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The impact of 150 years of anthropogenic pollution on the shallow marine ostracode fauna, Osaka Bay, Japan

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Abstract

Coastal bays adjacent to metropolitan areas are commonly polluted heavily, and the direct and indirect results of pollution (e.g., heavy metal pollution, eutrophication, and hypoxia) seriously influence metazoan benthos. Historical metazoan trends, however, remain poorly documented and understood. Using the ostracode record of the past 150 years (^{210}Pb and ^{137}Cs age information), we show that anthropogenic impacts during industrialization seriously influenced the benthic metazoan ecosystem in a bay adjacent to a metropolis (Osaka Bay, Japan). Ostracode absolute abundance decreased by 90% from ca. A.D. 1910–1920 to ca. A.D. 1960–1970 as a result of Japan's rapid industrial development, coinciding with a rapid increase in concentration of various pollutants and the Osaka City population. The ostracode abundance has not recovered despite environmental legislation enforced after ca. A.D. 1960–1970.

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Keywords: Ostracoda; Pollution; Eutrophication; Hypoxia; Industrialization; Japan

1. Introduction

Japan had industrialised more rapidly than most other countries after its industrial revolution (ca. A.D. 1900). Pollution is a negative outcome of this rapid development and industrialisation. Marine bays adjacent to metropolitan areas have been strongly polluted by domestic wastewater, factory disposal, and other

sources, and anthropogenic impacts have seriously influenced metazoan benthos. 'Anthropogenic impacts' are defined in this study as the direct and indirect results of pollution, such as heavy metal pollution, eutrophication, and hypoxia.

Osaka Bay's surrounding area (population of more than ten million) is one of Japan's economic centers. It produces great amounts of pollutants, released as domestic and industrial wastewaters to Osaka Bay (Association for New Social Infrastructure of Osaka Bay, 1996). In particular, Osaka City, the second largest metropolitan area in Japan, is a main source of

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pollutants. Pollutants are mainly transported through the Yodo River to the inner part of the Bay (Association for New Social Infrastructure of Osaka Bay, 1996). Levels of several pollutants and indicators of pollution in surface sediments—e.g., heavy metals, chemical oxygen demand (COD), and total sulphide—are extremely high and intense summer-hypoxia occurs in the inner part of the Bay (Joh et al., 1974; Association for New Social Infrastructure of Osaka Bay, 1996).

Benthic faunas are strongly influenced by these anthropogenic impacts in the inner part of the Bay (Association for New Social Infrastructure of Osaka Bay, 1996). Modern (i.e., living and dead) ostracodes in surface sediments are especially rare in the innermost part (Fig. 1; Yasuhara and Irizuki, 2001). Yasuhara and Irizuki (2001) suggested that this low abundance was caused by hypoxia, but other anthropogenic impacts, e.g., eutrophication, hypoxia, and heavy metal pollution, probably also play a role (Modig and Ólafsson, 1998; Mazzola et al., 1999; Samir, 2000). Ostracodes, like many other metazoan taxa, are rare under stressed conditions caused by anthropogenic impacts (Modig and Ólafsson, 1998; Mazzola et al., 1999; Samir, 2000). Bottom water temperature, salinity, and pH are normal, with little variability throughout the study area (e.g., about 15–18 °C, 31–32‰, and 7.9–8.2) except for one station (about 23‰) in May 1999 (Yasuhara and Irizuki, 2001). This evidence strongly supports the hypothesis that the low abundance of ostracodes is caused by anthropogenic impacts, but it remains unclear when and how this ecosystem destruction occurred.

There is a large literature regarding modern and historical relations between anthropogenic impacts and the protist foraminifera (e.g., McGann et al., 2003; Hayward et al., 2004; also see reviews by Alve, 1995). In contrast, despite studies of the relations between anthropogenic impacts and metazoan benthos (e.g., Mazzola et al., 1999; Millward et al., 2001; Gray et al., 2002), historical metazoan trends remain poorly understood for two reasons. First, fixed-point observation is impossible for periods of a century or more. Second, stratigraphical studies have been rare because most metazoan benthic species are not preserved as fossils.

The stratigraphical ostracode record is the only fossil record of historical metazoan trends because

