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Report

Late Holocene diatom assemblages and sea-level observation at a site in Okayama City along the northeastern coast of the Seto Inland Sea

Hiroshi Sato

Division of Earth Sciences, Institute of Natural and Environmental Sciences, Himeji Institute of Technology / Museum of Nature and Human Activities, Hyogo, Yayoigaoka 6, Sanda, 669-1546 Japan

Abstract

Late Holocene sea-level observation was obtained at a site in Okayama City. For the evaluation of relative sea level, diatom assemblages and sulfur content in Holocene sediments were analyzed. The combination of litho-stratigraphy, diatom, and sulfur data of sediments provides the basis for distinguishing five paleoenvironmental phases. Mid-and upper intertidal conditions occurred in phases I and II-A. A decrease of the brackish-water diatom *Pseudopodosira kosugii* indicates that sedimentation took place under upper intertidal conditions in phase II-B. Sedimentation may have occurred in the supratidal zone in phase II-C, whereas freshwater conditions are apparent in phase III. Based on the diatom assemblages, the height of the marine limit at this site is regarded to be +1.02 m altitude as the highest trace of marine influence during the late Holocene. Although significant tidal effect for sea-level observation is suggested at this site, the paleo-mean sea level is considered to have been between +0.32 m and -0.38 m altitude at 4380−4090 cal BP.

Key words: diatom assemblage, Holocene, marine limit, Okayama City, paleo-mean sea level, sulfur

Introduction

A major expansion of ice sheets and glaciers took place in high-latitude regions at the maximum of the last glacial time. A retreat of the ice sheets then caused eustatic sea levels to rise from about -55 m at the beginning of the Holocene to roughly today's elevation about 6000 years ago (Roberts, 1998). The Holocene marine transgression known as the "Jomon marine transgression" in Japan culminated around 7000−6000 years ago. At that time the sea reached its most landward position in many coastal regions, and coastal inlets or embayments were most extensive. After this period a lowering of relative sea level occurred and shorelines advanced seaward to their present positions.

Diatom assemblages in sediments have been used to both clarify the changes in sedimentary environments caused by the Jomon marine transgression and identify the upper limit of marine facies; the transition from marine sediment sequences formed as a result of the transgression to overlying freshwater sediments (e.g., Sato et al., 1983). Since the upper limit of marine facies can provide information on former sea levels during the transgression, its identification is important for studying local relative sea-level changes during the Holocene (Maeda et al., 1982).

In this paper, observational evidence is presented for relative sea level (RSL) during the late Holocene on the Okayama Plain. Holocene sea-level observations have been reported from some coastal lowlands along the eastern part of the Seto Inland Sea (Maeda, 1980; Sato et al., 1983; Naruse and Onoma, 1984; Naruse et al., 1985; Sato and Katoh, 1998). As regards the Okayama Plain, Utashiro et al.

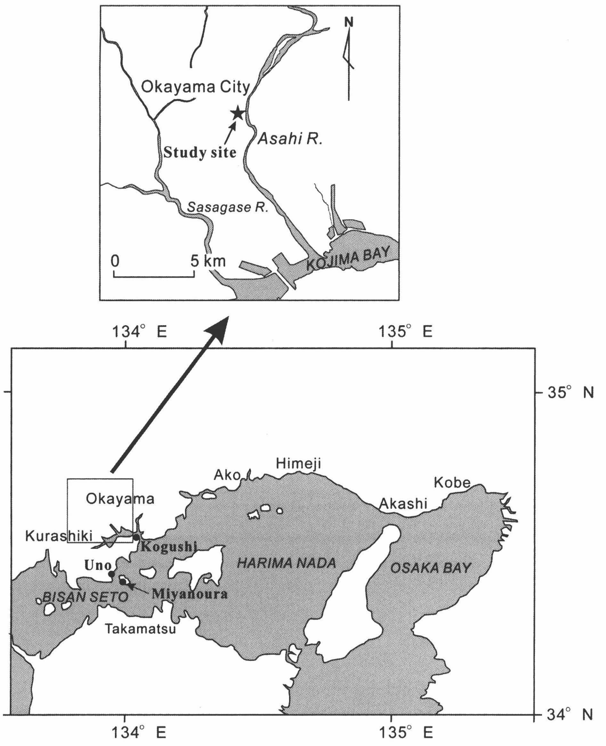

Fig.1. Location map of the study site along the northeastern part of the Seto Inland Sea.

