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High tide dispersion of marine benthic foraminifera into brackish waters: implications for dispersion processes during sea-level rise

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Abstract: We observed that benthic foraminifera utilize suspended particles as a transportation medium during dispersion to other areas. Six cylindrical bottles (7.3 cm diameter, 15.5 cm height), placed at 1 meter depth intervals at one location in brackish Lake Nakaumi (sample location depth 6.5 m), contained a number of live individuals of *Quinqueloculina tubilocula*. The occurrence of *Quinqueloculina* was associated with an exceptionally high tide event related to a low atmospheric pressure front on September 1st, 2002. They were most abundant in the bottle at 3 meters depth and least abundant at 6 m depth. The high tide event was very unusual in this region, which normally has very moderate tidal amplitudes. The presence of this exotic marine benthic foraminifer in a brackish lake indicates that one of the most effective methods of dispersion for both live and dead foraminifera is on suspended particles during high tides. High organic matter content in suspended particles provides sufficient food to maintain live foraminifera. The occurrence of *Q. tubilocula* in an oligohaline to mesohaline brackish water system is good evidence that high tides can contribute to dispersion, and thus dispersion can also be facilitated by a rise in sea-level.

Key words: high tide dispersion, foraminifera, suspended particles, sea-level rise, lagoon

Introduction

There has been a long standing discussion on the dispersion processes of benthic foraminifera. Many micropaleontologists have encountered occurrences of exotic foraminiferal taxa in indigenous assemblages. In ecological studies of planktonic foraminifera using plankton tows, live and dead benthic foraminifera have been collected combined with the expected planktonic assemblages (Murray, 1965; Lidz, 1966; Loose, 1970; Hueni et al., 1978). Although live benthic foraminifera are able to move in and on the sediment surface, they are surprisingly slow, moving at speeds of a few millimeters per hour (Kitazato, 1988). Some sort of transport mechanism is therefore needed to account for the long distance transport implied by the presence of exotic foraminifera in local assemblages. Alve (1999) suggested four different ways of dispersion: (1) release of both sexually and asexually produced individuals into the water column, (2) meroplanktonic adaptation, (3) self locomotion, and (4) passive entrainment into the water column. Post-mortem transportation mechanisms

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have been well studied (summarized by Murray, 1991). Suspension load transport is the most commonly reported mechanism, although others are attested, such as bed load and turbidity currents. Small and well preserved foraminiferal tests in suspension loads are almost always due to dead individuals. Empty tests are easy to suspend in the water column and disperse widely under turbulent conditions. However, there have been very few observations of transport of living individuals. The increased mass may make living individuals more difficult to suspend initially, but there are a number of mechanisms that will keep foraminiferal tests in suspension. Tidal effect and the mixing potentials of freshwater and seawater can be major causes for maintaining suspension in estuary systems (Wang and Murray, 1983). Murray (2006) summarized the recent work on foraminiferal dispersion in both coastal and deep-sea areas. Propagule dispersion at the early reproductive stage, as proposed by Alve and Goldstein (2002, 2003), is clearly an attractive mechanism when considering the mixed occurrence of both indigenous and exotic foraminifera.

In order to examine annual change in estuarine foraminiferal productivity, the dynamics of bottom sediments, and the dispersion processes of sedimentary particles in relation to wind stresses, tidal effects, and the magnitude of precipitation, we placed plastic bottles at different depths in brackish Lake Nakaumi from December, 2001 to January, 2003. During the early stages of this research, we found live foraminifera in these traps associated with suspended particles (Nomura and Seto, 2004). This observation, foraminifera using suspended organic particles, seems to be good evidence for dispersion by passive entrainment, which would be an effective way to expand a species' habitat. In this paper we report the occurrence of marine foraminifera in brackish waters and discuss the implications of the presence of these exotic foraminifera in terms of a response to sea-level rise.

