Distribution of living (stained) benthic foraminifera (Protista) in the Ohashi River, southwest Japan: a clue to recent faunal change in the Lake Shinji-Nakaumi system

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With 3 figures and 1 table

Abstract: The modern distribution of benthic foraminifera in the Ohashi River (southwest Japan) was compared with the prevalent types of bottom substrates. Bottom substrates in the upper ranges of the river were characterized by relatively coarse-grained sediment, low total organic carbon (TOC) and total sulfur (TS) contents, whereas those in the lower ranges were characterized by relatively fine-grained sediment, high TOC and TS contents. Two macrobenthic species, Corbicula japonica and Musculista senhousia, were associated with both the coarse- and fine-grained bottom substrate areas, respectively. Ammonia beccarii forma 1 was the dominant foraminiferal species in the Ohashi River and Haplophragmoides canariensis was common in the middle reaches of the river. Variable salinity and biological substrate disturbance, caused especially by M. senhousia, accounted for this foraminiferal distribution. A transition from the H. canariensis assemblage to the A. beccarii forma 1 assemblage has been found in the 20th century sedimentary record not only in the Ohashi River but also in Lake Shinji. Although the habitat of H. canariensis has not been specified well in the Lake Shinji-Nakaumi system, our result of the modern distribution of benthic foraminifera in the Ohashi River suggests that the faunal transition in Lake Shinji can be explained by the replacement of the dominant foraminiferal species in the Ohashi River.

Key words: benthic foraminifera, substrate, Ammonia beccarii forma 1, Haplophragmoides canariensis, faunal change.

Introduction

The Ohashi River in southwest Japan is a tidal river located between brackish Lakes Shinji and Nakaumi, and strongly affected by the salt water entering from the Sea of Japan (East Sea) (Fig. 1). The hydrology of this river is central to the study of the mass balance of riverine and marine-origin materials in the Lake Shinji-Nakaumi system (e.g. Nakata et al. 2000). During the past 100 years, the hydrological status of this river has significantly changed. The river was narrower during the 19th century than today, as the river channel was dredged and widened early in the last century (e.g. Hiratsuka et al. 2006). These modifications have drastically increased the seawater influx from the Sea of Japan (East Sea) (Toyohara 1938). The sediment discharge from the Ohashi River to Lake Shinji also changed. Today the Hii River is the largest source of sediment for Lake Shinji, whereas before the middle 17th century the Ohashi River played that role (Seto et al. 2006). The sedimentology and paleontology of Lakes Shinji and Nakaumi have been well studied...
(e.g. Kanai et al. 1997, 2002, Yamamuro & Kanai 2005, Nomura & Seto 2002, Nomura 2003), but little work has been done on the Ohashi River connecting them. Thus, understanding the limnological and sedimentological signatures of the modern Ohashi River is instrumental to any paleoenvironmental reconstruction of the Lake Shinji-Nakaumi system. Nomura & Endo (1998) studied fossil benthic foraminifera and organic matter in sediment cores from this river. They reported on a distinct transition in the fossil benthic foraminiferal assemblages in the middle part of the 20th century, suggesting a major environmental alteration during the 20th century.

Faunal analysis of fossil benthic foraminifera is a useful method of paleoenvironmental reconstruction in the Lake Shinji-Nakaumi system (e.g. Nomura & Seto 2002, Nomura 2003). Particularly, based on foraminiferal analysis, Nomura (2003) suggested that the lagoonal environment of Lake Nakaumi during the 20th century was closely related to the decadal-scale sea-level changes in the Sea of Japan (East Sea). Such a phenomenon should be important to appreciate the relationship between the neritic conditions and the global climatic oscillations. Because this system consists of a connected set of brackish lakes, information on the modern fauna in all of these lakes and their connecting river enables a more precise paleoenvironmental reconstruction. Thus, the survey of the modern environment in the Ohashi River is important for the conservation of the Lake Shinji-Nakaumi system. Hence, the objectives of the present study are (1) to characterize the modern bottom substrate and benthic foraminiferal distribution and (2) to investigate the relationships between the benthic foraminiferal distribution and the sediment characteristics in the Ohashi River. It is expected that these results will further the understanding of the recent environmental transitions in the Lake Shinji-Nakaumi system.

