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Acoustic characters and distribution pattern of modern fine-grained deposits in a tide-dominated coastal bay: Jinhae Bay, Southeast Korea

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Abstract Jinhae Bay, a semi-enclosed, tide-dominated coastal embayment on the southeastern coast of Korea, receives large amounts of sediment derived from the Nakdong River. The irregular surface of the acoustic basement is overlain by a modern sedimentary sequence up to 25 m thick, characterized by an acoustically semitransparent subbottom. Sediments, consisting mainly of terrigenous and bioturbated mud, accumulate at a rate of 2–5 mm/yr. About 21% of the suspended sediments discharged from the Nakdong River, that is approximately 1.0×10^6 tons per year, accumulate in Jinhae Bay. Modern sedimentation began probably at about 5000 yr BP, when sea level approached its present level.

Introduction

The southern coast of the Korean Peninsula is characterized by many coastal embayments and islands, related to the postglacial transgression (Fig. 1). This area is generally considered as a depositional environment dominated by tidal sedimentation. Many studies have been carried out to understand the modern depositional environments. The results indicate that the coastal embayments, as well as the inner shelf off the southern coast of Korea, contain thick accumulations of modern fine-grained sediments (Jang et al. 1980; Park et al. 1984, 1990; Park and Yoo 1988). Although some parts of these sediments are inferred to be transported from the East China Sea and Yellow Sea (Wells 1988; Lee and Chough 1989), most fine-grained sediments on the southern coast of Korea are considered to be mainly derived from the adjacent rivers, including the Seomjin and Nakdong rivers (Park and Yoo 1988; Part et al. 1990; Park and Chu 1991).

Jinhae Bay is one of the largest coastal embayments in the southern coast of the Korean Peninsula (Fig. 2). The bay receives large amounts of fine-grained sediments from the Nakdong River, the largest fluvial system in the southeastern province of Korea. According to Park and Chu (1991), this river contributes annually about 4.6 million tons of suspended sediments. A large portion of these sediments accumulates on the adjacent coastal area, while some part is further transported to other parts of the sea floor along the southeastern coast (Park and Chu 1991). The tidal and coastal currents play a major role in the sediment transport and dispersal.

The purpose of this study is to describe the distribution pattern and acoustic characters of modern sediments in Jinhae Bay, by means of analyzing high-resolution seismic profiles (3.5 kHz) and sediment samples. The sediment accumulation rate and sediment sink are also estimated from the isopach map of modern sediments. The 3.5-kHz subbottom profiles were collected during the cruises in September 1989 and May 1990, utilizing an O.R.E. Pinger system (2–7 kHz transducer) (Fig. 3). A precision depth recorder (Raytheon model DE-719C) was also employed for detailed bathymetry and bottom features. Along with the seismic survey, 12 gravity cores were also collected (Fig. 3). Positioning was maintained with a combination of GPS and radar navigation systems.

Regional settings

Jinhae Bay is a semienclosed, coastal embayment surrounded by land and islands (Fig. 2). The bay is connected to the offshore through the Gadeog Channel in the eastern part of the bay, through which tidal currents flow into the bay during flood and flow out during ebb, with a maximum velocity of up to 135 cm/s (Korea Hydrographic Office

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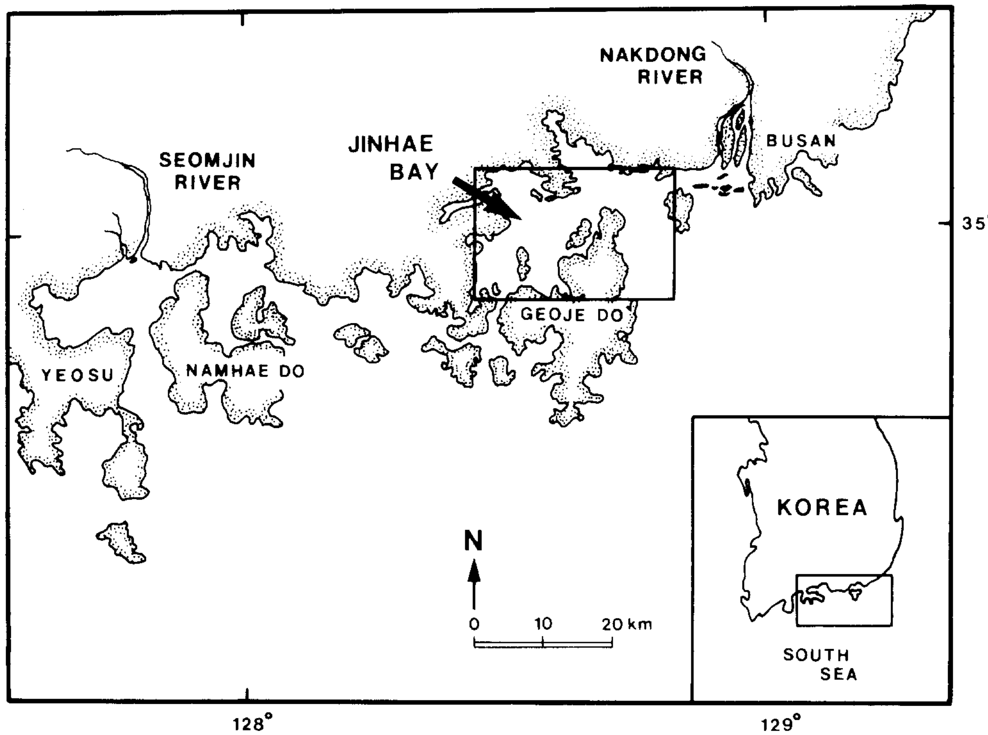


