Journal of the Korean Society of Oceanography
Vol. 39, No. 1, pp. 96 — 106 March 2004

The Records of Origin and Transport of Sediments From the Past to the Present in the Yellow Sea

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A total of 116 surface sediment samples were obtained on the Yellow Sea and analyzed for grain size and geochemical elements in order to interpret the present sediment transportation. Thirty-nine cores and 3,070 line-km shallow seismic profiles are analyzed for sedimentary records of Yellow Sea in the past. Results show that the boundary of sediment transport between Korean side and Chinese side is about between 123°E and 124°E. The similar result is produced from Shi *et al.* (in this publication). Two cyclonic patterns of surface sediments are recognized in the northeastern and southwestern Yellow Sea, while the strong front zone of the mud patch and sandy sediments are found in the southeastern Yellow Sea (the southwestern part of Korean coasts). The formation of fine-particle sediment packages, called for Northwest Mudbelt Deposit (NWMD), Hucksan Mudbelt Deposit (HSMD) and Jeju Mudbelt Deposit (JJMD), are resulted from eddies (gyres) of water circulations in the Yellow Sea. NWMD has been formed by cyclonic (anticlockwise) eddy. NWMD is composed of thick, homogeneous, relatively semi-consolidated gray clay-dominated deposit. On the other hand, HSMD and JJMD are formed by anticyclonic (clockwise) eddies. They are thick, homogeneous, organic-rich gray, silt-dominated deposit. Both core and surface sediments show that the middle zone across Chinese and Korean side contains bimodal frequency of grain-size distribution, indicating that two different transport mechanisms exist. These mud packages are surrounded by sand deposits from both Korea and China seas, indicating that Yellow Sea, which is the shallow sea and epicontinental shelf, is formed mostly by sand deposits including relict sands. The seismic profiles show such as small erosional/non-depositional channels, sand-ridges and sand-waves, Pleistocene-channel-filled deposits, a series of channels in the N-S major channel system, and thick Holocene sediment package, indicating that more complex sedimentary history exists in the Yellow Sea.

Key words: Yellow Sea, Cyclonic Patterns, Mudbelt Deposit, Sand-Ridges

INTRODUCTION

The Yellow Sea is the epicontinental shelf, which is faced by Korea and China. Its water depth is about 55 m in average and more than 100 m in the maximum (Fig. 1). The Yellow Sea provides various textural and geochemical characteristics of sediments and has a different sources and dispersal patterns (Zhao *et al.*, 1995; Oh and Lee, 1998; Cho *et al.*, 1999). The Yellow Sea depositional systems are complex because of their numerous and variable controlling factors, such as sources and sediment grain size, tidal and wave energy and direction. Furthermore, the sediment front, including forming a tyical mudbelt deposits and rearrangement of relict sands, is poorly understood in the Yellow Sea sediments.

The distribution of surface sediments in the Yellow Sea has been studied by many researchers (Shepard *et al.*, 1949; Niino and Emery, 1961; Lee and Chough, 1989; Milliman *et al.*, 1989; Yang *et al.*, 1995; Saito and Yang, 1995). Most of the Yellow Sea sediments play an important role in sedimentary processes such as transportation, deposition, and erosion by the action of tidal cuurent, wave, and energetic events (storms and typhoons). The grain composition of these sediments is determined by the composition of both the meteorological and oceanic components. Folk's grain classification were mainly focused on

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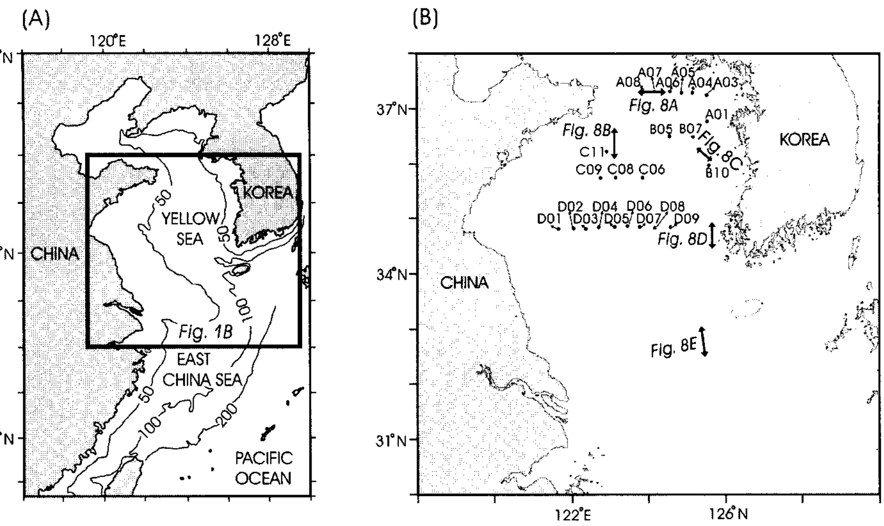

