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Seafloor environmental changes resulting from nineteenth century reclamation in Mishou Bay, Bungo Channel, Southwest Japan

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Abstract This study reconstructed environmental changes to the seafloor associated with reclamation in Mishou Bay, Bungo Channel, Japan, based on measurements of sediment grain size, organic matter and sulfur contents of surface sediments and data from sediment cores. Grain size within sediment cores from the middle of Mishou Bay decreased from the beginning of the 1800s to the 1900s. In contrast, a grain size profile from the river mouth shows a gradual increase in grain size up through the sediment core. These changes in grain size indicate a decrease in tidal current velocity within the middle of the bay and that the delta system is gradually prograding from the river mouth. Records of organic matter composition and sulfur contents indicate that the effect of the river on seafloor sedimentation became stronger during the nineteenth century. These changes are related to reclamation during the late 1700s and 1800s. The decrease in sea area resulting from reclamation probably led to a decrease in tidal prism and current velocity. It is likely that the increasing effect of river water on sedimentation is associated with reclamation-related progradation of the river delta system.

Keywords Grain size · Total organic carbon · Total sulfur · Reclamation · Sedimentary environment

Introduction

Coastal areas have high productivity in terms of both the ecosystem and human society and as such are recognized as important environments. Enclosed areas in Japan such as lagoons, bays, mud flats, and marshlands have been reclaimed for farmland since the Middle Ages (e.g., Miura and Okamoto 2004). During the twentieth century, rapid and extensive reclamation of coastal areas has been carried out for the construction of ports and associated industrialization.

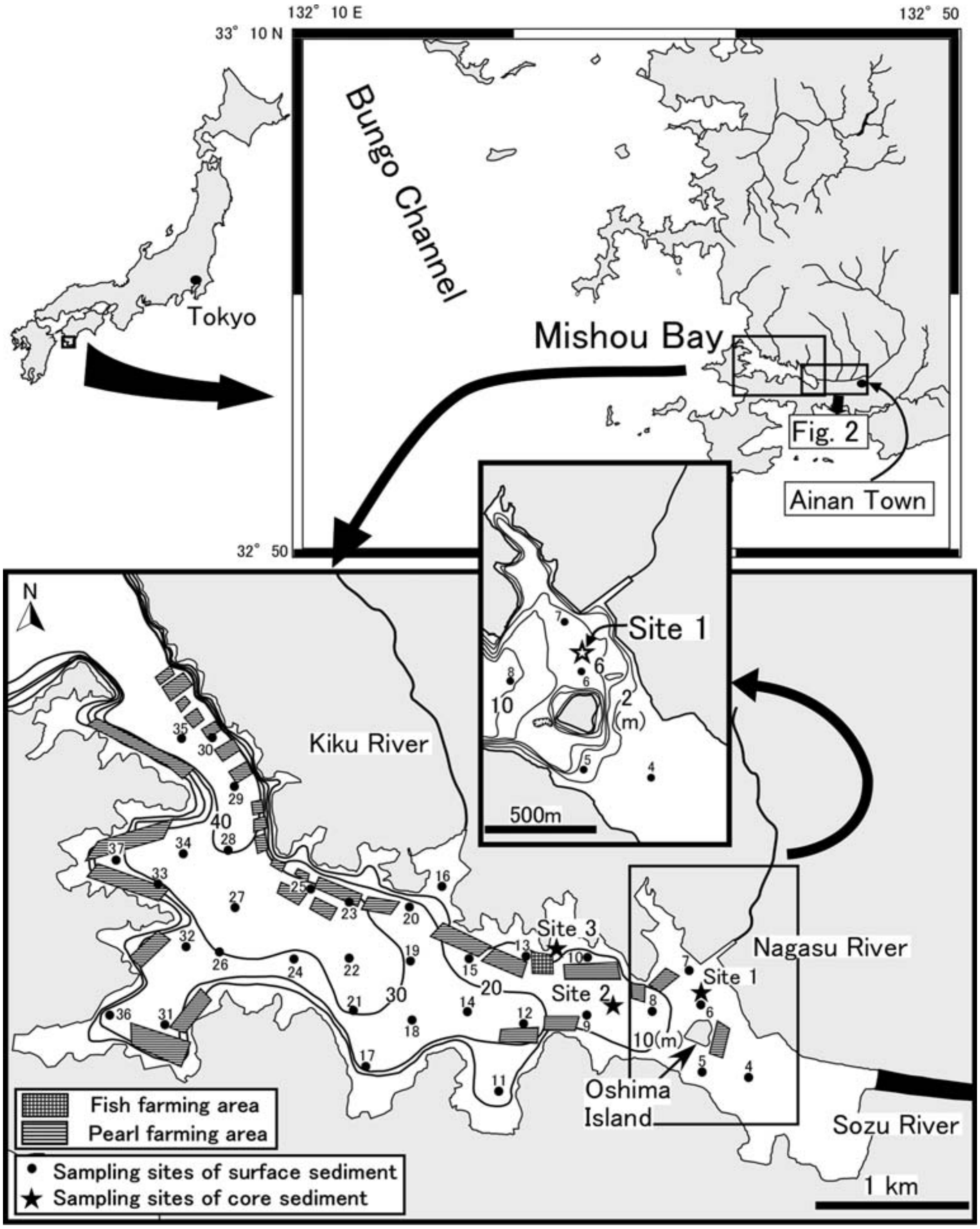
Reclamation affects the hydrodynamic and sedimentary environment and ultimately changes the coastal ecosystem. Tönis et al. (2002) and Van der Wal et al. (2002) documented morphological changes in the sedimentary environment and estimated the volume of buried sediment from bathymetrical and topographical data. Chaumillon et al. (2004) used seismic and sediment profiles to propose that land reclamation is responsible for the rapid infilling of bays, decreased tidal current energy, and the deposition of muddy sediments. Saito and Kayane (1991) and Yanagi and Ohnishi (1999) documented similar phenomenon in Tokyo Bay using grain size distribution data and a numerical model. Owen and Lee (2004) studied sediment cores from Hong Kong and noted that large-scale reclamation and urbanization resulted in increased rates of marine deposition.