(1975) investigated late Quarternary environments in Kurashiki City, using diatom analysis of sediments. Fujiwara and Shiragami (1986) also discussed geomorphic development and sea-level changes on the Plain during the mid-to-late Holocene. However, observational evidence of the RSL derived from diatom analysis of sediments has not been described. The observation presented here will be helpful, not only to reconstruct local histories of Holocene sea-level changes, but also to evaluate mechanisms such as glacio-hydro-isostasy and local tectonism in the area.

Materials and Methods

Samples

For the evaluation of the RSL, I performed diatom and sulfur analyses of Holocene sediments. Samples for these analyses were obtained from an outcrop of the Minamigata-Kamata archaeological site in Okayama City, which is located near the Asahi River about 10 km from the coast along Kojima Bay, in the eastern part of the Seto Inland Sea (Fig.1).

Ground surfaces were instrumentally levelled to mean sea level (MSL) in Tokyo Bay (T.P.), and the altitude for each outcrop was determined relative to T.P. by levelling from permanent benchmarks. All altitudes quoted in this study are related to T.P..

At the outcrop, the sediments are sandy below +0.20 m altitude. Between +0.20 m and +0.45 m, a fine sand occurs. A homogenous clay occurs between +0.45 m and +1.02 m, and trace fossils are found at +0.85 m. In the upper part, sediments are silt from +1.02 m to +1.22 m. In the present study, the sediments are divided lithostratigraphically into three units, I (+0.20−0.45 m), II (+0.45−1.02 m) and III (+1.02−1.22 m).

For AMS ^{14}C analysis charred detrital materials were collected in the sample at +0.77 m. They were carefully removed with tweezers, dried, and weighed before they were sent to the dating laboratory.

Procedure

For diatom and sedimentary sulfur analyses, subsamples of 1 g were leached subsequently with 1N HCl and 30% H_2O_2. The residue, consisting almost entirely of clay and other silicate minerals, was used for the diatom analysis (Sato, 1991, 1995). Sulfate in the 1N HCl and 30% H_2O_2 soluble fractions was determined through turbidimetric analysis (Sato, 1989).

Since much more pyrite, a major end product of sulfate reduction (Howarth, 1979), is usually found in muddy sediments from marine and brackish water than from freshwater, the sulfur content of sediments can be used to trace marine influence (Postma, 1982; Berner, 1984; Sato, 1989). In the present study, the sum of HCl soluble and H_2O_2 soluble sulfur in sediments is referred to as sedimentary sulfur.

Residual silicate fractions were dispersed in 200 ml of 1% sodium pyrophosphate in water. The solution was allowed to stand for at least 3 hours and the fine mineralogenic material was removed by decantation. Care was taken not to affect the diatom fraction of the samples. The diatom fraction was separated from the coarser material by vibration and subsequent decatation of the suspension containing diatom valves. The diatom fraction was made up to a definite volume and 0.5 ml of the suspension was pipetted onto a cover slip. The sample was then dried on a hot plate. The preparations were mounted in Mountmedia (Wako Chemical, Japan).

At least 200 valves were counted in the samples. Diatom identification primarily followed Krammer and Lange-Bertalot (1986, 1988, 1991). Ecological interpretations are also based on Kashima (1986) and

