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Modern Sedimentary Environment of Jinhae Bay, SE Korea

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Jinhae Bay, one of the largest tidal bays on the southern coast of Korea, is an area with thick accumulations of recent, fine-grained sediments, mainly supplied from the Nakdong River. The preponderance of silt and clay particles reflects the large quantity of sediments transported in suspension. Although the clay mineral assemblage is similar to that derived from the nearby Nakdong River, relatively high concentration (3-9%) of smectite suggests some local input of fine particles from several streams around the bay or some contribution from the offshore water that may be influenced by the Tsushima Current. The content of organic matters in sediments is as high as 12%, and their C/N ratios imply that they are comprised of mixtures derived from marine plankton and terrestrial plants. ^{210}Pb excess activity profiles of sediment cores yield an average sedimentation rate (a 100-year time scale) of about 2-5 mm/yr, which coincides well with the long-term sedimentation rate (a 1000-year time scale) estimated from the sediment isopach map. On the basis of sediment bulk density and sedimentation rate, an annual sink of mud in the bay is estimated approximately 1.0×10^6 tons per year.

INTRODUCTION

As a result of the recent postglacial sea-level rise, coastal areas adjacent to Korean major river systems are presently receiving the riverine sediments discharged into the marine environment. Jinhae Bay, one of the largest coastal embayments on the southern coast of Korea, is an area with thick accumulations of recent sediments (Park *et al.*, 1995). The bay receives large amounts of suspended, fine-grained sediments mainly derived from the nearby Nakdong River, the largest fluvial system in the southeastern province of Korea (Kim *et al.*, 1986). This river annually discharges about 10 million tons of sediments, most of which are concentrated during the summer rainy season (Park and Chu, 1991). However, we do not know how much of these sediments accumulate in the near-coastal area and what percent of those are transported to the offshore. This information is very necessary to better understand the magnitude of accumulation and bypassing of riverine sediments in the coastal area.

Analyses of high-resolution (3.5 kHz) seismic profiles (Park *et al.*, 1995) reveal that Jinhae Bay is covered with recent sediments up to 25 m thick. They suggest that these sediments began to accumulate during the late Holocene time when sea level approached the present level. On the basis of the ^{14}C age determined from the core, the sediments have accumulated approximately at a rate of 417 cm/1000yr (Korea Navy Archaeology Research Group, 1991). This rate is about three times higher than that reported from the previous study of the nearby Gamagyang Bay on the southern coast of Korea (Kang and Chough, 1982). It is likely that the high sediment load from the Nakdong River produced thick accumulation of fine-grained sediments in Jinhae Bay. However, the mechanism of sediment transport has not been clearly explained, and only speculation is made in terms of hydrographic features of Jinhae Bay (Chang, 1994). The purpose of this paper is to understand the recent sedimentary environment of Jinhae Bay, by means of analyzing sediment texture, composition, and geotechnical properties. The sediment sink and budget are also estimated from the data of long-term accumulation

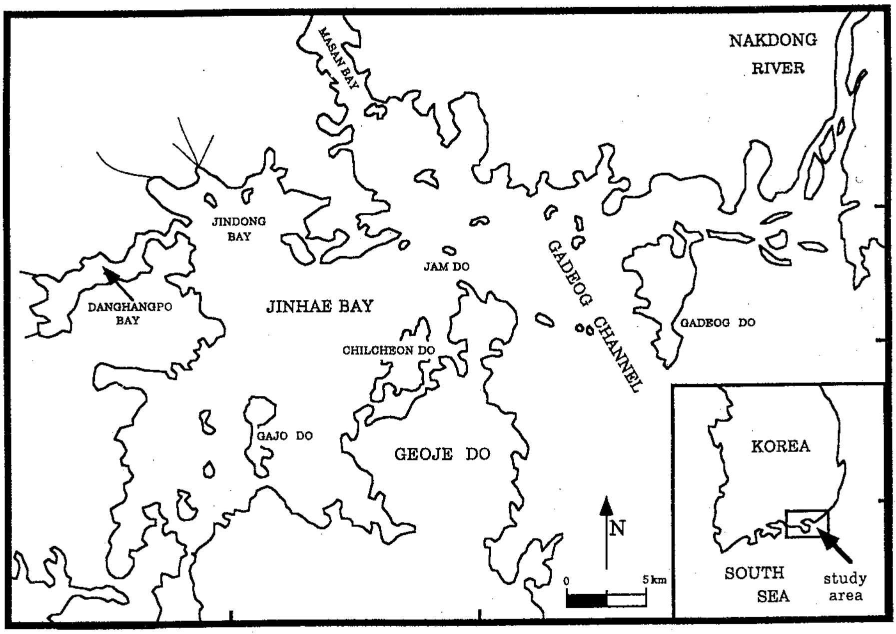

Fig. 1. The index map of the study area.

rates based on the thickness of late Holocene sediments as well as ^{210}Pb accumulation rates of sediment cores.