Thus, previous studies that investigated changes in the sedimentary environment related to reclamation focused on changes in hydrodynamics and deposition volumes, but largely failed to document the physical and chemical properties of the sediment. The present paper focuses on physical and chemical changes in the seafloor environment, based on analyses of grain size, organic matter composition, and carbon, nitrogen, and sulfur concentrations within sediments. To provide a high-resolution reconstruction of environmental change, sediment samples were collected in Mishou Bay, which is a small, enclosed bay. This study reconstructed seafloor environmental changes with a focus on the hydrodynamic system and the supply and deposition of organic matter, based on measurements of grain size, total organic carbon (TOC), total nitrogen (TN) content, total sulfur (TS) content, ratio of TOC to TN (C/N ratio) and total sulfur (C/S ratio), kerogen-like material (KL) composition, and sedimentation rate as determined by ^{210}Pb analysis. The causes of the documented changes are discussed with reference to historical records.

Description of the study area

Mishou Bay is a semi-enclosed bay located in the southeast part of Bungo Channel. The bay has a length of 6.0 km in the east–west direction and 2.5 km in the north–south direction and an area of 7.0 km^2 (Fig. 1). A small island, Oshima Island, with an area of 0.02 km^2

Fig. 1 Map of the study area and locations of sampling sites



and perimeter of 0.6 km, lies in the eastern part of the bay. Water depth increases from the eastern part of the bay to the bay mouth, where it exceeds 40 m. The eastern part of the bay, from Oshima Island, is shallow, less than 2 m in depth. Three rivers flow into Mishou Bay; the Sozu River is the largest of these rivers and flows into the eastern bay, with tidal flats at its mouth. Pearl culturing was introduced to the area in the 1930s and now occupies a large area of the bay, as shown in Fig. 1. Fish farming is carried out only in a small part of the bay.

At present, urban districts are located on the lower Sozu River. Archives of the Konishi family (kept by Mr. Fujita, Ainan Town, who serves as a member of the Committee for the Protection of Culture Properties) describe reclamation for developing a paddy field during the late 1700s and 1800s. This record can be verified from a topographic map (1:50,000) of the mouth of the Sozu River area (Area A in Fig. 2) published by the Geographical Survey Institute in 1907; the map shows a paddy field in the area described in the archives. It is difficult to determine the exact location of the reclaimed land on a current topographic map; however, archives indicate that the Konishi family submitted the application document to the local government in 1798 for developing a paddy field by reclamation at the river mouth. Production at the paddy field was recorded by the local government in 1822. The Konishi family therefore carried out the reclamation and succeeded in harvesting rice some time in the period 1798–1822; this represents the earliest documented reclamation in Mishou Bay.

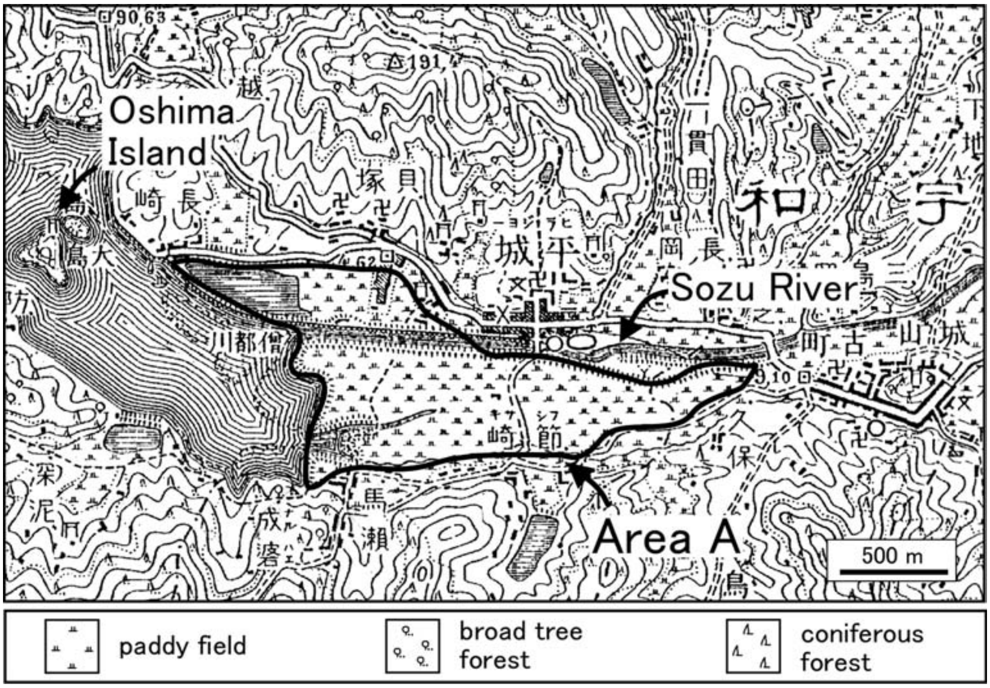
In 1840, an application was submitted to construct an offshore embankment, while an application to construct an embankment at the present estuary line was submitted in 1868. The interior area between the two embankments was later reclaimed. A total of 1.1 km^2 of tidal flat and sea around the Sozu River mouth was pioneered by reclamation. As a result of reclamation, the sea area in Mishou Bay decreased by about 14%. Additional coastal area has been reclaimed during the twentieth century for constructions such as a fishing port; however, these areas are much smaller than those reclaimed during the nineteenth century.