Fig. 1 Index map showing the study area (box) in the southeastern coast of Korea

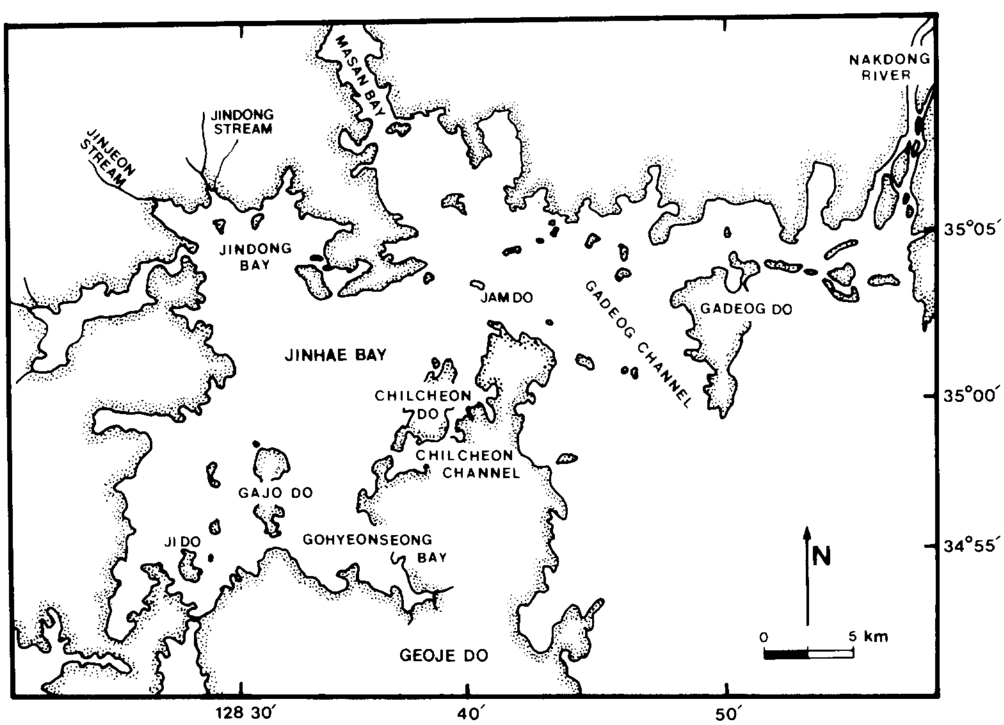


Fig. 2 Detailed geographic map of Jinhae Bay

1982). The tide is semidiurnal, with a tidal range between 0.3 m during neap tide and 2.1 m during spring tide. The tidal current velocity decreases considerably from the Gadeog Channel toward the inner (western) part of the bay. Jinhae Bay, including several small bays such as Jindong Bay, Gohyeonsung Bay, and Masan Bay, is about 400 km^2 in area. The drainage systems around the bay are extremely limited except a few streams in the northwestern part of the bay (Fig. 2). The discharge of feshwater from these streams is negligible. In contrast, the bay is influenced dominantly by the discharge of the Nakdong River. This river annually discharges about 63 billion tons of freshwater, about 70% of which occur during rainy season from June to August (Park and Chu 1991). The concentration