REGIONAL SETTINGS

The southern coast of the Korean Peninsula is characterized by many coastal embayments and islands, related to the postglacial transgression. Jinhae Bay, covering an area of about 400 km^2, includes several small bays such as Jindong Bay, Danghangpo Bay, and Masan Bay (Fig. 1). The bay is shallow (20-40 m), semi-enclosed and connected to the offshore mainly through the Gadeog Channel in the eastern part of the bay (Fig. 2). Because of the distinct nature of the semi-enclosed basin, the bottom waters of the inner part of the bay are not well communicated with those of the outer bay. Kim *et al.* (1989) show that tidal current in the inner part of the bay is very weak and somewhat isolated from the main axis of tidal current near the mouth of the bay. At the mouth of the bay (Gadeog Channel), tidal currents flow into the bay during flood and flow out during ebb (Korea Hydrographic Office, 1982; 1986; Korea Agency for Defence Development, 1988) (Fig. 3). The tide is semidiurnal, with a tidal range between 2.1 m during spring tide and 0.3 m during neap tide. The drainage system of Jinhae Bay is extremely limited except a few streams in the northwestern part of the bay. The discharge of fresh water from these streams is negligible. In contrast, the bay is influenced dominantly by the discharge of the Nakdong River; the drainage basin of which comprises an area of about 24,000 km^2 (Kim and Park, 1980).

MATERIALS AND METHODS

Thirty-one bottom sediment samples and 13 cores were collected from Jinhae Bay in 1989 and 1990, on board the Korean navy ship (Fig. 4). A Dietz-Lafond grab sampler and a piston corer were utilized for surface and core sediments, respectively. In the laboratory, the core liners were immediately opened and cut into two halves. One half of core was visually described and subsequently examined for the present study. X-radiographs were conducted on sediment slabs (5×25×1 cm) to examine the internal sed-

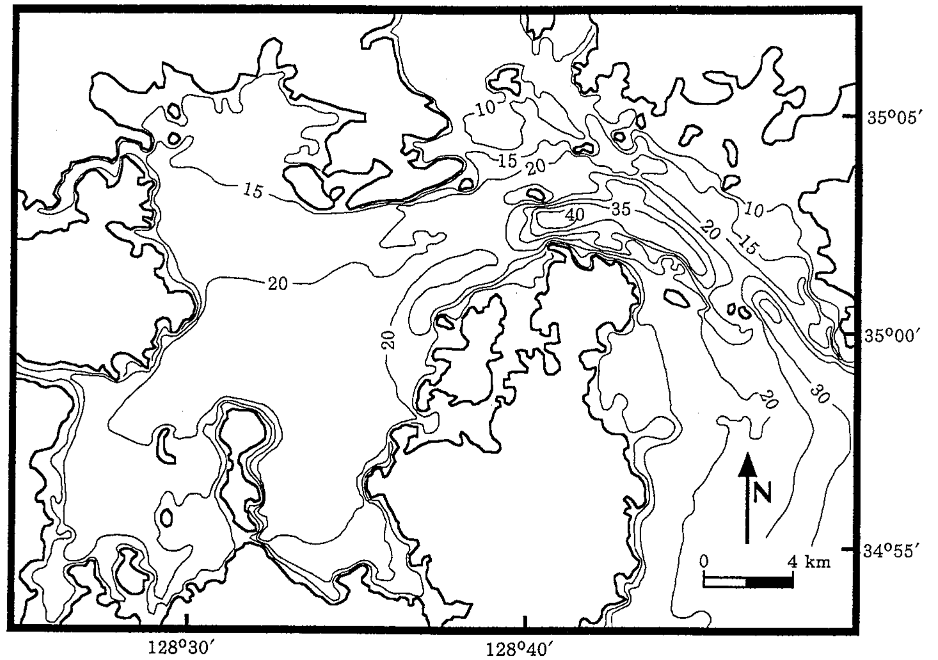

Fig. 2. Bathymetry of the study area (contour in meters) based on the maritime chart (Korea Hydrographic Office, 1986) and sounding data.

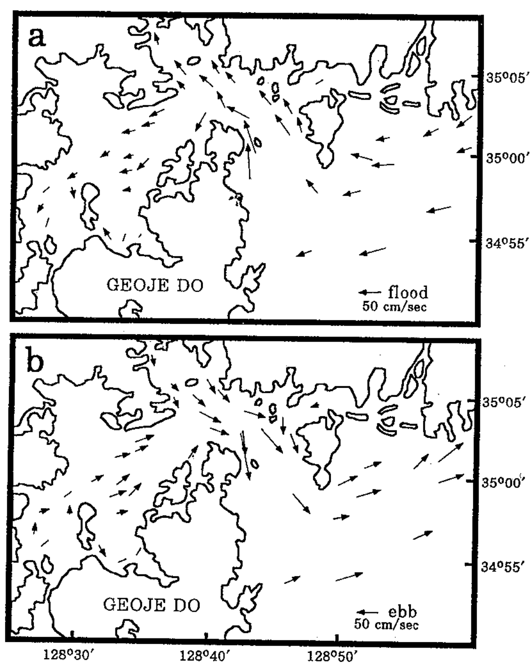

Fig. 3. Maximum velocity (cm/sec) and direction of flood (a) and ebb (b) tidal currents during spring tide (Korea Hydrographic Office, 1982).

imentary structures and lithology.

