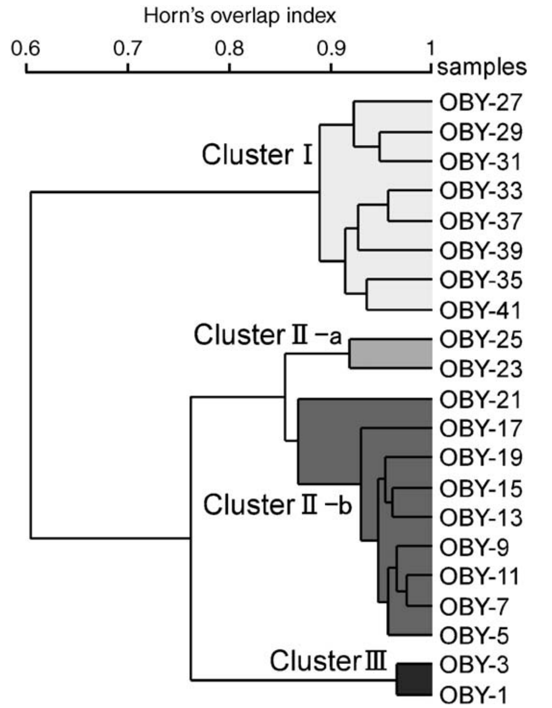

Fig. 6. Dendrogram of the Q-mode cluster analysis of core OBY.

Table 1
Faunal characters in core OBY

Cluster	Core depth (cm)	Dominant species	Common or characteristic species	Density (number of specimens per 1 g dry sediment)	Diversity	Evenness
III	0–6	*Ammonia beccarii* (Linné) *Eggerella advena* (Cushman) *Trochammina hadai* Uchio *Uvigerinella glabra* (Millett)	*Buliminella elegantissima* (d'Orbigny)	111–114	1.76–1.77	0.28–0.37
II-b	8–42	*Ammonia beccarii* (Linné) *Eggerella advena* (Cushman) *Trochammina hadai* Uchio	*Buccella frigida* (Cushman)	121–226	1.26–1.74	0.25–0.39
II-a	44–50	*Ammonia beccarii* (Linné) *Eggerella advena* (Cushman) *Trochammina hadai* Uchio	*Ammonia tepida* (Cushman) *Buccella frigida* (Cushman) *Elphidium advenum* (Cushman)	87–147	2.24–2.27	0.35–0.36
I	52–82	*Ammonia beccarii* (Linné) *Buccella frigida* (Cushman) *Miliolinella subrotunda* (Montagu) *Valvulineria hamanakoensis* (Ishiwada)	*Ammonia tepida* (Cushman) *Elphidium advenum* (Cushman) *Elphidium clavatum* (Cushman) *Elphidium reticulosum* Cushman *Elphidium somaense* Takayanagi *Elphidium subarcticum* Cushman *Reussella aculeata* Cushman	42–62	2.42–2.75	0.46–0.60

A. beccarii is a euryhaline species, and is widely distributed in intertidal and subtidal zones (Alve and Murray, 1999). It survives under a wide range of values of dissolved oxygen (Moodley and Hess, 1992), salinity, and temperature (Murray, 1991) as well as in heavily polluted waters (Alve, 1995a). Thomas et al. (2000) suggested that