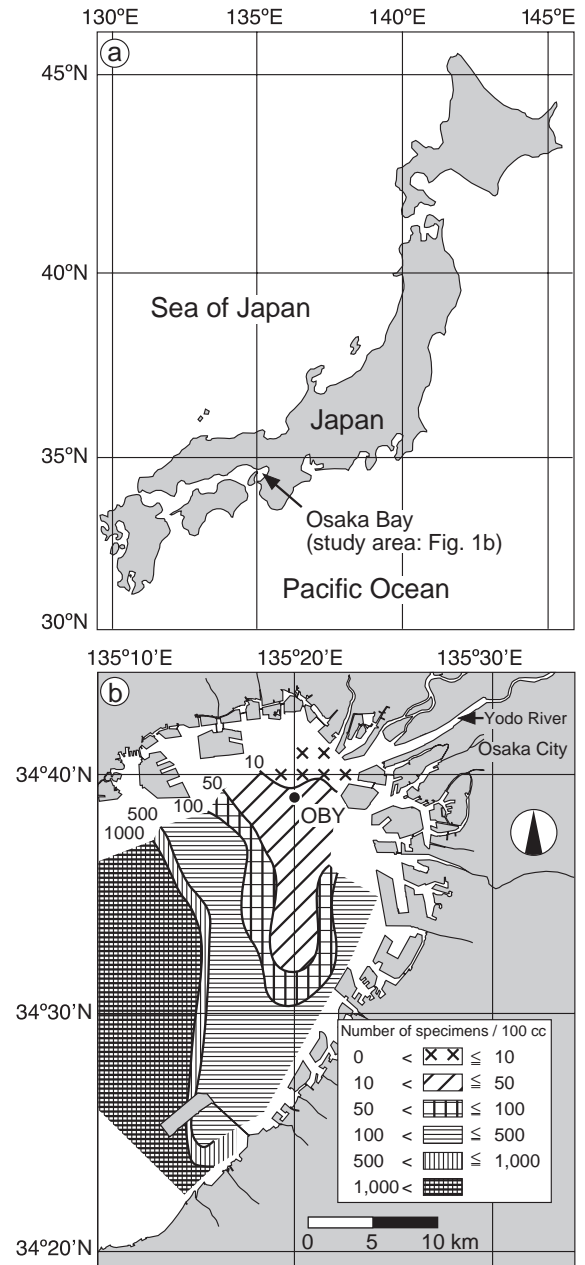


Fig. 1. Index and location maps: (a) index map showing location of Osaka Bay; (b) location of core OBY and modern ostracode abundance (number of specimens per 100 cm³ wet sediment) in Osaka Bay (Yasuhara and Irizuki, 2001).

Ostracoda (Crustacea) are the only metazoan group occurring abundantly enough to enable quantitative assemblage analysis in sediment cores (Cronin and Vann, 2003), and ostracodes are sensitive to

anthropogenic impacts (e.g., Cronin and Vann, 2003; Yasuhara et al., 2003). The relationship between ostracodes and anthropogenic impacts has been studied by a number of authors (see Yasuhara et al., 2003 and references therein), but many studies concentrated on the spatial distribution of recent ostracodes (e.g., Rosenfeld et al., 2000; Ruiz et al., 2000; Schornikov, 2000), and studies of historical relationships between marine ostracodes and anthropogenic impact are few (e.g., Alvarez Zarikian et al., 2000; Cronin and Vann, 2003; Yasuhara et al., 2003; Ruiz et al., 2004). Such studies are nonexistent for inner bays adjacent to a metropolis, in which the modern ostracode distribution has been documented in detail. Core sediments excavated from muddy inner bays are suitable to document the influences upon ostracodes of anthropogenic impacts. Natural environmental factors are often more stable in inner bays than in river mouths and estuaries, therefore, historical changes can be continuously observed at the same site. Furthermore, inner bay sediments have a high sedimentation rate making high-resolution studies possible.

The aim of this project was to elucidate the history of impacts on metazoan benthos caused by anthropogenic impacts, using the high-resolution ostracode record of the past 150 years in a sediment core from Osaka Bay.

2. Materials and methods

We studied ostracodes in core OBY (34°39' 00"N, 135°19' 50"E, 14 m water depth) from the inner part of Osaka Bay (Fig. 1) in September 2001. Sediments are composed of homogenous clay with molluscan shells throughout the core.

For ostracode analysis, sediment core samples, each of 2 cm stratigraphic thickness, were washed through a 75- μm sieve, oven-dried, and then dry-sieved into >125 μm fractions. Only ostracodes larger than 125 μm were studied. Dry weights, which were used for ostracode absolute abundance (i.e., number of specimens per 10 g dry sediment), were calculated from original sample weights (i.e., wet weight) and water content. Ostracode-rich samples were split into fractions using a splitter, and all specimens contained

in a fraction were picked. Around 200 specimens were picked, mounted, and identified from each ostracode-rich sample. In ostracode-poor samples, all specimens contained in a sample were picked. The number of specimens refers to the sum of the number of left and right valves and carapaces. Each valve and carapace was counted as one specimen respectively (Table 1). Most of specimens are separate valves and carapaces are few.

The activities of ^{210}Pb and ^{137}Cs in sediments were analyzed by gamma spectrometry following the procedures of Yamazaki et al. (2001). For radiometric dating, sediment core samples (bulk samples), sliced into 2 cm thick sections, were dried at 105 °C and homogenized using an agate mortar. The activity in each section was determined by gamma counting 20 g of the samples for up to 2×10^5 s using an ORTEC HPGe Detector (LO-AX/30P) coupled to a 4096 channel multichannel analyzer. An activity standard, having essentially the same geometry and density was used. This was prepared from NIST Standard Reference Material 4350B (River Sediment), 4354 (Freshwater Lake Sediment), and 4357 (Ocean Sediment). The detection limits for ^{210}Pb (E_γ : 46 keV) and ^{137}Cs (E_γ : 662 keV) by this method are 0.5 Bq/kg and 6 Bq/kg and the counting errors are $\leq \pm 10\%$ and $\leq \pm 3\%$ in the upper layers of the core, respectively.