Fig. 1. Map of the study area (A) on the Yellow Sea showing station and track lines, (B) for acquisition of sedimentological and geophysical data.

grain-size classification of rocks and fluvial deposits, not modern unconsolidated marine sediments. Marine sediments contain fine particles such as fine sand, silt and clay. Therefore, the importance of silt and clay's role in the marine environments is very crucial for transportation, deposition, erosion and resuspension. Recently, the new grain classification for the epicontinental sea sediments has been studied (Yi, 2000). This work contributes to knowledge of the sediment transportation of the Yellow Sea.

The objectives of this study are to interpret the depositional environments, to understand the nature of depositional processes, and to delineate sediment fairways in the Yellow Sea. We also emphasize the present sediment patterns and the past record of sedimentary sequences from cores and chirp seismic profiles in the Yellow Sea and East China Sea.

MATERIALS AND METHODS

Total 116 surface sediments and major and minor elements are analyzed (Fig. 2). Also, 32 core sediments in the northern Yellow Sea during the survey of 1998 and 39 core sediments in the middle and southern Yellow Sea, which are collected in 1999, are studied. This study is the result from "Korea-China Joint Study of Sedimentary Dynamics and Paleoenvironments in the Yellow Sea" cooperated since 1998 until the present by KORDI (Korea Ocean Research and Development Institute) of MOMAF (Ministry of Marine affairs and Fisheries) and FIO (First Institute of Oceanography) of SOA (State of Ocean Administration).

All sediment samples are selected only on the surface part including less than 1 cm deep from the grab sampler. Analysis of sediment grain size was done by a sieving method for the sediments larger than 63 μm, and by a pipette method for the sediments smaller than 63 μm. Coarse sediments greater than sand size (>63 μm) sieved in 0.5Φ interval by the rotap shaker, while fine sediments (silt and clay size) are analyzed by the sedigraph 5100D machine. These results of surface sediment distribution can be scrutinized and compared with those from the previous studies. For the geochemical elements, the powdered surface sediment samples were digested with solution and then leached with dilute HNO_3 solution. The solutions were analyzed for major and minor elements using ICP-AES (Royal Hollyway, University London).

KORDI conducted a geophysical data such as Chirp sonar system and Sparker to interpret seismic sequences in the Yellow Sea (Fig. 1B). KORDI had also collected Side Scan Sonar survey in the sand wave/sand ridges complex area offshore Korea and delta area offshore China.

RESULTS AND DISCUSSION

Characteristics of Surface Sediments

Folks grain-size classification (Fig. 2A), mud is composed of silt and clay together, while sand and gravel are separated respectively. Sands are named in which the percentage of sand amounts (2 mm; 64 μm) is over 90 wt.% of total sediments. Muddy sands range from 50-90 wt.% of sands and rest of them are muds (silt and clay). Conversely, sandy muds range from 50-90 wt.% of muds (silts and clays) and the rest of them are sands. Muds are defined