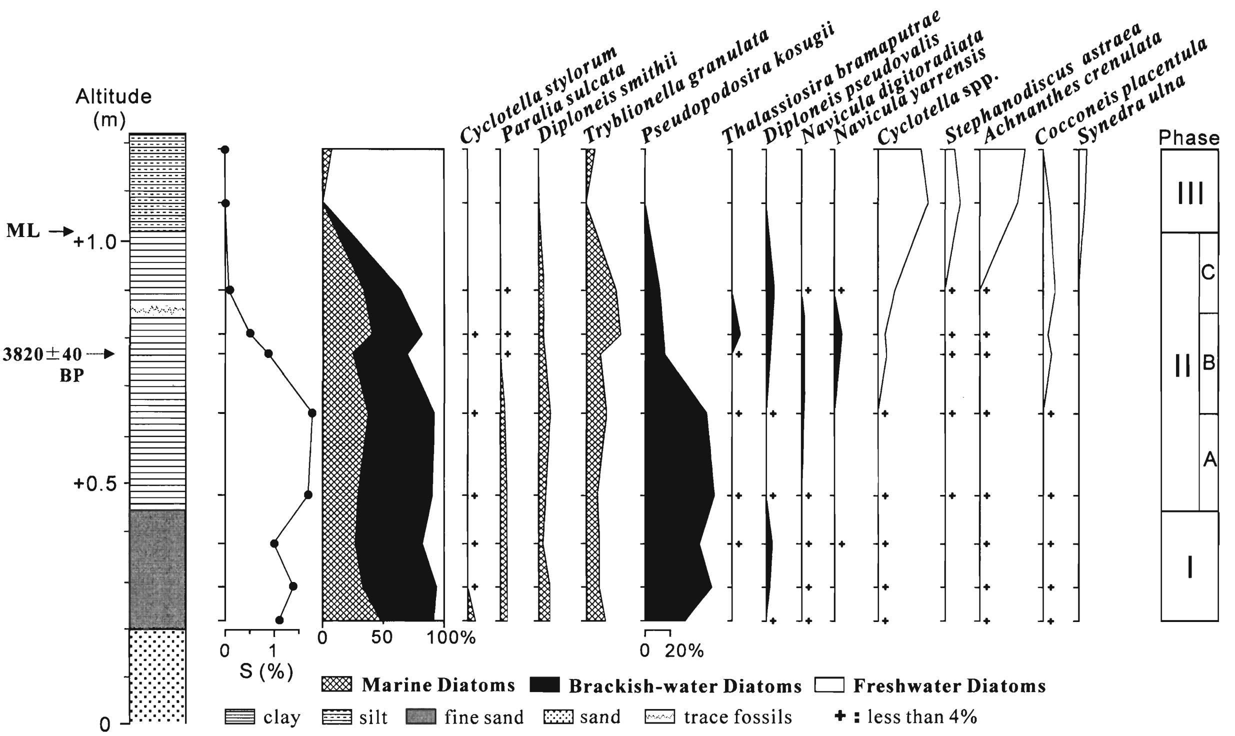

Fig.2. A summary diagram showing columnar section, ^{14}C age, marine limit (ML), variations in sedimentary sulfur (S%), occurrence of significant freshwater, brackish-water and marine diatom taxa, and paleoenvironmental phase for the Minamigata-Kamata archaeological site.

Kosugi (1988). Although many authors have proposed new names for some species, I mainly followed the nomenclature in Round et al. (1990). The ecological data provided by the above-mentioned authors have enabled most taxa to be grouped into one of three ecological categories: marine, brackish-water, or freshwater. Compositional changes in the diatom assemblages based on habitat preference, and the relative abundance of each dominant or common taxon are shown for the sediment profile. (Fig.2.)

Evaluation of paleo-sea level

The effect of the tidal range on the evaluation of Holocene sea-level changes is very important (Chappell, 1987). Tidal effect is significantly large in the Bisan-Seto area. At present, the mean spring tidal range is 1.8 m with a maximum range of 2.8 m at Uno (Fig.1.). The spring tidal range and its maximum range at Kogushi are 1.4 m and 2.4 m, respectively (Japan Maritime Safety Agency, 1998).

The depositional environment of the sediment at a given horizon would be freshwater when the RSL was below it. The environment would be marine when the RSL was above the horizon. When the RSL was at or below it, the environment would be brackish. The total abundance of brackish-water diatoms possibly indicates a former RSL. Among the diatom assemblages, brackish diatoms such as *Pseudopodosira kosugii,* living in the mid-and upper intertidal zones, is a useful indicator for the former sea level during the Holocene (Sato et al., 1996; Tanimura and Sato, 1997), and has been used for identifying the RSL position (Sato and Katoh, 1998). The RSL identified by the intertidal diatoms is an approximate index of the paleo-mean sea level (PMSL).