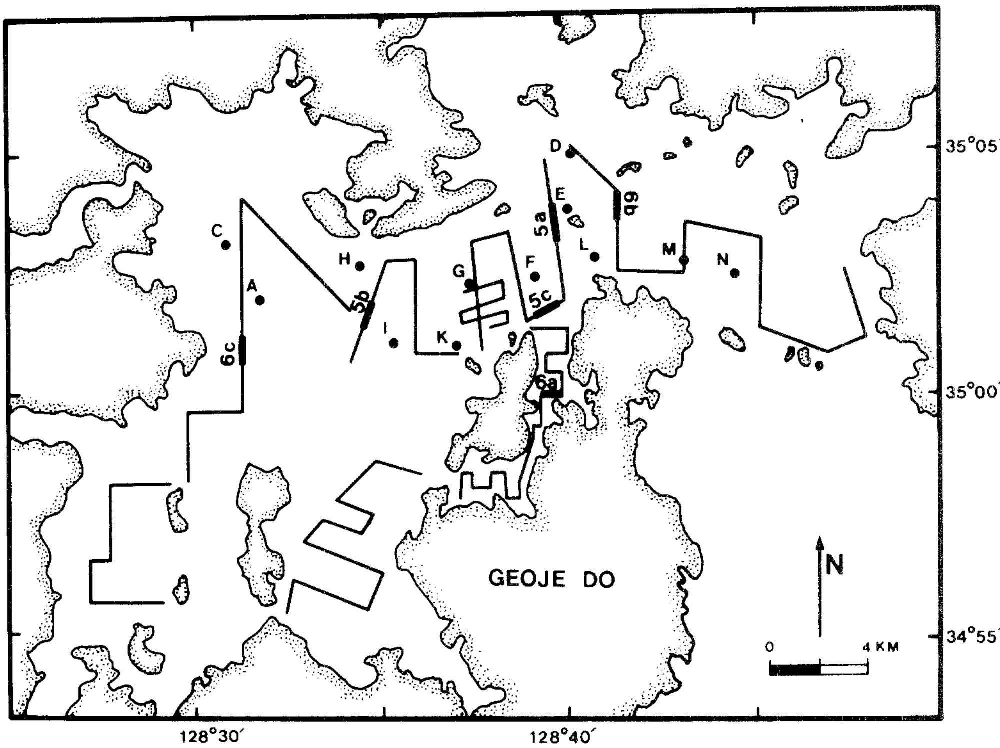


Fig. 3 Map showing the tracklines of the high-resolution (3.5-kHz) seismic survey (solid lines) and location of stations (dots) of sediment cores (A–N). Heavy lines with numbers (5a to 6c) indicate seismic profiles shown in Figs. 5 and 6

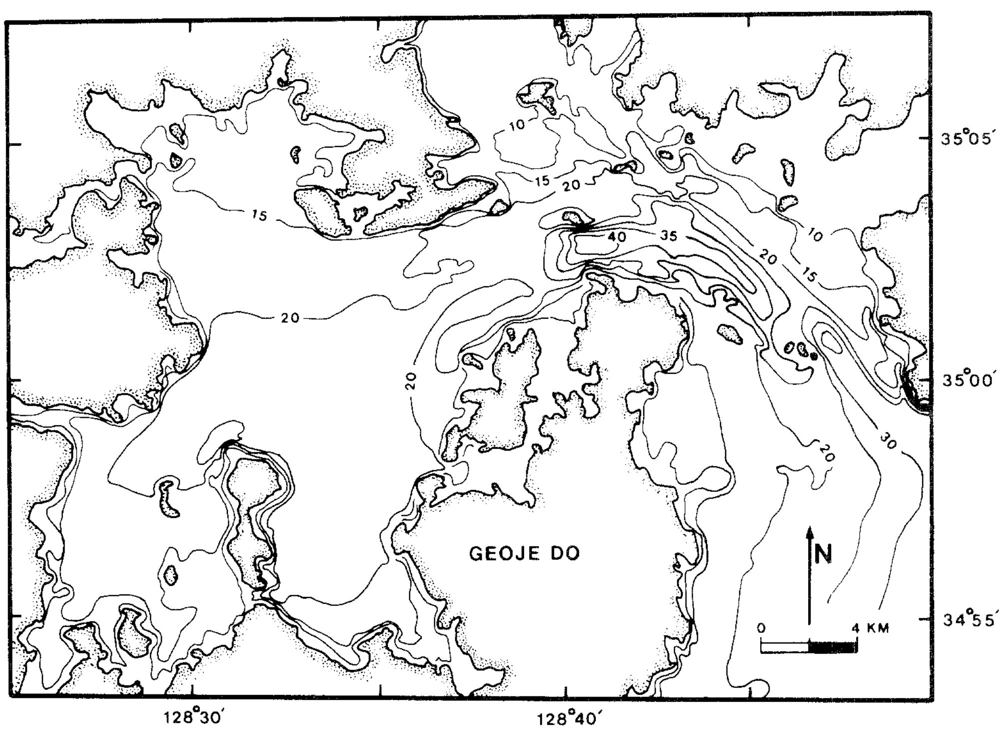


Fig. 4 Detailed bathymetric chart (contour in meters) compiled from sounding data and maritime chart of Korea Hydrographic Office (1986)