Materials and methods

Sampling methods

During October 2003, samples of seafloor sediments at 34 sites were collected using a Smith-McIntyre grab sampler (Fig. 1, Sites 4–37). Cylindrical acrylic pipes were removed from the grab sampler without being disturbed, and a 1 cm thickness of surface sediments was analyzed for grain size and chemical composition. At the same time, cored sediments (Fig. 1, Sites 1–3) were sampled using a gravity corer with a length of 1 m and diameter of 6 cm. Three core samples were separated at 1 cm intervals for analysis.

Fig. 2 Topographic map of the area around the mouth of the Sozu River, as published by the Geographical Survey Institute in 1909. The contour interval is 20 m. Archives of the Konishi family describe that paddy fields within area A, indicated by the *black line*, were developed by reclamation during the late 1700s and early 1800s



Grain size analysis

The grain size of surface sediments with mud contents of less than 20% was determined by sieving, while sediments with more than 20% mud were analyzed by the hydrometer method. The grain size of samples is represented by the median diameter according to the φ scale (Mdφ). The Mdφ of all cored sediments was measured using a SALD-2100 laser diffraction particle size analyzer (Shimazdu Co.). As pretreatment for grain size analysis, 10 cc of 10 wt% H_2O_2 was added to approximately 1 g of dry sample in a beaker; this was left to settle at room temperature for 24 h for the removal of organic matter. Immediately before analysis, distilled water was added and dispersed using ultrasonic cleaner for 3 min. During analysis, 4 ml of 0.1 mol/l $(NaPO_3)_6$ aqueous solution was added to the samples.

CNS element analysis

The TOC, TN, and TS content of all surface and core samples were measured at 2 cm intervals. The TOC, TN, and TS contents of surface sediments were measured at Shimane University using an EA1108 elemental analyzer (Carlo Erba Co.) via the combustion method at 1,000°C. Cored samples were analyzed at Kochi University using a Flash EA1112 elemental analyzer (Thermo Finnigan Co.). For pretreatment, about 10 mg of dry sample was placed in a thin Ag film cup, and 1 mol/l HCl was added several times and dried at 70°C for 2 h. The dried sample was then wrapped in a thin Sn film for combustion and measurement.

Fluorescent visual kerogen analysis

Hunt (1995) defined kerogen as the organic matter within sedimentary rocks that is insoluble in non-oxidizing acids, bases, and organic solvents, and that organic matter in unconsolidated sediments is a precursor substance that is converted to kerogen during diagenesis. Therefore, organic matter isolated by the following method was considered to be KL. KL composition in the cores was measured by fluorescent visual kerogen analysis at 10 cm intervals at Sites 1 and 3. For details of the following method of KL isolation, refer to Garcette-Lepecq et al. (2000) and Omura and Hoyanagi (2004). Ten grams of dry sediment was removed clastic sediments with HCl/HF treatment. $NaBH_4$ and $(Na_4)_2CO_3$ saturated solution was added to remove pyrite and fluoride. Following this treatment, residual organic matter consists of KL. KL classification was determined according to the method of Sawada and Akiyama (1994). At least 300 points were counted at each 200 μm interval using a microscope under fluorescent and natural transmitted light; the compositions of vitrinite, cutinite, sporinite, and alginite were then determined.

Sedimentation rate derived from ^{210}Pb analysis

At the beginning of the 1970s, Krishnaswamy et al. (1971) and Koide et al. (1972, 1973) measured sedimentation rates using ^{210}Pb isotopes (half-life 22.3 years) from lacustrine and marine sediments. The ^{210}Pb dating method then became the principal technique for dating sediments deposited during the last 100 years. In the present study, excess ^{210}Pb ($^{210}Pb_{ex}$) activity was measured, and the sedimentation rate was calculated using the following method. Samples, 2 cm thick, from Sites 1 and 2, and a 4 cm thick sample from Site 3 were dried and crushed to powder. Powder samples of approximately 5–10 g were sealed in plastic jars and equilibrated with ^{226}Ra, ^{222}Rn, and ^{214}Pb for 30 days. The activities of these radionuclides were measured by gamma ray spectrometry using a GXM25P Ge detector (ORTEC Co.). ^{210}Pb activity was measured from the 46.5 KeV gamma peak and ^{214}Pb activity from the 351.9 KeV peak. $^{210}Pb_{ex}$ activity was calculated by subtracting ^{214}Pb activity from ^{210}Pb activity. The Content Initial Concentration model (e.g., Appleby and Oldfield 1978) was applied to the treatment of Pb-210 data.