Material and methods

The Ohashi River is located between Lakes Shinji and Nakaumi in southwest Japan (Fig. 1). The river is approximately 7.5 km long, and the maximum width and water depth are about 200 m and 7 m, respectively. Three small rivers, Asakumi, Tenjin and Mabashi Rivers, merge into the middle reaches of the Ohashi River. Saline water enters the river from the Sea of Japan (East Sea) through the Sakai Channel and Lake Nakaumi. As a result, the river is often density-stratified (Fujii 1998, Ishitobi et al. 1999, Kurata et al. 2008). Accordingly, the surface layer is commonly characterized by oligohaline water from Lake Shinji, whereas the bottom layer is characterized by mesohaline and often dissolved oxygen-depleted water from Lake Nakaumi.

Surface-sediment samples from the river bottom were collected at twenty-five stations (OH-1 to OH-25) using an Ekman-Birge type sampler (15 cm × 15 cm) in June 2004 (Fig. 1). The samples were taken from the uppermost one centimeter of the sediment surface. The water temperature and salinity were measured at 10 cm increments using a “Chlorotec” Data Logger (Alec Electronics Co., Ltd). The sediment samples were divided for separate foraminiferal and sedimentological analyses.

![Fig. 1. Geographical location of the Ohashi River and sampling localities (open circles): (a) location in Japan, (b) location in the Lake Shinji-Nakaumi system and (c) twenty-five sampling localities in June 2004.](image-url)
The weights of these subsamples were determined immediately. The subsamples for the sedimentological analysis were dried at 70°C for 24 hours. The water contents were derived from a comparison of the pre- and post-dried weights. We calculated the dry weights of the subsamples for the foraminiferal analysis based on their wet weights and the water contents.

These foraminiferal subsamples were washed through a 200 mesh sieve (75 µm openings). The residues were stained with 0.5% rose Bengal solution in 70% ethanol/tap-water for 24 hours, and subsequently washed with warm water to remove excess dye, and dried at 50°C. Living (stained) foraminiferal specimens were picked from the residues using a stereo-binocular microscope. Additionally, dead (unstained) specimens were counted. The number of specimens per dry sediment weight (# g⁻¹) was calculated for each species in each subsample.

After the dried sedimentological subsamples were crushed and homogenized in an agate mortar, the total organic carbon (TOC), total nitrogen (TN) and total sulfur (TS) contents of these sediment powders were analyzed using a Fisons CHNS-elemental analyzer EA1108, according to the technique of Sampei et al. (1997). Ten mg of each sample was placed in a thin silver foil container, to which 1N-HCl was added twice and dried at 110°C for 4 hours. The dried subsample was then wrapped in a thin tin foil capsule. BBOT (2, 5-Bis-(5-tert-butylbenzoxazol-2-yl)-thiophen) was used as a standard and contents were calculated based on a standard regression method.

A grain size analysis was carried out on the dried subsamples as part of a broader sedimentological analysis. The sediment subsamples were soaked in 15% hydrogen peroxide solution for 24 hours. The grain size was measured between one and ten phi-scale at every 0.25 phi-scale using a Shimazu grain size analyzer SALD-3000S. The mean grain size was calculated based on Folk & Ward (1957)'s scheme.

In order to evaluate the relationship between macro-organisms and sediment characteristics, the occurrences of Corbicula japonica Prime and Musculista senhousia (Benson), two major macrobenthos (Bivalvia) in the Ohashi River, were mapped. The remaining subsamples for the sedimentological analysis were washed through a 9 mesh sieve (1 mm openings). Both the articulated and disarticulated valves of each species were counted. The minimum number of individuals per gram of dry sediment (# g⁻¹) was calculated for each species in each subsample by dividing disarticulated valve number by two.