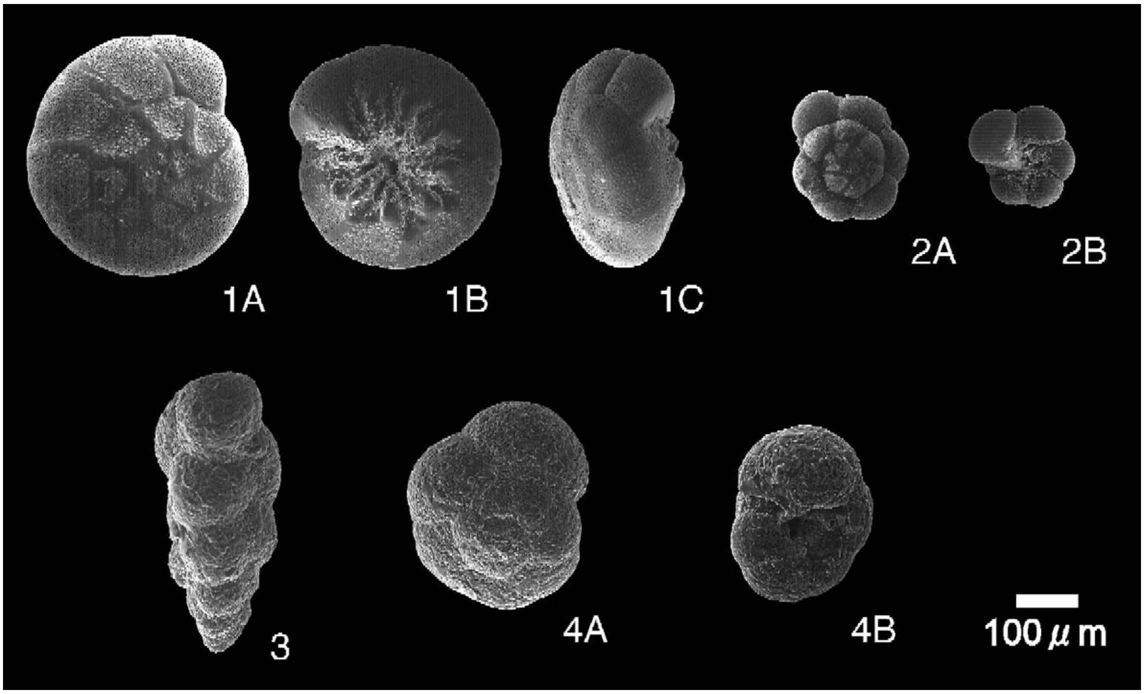

Fig. 7. Scanning electron micrographs of the foraminifera from core OBY (scale bar = 100 μm). 1A–1C: *Ammonia beccarii* (Linné). 2A, 2B: *Ammonia tepida* (Cushman). 3: *Eggerella advena* (Cushman). 4A, 4B: *Trochammina hadai* Uchio.

an abundance of *A. beccarii* might be associated with high sewage inputs, and, Thomas et al. (2004) suggested that an increase in nitrogen–silicon ratio, which gives the competitive advantage to organic-walled primary producers over diatoms, might cause shift in dominance from the diatom consuming *Elphidium* to the omnivorous *A. beccarii*.

E. advena, an agglutinated species, survives in highly polluted waters in the vicinity of organic waste discharge (Watkins, 1961; Clark, 1971; Schafer and Cole, 1974; Bates and Spencer, 1979; Alve and Nagy, 1986; McGann et al., 2003). *T. hadai*, another agglutinated species, dominates in many Japanese and American brackish waters and prefers sediment with a high organic matter content (Uchio, 1962; Matoba, 1970; Matsushita and Kitazato, 1990; McGann and Sloan, 1999; Nomura and Seto, 1992, 2002; Nomura, 2003). This species increases with increasing pollution (Matsumoto, 1981), especially with an increase in eutrophication (Konda and Chiji, 1987, 1989; Nomura and Seto, 1992, 2002; Nomura, 2003). Tsujimoto et al. (2006) suggested that an *E. advena–T. hadai* assemblage, dominated by these two species, is present in the eutrophic and hypoxic waters in the surface sediment of Osaka Bay. We conclude, therefore, that all three dominant species found in core OBY, *A. beccarii*, *E. advena*, and *T. hadai*, are tolerant of anthropogenic impacts. Based on these foraminiferal characteristics, we discuss four stages in the environmental evolution of Osaka Bay over the last 150 years.

4.2. Historical changes in foraminifera over the last 150 years

4.2.1. The first stage: pre-pollution

This stage is represented by cluster I, 82–52 cm depth, corresponding to the 1840–1920s. *A. beccarii*, *E. advena*, and *T. hada* were rare, calcareous foraminifers such as *Buccella frigida* (Cushman), *Miliolinella subrotunda* (Montagu), *Valvulineria hamanakoensis* (Ishiwada), *Ammonia tepida* (Cushman), *Elphidium*, and *Reussella aculeata* Cushman were abundant (Figs. 4 and 5), and the Shannon–Wiener index was the highest of the four stages. These combined factors reflect the fact that humans probably had little influence on the foraminiferal assemblage.