The concentrations of Pb, Cu, Zn, and Cr were also examined as indicators of heavy metal pollution. An X-ray fluorescence analyzer (XRF) (RIGAKU RIX 2000; Rh cathode: 50 kV–50 mA) was used to measure their concentration in the sediments following the procedures of Yamazaki et al. (1998). Standard reference material NIST 1646 (Estuarine Sediment) and NIES No. 2 (Pond Sediment) were used as a standard sample for XRF analysis. The sliced sediments were dried and homogenized as described above. The sample disks for the XRF measurements were prepared as following. The base disk of 4 cm diameters and 0.3 cm thickness was made in the cellulose powder (ADVANTEC No. A). The sediment of 1.2 g was uniformly put on the disk, and then it was molded by press at 1600 kg/cm² for 1 min. The standard samples were also prepared in the same way. The relative standard deviations were estimated to be within $\pm 3\%$ for the four heavy metals in the sediments of core OBY.

Table 1
List of fossil ostracodes in core OBY

Species	Depth (z: cm)																				
	0–2	4–6	8–10	12–14	16–18	20–22	24–26	28–30	32–34	36–38	40–42	44–46	48–50	52–54	56–58	60–62	64–66	68–70	72–74	76–78	80–82
<i>Amphileberis nipponica</i>							1						1		1						
<i>Ambtonia obai</i>	1												1		1						
<i>Bicornucythere bisanensis</i>	1	1	6	6	9	6	3	4	24	12	35	68	90	81	80	80	62	68	59	73	101
<i>Bicornucythere</i> sp.			2	1	1	5	3	1	3	8	21	25	26	22	21	28	22	22	23	25	10
<i>Callistocythere alata</i>																			2		
<i>Cytheromorpha acupunctata</i>		2	1	4	5	6	4	4	20	9	86	78	44	43	61	46	34	52	50	55	53
<i>Cytherois nakanoumiensis</i>	3										2					1	2		2	3	
<i>Cytherois uranouchiensis</i>	13	1		1		2			1	1		2	2	8		2	4	2	6		1
<i>Loxoconcha tosaensis</i>						7	1		3	3	9	12	25	25	54	51	59	30	43	44	45
<i>Loxoconcha uranouchiensis</i>														1							
<i>Loxoconcha viva</i>			1			5	1	2	2	9	40	57	47	28	34	22	8	19	10	15	8
<i>Nipponocythere bicarinata</i>						1														1	
<i>Paracytherois</i> sp.															4				1		
<i>Paracytherois?</i> sp. 1															1						
<i>Paracytherois?</i> sp. 2																			1		1
<i>Pistocythereis bradyi</i>					1	1	3					1	6	9	12	3	4	13	9	11	10
<i>Pontocythere</i> sp.	1																				
<i>Propontocypris</i> sp.									1			9			1		2	1			
<i>Spinileberis quadriaculeata</i>				1		1	1		2	4	4	8	4	13	11	11	18	18	13	11	16
<i>Trachyleberis scabrocuneata</i>			1				1		1			4	4	10	6	3	1	1		2	1
Gen. et sp. Indet.	6																				
No. of species	6	3	5	5	4	9	9	4	9	7	7	10	11	10	13	10	11	10	12	10	10
No. of specimens	25	4	11	13	16	34	18	11	57	46	197	264	250	240	287	247	216	226	219	240	246
No. of specimens per 10 g dry sediment	17.3	2.6	6.1	9.9	8.2	20.5	10.6	6.6	33.3	27.6	73.2	123.7	185.2	260.5	295.0	157.1	174.8	184.0	238.3	145.7	184.2

3. Chronology

The core chronology was constructed by radiometric dating. ^{210}Pb is a naturally occurring disintegration series radionuclide with a half life of 22.3 years. The part of the radionuclide ^{222}Rn diffuses from the crust into the atmosphere because it is rare-gas element. The ^{222}Rn decays in the atmosphere to form ^{210}Pb . The ^{210}Pb is removed from atmosphere and finally scavenged to sediments. Such atmospherically delivered ^{210}Pb is defined as $^{210}\text{Pb}_{\text{ex}}$. Krishnaswami et al. (1971) presented a simple model that successfully described the ^{210}Pb profile in sediments. In their model it is assumed that (a) the flux of excess ^{210}Pb to the sediment–water interface is constant, (b) the sedimentation rate is constant at all times, (c) there is no post-depositional migration of the radionuclide within the sediments, and (d) the activity of ^{210}Pb supported by ^{226}Ra in the sediments is independent of depth. Under these conditions the expected activity of $^{210}\text{Pb}_{\text{ex}}$ in Bq/kg dry weight of a sediment section with age t is expressed as

$$A(t) = \left(\frac{P}{w}\right)e^{-\lambda t} + A', \quad (1)$$

where P is the flux of ^{210}Pb at sediment–water interface in Bq/cm² year, w is the mass flux in kg/cm² year, A' is the activity of supported ^{210}Pb in Bq/kg dry weight, and λ is the radioactive decay constant (0.311 year⁻¹). If the sedimentation rate in cm/year over all the depths does not differ from that in the surface layer (S_0), that is, there is no compaction, Eq. (1) can be rewritten in term of depth z as follows;

$$A(z) = \left(\frac{P}{w}\right)e^{-\lambda z/S_0} + A', \quad (2)$$

where z is depth below the sediment–water interface in centimeters. However, the sediment porosity decreases with depth due to compaction. Robbins and Edgington (1975) and Matsumoto (1975) considered this effect in their treatment of ^{210}Pb profiles. We have applied the ^{210}Pb chronology to core OBY by using their models.