Waters of Lake Nakaumi and foraminiferal assemblage

Lake Nakaumi is a typical brackish lake, sitting in between Miho Bay, part of the Sea of Japan, and mesohaline Lake Shinji (Fig. 1). A stable halocline develops at depths 3-4 m throughout the year. The salinity of bottom water ranges from 21 ‰ in winter to 33 ‰ in summer, with an average of 29 ‰. Lake Nakaumi water is highly nutrient rich, which has triggered a red-tide event in every year of recent times. Because the lake is connected to the Sea of Japan through a narrow channel (about 230 m width), the water circulation of Lake Nakaumi is suppressed, and it has been estimated to take about one week for the replacement of lake water with coastal sea-water (Okuda, 1997).

Although foraminiferal abundance in sediment samples is very high in this eutrophic lake, the assemblage is very simple, only represented by *Ammonia* "*beccarii*" and *Trochammina hadai* (Nomura and Seto, 1992). These two taxa have different ecological preferences. *Trochammina hadai* is common in deeper, organic rich, argillaceous sediments, while *Ammonia* "*beccarii*" lives in a wider range of salinity and substrate conditions, including lower mesohaline conditions and coarse-grained sand sediments (Nomura and Seto, 1992).

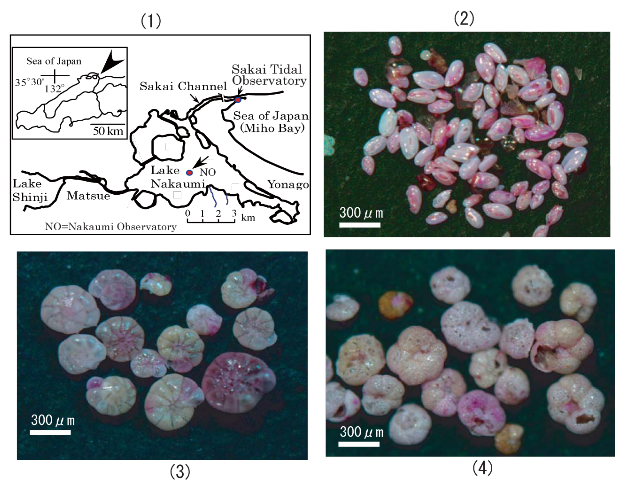

Fig. 1 Index map and major foraminiferal taxa. (1) NO with arrow indicating the position of the sediment trap and Nakaumi Observatory, depth ca. 6.5 m. (2) *Quinqueloculina tubilocula* Zheng collected in the sediment trap. (3) *Ammonia* "*beccarii*" (Linné) (4) *Trochammina hadai* Uchio. These specimens were stained with rose-bengal solution.

Methods and Results

A total of six plastic bottles (7.3 cm diameter; 15.5 cm height) were placed in the central part of the lake (latitude 35°27'58.59" N; longitude 133°11'25.92" E), approximately 10 km upstream of the Sakai Channel (Figs. 1, 2). Each bottle trapped suspended sediments over one meter intervals at a location of 6.5 meters depth. This trap was emplaced for intervals of approximately one month.

The above mentioned live and dead foraminifera were commonly found in these bottles, particularly in the three traps set below the halocline depth. Live foraminifera were trapped in these bottles, and they were common from July to October (Table 1; Fig. 2). Dead foraminiferal tests decreased significantly from