Grain size was analyzed using a Sedigraph 5000 ET (particle size analyzer) after wet sieving to remove the sand particles (>63 μm) which are usually less than a few percent. The sample was treated with 10 % H_2O_2 for organic matter removal and disaggregated before analysis by using sodium metaphosphate and by placing in an ultrasonic bath for 10 minutes. Sediment statistics were calculated using the method of moments (Griffith, 1967). Total organic matter was determined from subsamples by measuring the weight loss of samples heated to 550°C for 2 hours in a furnace, while the carbonate content was measured by the acid digestion method using 0.1N HCl. The C/N ratios in sediments were determined using a CNHS analyzer at the Korea Basic Science Institute.

Water content and bulk density were measured using the weight/volume method. Water content was determined by weighing of 20 cm^3 sediment sampled with a thin-wall calibrated cell, drying at 100°C for 24 hours in a ventilated oven, cooling in a desiccator and reweighing. Wet and dry bulk density are directly cal-

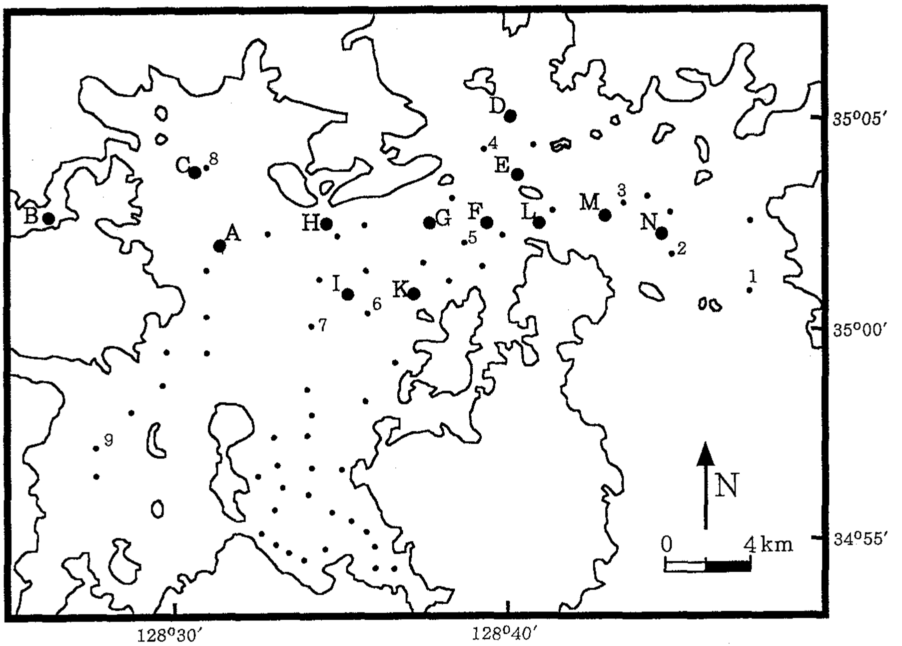

Fig. 4. Map showing the location of sediment cores (A to N) and surface sediments (small dots). Dots with numbers (1 to 9) represent the samples for clay mineral analysis

culated by the ratio of wet and dry weight to volume. Corrections have not been made for salt content.

Clay minerals were analyzed according to the standard technique suggested by Biscaye (1965). The sediments were initially treated with H_2O_2 to remove organic matter, and then disaggregated and dispersed in distilled water. The size fractions <2 μm were separated from the sediment suspensions by settling techniques and concentrated by centrifuging. The <2 μm fractions were smeared on glass slides and air-dried (Gibbs, 1965). Three smear slides were prepared for each sample; the first slide was untreated, the second slide was ethylene glycolated by vapour phase exposure for 24 h, and the third slide was heated at 550°C for one hour. The slides were run on a Rigaku X-ray diffractometer using nickel filtered CuKα radiation. For a semiquantitative estimation of different clay minerals, weighted percentages were calculated from the principal peak areas. The peaks and weighting factors used were: 17 Å glycolated peak area for smectite; 4 times the 10 Å glycolated peak area for illite; and 2 times the 7 Å glycolated peak area for kaolinite and chlorite divided in proportion to the relative areas of their 002 (3.58 Å) and 004 (3.54 Å) peaks, respectively (Biscaye, 1965).

^{210}Pb geochronologies were determined following the technique outlined in Nittrouer *et al.* (1979). One centimeter thick samples were obtained at numerous depths in a sediment core, and dried to determine porosity. About 5 to 10 g of dried samples were ground and spiked with a known amount of man-made ^{208}Po, for yield determination. The samples were leached and brought to dryness three times in the presence of concentrated HNO_3 and 6N HCl. After being brought up to volume with dilute HCl, the solution was separated from the residual solids by centrifuging. For each sample, the dissolved polonium isotopes were plated spontaneously onto a silver planchet. ^{210}Pb activity was determined by measuring the alpha activity of its granddaughter, ^{210}Po with a silicon surface barrier detector coupled to a multi-channel analyser.