Matsumoto (1975) assumed that the thickness of sediments at the interface, $(1+A)$ cm becomes 1 cm at a depth z in consequence of compaction. Then,

$$A = \frac{(\Phi_0 - \Phi)}{(1 - \Phi_0)}, \quad (3)$$

where Φ_0 and Φ are porosities of sediments at the water–sediment interface and at a depth z , respectively. The sediment porosity can be calculated using water content (WC) in following Eq. (4);

$$\Phi = \frac{\rho}{\rho + \frac{WC}{1 - WC}}, \quad (4)$$

where ρ is the effective dry density. The dry density was 2.48 ± 0.09 g/cm³ for several Osaka Bay cores, one of them was taken from close site to the site OBY (Yamazaki, H., unpublished data, 2004). We assume the density ρ to be 2.5 g/cm³ in our calculation of porosity. The depth of sediment without compaction z' is expressed by

$$z' = z + \int_0^z \Delta dz. \quad (5)$$

By combining Eqs. (2) and (5),

$$A(z') = \left(\frac{P}{w}\right)e^{-\lambda z'/S_0} + A', \quad (6)$$

the values of λ/S_0 and P/w can be obtained from $\ln(A - A')$ vs. z' plot for the layer where the sedimentation rate is fixed. Since λ is known, S_0 can be calculated. The age of sediment layer can be calculated by z'/S_0 . In the sediments of core OBY, the estimated error of the ^{210}Pb age from the least squares fit to the decay curve of $^{210}\text{Pb}_{\text{ex}}$ ($\ln(A - A')$ vs. z' plot) is ± 5 years. The summary of the ^{210}Pb chronology of core OBY is shown in Fig. 2 and Table 2.

We also employed a geochronology based upon the fallout of the fission product ^{137}Cs from the stratosphere where it was introduced by atmospheric nuclear testing. We have attempted to match the ^{137}Cs profile in the sediment as a function of the ^{210}Pb age with the annual fallout data in Japan (National Institute of Radiological Science, 1963–1989) as shown in Fig. 2 and Table 2, after correction for decay (half life: 30 years) during the time between the measurement and the sediment deposition.

The ^{137}Cs activities in core OBY have a broad single maximum which we have associated with 1963 fallout maximum. The shape of the ^{137}Cs profile in the sediment is probably governed by the direct deposition of fallout of ^{137}Cs from the atmosphere and redeposition of ^{137}Cs from the watershed into Osaka Bay. Post-depositional mixing may also influence the