Results

Surface sediments

The Mdφ of surface sediments decreases from river mouths to the interior of Mishou Bay (Fig. 3a). Muddy sediments with $>6.0\varphi$ occur in the eastern part of the bay, with sandy sediments of 3.0–4.0φ in the central part and sediments with $<3.0\varphi$ around the bay mouth. Notably, coarse sediments of 3.0–4.0φ are distributed around river mouths, and sediments with $<2.0\varphi$ occur in the southwestern part of the bay. TOC contents are relatively high (over 1.0%) in the eastern bay and river mouths and less than 1.0% in the southwest and western parts of the bay (Fig. 3b). Thus, TOC contents decrease from eastern parts of the bay to the bay mouth. TN contents are relatively high (over 0.15%) around the river mouth and decrease to less than 0.10% in the central part of the bay (Fig. 3c). TN content increases in the north central bay, but decreases toward the bay mouth. C/N ratios are high (>10) around all river mouths and decrease rapidly toward offshore regions (Fig. 3d); values of <4 are recorded in the southwest to western parts of the bay.

Sediment cores

Grain size

The grain size profile for Site 1 shows a gradual upward increase in grain size (Fig. 4). Mdφ is around 6.5φ between the bottom of the core and 45 cm depth, excluding a coarse interval at 52–56 cm; around 6.3φ at 45–20 cm depth; and $<6.0\varphi$ at less than 20 cm depth. At Sites 2 and 3, grain size decreases from lower to upper layers. Mdφ increases from 3.0 to 5.0φ between 20 and 35 cm depth at Site 2 and changes from 3.5 to 5.5φ between 40 and 20 cm depth at Site 3.

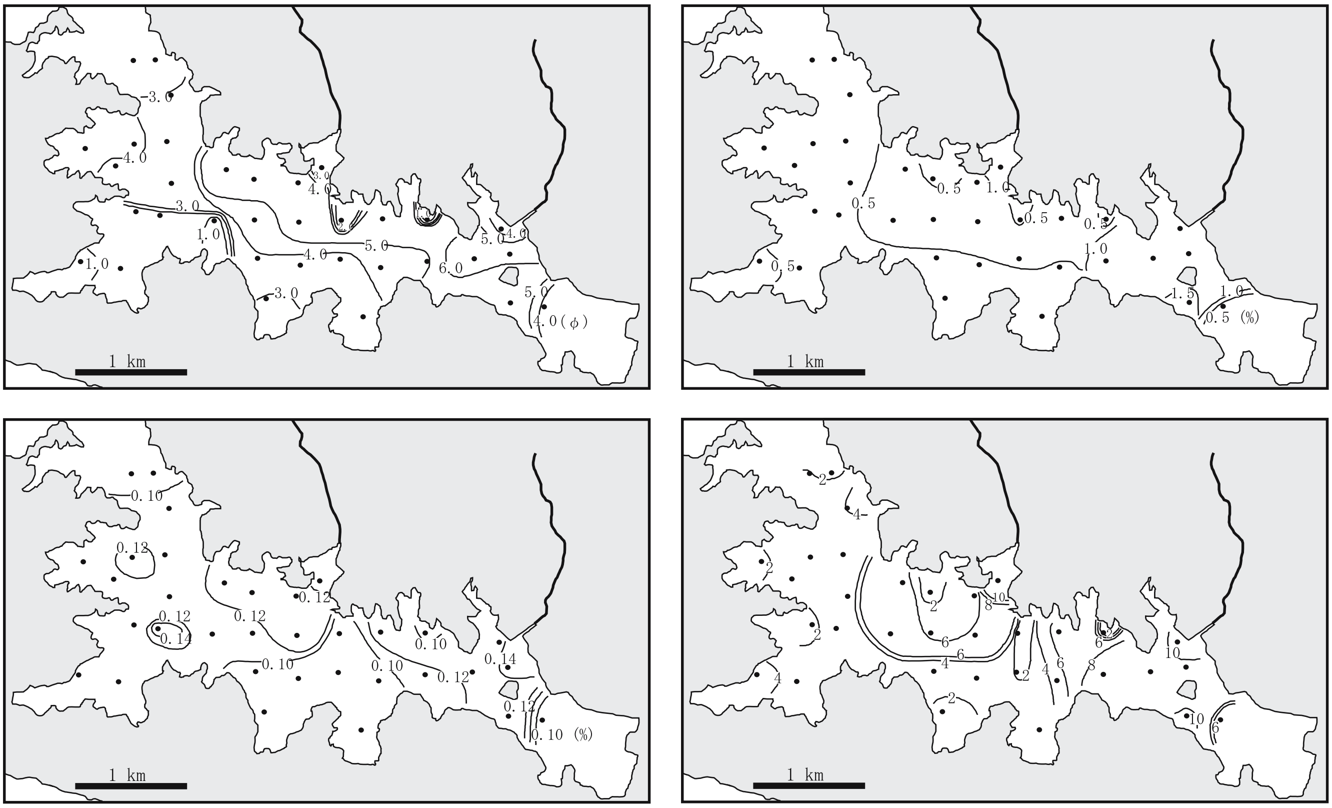
TOC, TN and TS contents and C/N and C/S ratios

The TOC and TN contents of cored sediment are constant at Site 1, but increase upward at Sites 2 and 3 (Fig. 4). TOC and TN contents at Site 1 are around 2.0 and 0.17%, respectively, but increase markedly within the interval 53–49 cm. At Site 2, TOC and TN contents increase from the bottom of the core to a depth of 15 cm; values are around 1.2 and 0.12%, respectively, above 15 cm depth. At Site 3, TOC and TN contents gradually increase from the bottom toward the top of the core. Measured C/N ratios are constant in all cores, as profiles of TOC and TN content show similar variation within the cores. C/N ratios are around 12 at Site 1 and 9 at Sites 2 and 3. The TS content of all cores decreases upward from depths of around 10 cm. At depths greater than 10 cm, rapid decreases in TS content coincide with increases in C/S ratios from the bottom of the core to a depth of 47 cm at Site 1. Above a depth of 47 cm, TS contents gradually decrease and C/S ratios increase. From 40 to 19 cm depth at Site 3, the TS content decreases to 0.4%, while the C/S ratio decreases to 3.4. TS contents increase to values in excess of 0.5% above 19 cm depth.