RESULTS

Sediment texture and structure

The sediments in Jinhae Bay mainly consist of

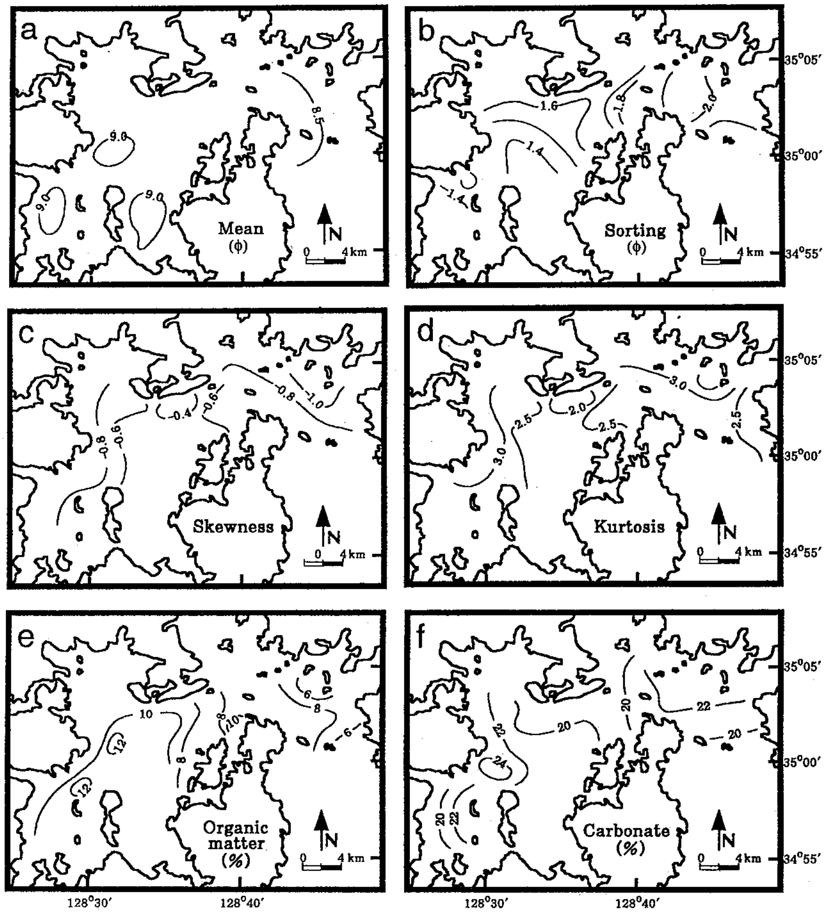

Fig. 5. Map showing the distribution of textural parameters, organic matter, and carbonate content in surface sediments.

silt and clay; the sand content is usually less than 10%. Average grain size variability in terms of mean diameter ranges from 8.5ϕ to 9.0ϕ (Fig. 5a). The sorting values of sediments range from 1.4ϕ to 2.1ϕ (Fig. 5b). The sediments in the inner part of the bay are relatively better sorted than the sediments near the Gadeog Channel. The skewness values range from -0.4 to -1.0 (Fig. 5c), while the kurtosis values are between 2.5 and 3.0 (Fig. 5d).

Figure 6 is the illustration and explanation of sediment cores based on the textural and structural characteristics identified in X-radiographs. The cores show a similar sediment type as the surface sediments, and do not show any vertical changes. The bioturbation, the disturbance of sediments as a result of the activity of benthic animals, is the most frequently observed structure in all cores. They occur generally as homogeneous layer or as mottled structures in which nests of broken shells are irregularly distributed. Some burrows with 0.5 cm to 1 cm in diameter were also observed. The cores often show the parallel laminated structures which are either well or faintly preserved. Thickness of individual laminae is in the range from 1 mm to 5 mm.

Organic matter and carbonate content

The organic matter content in surface sediments ranges from 6% to 12% in the bay (Fig. 5e). The amount of organic matter in Jinhae Bay is relatively high and shows an increasing trend toward the inner part of the bay. The carbonate content in the sed-

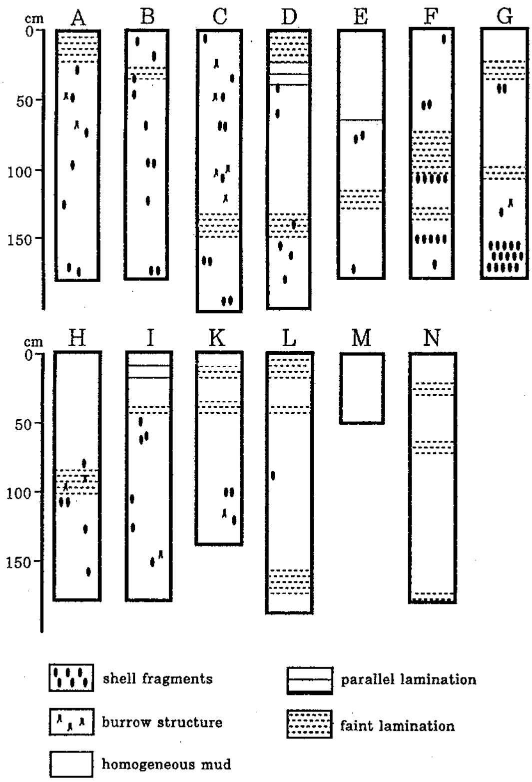

Fig. 6. Lithology and sedimentary structures of sediment cores.