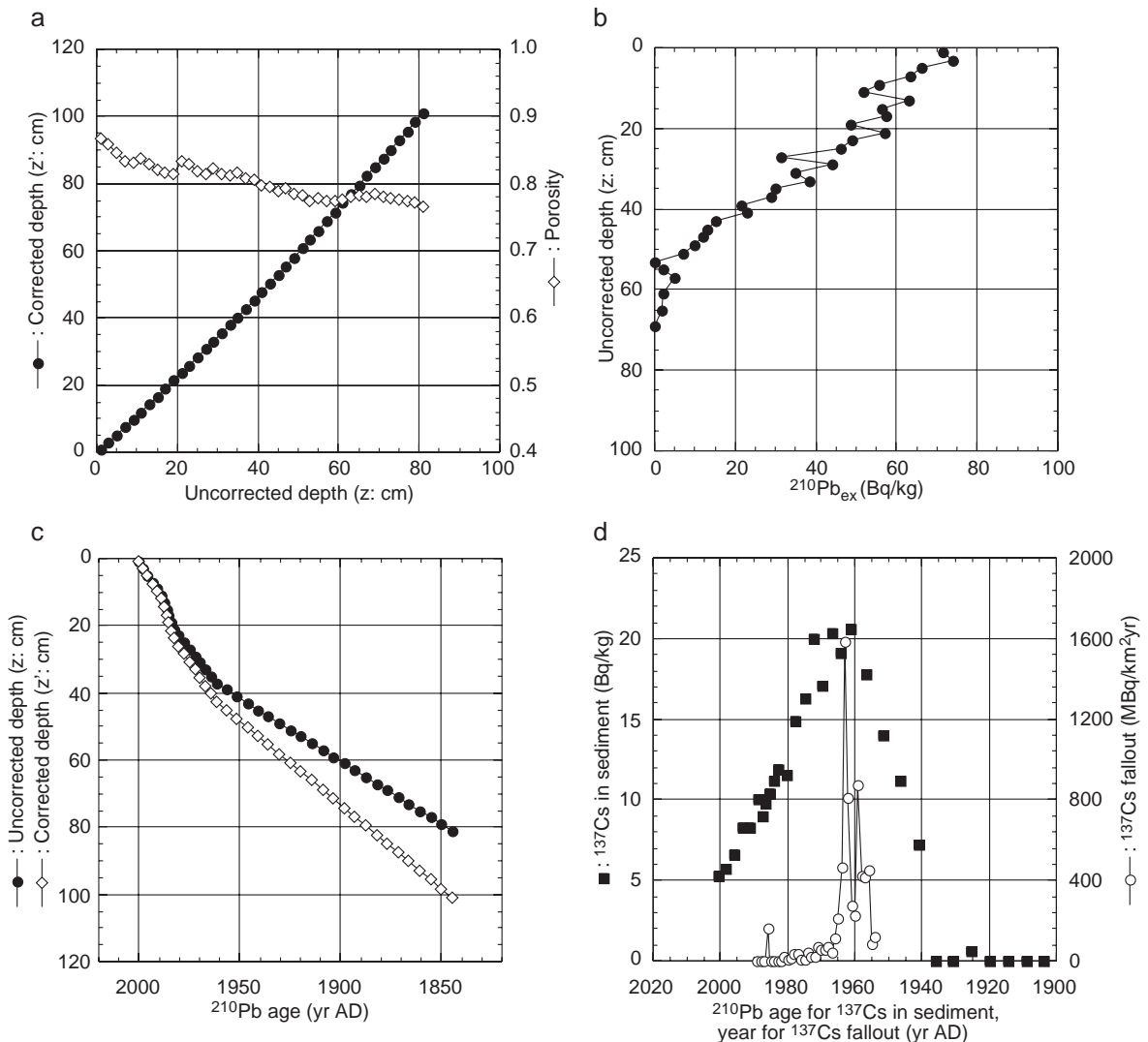


Fig. 2. Summary of the core chronology: (a) relationship between uncorrected depth (z), depth corrected for compaction (z'), and porosity; (b) vertical distribution of $^{210}\text{Pb}_{\text{ex}}$; (c) age-depth model; (d) ^{137}Cs profile in the core and the annual fall out data for Japan (National Institute of Radiological Sciences, 1963–1989).

vertical profile of ^{137}Cs . However, the concentration profile of ^{137}Cs and the historical trends of the annual fallout agreed very well, indicating that the ^{210}Pb ages for core OBY are reliable.

4. Results and discussion

The stable clay sedimentation throughout the studied core and the location of the core in an

enclosed muddy bay indicate that the sediments accumulated in a low-energy, stable environment. All common ostracode taxa have been described as living in enclosed, muddy bay environments (e.g., see Ishizaki, 1968; Ikeya and Shiozaki, 1993; Yamane, 1998; Yasuhara and Irizuki, 2001). These observations strongly suggest that the ostracodes are generally in situ and not redeposited.

Ostracode absolute abundance rapidly decreased by 90% from ca. A.D. 1910–1920 to ca. A.D. 1960–