KL composition

Kerogen-like material composition data reveal that KL from Sites 1 and 3 consists mainly of the terrestrial plant macerals vitrinite, cutinite, and sporinite (Fig. 5). KL from Site 1 near the river mouth contains little alginite of plankton origin. At Site 1, vitrinite increases and alginite decreases between 60 and 40 cm depth within the core. At Site 3, sporinite increases and alginite decreases within the equivalent interval.

Fig. 3 Distribution maps of surface sediment properties: **a** (*upper left*) grain size, **b** (*upper right*) total organic carbon (TOC), **c** (*lower left*) total nitrogen (TN), **d** (*lower right*) ratio of TOC to TN



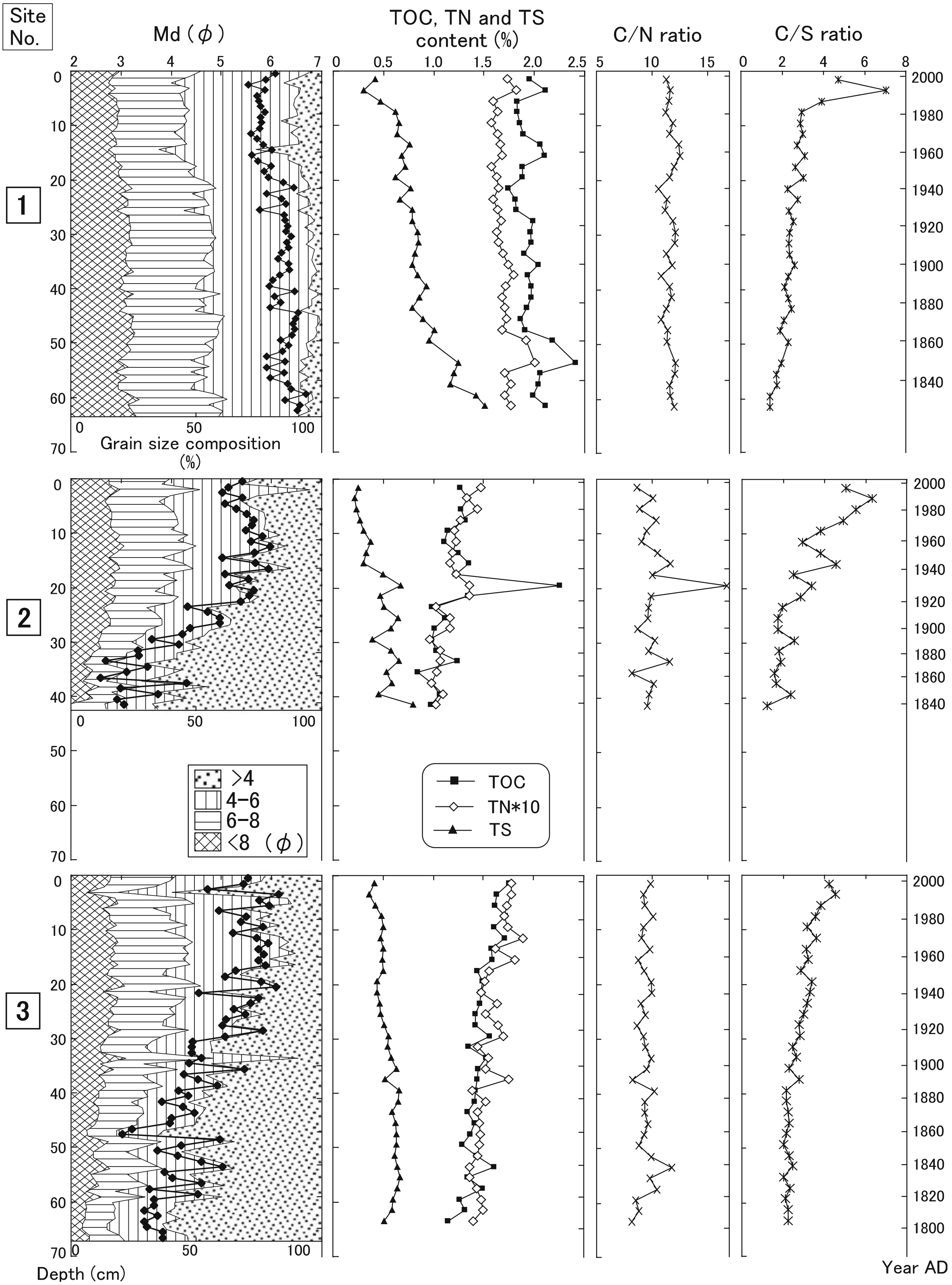


Fig. 4 Depth profiles of sedimentary cores from Sites 1, 2, and 3, showing (from *left* to *right*) grain size; TOC, TN, and total sulfur content; C/N ratio; and C/S ratio