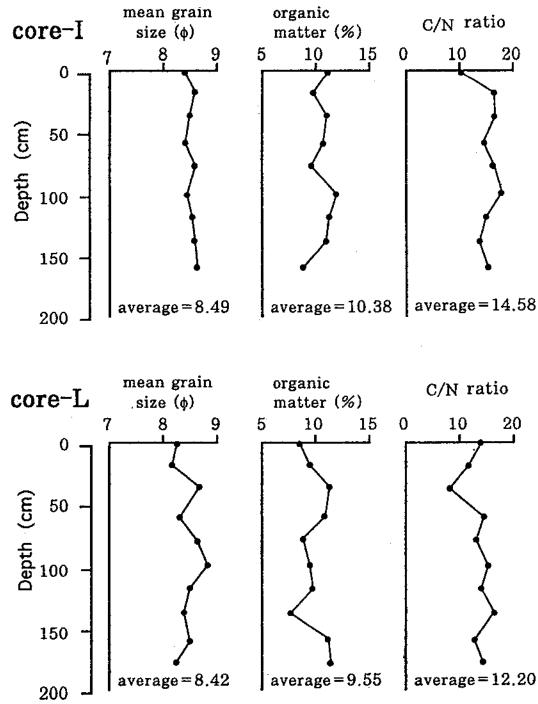

Fig. 7. Vertical distribution of mean grain size, organic matter, and C/N ratio in cores I and L.

iment samples is nearly uniform, showing a value between 20% and 24% (Fig. 5f). Most of the carbonate components consist of shell fragments of shallow marine bivalves. The sand fraction in the sediment samples is comprised mainly of the fragmented carbonate particles.

Figure 7 shows variations of mean grain size, organic matter content, and C/N ratios from two cores (I and L) selected. With burial depth, two cores attain uniform values in mean grain size. The organic matter content ranges from 8.05% to 11.40% in core I and from 7.35% to 10.75% in core L. The mean value is 10.38% and 9.55%, respectively. For C/N ratios, core I shows values between 10.16 and 17.15. The highest value occurs at a depth of 100 cm, while the uppermost part of core attains the lowest value. In core L, the C/N ratio ranges from 8.36 to 14.03. The highest value occurs at a depth of 140 cm, while the lowest value is observed at the depth of 40 cm. The mean value of C/N ratios in each core is 14.58 and 12.20, respectively.

Relative abundance of clay minerals

Clay minerals were determined on nine selected surface samples in Jinhae Bay (Fig. 4). Illite, kaolinite, chlorite, and smectite are the major clay minerals and their relative abundance are shown in Table 1. Illite is the most abundant mineral in the bay, varying from about 44% to about 64%. The average illite content in the bay is 57%, which is about 5-12% lower than the values reported from the Yellow Sea (Park and Khim, 1990). However, this value is very analogous to that reported from the Korea Strait (Park and Han, 1985). Kaolinite and chlorite are the second, and third abundant clay minerals in the bay, varying from about 17% to 27%, and from 11% to 23%, respectively. The average content is 20% for kaolinite and 18% for chlorite. Smectite is the fourth abundant mineral in Jinhae Bay; its concentration ranges from 3% to 9%, with

Table 1. Relative abundance of clay minerals in <2 μm fraction of the surface sediment

Sample No.	illite (%)	kaolinite (%)	chlorite (%)	smectite (%)
1	58.23	17.83	18.72	5.22
2	52.56	19.65	22.68	5.11
3	61.54	17.31	17.31	3.84
4	60.34	20.29	16.10	3.27
5	54.91	22.20	15.66	7.23
6	52.54	19.24	18.90	9.32
7	60.04	18.23	19.45	2.28
8	44.12	27.16	23.43	5.29
9	64.38	19.01	11.47	5.14
average	56.52	20.10	18.19	5.19

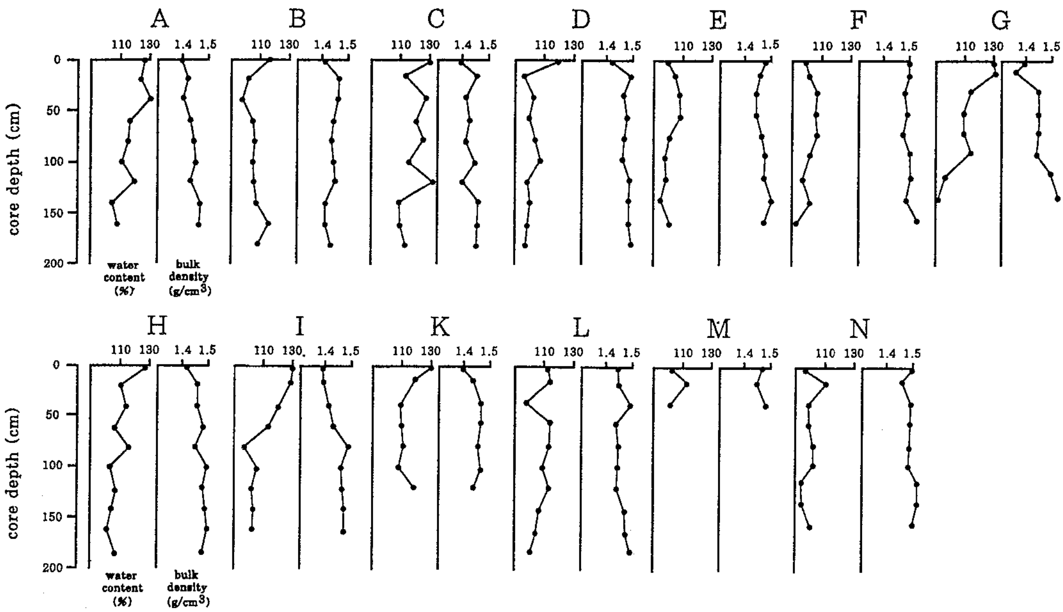

Fig. 8. Vertical distribution of water content (WC) and wet bulk density (BD) in cores.

an average content of 5%.