Results and discussion

Distribution of modern benthic foraminifera in the Ohashi River

The bottom substrate of the central channel in the upper reaches of the Ohashi River (OH-1, 2, 3 and 7) was characterized by relatively coarse-grained, low TOC and TS contents, whereas that in the lower reaches (OH-15, 19, 22 and 25) was characterized by fine-grained, high TOC and TS contents (Fig. 2, Table 1). The substrates in the middle range (stations OH-8, 9 and 10) of the river showed the transitional features between both the upper and lower reaches. The distributions of Corbicula japonica and Musculista senhousia between the upper and lower reaches of the river were distinctly different (Fig. 2, Table 1). Thus, we observed a spatial correlation between the sedimentological and organic geochemical features of the bottom substrate and the distribution of the macrobenthos. C. japonica and M. senhousia both have wide tolerances to fluctuations in salinity (1.5 to 22: Nakamura et al. 1996; 10 to >32: Nakamura et al. 1997, respectively). Because M. senhousia prefers mesohaline water and is often affected by intrusion of saline water into the Ohashi River from Lake Nakaumi, the two molluscs typically occupy contrasting habitats in the upper and lower part of the river, respectively; the middle part of the river being a transitional area between both habitats (Kurata et al. 2008). Infaunal C. japonica often lives in sediment, causing instability with significant bioturbation within that sediment to a depth of several tens of centimeters (e.g. Goshima et al. 1999), whereas epifaunal M. senhousia lives on the sediment (e.g. Crooks 1998). Because M. senhousia ingests large amounts of suspended matter and excretes this as faeces and pseudofaeces, excreted fine-grained sediment particles are often trapped within their colonies (Morton 1974, Crooks 1998), although the high current-velocity regime commonly winnows fine-grained sediment particles from the bottom surface. Hence, C. japonica and M. senhousia have very different impacts on the sediment, the former causing instability and the latter trapping fine-grained sediment particles. Thus, these two macrobenthos taxa lead to very different fine-grained sedimentation patterns. M. senhousia colonization also causes significant organic enrichment in the sediment (ca. 4% of TOC content) (Fig. 2). It is therefore likely that the differences in biological disturbances caused by these two molluscs result in the different sediment surface microenvironments observed in the sedimentological and organic geochemical data for the upper and the lower reaches of the Ohashi River.

Five genera with a total of five species were identified from the living (stained) benthic foraminifera community (Table 1). Ammonia beccarii (Linné) forma 1 Matoba (equivalent to Ammonia sp. of Nomura & Takayanagi (2000)), a calcareous species, dominated the foraminiferal fauna of the Ohashi River. Haplophragmoides canariensis d’Orbigny, an agglutinated species, had the second highest abundances in the middle ranges of the river (Figs 2 and 3). Dead specimens of this species were also observed in the middle part of the river, and these dead specimens had slightly wider distribution (stations OH-6, 7, 8, 9 and 10) than living (stained) individuals (Table 1). Near the confluence of the Asakumi, Tenjin and Mabashi Rivers (stations...
OH-13 to 18), *A. beccarii* forma 1 was most abundant in the central and deep areas of the river, whereas *H. canariensis* was most common at station OH-17, a shallow-water site close to the southern shore of the river (Fig. 2). Even in the middle ranges of the river, *H. canariensis* showed a different depth habitat preference. In the other transects across the river (stations OH-3 to 5, OH-11 and 12, and OH-22 to 24), *A. beccarii* forma 1 was dominant everywhere (Table 1). Although *H. canariensis* has been commonly reported in historical sediments of the Ohashi River and Lake Shinji as discussed below, its habitat in the modern Lake Shinji-Nakaumi system has yet to be described.

Nomura & Seto (1992) studied the foraminiferal assemblages from surface sediments in Lake Nakaumi collected in 1986, and suggested that *H. canariensis* was common at one locality in Lake Nakaumi adjacent to the Ohashi River, but they were unable to locate live specimens in their study. Now it becomes clear that the preferential habitat of this species is the middle range of the Ohashi River.

Because *Ammonia beccarii* forma 1 is euryhaline (Matoba 1970, Kosugi et al. 1991, Nomura & Seto 1992), it occurred predominantly in the highly variable salinity area of the Ohashi River (e.g., Kurata et al. 2008). The high concentration of organic matter in the lower reaches of the Ohashi River probably contributes to this high abundance of *A. beccarii* forma 1 (Fig. 2), because this species can tolerate organic-rich environments in brackish waters (Kosugi et al. 1991,
Table 1. Occurrence of living (stained) and dead (unstained) benthic foraminifera, total organic carbon (TOC), total nitrogen (TN) and total sulfur (TS) contents, mean grain size of surface sediment, and abundance of two bivalve species in the Ohashi River. The minimum number of individual bivalves is shown (one individual = one articulated or two disarticulated valves).