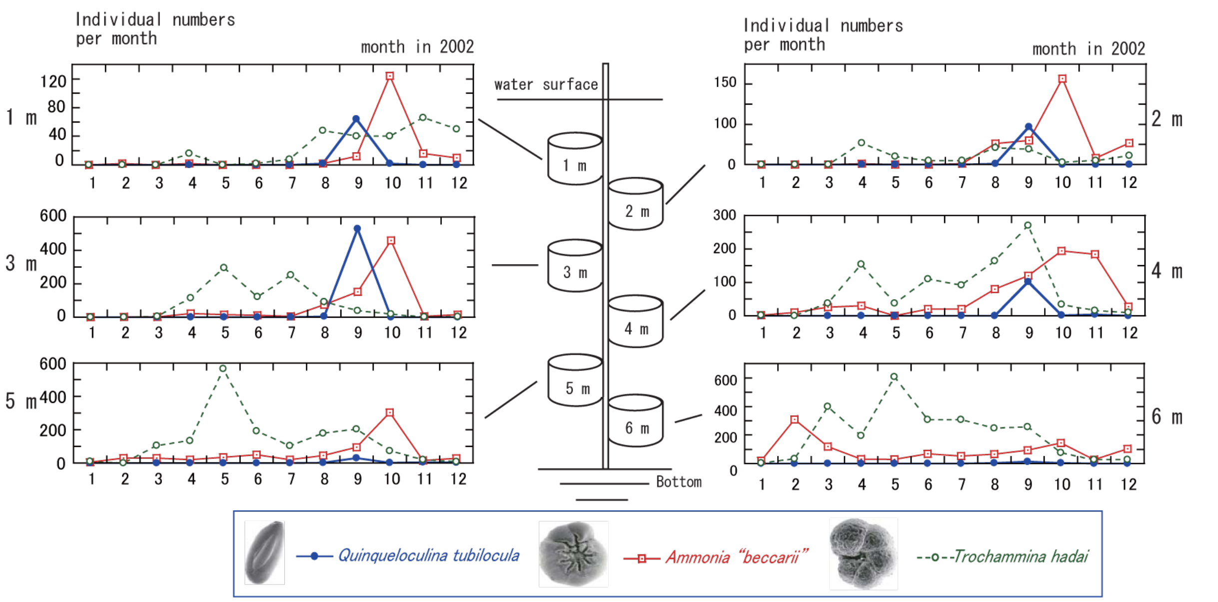

Fig. 2 Monthly occurrence of live foraminifera at different depths in 2002. Individual numbers are actual count per the bottle and per sampling interval. Interval 1 = Dec. 16, 2001 - Jan. 7, 2002; Interval 2 = Jan. 7 - Feb. 17; Interval 3 = Feb. 17 - Mar. 8; Interval 4 = Mar. 8 - Apr. 6; Interval 5 = Apr. 6 - May 6; Interval 6 = May 6 - Jun. 13; Interval 7 = Jun. 13 - Jul. 12; Interval 8 = Jul. 12 - Aug. 10; Interval 9 = Aug. 10 - Sep. 11; Interval 10 = Sep. 11 - Oct. 13; Interval 11 = Oct. 13 - Nov. 8; Interval 12 = Nov. 8 - Dec. 5. Note abundant *Quinqueloculina tubilocula* occurred at 3 m depth in the Interval 9.

Table 1 Foraminiferal occurrences shown in Figure 2.

Individual number of live *Ammonia "beccarii"*

Interval / Depth (m)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	2001.12.16-2002.1.7	2002.1.7-2.17	2002.2.17-3.8	2002.3.8-4.6	2002.4.6-5.6	2002.5.6-6.13	2002.6.13-7.12	2002.7.12-8.10	2002.8.10-9.11	2002.9.11-10.13	2002.10.13-11.8	2002.11.8-2002.12.5
1m	0	2	0	2	0	0	0	2	12	124	16	10
2m	0	0	0	2	0	0	2	52	60	214	16	54
3m	0	2	2	22	16	12	6	76	152	458	6	16
4m	2	10	26	30	0	20	20	80	120	194	184	28
5m	6	30	30	20	36	50	20	46	96	304	16	28
6m	20	310	120	32	30	68	52	66	94	144	28	104