Geotechnical properties of sediments

Figure 8 describes the vertical distribution of water content (WC) and wet bulk density (BD) in the cores. The water content fluctuates between 80% and 140%, and the wet bulk density between 1.3 g/cm^3 and 1.6 g/cm^3. Their vertical distribution patterns demonstrate intimate relationships each other: downcore decrease in water content generally causes wet bulk density to increase. The upper 70-130 cm sections of cores A, C, G, H, I, and K, collected from the central part of the bay, attain relatively high values (110-130%) in water content, whereas other cores retrieved from the outer part of the bay show low (less than 100%) values.

Average values of water content, void ratio, porosity, and wet and dry bulk density in the upper 100 cm sections of each core are summarized in Table 2. Water content and wet and dry bulk density are the measured values, while void ratio and porosity were calculated from the measured water content and grain specific gravity, assuming that sediments are 100% water-saturated, as suggested by Lee *et al.*, (1987). The low water content in core B,

Table 2. Average values of geotechnical properties in the core sediments

Core No.	water content (%)	void ratio (%)	porosity (%)	wet bulk density (g/cm^3)	dry bulk density (g/cm^3)
A	116.67	3.16	75.87	1.44	0.65
B	85.77	2.32	69.78	1.54	0.82
C	117.19	3.16	75.53	1.44	0.66
D	101.20	2.73	73.13	1.48	0.73
E	101.22	2.73	73.18	1.48	0.72
F	98.97	2.67	72.74	1.49	0.74
G	113.05	3.05	75.01	1.45	0.67
H	107.43	2.90	74.29	1.46	0.69
I	110.40	2.98	74.73	1.46	0.68
K	113.89	3.07	75.40	1.44	0.66
L	106.84	2.88	74.20	1.46	0.70
M	105.05	2.84	73.91	1.47	0.70
N	98.64	2.66	72.67	1.49	0.74
average	105.87	2.86	73.88	1.47	0.71

retrieved from the innermost part of the bay, causes void ratio and porosity to be the minimal value, whereas wet bulk density reaches the maximal value. Over the study area, water content in sediments is between 86% and 114%, void ratio between 2.3 and 3.2, and porosity between 69% and 75%. These values are very similar to those of the nearshore muddy cores with abundant organic matter in the South Sea of Korea (Chough *et al.*, 1991).

Sedimentation rates

Accumulation rates of the sediments were estimated on the basis of ^{210}Pb profiles in cores. Generally, profiles of ^{210}Pb activity in nearshore sediment are affected by sediment accumulation, sediment mixing, and radioactive decay (Nittrouer *et al.*, 1979; DeMaster *et al.*, 1985). Assuming that sediment mixing is restricted to the surface mixing layer of constant ^{210}Pb activity (i.e., mixing is zero below surface mixed layer), sedimentation rate can be calculated from the following simplified equation:

$$S = \lambda z / (\ln A_o / A_z)$$

in which

S = sedimentation rate (cm/yr)

λ = decay constant of ^{210}Pb (0.031/yr)

z = sediment depth

A_o = unsupported ^{210}Pb activity at the sediment surface (dpm/g)

A_z = unsupported ^{210}Pb activity at depth z below the sediment surface (dpm/g)

The ^{210}Pb excess activity in sediments generally decreases logarithmically with depth and least square fits for logarithmic decrease give sedimentation rates. However, if some sediment mixing occurs below the surface mixed layer, the calculated sedimentation rate is the apparent rate greater than the actual rate.

Figure 9 shows ^{210}Pb excess-activity profiles obtained from selected five cores of Jinhae Bay. The upper part of the cores A, D, I, and L show well laminated structures, and disturbance of sediments due to bioturbation is expected to be minimal. The surface mixed layer was not observed in these cores. The sedimentation rates calculated from these profiles are 0.25 cm/yr, 0.35 cm/yr, 0.48 cm/yr, and 0. 20 cm/yr, respectively, and these rates are estimated to be analogous to the actual rates (Lee, 1992). However, the sedimentation rate (0.78 cm/yr) of core G is supposed to be greater than the actual rate, as the upper part of this core experienced extensive bioturbation and consequently, sediment mixing may have affected the slope of ^{210}Pb excess-activity profile. The sedimentation rates calculated from the ^{210}Pb excess profiles are plotted on the isopach map of recent sediments which is previously described by Park *et al.* (1995) (Fig. 10).