In glacio-isostatically uplifted areas, the highest trace of marine action preserved on a coast is called the marine limit (Pirazzoli, 1996). Here the term "marine limit" (ML) is used for the upper limit of marine facies. The ML usually indicates a high water level for sea-level variations (Sato et al., 1983; Eronen et al., 1987; Yokoyama et al., 1996). For sites where no tidal changes occurred during the past 6000 years, we can evaluate the PMSL by reducing half of the present tidal range from the ML height showing a mean high water level (Yakoyama et al., 1996). In the present study, a tidal range of 1.4−2.8 m in the Bisan-Seto area is adopted to evaluate the PMSL.

Although sedimentary sulfur content is very sensitive to the content of available organic matter metabolized by sulfate-reducing bacteria (Berner,

Table 1. Result of radiocarbon dating

Altitude (m)	Material dated	^{14}C age (BP)	δ ^{13}C (‰)	Calibrated age (cal BP) ± 2 σ (Intercept)	Laboratory No.
+0.77	charred material	3820 ± 40	-11.5	4380 − 4090 (4230)	Beta-143196

1970, 1984), more than 0.3% in muddy sediments usually indicates marine influence (Koma, 1992; Sato, 1995), except for highly organic freshwater sediments laid down under anoxic conditions. Sedimentary sulfur is employed in order to reinforce the results for the depositional environment derived from diatom analysis.

Results

The combination of lithostratigraphic units, plus diatom and sulfur data provides the basis for distinguishing five paleoenvironmental phases (Fig.2). The succession of diatom assemblages are shown in a percentage diagram for selected taxa that occurred with at least 4% abundance in any one sample (Fig.2).

Phase I (+0.20 m to +0.45 m)

Sedimentary sulfur contents range from 0.99% to 1.40%. The diatom assemblages are dominated by marine and brackish-water diatoms. Among the marine diatoms, *Paralia sulcata* (5.0−5.6%) occurs in this phase and *Cyclotella stylorum* occurs with a frequency of 6.3% at +0.22 m altitude. *Diploneis smithii* (4.0−8.8%) and *Tryblionella granulata* (10.0−15.0%) also occur. The brackish-water diatom *Pseudopodosira kosugii* (31.3−54.2%) dominate in this phase and *Diploneis pseudovalis* occurs with frequencies of 3.5% and 5.0% at +0.29 m and +0.38 m, respectively.

Phase II-A (+0.45 m to +0.65 m)

Sedimentary sulfur remains abundant, reflecting marine influence and anoxic depositional conditions. The assemblages are also dominated by marine and brackish-water diatoms, and resemble those encountered in Phase I. Marine diatoms such as *Paralia sulcata* (4.0−5.1%), *Diploneis smithii* (5.4−9.2%) and *Tryblionella granulata* (9.4−16.0%) occur and the brackish-water diatom *Pseudopodosira kosugii* (46.9−55.6%) dominates in this phase.

Phase II-B (+0.65 m to +0.85 m)

Sedimentary sulfur contents show gradual decrease from 0.87% to 0.51%. Marine and brackish-water diatoms dominate with more than 70% abundance. Among marine diatoms, *Diploneis smithii* (4.0−5.4%) occurs and *Tryblionella granulata* (23.4−27.7%) shows a slight increase. The brackish-water diatom *Pseudopodosira kosugii* (14.9−16.2%) decreases in this phase. Instead, brackish-water diatoms *Thalassiosira bramaputrae, Diploneis pseudovalis, Navicula digitoradiata* and *N. yarrensis* characteristically occur with frequencies of more than 4%.

The ^{14}C age for charred materials at +0.77 m altitude is 3820±40 BP. The age is calibrated to calendar years before A.D.1950 (cal BP) using the program INTCAL98 (Stuiver et al., 1998), yielding an adopted age of 4380−4090 cal BP. (Table 1).