Individual number of live *Trochammina hadai*

Interval / Depth (m)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	2001.12.16-2002.1.7	2002.1.7-2.17	2002.2.17-3.8	2002.3.8-4.6	2002.4.6-5.6	2002.5.6-6.13	2002.6.13-7.12	2002.7.12-8.10	2002.8.10-9.11	2002.9.11-10.13	2002.10.13-11.8	2002.11.8-2002.12.5
1m	0	0	0	16	0	2	8	48	40	40	66	50
2m	0	0	0	54	20	10	10	42	38	6	10	22
3m	0	0	6	116	296	122	252	92	38	18	2	4
4m	2	0	38	154	38	110	92	164	270	34	16	10
5m	10	0	106	134	566	192	104	178	204	74	20	8
6m	4	34	400	194	608	308	308	248	258	76	28	28

Individual number of live *Quinqueloculina tubilocula*

Interval / Depth (m)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	2001.12.16-2002.1.7	2002.1.7-2.17	2002.2.17-3.8	2002.3.8-4.6	2002.4.6-5.6	2002.5.6-6.13	2002.6.13-7.12	2002.7.12-8.10	2002.8.10-9.11	2002.9.11-10.13	2002.10.13-11.8	2002.11.8-2002.12.5
1m	0	0	0	0	0	0	0	2	64	2	0	0
2m	0	0	0	0	0	0	0	2	94	0	0	0
3m	0	0	0	0	0	0	0	6	528	0	0	0
4m	0	0	0	0	0	0	0	0	102	2	4	0
5m	0	0	0	0	0	0	0	2	30	2	6	0
6m	0	0	0	0	0	0	0	4	14	4	0	0

December to early May. Live *Trochammina hadai* was generally abundant in the deeper bottles and rare in the upper bottles above the halocline. Live *Ammonia* "*beccarii*" is active and occurred even at 1m depth. In the 2002 trapped sediment, *A.* "*beccarii*" was less abundant during the spring bloom, but in general *A.* "*beccarii*" is more common in comparison with *T. hadai*.

Quinqueloculina tubilocula is common in the Sakai Channel, but this form does not occur in the main body of Lake Nakaumi. In the sediment trap emplaced in August 10 to September 11, 2002, we found live individuals of *Q. tubilocula* in association with the Nakaumi assemblage of *A.* "*beccarii*" and *T. hadai* (Figs. 1, 2). Dead individuals of *Q. tubilocula* were not found in this assemblage. All individuals are small in size (< 250 μm length in max.). The maximum occurrence was 528 individuals in the bottle at 3 meters depth, and the minimum was 14 individuals in the bottle at 6 meters. The standing crop of this species accounts for 74 % of the assemblage. Only a few individuals of *Q. tubilocula* occurred in the months before and after the event-driven month. This event was clearly a very exceptional occurrence.

Discussion

Quinqueloculina occurrence in the time of high tide

Although these *Quinqueloculina tubilocula* individuals were clearly transported from the Sakai Channel population through the influx of seawater into Lake Nakaumi, the normal exchange of seawater in the Nakaumi system is not adequate to transport living *Q. tubilocula* into the lake. Tidal amplitudes are small in the Sea of Japan; for instance, the annual amplitude was usually 33.6-43.3 cm at the Sakai tidal observatory in recent 8 years (2002-2009). This event was the only occurrence of marine forms in our sediment traps throughout the life of this study. They did not occur under the normal tidal mixing regime in other seasons and other years, except for 2002 in the studied years (2000-2003).

An exceptionally high tide occurred on September 1st, 2002 (Fig. 3). This high tide was caused by an unusually strong atmospheric low pressure passing through this area. When the water level rose to about + 90 cm at the Mean Sea Level of Tokyo Bay [traditionally used as Tokyo Peil (T. P.) in Japan], the halocline depth shallowed when seawater influx triggered the mixing of deep high salinity water and shallow low salinity water. Immediately prior to this unusual tide the water level was + 48 cm at T. P., and the 42 cm level increase was made up of central Nakaumi water.