Table 2
Summary of radiometric dating and heavy metal analysis

Depth (z: cm)	Mean depth (z: cm)	Corrected depth (z': cm)	Water content	Porosity	²¹⁰ Pb age (year AD)	¹³⁷ Cs (detected) (Bq/kg)	¹³⁷ Cs (corrected) (Bq/kg)	²¹⁰ Pb (Bq/kg)	²¹⁰ Pb _{ex} (Bq/kg)	Cr (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)
0–2	1	1.0	0.724	0.868	2001	5.0	5.3	95.6	71.6	94	65.2	361	61.5
2–4	3	3.1	0.707	0.858	1998	5.0	5.7	97.8	73.8	97	66.9	375	63.9
4–6	5	5.2	0.686	0.845	1996	5.5	6.6	90.3	66.3	99	67.5	379	65.3
6–8	7	7.5	0.668	0.834	1994	6.6	8.3	87.5	63.5	103	69.3	393	68.8
8–10	9	9.8	0.665	0.832	1991	6.2	8.3	79.5	55.5	100	70.2	400	70.2
10–12	11	12.0	0.674	0.838	1989	7.1	10.0	75.9	51.9	103	70.7	388	69.5
12–14	13	14.3	0.658	0.828	1988	6.2	9.0	86.9	62.9	104	71.4	398	71.9
14–16	15	16.7	0.646	0.82	1987	6.6	9.8	80.3	56.3	107	71.8	407	73.0
16–18	17	19.0	0.640	0.816	1985	6.8	10.4	81.5	57.5	108	76.7	412	70.9
18–20	19	21.4	0.637	0.814	1984	7.1	11.2	72.6	48.6	110	74.1	419	74.3
20–22	21	23.7	0.666	0.833	1983	7.4	11.9	80.9	56.9	114	76.9	442	79.8
22–24	23	26.0	0.658	0.828	1980	6.7	11.5	72.8	48.8	123	81.7	488	86.4
24–26	25	28.4	0.644	0.819	1978	8.2	14.9	70.0	46.0	116	91.9	521	91.7
26–28	27	30.8	0.638	0.815	1975	8.4	16.3	55.4	31.4	119	89.2	546	96.0
28–30	29	33.1	0.648	0.822	1972	9.7	20.0	67.9	43.9	121	88.8	547	94.9
30–32	31	35.5	0.638	0.815	1970	7.8	17.1	58.9	34.9	131	82.3	538	96.0
32–34	33	37.9	0.633	0.812	1967	8.7	20.3	62.4	38.4	138	88.0	581	102.2
34–36	35	40.3	0.639	0.816	1964	7.7	19.1	54.0	30.0	140	92.1	612	104.9
36–38	37	42.8	0.628	0.808	1962	7.8	20.6	52.9	28.9	144	95.6	641	112.4
38–40	39	45.3	0.624	0.806	1957	6.0	17.8	45.6	21.6	130	91.3	621	109.8
40–42	41	47.8	0.612	0.798	1951	4.2	14.0	46.9	22.9	114	85.5	516	94.0
42–44	43	50.3	0.609	0.796	1946	3.0	11.2	39.3	15.3	101	80.9	453	88.2
44–46	45	52.9	0.598	0.788	1941	1.7	7.2	37.2	13.2	92	74.6	402	81.9
46–48	47	55.5	0.604	0.792	1936	nd	nd	36.0	12.0	89	72.4	382	81.1
48–50	49	58.1	0.592	0.784	1931	nd	nd	34.0	10.0	86	68.3	344	74.7
50–52	51	60.8	0.590	0.782	1925	0.1	0.6	31.2	7.2	82	64.8	285	69.5
52–54	53	63.5	0.580	0.775	1920	nd	nd	22.3	nd	77	59.4	273	67.9
54–56	55	66.1	0.585	0.779	1915	nd	nd	26.0	2.0	76	52.3	237	62.1
56–58	57	68.8	0.579	0.775	1909	nd	nd	29.0	5.0	74	47.0	205	57.0
58–60	59	71.6	0.578	0.774	1904					73	45.8	197	52.6
60–62	61	74.2	0.582	0.777	1898	nd	nd	26.2	2.2	72	40.5	174	48.7
62–64	63	76.9	0.587	0.78	1893					69	38.7	164	47.4
64–66	65	79.5	0.591	0.783	1888	nd	nd	25.9	1.9	73	38.2	164	44.8
66–68	67	82.2	0.588	0.781	1882					70	42.0	160	44.9
68–70	69	84.8	0.594	0.785	1877	nd	nd	22.2	nd	72	40.4	174	48.5
70–72	71	87.5	0.587	0.78	1872					70	34.8	160	50.9
72–74	73	90.2	0.583	0.778	1866					69	34.7	150	44.8
74–76	75	92.8	0.581	0.776	1861					68	32.0	141	43.4
76–78	77	95.5	0.580	0.775	1856					68	30.2	138	44.4
78–80	79	98.3	0.575	0.772	1850					67	29.9	133	41.6
80–82	81	101.0	0.567	0.766	1845					68	30.0	132	40.3

nd: not detected.

1970 (Fig. 3). This rapid decrease of ostracode abundance was not caused by an increase in sedimentation rate (i.e., dilution of ostracode abundance): ostracode abundance decreased by 90%, whereas the sedimentation rate increased only by a factor of 2 (Figs. 2 and 3).

During this period of ostracode decline, absolute abundances of all dominant species decreased, although the timing differs somewhat between species (Fig. 3). One species, known to have resistance against anthropogenic impacts and especially hypoxia, was included in those dominant species, i.e.,