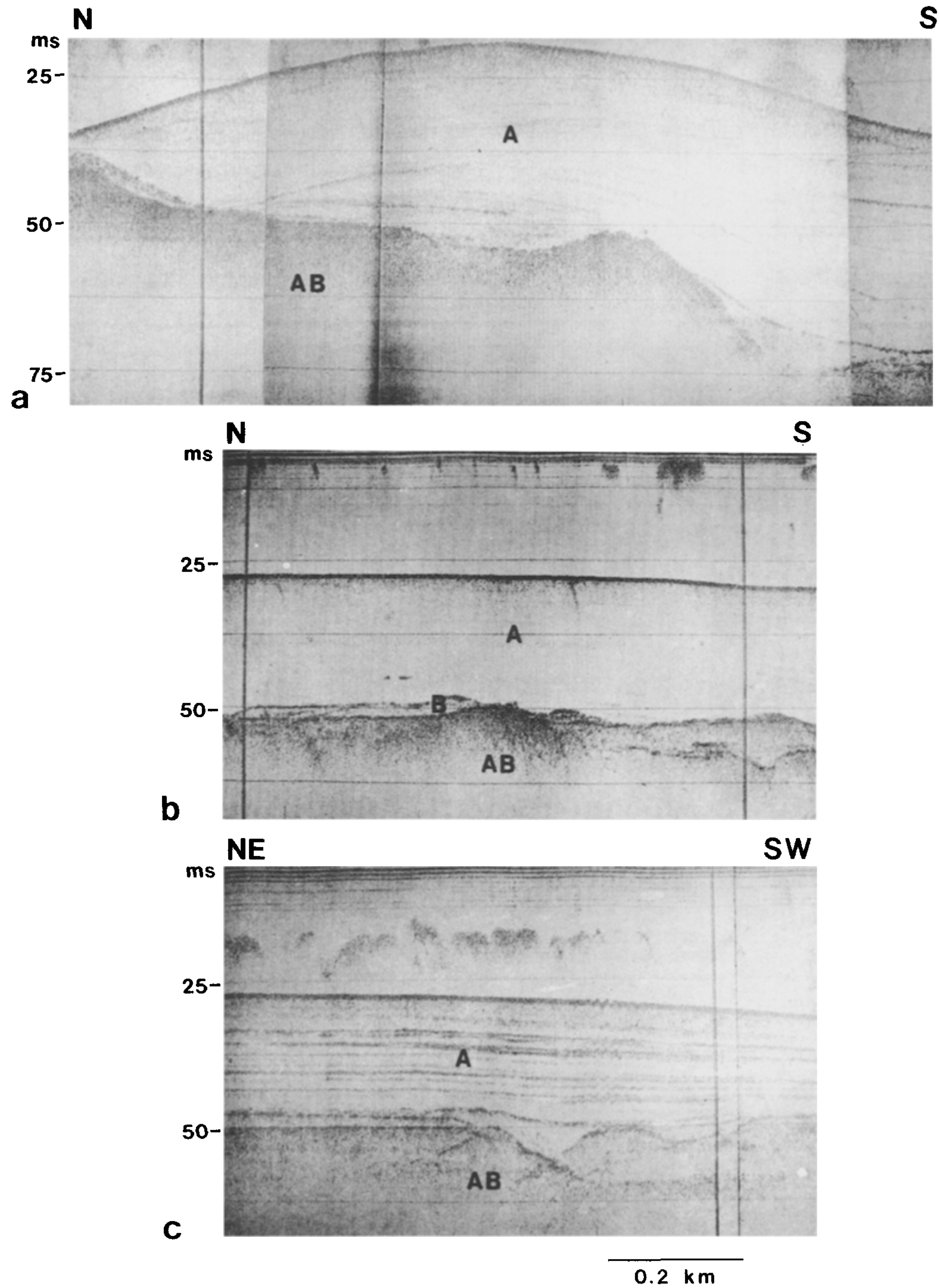
of total suspended matter near the river mouth is about 150 mg/l during rainy season, whereas it decreases to 30 mg/l during dry season (Kim et al. 1986).

Sounding data from different times of flood and ebb tide were corrected in terms of mean sea level by reference to the Jinhae Tide Station. Prior to this study, bathymetry was also available from the Maritime Chart (Korea Hydrographic Office 1986). The compiled bathymetric map (Fig. 4) shows the water depth ranging from 10 to 40 m. The sea floor in the western part of the bay is generally monotonous and flat, with a depth of 15–20 m. However, the water depth increases toward the Gadeog Channel, where the topography shows deep tidal channels. The channel in the south of Jam Do Island is as deep as 40 m and elongated in the east–west direction of flood and ebb currents.