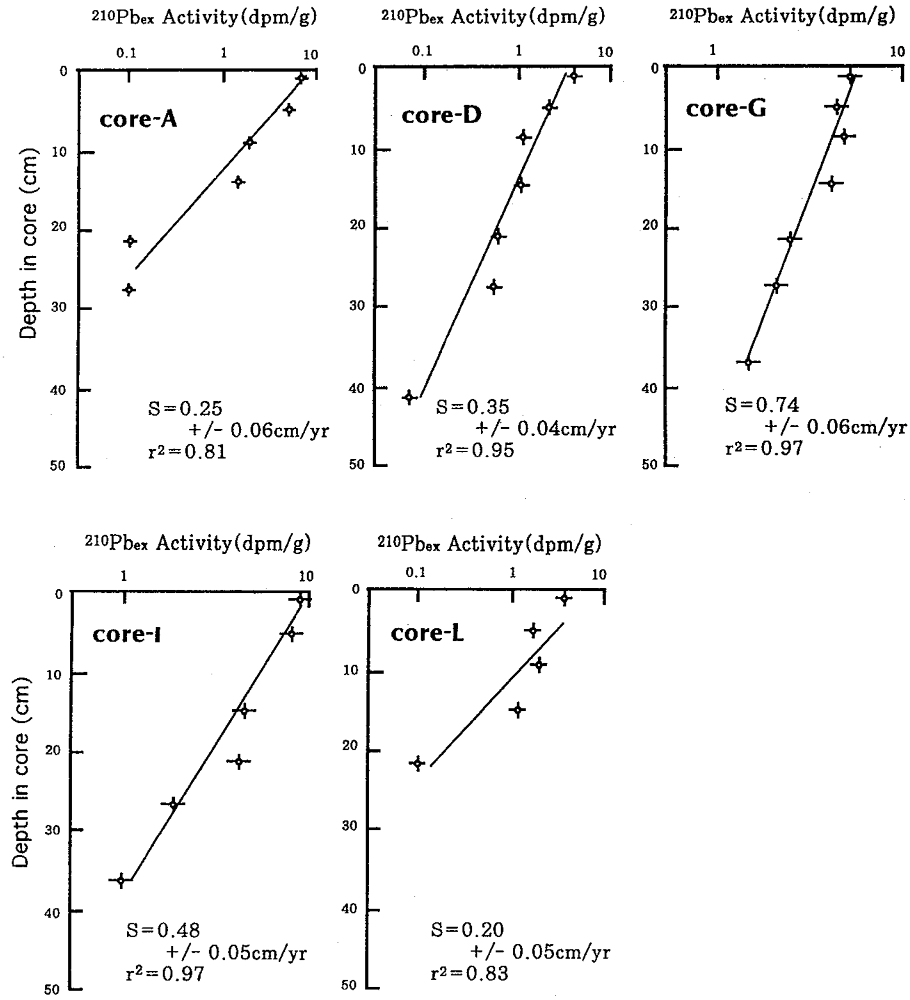

Fig. 9. Profiles of excess ^{210}Pb activity and calculated sedimentation rates (S) in the selected cores (r^2: goodness-of-fitness).

DISCUSSION

Origin of fine-grained sediments and their budget in the bay

Relative abundance of major clay minerals (illite, kaolinite, and chlorite) in the sediments derived from the Korean rivers show significant regional differences depending on their origin (Park and Khim, 1990). This difference provides a key to determine the provenance and dispersal pattern of fine-grained particles (Park and Han, 1985; Park and Khim, 1990; 1992). The transport direction of fine-grained sediments supplied from the Han, Keum and Yongsan Rivers on the western coast of Korea appears to be southward influenced by the wind-driven residual current, resulting in dominant mud accumulation in region of the southeastern Yellow Sea (Wells, 1988; Park and Khim, 1990). In contrast, the sediments derived from the Seomjin and Nakdong Rivers on the southern coast of Korea accumulate in the nearshore, thus forming a mud belt along the southern coast (Park, 1985; Park et al., 1990; 1996). Average concentration of illite, kaolinite, chlorite, and smectite in the sediments derived from the Nakdong River is 58.6%, 22.5%, 18.8%, and 0.1%, respectively (Park and Khim, 1990). The smectite concentration derived from the Korean riv-

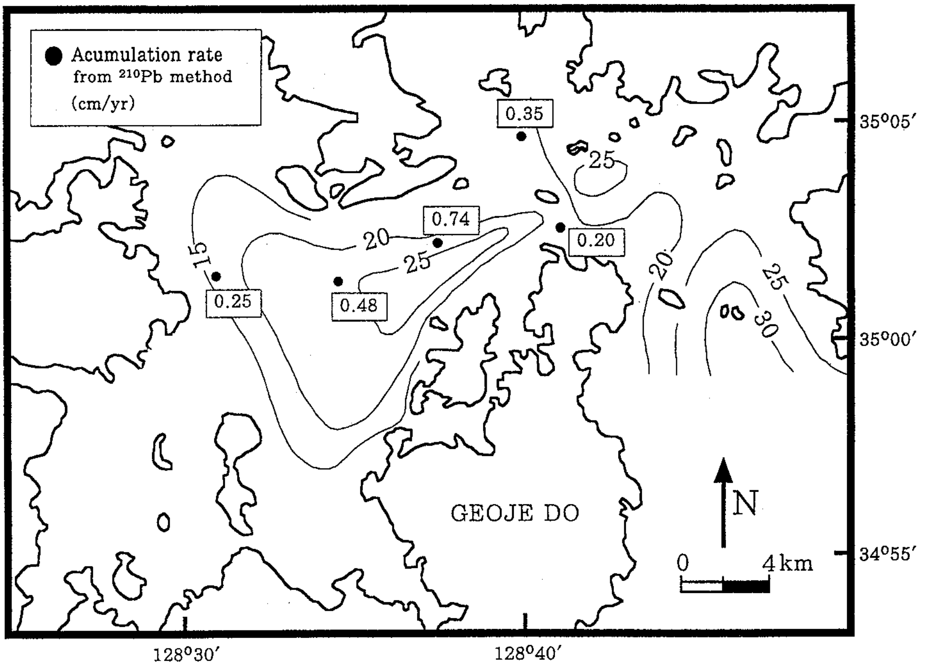

Fig. 10. ^{210}Pb sedimentation rates of cores superimposed on the isopach map of recent sediments (Park *et al.*, 1995) (contour in meters).