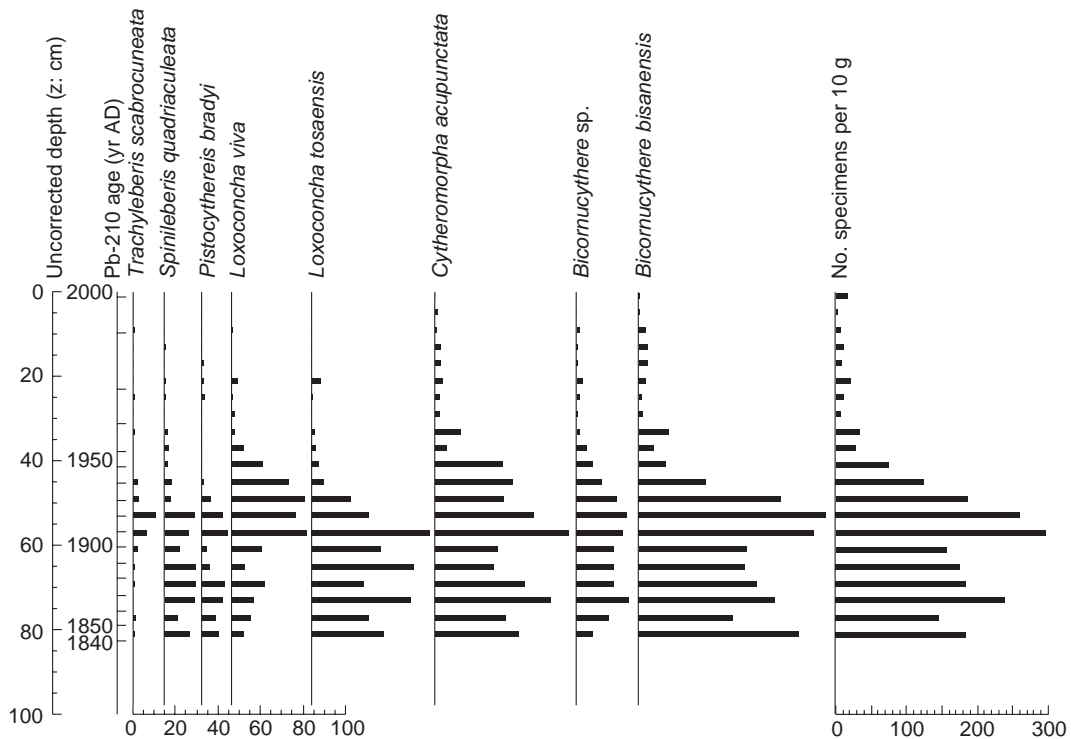


Fig. 3. Vertical distributions of number of specimens per 10 g dry sediment of dominant ostracode species and total ostracodes. *Bicornucythere* sp. is equivalent to form M (Abe and Choe, 1988) of *B. bisanensis*. Detailed ostracode list is shown in Table 1.

Bicornucythere bisanensis (Okubo) (Yasuhara et al., 2003; Irizuki et al., 2003), equivalent to form A (Abe and Choe, 1988) of *B. bisanensis*. Bodergat and Ikeya (1988) reported that *Cytheromorpha acupunctata* (Brady) may be more resistant to pollution than other ostracode species, because it is relatively abundant in polluted areas in Ise and Mikawa Bays, Japan.

This decline in abundance of ostracods coincided with a rapid increase in concentration of various pollutants, indications of pollution, and the Osaka City population (see Fig. 4). Heavy metal concentrations began to increase at around A.D. 1910–1920, reaching a maximum at ca. A.D. 1960 (Fig. 4; Table 2). By the 1920s, water quality had already deteriorated and eutrophication had begun (Fig. 4, Yamane et al., 1997). The foraminiferal record indicates that eutrophication and hypoxia started at ca. A.D. 1910–1920, at which time because the absolute abundance of *Ammonia beccarii* and *Trochammina hadai*, indicators of eutrophication and hypoxia (e.g., Konda and Chiji, 1987, 1989; Nomura and Endo, 1998), increased rapidly (Fig. 4; Tsujimoto, A., personal

communication, 2004). Loads of chemical oxygen demand, nitrogen, and phosphorous, which were calculated on the basis of the statistical data (population, livestock numbers, annual usage of chemical fertilizer, and annual industrial shipment value of the Osaka Prefecture; see Nakatsuji et al., 1998 for detail), increased rapidly at ca. A.D. 1960–1970, and all, except nitrogen, reached their maxima at ca. A.D. 1970 (Fig. 4, Nakatsuji et al., 1998). Summer hypoxia reached its maximum in the 1970s (Joh, 1986). The Osaka City population began to increase significantly at around A.D. 1900 and reached its peak of the post-World War II period in the 1960s (Fig. 4; Osaka City, 2002), although the largest peak is found at ca. A.D. 1940.

These observations indicate that anthropogenic impacts on the benthic metazoan ecosystem were serious, and that the decline in ostracodes was caused by anthropogenic factors. The destruction of the benthic ecosystem was accelerated by rapid land reclamation of shallow sea areas after World War II, because these areas are an important habitat and