Acoustic characters of sediments

High-resolution seismic records reveal thick accumulation of sediments above the acoustic basement in the bay. The sedimentary sequence (A) above the acoustic basement (AB) is acoustically characterized by a semitransparent subbottom usually with no reflectors (Fig. 5a, b). This type of reflection pattern indicates one predominant lithologic type. The seismic profile (Fig. 5a) on the west of Jam Do Island shows the topographic high with thick accumulation of sediments, which appears to be largely influenced by tidal currents. Some seismic records near the Gadeog Channel and south of Jam Do Island show weakly stratified internal reflectors (Fig. 5c). The inernal layering is concordant with the surface, showing parallel to subparallel reflection patterns. These reflectors are postulated to be interbeds of relatively coarse-grained materials (fine sand or coarse silt) in the subsurface. The closely spaced

Fig. 5 High-resolution seismic profiles (for location, see Fig. 3) showing modern sedimentary deposits (A), which are acoustically semitransparent or weakly stratified. AB is acoustic basement and B represents an older sedimentary layer. Vertical scale is two-way travel time (milliseconds) and 10 ms corresponds to approximately 8 m of sediment



sediment layers in the sedimentary sequence may be represented by an individual reflector, possibly due to a constructive interference pattern of reflections.

In the southern part of Jinhae Bay, especially in the area around the Chilcheon Do Island, a relatively strong mid-reflector (M) appears within the sedimentary sequence at the depth of about 4–6 m below the sea floor (Fig. 6a). This reflector is laterally continuous and can be traced over a wide area of the southern part of the bay. The concordant and flat-lying pattern of this reflector indicates a depositional origin, related to regional sedimentary changes in this area. It is a first subbottom reflector of regional extent and could be an indication of an important change in clime. However, direct correlation of sedimentological and acoustical properties was not possible because of short core length.

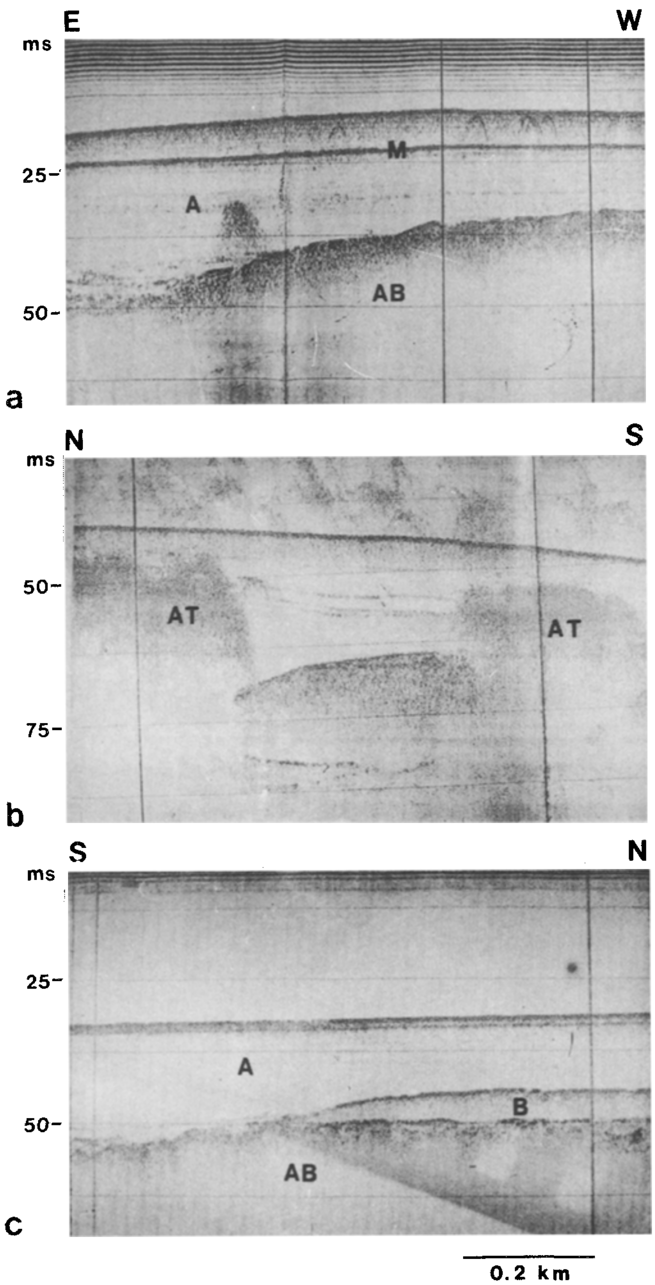


Fig. 6 High-resolution seismic profiles (for location, see Fig. 3) showing modern sedimentary deposits (A) above the acoustic basement (AB). M is a mid-reflector, which appears locally in the southern part of Jinhae Bay at the depth of about 4–6 m below the sea floor. AT is an acoustic turbidity in shallow sediments. For explanation of vertical scale, see Fig. 5