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<td>5.1</td>
<td>5.1</td>
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<td>5.3</td>
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<td>4.6</td>
<td>1.1</td>
<td>2.8</td>
<td>4.9</td>
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<td>5.2</td>
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<td>6.0</td>
<td>4.4</td>
<td>1.6</td>
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**Living (stained)**

- *Ammonia beccarii* (Linné) forma 1
  - Station 1: 157
  - Station 2: 207
  - Total: 364

- *Haplophragmoides canariensis* d’Orbigny
  - Station 1: 1
  - Station 2: 40
  - Total: 41

- *Miliammina fusca* (Brady)
  - Station 1: 1
  - Total: 1

- *Trochammina hadai* Uchio
  - Station 1: 1
  - Total: 1

- *Haynesina* sp.
  - Station 1: 1
  - Total: 2

**Dead**

- *Ammonia beccarii* (Linné) forma 1
  - Station 1: 207
  - Total: 207

- *Haplophragmoides canariensis* d’Orbigny
  - Station 1: 40
  - Total: 40

- *Ammobaculites exigus* Cushman & Bronnimnar
  - Station 1: 1
  - Total: 1

- *Miliammina fusca* (Brady)
  - Station 1: 1
  - Total: 1

- *Trochammina hadai* Uchio
  - Station 1: 1
  - Total: 1

**Sample weight (g) (foraminifera)**

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<td>Sample weight (g) (foraminifera)</td>
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**Sample weight (g) (macrobenthos)**

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<td>9.89</td>
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<td>5.64</td>
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Nomura & Seto 1992). *Haplophragmoides canariensis* is a common constituent of low salinity brackish environments in Japanese waters (e.g. Ishiwada 1958, Nomura & Seto 1992), although knowledge of its tolerance to salinity is limited. Nomura & Seto (1992) implied that the tolerance of modern *H. canariensis* to low salinity is narrower (< 10) than that of *A. beccarii* forma 1 (Fig. 13 of Nomura & Seto 1992), based on the distributions of this species in the Lake Nakaumi and Lake Hamana (central Japan). Low salinity might partly account for its abundance in the Ohashi River (e.g., Nomura & Endo 1998). Based on monthly observations of salinity of river water during November 2005 to August 2007 at three stations (station O-5: upper part; station O-3: middle part; station O-1: lower part) in the Ohashi River (Kurata et al. 2008), salinity at 4 m water depth of the stations O-5 (near our station OH-1), O-3 (between our stations OH-7 and 8) and O-1 (near our station OH-22) range between 2.7–24.9 (mean 10.0), 2.6–25.9 (mean 12.3) and 2.7–26.2 (mean 15.6), respectively. Hence, the preference for lower salinities cannot be a sole explanation for a distribution limited to the middle ranges of the river. The sediment substrate in the area (stations OH-8, 9, 10, 12 and 17), where *H. canariensis* was common, was characterized by moderate TOC contents (1.28–4.36 %), variable grain size (silt to fine sand) and it was also the transitional zone between the *Corbicula japonica* and *Musculista senhousia* habitats (Fig. 2). Whereas *M. senhousia* often makes sheet-like colonies on the sediment surface in the lower reaches of the Ohashi River (from the confluence of the Asakumi, Tenjin and Mabashi Rivers to Lake Nakaumi), it occurs only sporadically in the middle ranges of the river (Kurata et al. 2008). Therefore, the abundance peak of *H. canariensis* in the middle ranges of the river is related to a specific microenvironment characterized by moderate organic enrichment and variable grain size caused by patchy *M. senhousia* colonization. According to Nomura & Endo (1998), fossils of this species were abundant in relatively low TOC intervals of sediment cores from the Ohashi River. Therefore, modern foraminiferal occurrence in the Ohashi River is governed by highly variable salinity, variable levels of organic enrichment in the sediment, and variable sediment grain size, probably influenced by the *M. senhousia* colonization.