Phase II-C (+0.85 m to +1.02 m)

Sedimentary sulfur content is less than 0.1%. Although marine and brackish-water diatoms remain dominant, freshwater diatoms such as *Cyclotella* spp. (13.8%) and *Cocconeis placentula* (9.6%) increase in this phase. The marine diatom *Tryblionella granulata* occurs with a relatively high frequency (23.4%). Among brackish-water diatoms, *Pseudopodosira kosugii* (11.9%) and *Diploneis pseudovalis* (6.9%) occur.

Phase III (+1.02 m to +1.22 m)

In this phase, sedimentary sulfur is not detected and freshwater diatoms dominate the assemblages, although the marine diatom *Tryblionella granulata* occurs at 1.19 m. Among the freshwater diatoms, *Cyclotella* spp. (35.7−41.9%), *Stephanodiscus astraea* (7.1−11.6%), *Achnanthes crenulata* (30.2−35.7%), *Cocconeis placentula* (4.7%) and *Synedra ulna* (4.7−7.1%) occur.

Discussion

Large amounts of sedimentary sulfur are indicative of marine influence and diagenetically occurring anoxic conditions in phases I and II-A. The brackish-water diatom *Pseudopodosira kosugii* dominates in the diatom assemblages, indicating the mid- and upper intertidal conditions in these phases. Sedimentation, therefore, occurred at intertidal conditions in phases I and II-A, indicating that the height of the PMSL may have been between +0.20 m and +0.65 m at that time.

Although the marine diatom *Tryblionella granulata* increases, brackish-water diatoms such as *Thalassiosira bramaputrae, Navicula digitoradiata,* and *Navicula yarrensis* characteristically occur in phase II-B. Characteristic occurrence of these brackish-water diatoms and the decreasing sedimentary sulfur may reflect the decline of marine influence. Judging from the decrease of *Pseudopodosira kosugii,* sedimentation is considered to have occurred at upper intertidal conditions in this phase. Sedimentary environments and the depositional age in this phase indicate that the height of the PMSL was apparently below +0.77 m at 4380 —4090 cal BP.

There is a major change in sedimentary sulfur content at the boudary (+0.85 m altitude) of phases II-B and II-C, where trace fossils were found. Sedimentary sulfur is less than 0.1%, but marine and brackish-water diatoms remain dominant in phase II-C, indicating marine influence in sedimentary environments. Although there is a discrepancy for the trace of marine influence between diatom and sulfur records, diagenetically occurring oxidative conditions may be responsible for the paucity of sedimentary sulfur in this phase. Sedimentation may have occurred in the supratidal zone.

In phase III, freshwater diatoms dominate and sedimentary sulfur is absent. Thus freshwater conditions are apparent in this phase. Among freshwater diatoms, planktonic diatoms such as *Cyclotella* spp. and *Stephanodiscus astraea* occur in relatively high frequencies, suggesting lacustrine conditions. On the contrary, the occurrence of *Achnanthes crenulata* and *Synedra ulna* indicates fluvial conditions in this phase. Planktonic diatoms may be allochthonous, as their valves were not well-preserved.

Based on the diatom assemblages, the height of the ML is identified to be +1.02 m altitude at this site. The height of the PMSL, determined by considering the observed height of the ML and half of the tidal range in the Bisan-Seto area stands between +0.32 m and -0.38 m altitude. This estimate seems to explain the overall succession of diatom assemblages at this site during the late Holocene. Based on the dated sample from +0.77 m altitude, the diatom-inferred PMSL for this site is considered to have been between +0.32 m and -0.38 m altitude at 4380-4090 cal BP.

Based on the geomorphology of the coastal barrier and the present tidal range, Fujiwara and Shiragami (1986) considered that the height of the PMSL on the Okayama Plain had been about +0.4 m altitude at the culmination of the Jomon marine transgression and between -0.12 m and -0.35 m altitude at about 3500 ^{14}C BP. This estimate is consistent with that derived from the diatom assemblages of sediments. Thus the Jomon transgression did not produce relative sea levels several meters above present sea level during the mid-to-late Holocene in this area.

Tidal effect and its accurate evaluation for sea-level observation are essential in reconstructing the exact PMSL. On the Okayama Plain, tidal effect is considered to have been significantly large during the Holocene. To examine tidal effect more accurately, further systematic observations for spatial variations in sea level during the Holocene are expected for this area.

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