ers is equally extremely low (less than 1%) regardless of the source area (Park and Khim, 1990). The clay mineral data (Table 1) of Jinhae Bay are very similar to those of fine-grained sediments derived from the nearby Nakdong River, although the smectite concentration is significantly higher. This high concentration of smectite suggests some local input of clay particles from several streams around Jinhae Bay or some contribution from the Korea Strait shelf, as suggested by Park *et al.* (1976). Park and Han (1985) described that the bottom sediments of the Korea Strait contain 4% smectite on the average, and suggested that the distribution of clay minerals in the Korea Strait is influenced by the supply of fine-grained sediments by the warm Tsushima Current from the East China Sea. Park *et al.* (1976) suggested that clay fractions in Jinhae Bay sediments are mixed with sediments transported landwards from the East China Sea. Chang (1994) also reported that the offshore water with high salinity and temperature often reaches Jinhae Bay during the dry season and discussed a possibility of some contribution of fine particles from the offshore water.

The Jinhae Bay sediments contain relatively high amounts of organic matters, and their possible biochemical degradation forms gas bubbles in the sediments which may scatter and attenuate the acoustic energy (Park and Yoo, 1988; Park *et al.*, 1990). Kim *et al.* (1990) reported that the gas content in the sediments increases with the decreasing sediment grain size. The presence of gas-charged layers in the Jinhae Bay sediments is evidenced by various forms of acoustic patterns such as acoustic turbidity and gas chimneys on the high-resolution seismic profiles (Park *et al.*, 1995). Generally, C/N ratios are useful for determination of the origin of organic matters. Nakai *et al.* (1982) suggested that the C/N ratio of sedimentary organic matters is about 6 in the case of marine zoo- and phytoplankton, whereas it is more than 20 for terrestrial plants. The mean C/N ratios observed in our cores from Jinhae Bay are 14.28 and 12.20 respectively, indicating that organic matters in sediment consist of mixtures derived from marine plankton and terrestrial plants. These C/N ratios are somewhat higher than the data reported by Kim *et al.* (1993) in the surface sediments of Jinhae Bay. They suggest that the bay recently supports high primary productivity year round, which may be responsible for the low C/N ratio in surface sediments.

The mud deposit in Jinhae Bay ranges from 10 m to 25 m in thickness, covering an area of approximately 400 km^2 (Lee, 1992). The lower boundary of recent mud deposit is estimated about 5000 yrs B.P. and their long-term (a 1000-year scale) accumulation rate is reported to be about 0.2 - 0.5 cm/yr on the basis of the sediment isopach map (Park *et al.*, 1995). This rate coincides well with the short-term (a 100-year time scale) accumulation rates determined from ^{210}Pb profiles in this study (Fig. 10). Then, the total sink of mud in the bay, on the basis of the sedimentation rates and average dry bulk density of sediments (0.71 g/cm^3; Table 2), is estimated about 1.0×10^6 tons per year. According to Park and Chu (1991) and Jang (1990), the total discharge of suspended sediments from the Nakdong River is about 4.6×10^6 tons per year which is about the half of the total sediment discharge by the Nakdong River. They reported that about 0.64×10^6 tons of mud per year, which is about 14% of the annual discharge of suspended sediments by the Nakdong River, accumulate near the river mouth, and the remaining 84% are transported to other parts of the sea floor. Kim *et al.* (1986) suggested that these sediments are mainly transported along the coast as a result of the combined influence of coastal and tidal currents. We suspect that Jinhae Bay is one of the major sink areas of these fine-grained sediments. A further research is needed to understand the distribution pattern and accumulation rates of these river-derived, fine-grained sediments.

CONCLUSIONS

Sediments in Jinhae Bay consist mainly of silt and clay particles, with a progressive decrease of grain size and better sorting toward the inner part of the bay. Relative abundance of clay minerals in sediments is similar to that derived from the nearby Nakdong River, although smectite concentration is relatively high. This high concentration implies some local input of clay particles or some contribution from the offshore water that may be influenced by the Tsushima Current. Sediments contain high amounts (up to 12%) of total organic matters.The C/N ratios indicate that the organic matters are comprised of mixtures derived from marine plankton and terrestrial plants. ^{210}Pb excess profiles of the cores yield sedimentation rates (a 100-year time scale) of about 0.2 - 0.5 cm/yr, which coincide well with the long-term (a 1000-year scale) rate estimated from the sediment isopach map. An annual accumulation of mud in the bay is estimated about 1.0×10^6 tons.

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