**Significance of the modern distribution of benthic foraminifera in the Ohashi River; implication for the understanding of faunal change in Lake Shinji-Nakaumi system**

This study demonstrated that the modern distribution of *Haplophragmoides canariensis* is restricted to the middle part of the Ohashi River. However, *H. canariensis* has been reported as the dominant species in fossil fauna from sediment core, not only from the Ohashi River but also from Lake Shinji (Nomura & Yoshikawa 1995, Nomura & Endo 1998). Nomura & Endo (1998) described a transition from the *H. canariensis* assemblage to the *Ammonia beccarii* forma 1 assemblage during the 20th century in two sediment cores collected from the upper and lower reaches of
the Ohashi River. In addition, Nomura & Yoshikawa (1995) analyzed fossil foraminifera from five sediment cores in Lake Shinji and showed a similar 20th century faunal transition. They described a gradual decrease of *H. canariensis* starting in the 1930s as well as a rapid increase of *A. beccarii* forma 1 in the 1980s. Takata et al. (2007) also recognized a very similar faunal transition in a sediment core collected from the central part of Lake Shinji. The abundance of *H. canariensis* progressively decreased from the 1950s, whereas that of *A. beccarii* forma 1 rapidly increased from the 1980s. This indicates that *H. canariensis* was the dominant species in the early 20th century, not only in the Ohashi River, but also in Lake Shinji. An increase in salinity in 1930s as a result of the construction of the Sakaiminato dyke around the entrance of the Sakai Channel along the Sea of Japan (East Sea) (e.g. Nomura 2003) and increased chemical oxygen demand in the 1980s (Nomura & Endo 1998) in the waters of Lake Shinji and the Ohashi River most likely resulted in the faunal change. It has been difficult to specify the exact reason of the faunal transition, because information about the habitat of *H. canariensis* was limited in the Lake Shinji-Nakaumi system. Additionally their interpretations depended on the timings among faunal change of benthic foraminifera and records of water chemistry and anthropogenic constructions. The fact that the modern distribution of *H. canariensis* is restricted to the middle part of the Ohashi River implies that the faunal transition during the 20th century is a result of the reduction of the habitat of *H. canariensis* and the expansion of that of *A. beccarii* forma 1 in the upper and the lower reaches of the Ohashi River. Seto et al. (2000) suggested, based on comparison of the modern foraminiferal faunas in 1982 and 1993, that *A. beccarii* forma 1 migrated, expanding its habitat from the eastern to the central area of Lake Shinji over a period of twelve years. These data support our interpretation that benthic foraminifera individuals were supplied to Lake Shinji from populations into the Ohashi River. It is, however, unclear at present why *H. canariensis* abundance decreased in both the upper and the lower reaches of the river, although this might be related to the macrobenthos modifications to the sediment surface microenvironments through an environmental change, such as salinity or chemical oxygen demand. Further studies based on sediment core analysis will be necessary in order to explain this phenomenon.

It is likely that the flow of salt water from the Sea of Japan (East Sea) into Lake Nakaumi decreased from the 1960s (Nomura 2003) when *H. canariensis* abundance also decreased in Lake Shinji (Takata et al. 2007). Additionally, the eutrophication of Lake Nakaumi was enhanced by dyke construction surrounding the Honjo Area (e.g. Nomura & Seto 2002) and the chemical oxygen demand increased in Lake Shinji and the Ohashi River during the 1980s (Nomura & Endo 1998). Thus, changes in the environment have occurred roughly simultaneously in Lakes Shinji and Nakaumi during the 20th century. Because this foraminiferal transition is one of the critical biotic events in the sedimentary records of the Ohashi River and Lake Shinji, the study of the pertinent modern and fossil foraminiferal fauna of the Ohashi River contributes to our understanding of the impact of these environmental changes on the Lake Shinji-Nakaumi system.

**Conclusions**

Bottom substrates in the upper ranges of the Ohashi River were characterized by relatively coarse-grained sediment, low total organic carbon (TOC) and total sulfur (TS) contents. In contrast, those in the lower ranges were characterized by relatively fine-grained sediment, high TOC and TS contents. Biological disturbances by two macrobenthos species (*Corbicula japonica* and *Musculista senhousia*) cause differences in bottom substrates. *Ammonia beccarii* forma 1 was the dominant foraminiferal species in the Ohashi River and *Haplophragmoides canariensis* was common only in the middle reaches of the river. Based on the information about the habitat of *H. canariensis* that can be characterized in the Lake Shinji-Nakaumi system in this study, the transition from the *H. canariensis* assemblage to the *A. beccarii* forma 1 assemblage of the 20th century sediment record of Lake Shinji, can be explained by the replacement of the dominant foraminiferal species in the Ohashi River.

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