^{210}*Pb dating*

^{210}Pb$_{ex}$ activity profiles record a downward decrease within core from Site 1, while values are constant above 10 cm depth at Sites 2 and 3 (Fig. 6). ^{210}Pb$_{ex}$ activity at Site 1 is detected between the top of the core and 36 cm depth and decreases toward the lower part of the core. The sedimentation rate at Site 1, as calculated using all ^{210}Pb$_{ex}$ activity data, is 0.32 g/cm^2/year. ^{210}Pb$_{ex}$ activity is constant in the horizons above 8 cm depth at Site 2 and 16 cm at Site 3; these horizons are probably affected by bioturbation. The sedimentation rate was therefore calculated excluding data from the surface horizon. The sedimentation rate at Site 2, as calculated using ^{210}Pb$_{ex}$ activity data between 16 and 24 cm depth, is 0.30 g/cm^2/year. The rate at Site 3, calculated from ^{210}Pb$_{ex}$ activity between 16 and 48 cm depth, is 0.34 g/cm^2/year. The sedimentation rates were then used to calculate the age of deposition in terms of core depth (Figs. 4, 5).

Interpretation and discussion

Present seafloor environment

The Mdφ of seafloor sediments shows that the seafloor of Mishou Bay consists of coarse sand around the bay mouth, finer sediment toward the eastern part of the bay, and silt of $>6.0\varphi$ around Ohshima Island (Fig. 3a).

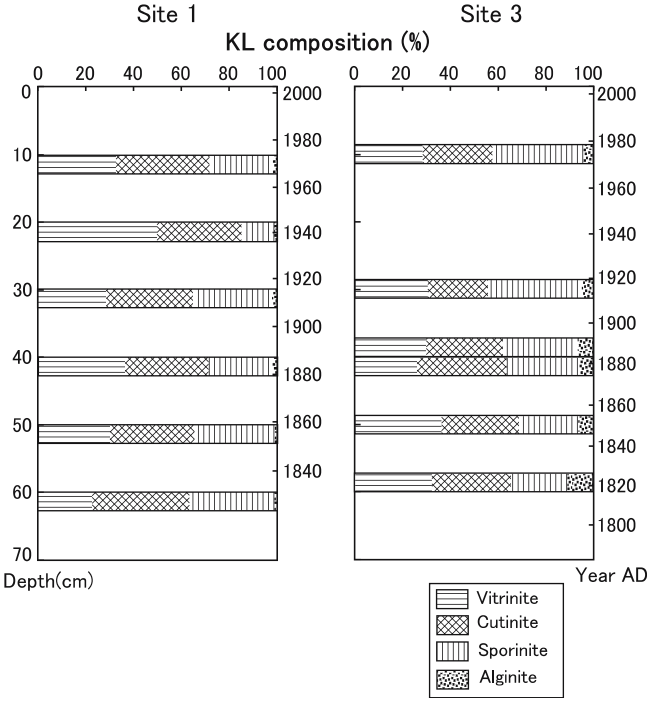


Fig. 5 Depth profiles of KL compositions at Sites 1 and 3

The grain size distribution pattern indicates that the nature of the seafloor environment is mainly influenced by the progressive reduction in tidal current velocity from the bay mouth to the bay interior; however, coarse sediments of $<2.0\varphi$ occur in the southwest part of the bay. This suggests that waves from the open sea have a large influence on the distribution of surface sediments in this area, as water depth is generally less than 30 m.

Total organic carbon contents are relatively high around all river mouths and decrease toward the bay mouth (Fig. 3b). C/N ratios are also high around all river mouths and decrease toward the bay mouth; values are <4 at the southern and western parts of the bay (Fig. 3d). The C/N ratio reflects the composition of the source organic matter. Organic matter derived from planktonic organisms has C/N ratios of 5–9 (Bordovskiy 1965a; Prahal et al. 1980; Biggs et al. 1983). In contrast, organic matter from terrestrial vascular plants has values of 15 or higher (Bordovskiy 1965b; Ertel and Hedges 1984; Ertel et al. 1986; Hedges et al. 1986). In some areas at river mouths, high TOC contents and high C/N ratios (over 10) indicate that organic matter is mainly derived from terrestrial plants. These results indicate that terrestrial organic matter supplied by rivers is largely deposited around river mouths. In the southern and western parts of the bay, C/N ratios are much lower (under 4). For sediments with low concentrations of organic matter (organic carbon content $<0.3\%$), the proportion of inorganic nitrogen can be a large component of residual nitrogen, and C/N ratios based on TN contents are low (Meyers 1997; Sampei and Matsumoto 2001). TOC contents are $<0.5\%$ in the southwestern and western parts of the bay (Fig. 3b); this demonstrates that the organic matter content is minor. Therefore, the influence of inorganic nitrogen is strong, and C/N ratios are extremely low in these parts of the bay. The KL compositions of cored sediments contain more than 90% terrestrial organic matter such as vitrinite, sporinite, and cutinite; this is true not only for Site 1 but also for Site 3 far from the river mouth. This result indicates that sediments in Mishou Bay contain mainly terrestrial organic matter. In conclusion, that organic matter in surface sediments is mainly derived from the river drainage area and is largely distributed around river mouths.