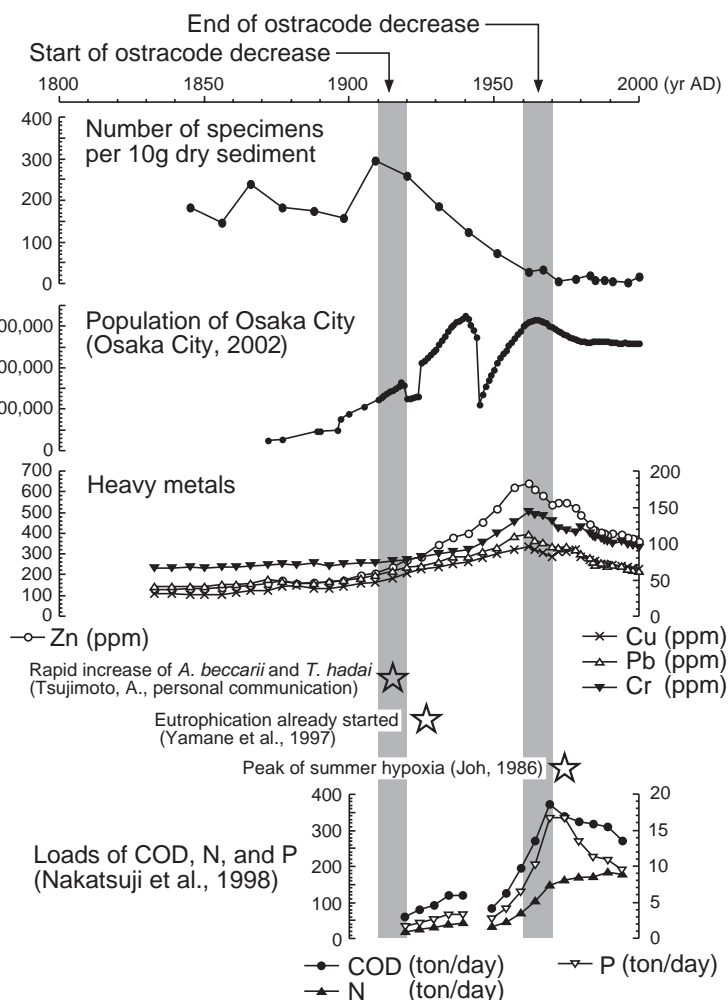


Fig. 4. Temporal distributions of number of oyster specimens per 10 g dry sediment, the Osaka City population, heavy metal concentrations (Zn, Cu, Pb, Cr) in core OBY, and loads of COD, nitrogen, and phosphorous from the Osaka Prefecture, along with information related to pollutants.

incubator of benthos and fulfil a natural purification function in Osaka Bay (Association for New Social Infrastructure of Osaka Bay, 1996).

After ca. A.D. 1960–1970, the pollutant concentrations decreased gradually as a result of environmental regulations (see Fig. 4; Association for New Social Infrastructure of Osaka Bay, 1996), although summer hypoxia remains serious (Yamane et al., 1997). Notwithstanding these efforts, oyster abundance has not recovered. One main cause of this phenomenon may be the summer hypoxia (see Diaz and Rosenberg, 1995 for the review of marine

benthic hypoxia and its ecological effects), because dissolved oxygen levels have not recovered to optimum levels for benthic organisms (Yamochi et al., 2001). The distributional patterns and abundance of many modern benthic taxa in the Bay have a strong seasonality controlled by summer hypoxia (Ariyama et al., 1997a,b), but living oysters were absent in the inner part of present Osaka Bay in May 1999 (Yasuhara and Irizuki, 2001) and the oyster absolute abundance (dead valves) in surface sediment was very low (Fig. 1; Yasuhara and Irizuki, 2001). Oysters thus are rare, not only in summer,

but also in seasons with little or no hypoxia. Other benthic taxa are relatively abundant in seasons other than summer because they have high mobility and numerous juveniles in the planktonic stage migrate rapidly from the middle part of the Bay, where seasonal hypoxia does not occur, to the inner part of the Bay (Ariyama et al., 1997a,b). These benthic taxa cannot complete their life cycle because of summer hypoxia.

Ostracode abundance does not recover after the cessation of summer hypoxia, unlike that of other benthos. One reason for this low year-round abundance may be that ostracodes do not have a planktonic juvenile stage; therefore their ability to migrate is very low (Smith and Horne, 2002). The record of ostracodes in our core thus reflects the anthropogenic impacts on benthic metazoans at the core location: there is no (or little) immigration of new individuals from non-polluted areas. The abundance of *Bicornucythere bisanensis*, which is resistant to hypoxia (Irizuki et al., 2003), also does not recover, possibly because the water depth of the study site (14 m) is more than the optimum depth of the *B. bisanensis* habitat (5–9 m water depth; Ikeya and Shiozaki, 1993). *B. bisanensis* remained the dominant species at this site until ca. A.D. 1910—the period preceding pollution.

These observations probably indicate that the direct and indirect results of pollution, not only hypoxia, remain a serious threat to the benthic metazoan ecosystem and continue to put pressure on the life cycle of benthic metazoan faunas. The destruction of the benthic ecosystem can easily occur as a result of development that is insensitive to environmental protection. Despite regulation, anthropogenic impacts remain more serious than pre-industrialization and natural recovery is slow or nonexistent.

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Appendix A. Taxonomic list

All ostracode species mentioned in this paper are listed below in alphabetical order. The original name and reference is given for each taxon.

Amphileberis nipponica (Yajima)—*Lixouria nipponica* Yajima, 1978.

Ambtonia obai (Ishizaki)—*Basslerites obai* Ishizaki, 1971.

Bicornucythere bisanensis (Okubo)—*Leguminocythereis bisanensis* Okubo, 1975.

Bicornucythere sp.—form M (Abe and Choe, 1988) of *Bicornucythere bisanensis*.

Callistocythere alata Hanai, 1957.

Cytheromorpha acupunctata (Brady)—*Cythere acupunctata* Brady, 1880.

Cytherois nakanoumiensis Ishizaki, 1969.

Cytherois uranouchiensis Ishizaki, 1968.

Loxoconcha tosaensis Ishizaki, 1968.

Loxoconcha uranouchiensis Ishizaki, 1968.

Loxoconcha viva Ishizaki, 1968.

Nipponocythere bicarinata (Brady)—*Cythere bicarinata* Brady, 1880.

Paracytherois sp.

Paracytherois? sp. 1.

Paracytherois? sp. 2.

Pistocythereis bradyi (Ishizaki)—*Echinocythereis bradyi* Ishizaki, 1968.

Pontocythere sp.

Propontocypris sp.

Spinileberis quadriaculeata (Brady)—*Cythere quadriaculeata* Brady, 1880.

Trachyleberis scabrocuneata (Brady)—*Cythere scabrocuneata* Brady, 1880.

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