4.2.2. The second stage: the beginning of pollution

This stage is represented by cluster II-a, 50–44 cm depth, corresponding to the 1920–1940s. Many calcareous foraminifers decreased in abundance, but *A. beccarii*, *E. advena*, and *T. hada* began to increase (Figs. 4 and 5), resulting in an abrupt decrease in diversity and evenness, coinciding with an abrupt decline in the abundance of Ostracoda, micro-crustacea sensitive to anthropogenic impacts (Ruiz et al., 2005) in core OBY (Yasuhara and Yamazaki, 2005). These foraminiferal changes corresponded in time to the increase in the amount of nutrients (phosphorus and nitrogen) discharged from Osaka City through the Yodo River, and the increase in the population of Osaka City. Nakatsuji et al. (1998) calculated the loads

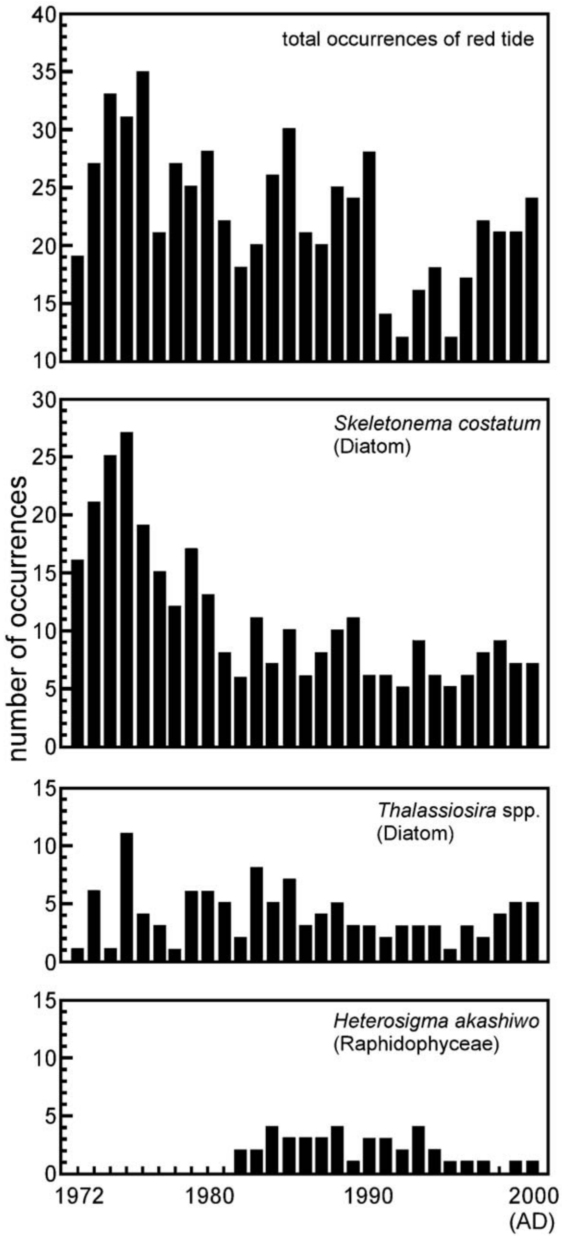

Fig. 8. Secular change in the total number of outbreaks of red tide and the number of outbreaks due to specific red tide-causing algae. Each vertical axis represents the number of occurrences (Osaka Prefectural Fisheries Experimental Station, 1973–2002).

of nitrogen and phosphorous on the basis of the statistical data (population, livestock numbers, annual usage of chemical fertilizer, and annual industrial shipment value of the Osaka Prefecture) (Fig. 3). The noticeable increase in nitrogen and phosphorous content began around 1950, but the Osaka City population began to increase significantly around 1900. There is a slight increase in nitrogen and phosphorous influx around 1920 (Fig. 3; Nakatsuji et al., 1998). Data on underwater visibility and COD indicate that the water quality of Osaka Bay had already deteriorated and eutrophication had begun by the 1920s (Yamane et al., 1997). Thus, we concluded that the noticeable increase in the population of Osaka City (i.e., urbanization) led to eutrophication and bottom water hypoxia since the 1920s at the least.