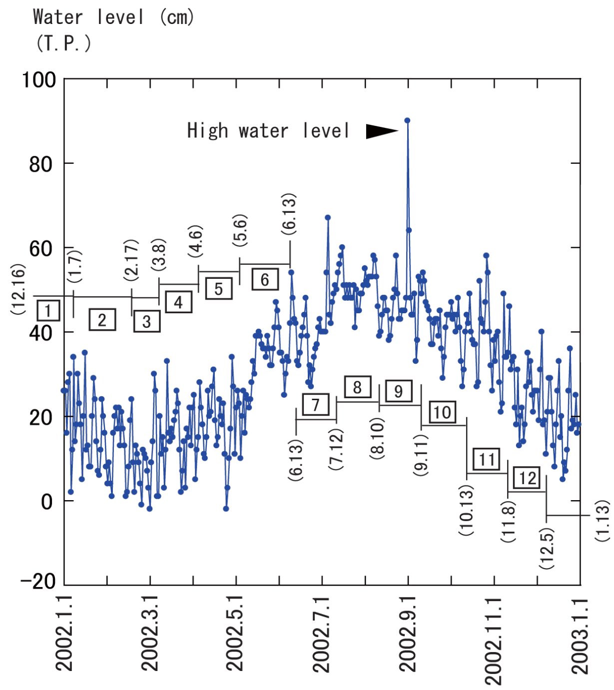

Fig. 3 Tide level changes at the Nakaumi Observatory in 2002. Abnormal tidal height occurred on September 1, 2002. (Data from Ministry of Land, Infrastructure and Transport). Numerals in parentheses indicate the date of bottle exchange. Number in box indicates the month of each sample.

Implications for marine foraminifera in lagoon environments and in response to sea-level rise

Suspended load transport is clearly the most likely explanation for the occurrence of exotic foraminifera in the Lake Nakaumi traps. Suspended material in tidal currents can be transported for long distances and these can contribute to assemblages that mix exotics with indigenous taxa. The chances of long distance transport of foraminiferal tests increase with increased tidal strength. Wang and Murray (1983) discussed the transport of foraminifera in brackish systems as based on the mixing of freshwater and seawater. Under microtidal conditions (when mixing is weak), however, the potential for foraminiferal transport is small. Our observations indicate that dispersion of marine forms into brackish regions is effective when there is a marked increase in sea level even though the tidal effects are small. This makes sense because there is a strong counter-flow of marine water carrying significant quantities of suspended matter. In addition we have noted that all the miliolid individuals in our traps were small in size and live (stained in rose bengal). Nomura and Seto (2004) reported that suspended particles in Lake Nakaumi contain numerous live foraminifera of the major taxa in Lake Nakaumi, *A.*"*beccarii*" and *Trochammina hadai*. Suspended particles are primarily composed of the dinoflagellate *Procentrum minimum*, both live and dead, and contain high amounts of organic matter. Although we did not confirm the occurrence of *Quinqueloculina tubilocula* actually attached to the suspended particles in situ in either that report or this study, sediments in the respective bottles are clearly derived from suspended particles (Fig. 4). Underwater photographs in Lake Nakaumi show numerous suspended particles, similar to marine snow, and they are mostly composed of organic-rich phytodetritus. Foraminifera are able to utilize these particles for food resources during the time when they are being transported on the particles.The trapped sedimentary organic carbon content in our sampler bottles varies with season and depth, but a high rate of sediment deposition is observed in summer and autumn, when the average flux was 0.2~0.35 mgC/cm^2/day (Fig. 5). In the deep-sea, benthic foraminifera are able to utilize seasonally variable inputs of organic matter, as a food resource (Gooday, 1988; Gooday and Turley, 1990), and similarly coastal foraminifera show a strong response to the input of large amounts of organic matter (Schönfeld and Numberger, 2007). The flux of sedimentary organic matter trapped in the bottles seems to be sufficient to maintain live foraminifera for some time. Deep-sea foraminifera have different feeding strategies. Some forms are able to ingest 8.8 mgC/m^2/day of sedimentary organic matter. Phytophagous taxa ingest 2.9 ± 2.4 mg/m^2/day (Nomaki et al., 2006). Compared with these deep-sea benthic foraminifera ingestion potentials, the suspended particles in Lake Nakaumi contain much more than sufficient organic carbon.