Temporal variation in grain size and its influence on TOC content

From the 1820s to the 1920s, grain size at Sites 2 and 3 decreased markedly (Fig. 4). It is unlikely that clastic sediments supplied from the river drainage areas became finer during this time, as the grain size profile for Site 1, near a river mouth, shows a coarsening trend over this time interval. The distribution map of grain size in

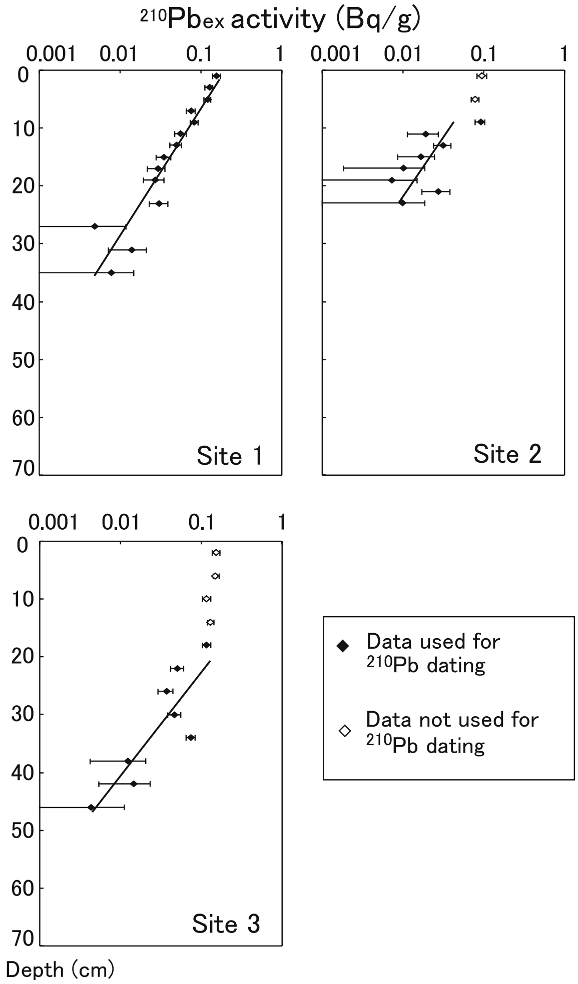


Fig. 6 Depth profiles of $^{210}\mathrm{Pb}_{\mathrm{ex}}$ activity in cored samples from Sites 1, 2, and 3

seafloor sediments shows that the flood tidal current affects the sedimentary environment in Mishou Bay. Decreases in grain size at Sites 2 and 3 suggest that the tidal current velocity in the bay decreased over time. Grain size at Site 1 gradually increased upward through the sedimentary core. Bathymetric data suggest that the area of 2–6 m water depth contains foresets of the Sozu River delta and that the area of 7 m depth at Site 1 is bottomset beds (Fig. 1). Therefore, the increase in grain size recorded at Site 1 indicates that the delta system at the mouth of the Sozu River is gradually prograding.

Increases in TOC and TN contents coincide with decreases in grain size at Sites 2 and 3. TOC content shows a positive correlation with mud (particle size $>4.0\varphi$) content in those horizons in which grain size decreases (Fig. 7). Most of the organic matter is sorbed onto clay surfaces; TOC content is determined by dilution, with sand grains containing little absorbed organic matter (Mayer 1994a, b; Volkman et al. 2000). TOC contents and C/N ratios in surface sediments show that organic matter deposited in sediments is mainly derived from the river drainage area. For the case that the amount of organic matter supplied from the drainage area remains constant over time, an increase in the proportion of muddy sediments leads to an increase in the deposition of organic matter; TOC content therefore increases. The cause of the recorded increase in TOC content at Sites 2 and 3 is therefore the reduced dilution effect of coarse sediments. While grain size at Site 1 gradually increases toward the top of the core, TOC content remains steady at around 2.0% (Fig. 4). If the flux of supplied organic matter remains constant, TOC contents should decrease with dilution by clastic sediments. Therefore, the TOC content profile for Site 1 suggests an increase in deposited organic matter.

Changes in sedimentary environment indicated by KL composition

Kerogen composition provides an indication of the sedimentary environment. Omura and Hoyanagi (2004) classified kerogen in sedimentary rock as either marine plankton, herbaceous-pollen, or woody-coaly and interpreted sedimentary environment accordingly. A shift in the sedimentary system from marine to estuarine and pro-delta is indicated by a decrease in kerogen of marine plankton and increase in woody-coaly kerogen.

At Site 1, the recorded increase in vitrinite coincided with a decrease in sporinite from the early to late 1800s (Fig. 5). At the same time, an increase in sporinite coincided with a decrease in alginite at Site 3. These results indicate that the sedimentary environment changed to river mouth conditions at Sites 1 and 3. The influence of the river therefore became stronger in the eastern and central parts of Mishou Bay during the nineteenth century. C/N ratios at Site 3 indicate that organic matter composition was constant over this period (Fig. 4). KL compositions at Site 3 contain more than 90% terrestrial organic matter. As a result, the decrease in marine plankton indicated by KL composition does not appear on the C/N ratio, as most of the organic matter in sediments is derived from terrestrial plants.