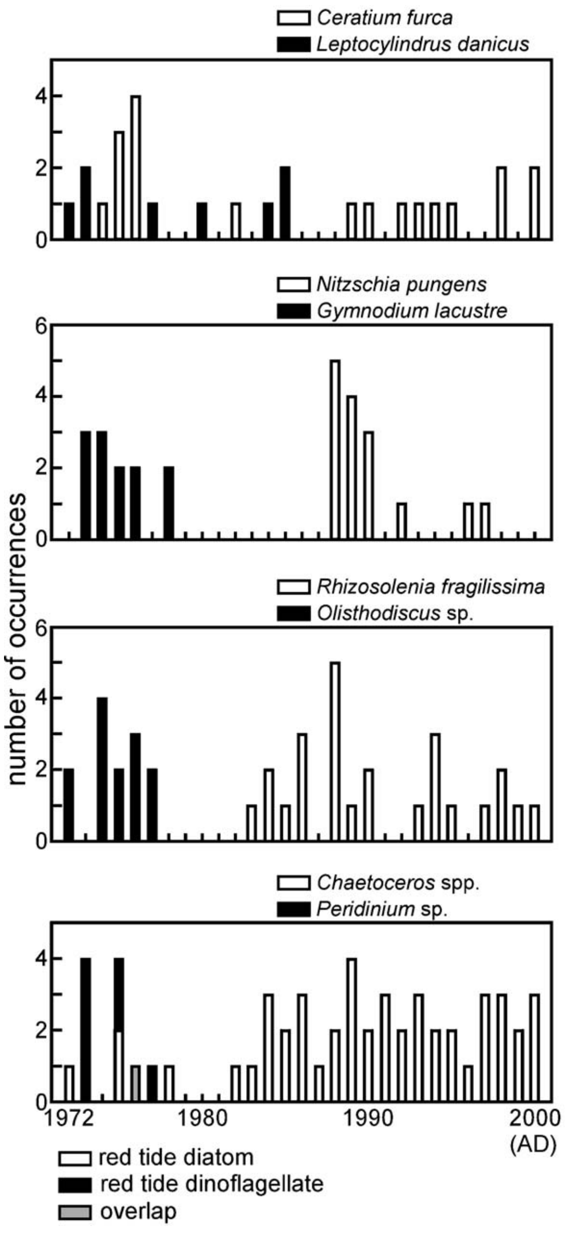

Fig. 9. Secular change in the composition of red tide-causing diatom and dinoflagellate algae. Each vertical axis represents the number of occurrences of red tide (Osaka Prefectural Fisheries Experimental Station, 1973–2002).

4.2.3. The third stage: maximum pollution

This stage is represented by cluster II-b, 42–8 cm depth, corresponding to the 1940–1990s. The absolute abundance of *A. beccarii*, *E. advena*, and *T. hada* was greater than in cluster II-a, and peaked between the 1960s and 1970s (Figs. 4 and 5). Many calcareous foraminifers, such as *B. frigida*, *M. subrotunda*, *V. hamanakoensis*, *A. tepida*, *Elphidium*, and *R. aculeata*, nearly disappeared, so that the diversity index reached its minimum value. These changes in foraminiferal populations coincided with the increase in severity of bottom water hypoxia during the high economic growth period from 1953 to 1971 (Nakatsuji et al., 1998; see Fig. 3). As a result, summer hypoxia and anoxia reached their peak during the 1970s (Joh, 1986). This summer hypoxia strongly influenced the distributions of megabenthos, macrobenthos, and meiobenthos (Ariyama et al., 1997a,b; Yasuhara and Irizuki, 2001; Tsujimoto et al., 2006), and probably caused an abrupt decline in abundance of most species of calcareous foraminifers, whereas the anthropogenic impact-tolerant species (*A. beccarii*, *E. advena*, and *T. hadai*) prospered.