The occurrence of this marine form as a result of the unusually high tide event suggests that future increases of sea-level could affect foraminiferal dispersal. In core sediments from the central part of Lake Nakaumi, the same form of miliolid foraminifera frequently occurred

Fig. 4 Underwater photograph showing suspended particles (marine snow) and a sediment trap bottle. Scale bar = 7 cm.

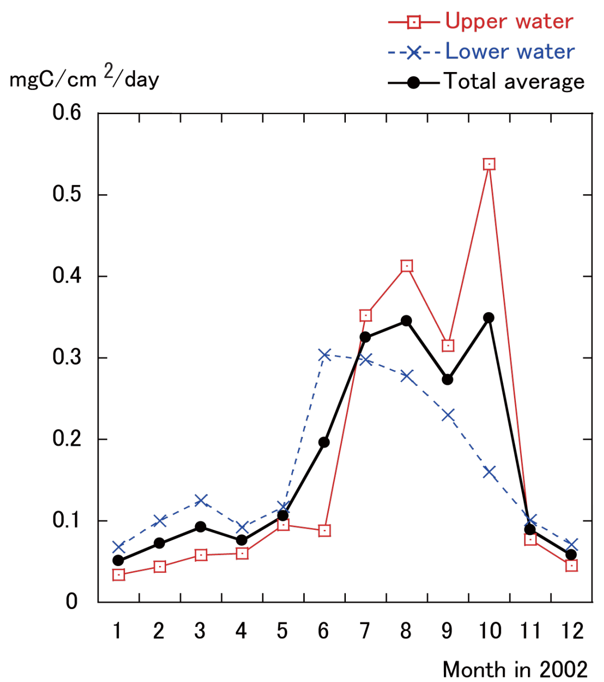

Fig. 5 Annual change and depth difference of the organic carbon flux. Fluxes in upper and lower water are the average of 1-3 m and 4-6 m depths, respectively.

during the 1940s and 1950s (Nomura, 2003). Sea-level during this period was characterized by a higher position measured at various locations around the island of Honshu (Senjyu et al., 1999). In these periods, suspended particles with live miliolids may have been transported into Lake Nakaumi by counter-flow and particles settled to deposit foraminiferal tests on the lake floor. High tide during a period of sea-level rise makes it easy to set up a strong counter-flow current and consequently transport marine suspended particles into estuarine lakes. Our long-term monitoring underwater camera has shown that the soft bottom sediments are easily re-suspended as particles by wind-induced bottom currents. In this case the wind speed was greater than 10 m/s. Suspended foraminiferal tests or sediment particles with included foraminifera are able to combine with other suspended organic particles and be transported upstream into the brackish lake system.

We are therefore able to use these occurrences of marine exotic foraminifera in the sediments of oligohaline to mesohaline water bodies as an indicator of marine water intrusion. This could be very useful in the study of recent sea-level change; exotic forms are a good indicator of marine water movement.

Conclusions

Marine *Quinqueloculina tubilocula* was found in small sediment traps (7.3 cm diameter; 15.5 cm height) placed in central Lake Nakaumi, where the two native forms *Ammonia "beccarii"* and *Trochammina hadai* make up the entire foraminiferal assemblage. The occurrence of this form coincided with an unusually high tide on September 1st, 2002. Based on our observation (Nomura and Seto, 2004) that benthic foraminifera live on or in suspended organic particles, we conclude that this marine form was transported along with suspended particles in water column from the nearest marine source, the Sakai Channel, a distance of about 10 km. We suggest that marine foraminifera in oligohaline to mesohaline brackish water sediments are a good indicator of the counter-flow of marine water, and that the monitoring of marine exotics in brackish lagoonal lake sediments would be useful to understand recent sea-level variations.

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