The other characteristic feature within the sedimentary sequence below the sea floor is acoustically turbid (AT) layers in shallow sediments, which sometimes mask the underlying sedimentary layers (Fig. 6b). It occurs in isolated areas or is sometimes present over a distance of several hundred meters. It is thought to be entrapped gas bubbles produced by biochemical degradation of organic matter in the sediments, which scatters and attenuates the acoustic energy. According to Judd and Hovland (1992), the presence of gas in shallow marine sediments is evidenced by various forms of acoustic patterns such as acoustic turbidity, acoustic blanking, gas chimneys, and enhanced reflections on the seismic profiles. Acoustic turbidity is the most frequent feature in Jinhae Bay, although some gas chimneys have been identified as vertical features in which the normal sequence is destroyed. Lee (1992) indicates that the organic matter content in sediments of Jinhae Bay reaches up to 12%. This organic rich sediment probably provided favorable conditions for forming the gas-charged layer. The same type of acoustic turbidity has been previously observed in shallow marine sediments around the Korean Peninsula (Kang and Chough 1982; Park and Yoo 1988; Park et al. 1991).

Acoustic basement and sediment thickness

The acoustic basement (AB) is generally characterized by a relatively large acoustic impedance contrast beneath the sedimentary sequence (Figs. 5 and 6). It shows the irregular surface, which can be traced onto the adjacent land and island. The uneven surface is probably the result of differential erosion. In some places, th acoustic basement is not easily identified on the seismic profiles, because of the limit of acoustic penetration into thick sedimentary layers. Generally, the transparent sedimentary sequence (A) directly overlies the irregular surface of the acoustic basement. However, seismic records from the central and western part of the bay reveal a thin layer (B) of an older sedimentary deposit covering the acoustic basement (Figs. 5b and 6c). This layer is clearly separated from the overlying semi-transparent sedimentary sequence (A) by strong reflection patterns, indicating a different lithologic type. Various erosional depressions can be also identified on top of this layer as well as on the acoustic basement.

The acoustic basement generally occurs at the depth between 30 m and 50 m below mean sea level in the bay (Fig. 7). The basement depth deepens progressively toward the Gadeog Channel, where it reaches up to 65 m. The acoustic basement is regarded as the extension of onshore sequences such as andesite, biotite granite, sandstone, and