Profiles of TS contents and C/S ratio

The TS content of sediments indicates the quantity of pyrite formed by sulfate-reducing bacteria from organic matter, dissolved sulfate, and iron minerals under anoxic conditions (Berner 1983). The C/S ratio is a useful tool for determining the conditions of the paleodepositional seafloor environment, including discriminating between freshwater and marine environment and understanding

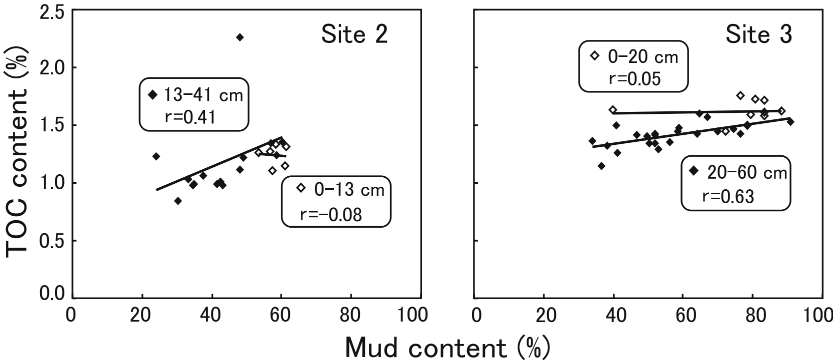


Fig. 7 Correlation of TOC content and mud content at Sites 2 and 3. The interval with a decrease in grain size shows a positive correlation with TOC content

redox conditions (e.g., Berner and Riswell 1983; Terashima et al. 1983; Glenn and Arthur 1985; Sohlenius et al. 1996; Sampei et al. 1997; Müller 2002). However, decreases in TOC content and increases in TS content over the top 20 cm of cores analyzed in the present study are due almost entirely to the progressive consumption of reactive organic compounds during diagenetic burial (Berner 1983). As a result, the C/S ratio increases over the upper 10 cm in all cores (Fig. 4).

Berner and Riswell (1983) noted that a C/S ratio of 2.8 indicates normal marine conditions, while lower values indicate euxinic marine conditions and higher values indicate freshwater conditions. At Site 1, TS content decreased from the 1820s to the 1880s, while TOC content is constant over this period. The C/S ratio increased from 1.4 during the 1820s to 2.4 during the 1880s. At Site 3, TS content and grain size decreased from the 1880s to the 1940s; TOC content increased because of muddy sediments that contain absorbed organic matter. This indicates that seafloor conditions at Site 1 changed from anoxic to oxic; however, grain size and TOC content show little variation, indicating that changes in the supply of organic matter and the hydrodynamic system that affect redox conditions did not occur from the1820s to the 1880s. The recorded decrease in grain size at Sites 2 and 3 proves that tidal current velocity decreased; it is then difficult to prove that seafloor conditions in the bay changed to oxic conditions. These results suggest that increases in the recorded C/S ratio at Sites 1 and 3, accompanied by decreases in TS content, reflect decreasing concentrations of dissolved sulfate in sea water; the effect of freshwater became stronger during the nineteenth century. TS contents at 10–20 cm depth at Site 3, i.e., since ca. 1950, record an increase over time. Increases in TOC content and grain size suggest that the supply of organic matter increased. Therefore, it is likely that human activity and urbanization in the drainage area since ca. 1950 caused an increase in the supply of organic matter and a related increase in pyrite formation within the sediments.

Impact of reclamation on the seafloor environment

As noted above, profiles of grain size, KL composition, C/S ratio, and TS content demonstrate that tidal current velocity decreased during the nineteenth century and that during this time the effect of river water on sediment patterns became stronger. Based on historical documents, the lower area of the Sozu River was reclaimed for developing a paddy field during the late 1700s and early 1800s. As a result, the sea area decreased by 14% (Fig. 2); however, ^{210}Pb dating at Sites 2 and 3 indicates reclamation at a later date due to the effects of bioturbation. Pendon et al. (1998) and Van der Wal et al. (2002) noted that infilling and shoreline progradation within bays and estuaries leads to a decrease in tidal prism and current velocity, which in turn leads to positive feedback and increased sedimentation. It is likely that the decrease in sea area in Mishou Bay related to reclamation resulted in a decrease in tidal prism and current velocity; as a result, grain size also decreased. Profiles of TS content and C/S ratio also show that the effect of the river current became stronger with time. This phenomenon led to reclamation-related progradation of the mouth of the Sozu River. The TOC content at Site 1 is constant despite the recorded increase in grain size. Given the dilution of TOC with increasing amounts of sand-sized sediment, TOC content should decrease. This means that it is possible to increase the supply of organic matter. In addition, the TOC content of seafloor sediments around river mouths is high. It is probable that the progressive change in sedimentary environment at Site 1 to that of a river mouth led to an increase in the deposition of organic matter. Increases in TOC content at Sites 2 and 3 resulted from dilution by sand-sized sediment; however, KL composition data show that terrestrial organic matter increased. This indicates that the deposition of organic matter might have increased not only at Site 1, near a river mouth, but also at Sites 2 and 3 in the middle of the bay.

Conclusions

The grain size of seafloor surface sediments shows that tidal current velocity decreases from the mouth of Mishou Bay to the bay interior; this is the primary influence on the distribution of seafloor sediments within the bay. High values of TOC content and C/N ratios around river mouths indicate that sediments in Mishou Bay contain mainly terrestrial organic matter, which is mostly distributed around river mouths. Grain size profiles indicate that tidal current velocity decreased during the nineteenth century. C/S ratios and KL composition indicate that the effect of river water and transport on sedimentation became stronger over this period. These changes are likely to relate to reclamation around the mouth of the Sozu River during the late 1700s and the 1800s. The reduction in sea area resulting from reclamation led to decreased tidal prism and current velocity; as a result, grain size also decreased. The effects of reclamation led to the increased influence of river water on sedimentation patterns, which in turn resulted in progradation of the delta system.

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