4.2.4. The fourth stage: post-pollution

This stage is represented by cluster III, 6–0 cm depth, corresponding to the 1990–2000s. *A. beccarii* decreased in abundance while *E. advena* and *Uvigerinella glabra* increased (Figs. 4 and 5). After about 1970, a national conservation effort placed restrictions on the discharge of substances capable of increasing COD although these did not result in large changes in COD, phosphorous, and nitrogen concentrations during the following decade (Association for New Social Infrastructure of Osaka Bay, 1996). Therefore, we are not certain what exactly caused the change in foraminiferal assemblages, but we speculate that it might be related to changes in the organic supply to the bottom. Tsujimoto et al. (2006) suggested that the changes in foraminiferal assemblages over the last 20 years in Osaka Bay might be related to the changes in the composition of red tide-causing algae. They noted that the number of outbreaks of red tide decreased gradually after the environmental regulation was initiated in 1973, with an abrupt decline in the number of outbreaks during the 1990s (Osaka Prefectural Fisheries Experimental Station, 1973–2002; Fig. 8), and a change in composition of the dominant red tide-causing algae (Osaka Prefectural Fisheries Experimental Station, 1973–2002; Figs. 8 and 9). The number of outbreaks due to the diatom *Skeletonema costatum* decreased rapidly after 1975. Although red tide due to dinoflagellates (e.g., *Ceratium furca*, *Gymnodium lacustre*, *Olisthodiscus* sp., and *Peridinium* sp.) occurred frequently during the 1970s, they decreased after the 1980s–1990s. On the other hand, outbreaks of red tide due to diatoms (e.g., *Chaetoceros* spp., *Nitzschia pungens* and *Rhizosolenia fragilissima*) increased. The food supply substantially influences benthic foraminiferal populations (e.g., Alve, 1995b, 1999; Gustafsson and Nordberg, 1999, 2000; Thomas et al., 2000; Ward et al., 2003; Topping et al., 2006). The red tides caused an accumulation of a large amount of detritus at the bottom of the sea, which becomes food for detritivores. *E. advena* is one such detritivorous species, for which Murray (1991) and Thomas et al. (2000) suggested that changes in abundance might be related to a change in the composition of the food supply. Consequently, the change in red tide from red tide dinoflagellate to red tide diatom may have caused the changes in food supply for detritivorous foraminifers and, consequently, the increase in abundance of *E. advena* and *U. glabra*. Further study is needed to confirm the relationship between changes in the benthic foraminiferal assemblages and in the food supply.

5. Conclusion

The history of anthropogenic impact on shallow marine foraminifers was reconstructed in core OBY collected in Osaka Bay, one of the most polluted marine areas in the world. Fossil foraminiferal records in this core closely relate to the history of human activities in Osaka City, which surrounds the inner part of Osaka Bay. The inflow of nutrients into the bay through the Yodo River and the resulting development of hypoxic bottom waters were the main factors responsible for the changes in the foraminiferal assemblages.

The amount of discharged nutrients increased with the increase in the population of Osaka City after the 1920s. The decline in populations of many calcareous foraminifers and the increase in populations of *A. beccarii*, *E. advena*, and *T. hada* occurred in phase with the increasing nutrients, and was thus probably caused by bottom water hypoxia related to eutrophication at the beginning of pollution.

During the period of maximum pollution (1960s–1970s), the abundance of the anthropogenic impact tolerant species (*A. beccarii*, *E. advena*, and *T. hadai*) peaked. Whereas these three species prospered with increased nutrients and reduced competition, other calcareous foraminifers nearly disappeared. These foraminiferal changes coincided with increased bottom water hypoxia, related to the rapid increase in nutrients.

After the 1990s, *A. beccarii* decreased in abundance while *E. advena* and *U. glabra* increased, possibly because red tides changed from being dominated by dinoflagellates to being dominated by diatoms. These records are important in order to assess the relationship between anthropogenic impacts and organisms, and to evaluate possible future development of aquatic environments and ecosystems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.marmicro.2006.06.001.

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