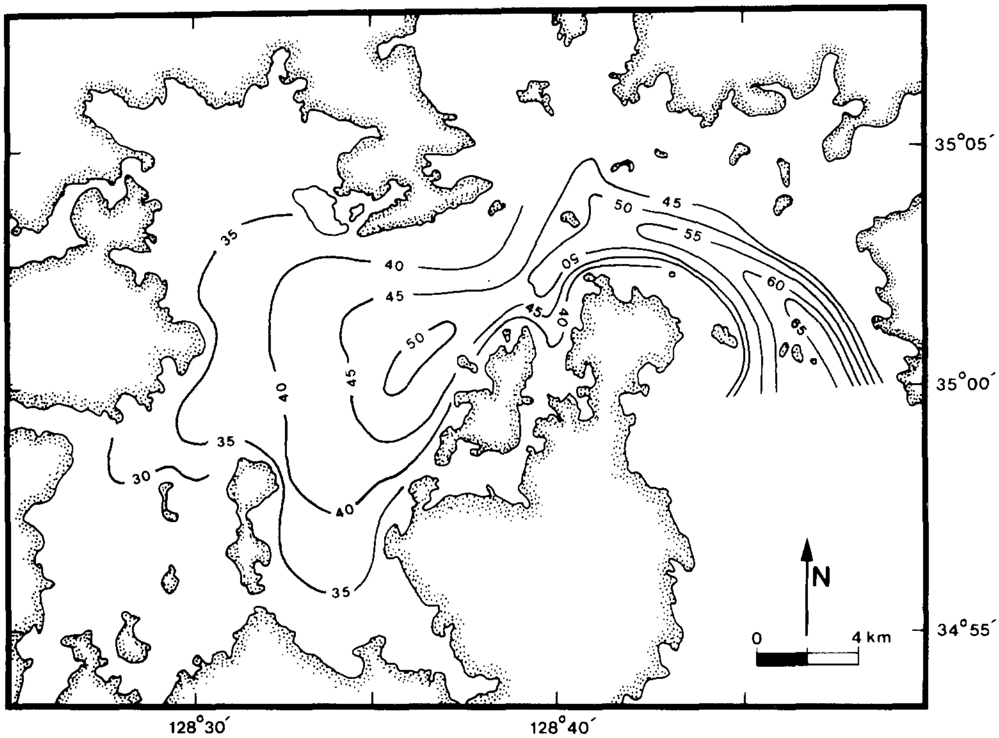


Fig. 7 Depth in meters of the acoustic basement below the mean sea level

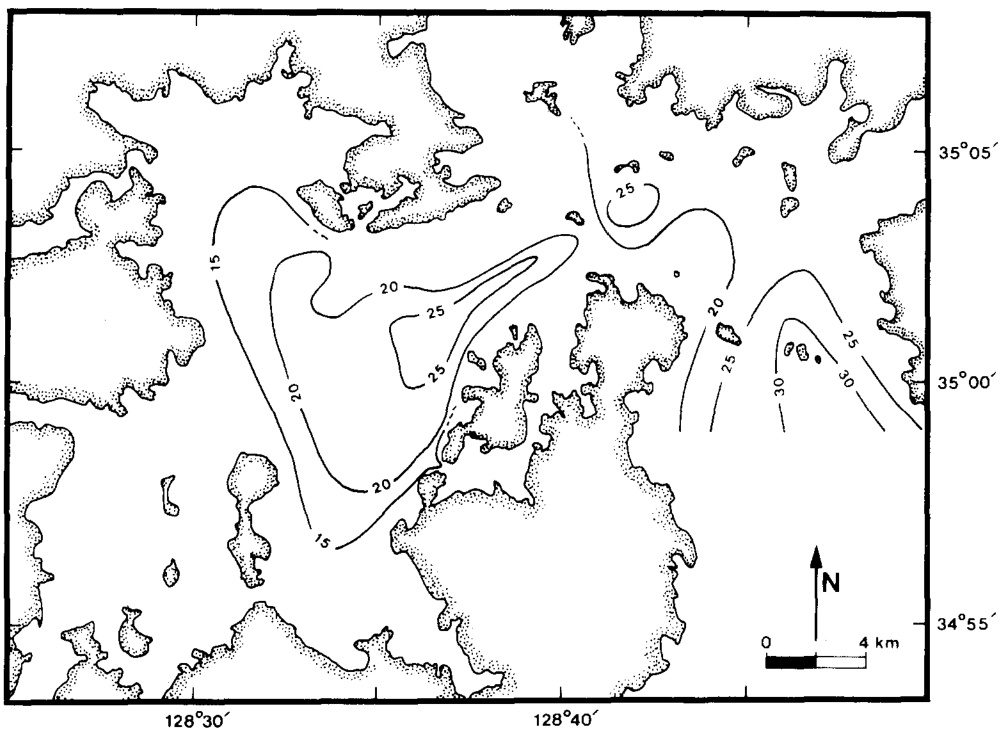


Fig. 8 The thickness of modern sedimentary deposits (A) above the acoustic basement (contour in meters)

shale (Chang 1966). The thickness of the sediment above the acoustic basement ranges from 10 to 25 m in the bay (Fig. 8). Thick accumulation occurs in the central part of the bay and near the Gadeog Channel. The thickness of sediments becomes thinner toward the western part of the bay.

Sediment textures

Analysis of surface sediments shows that mud is the dominant sediment type in the bay. Table 1 shows the textural characteristics of the topmost (0–10 cm) sediment of the

Table 1 Texture, composition and sediment type of surficial sediments in Jinhae Bay (station locations are shown in Fig. 3)

Station	Sand (%)	Silt (%)	Clay (%)	Mean (ϕ)	Sorting (ϕ)	Sediment Type
A	0.19	47.90	51.90	8.96	1.42	Mud
C	1.61	52.20	46.30	8.61	1.72	Mud
D	1.30	47.40	51.30	8.84	1.66	Mud
E	1.09	45.50	53.40	8.93	1.57	Mud
F	2.04	49.00	49.00	8.62	1.87	Mud
G	0.47	47.80	51.80	8.83	1.65	Mud
H	0.33	51.80	47.80	8.75	1.56	Mud
I	0.30	48.80	50.80	8.92	1.49	Mud
K	0.30	48.90	50.90	8.82	1.63	Mud
L	1.63	43.30	55.90	8.95	1.66	Mud
M	2.93	46.60	50.50	8.64	1.92	Mud
N	6.00	47.90	46.10	8.39	2.07	Mud

cores. The core length ranges from 1.5 to 3 m. Most of the sediment samples contain less than 10% sand. Average grain size variability in terms of mean diameter ranges from 8ϕ to 9ϕ. The sorting values of the sediments range from 1.4ϕ to 2.1ϕ. The sediments in the central part of the bay are relatively better sorted than the sediments near the Gadeog Channel. Lee (1992) indicates that the cores do not show any significant vertical facies changes. On the basis of lithology and sedimentary structures examined by X-radiographs, most cores are mottled or homogeneous due to extensive bioturbation, although some core sections are faintly laminated. Large burrows and shell fragments are scattered throughout the cores.

Modern sedimentation in the bay

On the basis of high-resolution seismic profiles, the thickness of modern deposits (A) below the sea floor is in the range from 10 to 25 m. The acoustically semitransparent aspect of this sequence, as well as sediment samples, suggest that the sediments consist of relatively homogeneous mud. On the basis of the ^{14}C age, determined from the shell and wood fragments (Korea Navy Archaeology Research Group 1991) in a core retrieved from the southern part of Jinhae Bay, the sediments have accumulated approximately at a rate of 417 cm/1000 yr (1440 $\pm$ 70 yr BP at the depth of 6 m below the sea floor). Extrapolated at constant rate, it yields an age of about 4800 yr for the lower boundary of the mud deposit, which is found at approximately 20 m beneath the sea floor. This accumulation rate is about three times higher than that reported from the nearby Gamagyang Bay in the southern coast of Korea. It is possible that the high sediment load from the Nakdong River produced thick accumulation of fine-grained sediments in Jinhae Bay. Sea level data on the Korean continental shelf indicate that sea level approached its present level at approximately 5000 yr BP, prior to which sea level rose very rapidly (Bloom and Park 1985). These data suggest that modern sedimentation in Jinhae Bay began about 5000 yr BP when sea level rose enough to cover the bay with a considerable depth, placing the bay below the depositional base level. A shallow, flat-lying mid-reflector (M) within the sedimentary sequence in the southern part of Jinhae Bay is postulated to result from the large-scale impedance variations in the sediments, not from the individual layer. According to the study of geotechnical properties in this area (Korea Agency for Defence Development 1988), shear stress as well as bulk density abruptly increase at the depth of 4–5 m below the sea floor. The high consolidation of sediments at this horizon locally may provide a favorable condition for the strong reflectivity of acoustic energy, thus forming a mid-reflector. As we did not recover any cores that reach this horizon, further research is needed to clarify the origin of this reflector.

An older sedimentary layer (B) below the thick mud deposits, which is locally found in the central part of Jinhae Bay, probably represents the subaerial deposits formed prior to the onset of recent marine transgression. The strong reflectivity of this layer indicates a different lithologic type from the overlying modern deposit (A). Hahn and Kim (1977) reported a sand and gravel layer formed during the late glacial low sea level at the depth of 16.5 m below the sea floor in a core retrieved in the northwestern part of Jinhae Bay (Jindong Bay, see Fig. 2). The thin sedimentary layer in the central part of the bay is inferred to be the same kind of material, probably originated from the subaerial erosion. The erosional depressions on the top of this layer as well as on the acoustic basement support this supposition.

The acoustic and textural characteristics of the mud deposit in Jinhae Bay indicate that the sedimentary process in the bay is dominated by suspension transport of fine-grained sediments. It is clear that the influx of suspended sediments has occurred through the Gadeog Channel and the main source of suspended sediments in this area is the Nakdong River. This river discharges about 4.5 $\times$ 10^6 tons of suspended sediments per year, of which about 70% occurs during summer (Park and Chu 1991). Kim et al. (1986) observed two turbid plumes on the satellite image in the coastal area, which are discharged from the Nakdong River during summer flood. One plume flows toward the Jinhae Bay (westward), mainly influenced by flood tidal currents, whereas the other is transported northeastward along the coast as a result of the combined influence of coastal and ebb tidal currents. As the tidal currents enter the bay, the current velocity progressively decreases and suspended particles are deposited.

If 5000 yr BP is taken as the lower boundary of the modern sedimentary sequence (A), an average long-term accumulation rate estimated from the sediment isopach map is 2–5 mm/yr. This rate coincides well with the ^{210}Pb accumulation rates determined from the sediment cores in this area (Lee 1992). The mud deposit in Jinhae Bay occupies approximately 400 km^2 in area. The average dry bulk density determined from the cores is 0.71 g/cm^3 (Lee 1992). These data indicate that the accumulation rate for the mud in Jinhae Bay is about 1.0×10^6 tons per year, which is about 21% of the annual discharge of suspended sediments by the Nakdong River.

Conclusions

A modern sedimentary sequence up to 25 m thick overlies the acoustic basement in Jinhae Bay. This sequence usually shows an acoustically semitransparent aspect without subbottom reflectors, indicating one lithologic type. Sometimes, the acoustic turbidity due to entrapped gas in shallow sediments disturbs the reflections, masking the underlying sedimentary layers. A thin, older sedimentary layer below the modern sedimentary sequence is postulated to be the subaerial deposits formed prior to the onset of recent marine transgression.

Sediments in the bay are comprised of fine-grained materials with a mean size between 8ϕ and 9ϕ. Some parallel, indistinct reflectors near the Gadeog Channel indicate the interbeds of relatively coarse-grained materials (coarse silt and fine sand). Modern sedimentation began approximately 5000 yr BP, when sea level approached its present level. The average long-term accumulation rate of modern sediments is estimated to be about 2–5 mm/yr on the basis of the isopach map. About 21% of the annual discharge of the Nakdong River-derived suspended sediments, that is about 1.0×10^6 tons per year, accumulates in the bay.

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