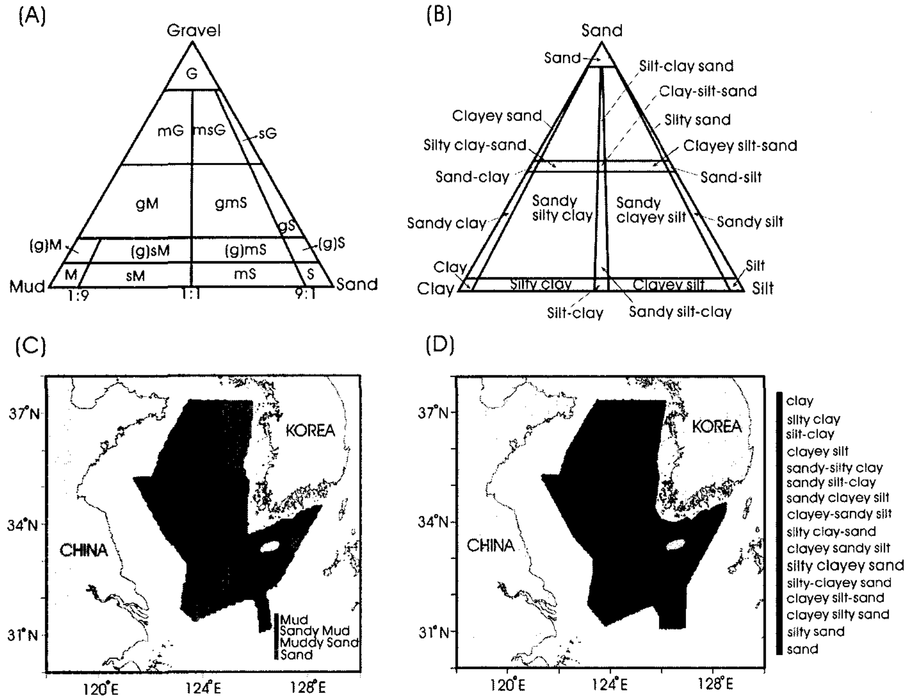

Fig. 2. Classification of sediment types and distribution of surface sediments. (A) Folk's classification, (B) Yi's classification, (C) patchy distribution on the basis of sediment type by Folk's classification, (D) patchy distribution on the basis of sediment type by Yi's classification.

as more than 90 wt.% of muds. In this case, muds are composed of silts and clays.

Fourteen divisions of sediment types are identified in this study area based on the modification of Folk's method (1968) (Fig. 2A). The fourteen sediment types are as follows: 1) clay, 2) silty clay, 3) silt-clay, 4) clayey silt, 5) sandy-silty clay, 6) clayey-sandy, 7) clayey-sandy silt, 8) silty clayey-sand, 9) clayey-sandy silt, 10) silty clayey sand, 11) silty-clayey sand, 12) clayey silt-sand, 13) clayey silty sand, and 14) sand (Fig. 2B). The four divisions of sediment types, which are typically used in the rocks and fluvial deposits, are too simplified to the detailed changes of grain sizes. Yis grain-size classification (Yi, 2000) is composed of fourteen clässifications of sediment type. The detailed division of grain particles presents more clearly the pattern and source direction of sediments. Here, the classification of clay ranges 90-100 wt.% of clay/total sediment sample. The same ranges are applied to those of sand and silt, i.e., 90-100 wt.% of sand/total sediment sample and 90-100 wt.% of silt/total sediment sample, respectively. The advantage of this classification shows the specific direction of sediment transportation (Fig. 2D). Of course, the simple classification can be used a general picture of sediment distribution. The mud deposits in Fig. 2C are almost corresponded to the five groups of clay, silty clay, silt-clay, clayey silt, and silt in Fig. 2D.

The mud sediments are broadly distributed in the northwestern and middlewestern part of Yellow Sea (Fig. 3). These muds are called "Central Yellow Sea Mud (CYSM)" by previous studies (Park and Khim, 1992). However, the position of mud package is more or less located in the northwestern part of the Yellow Sea. The origin of this mud formation is still debatable. The other mud deposit is recognized offshore of the southwestern Korean coasts called Hucksan Mudbelt Deposit (HSMD; Chough *et al.*, 2002). The Hucksan is named by the Hucksan Island within HSMD. The origin of sediment source of HSMD is also debated by many previous workers. Another mud deposit in the south of Jeju Island is also recognized. This mud deposit is named as Jeju Mudbelt Deposit (JJMD) in this paper first time. At least these three mud deposits in the Yellow Sea have their own characteristics of formation history.

Shi *et al.* (2000) suggested that these mud deposits are formed by cyclonic and anticyclonic eddy dynamics. NWMD has been formed by cyclonic eddy of cold seawater. They are formed by weaker sediment dynamics and strong reducing conditions and are composed of finer sediments with mean size of 8.5 Φ and high pyrite content and low sedimentation rate. On the other hand, both HSMD and JJMD are formed by anti-cyclonic eddy of warmer water compared to cyclonic cold eddy mentioned above. These deposits are formed by stronger dynamics and coarser sediment with low pyrite content and higher sedimentation rate, and greater thickness and a smaller dimension than NWMD formed by cyclonic cold eddy

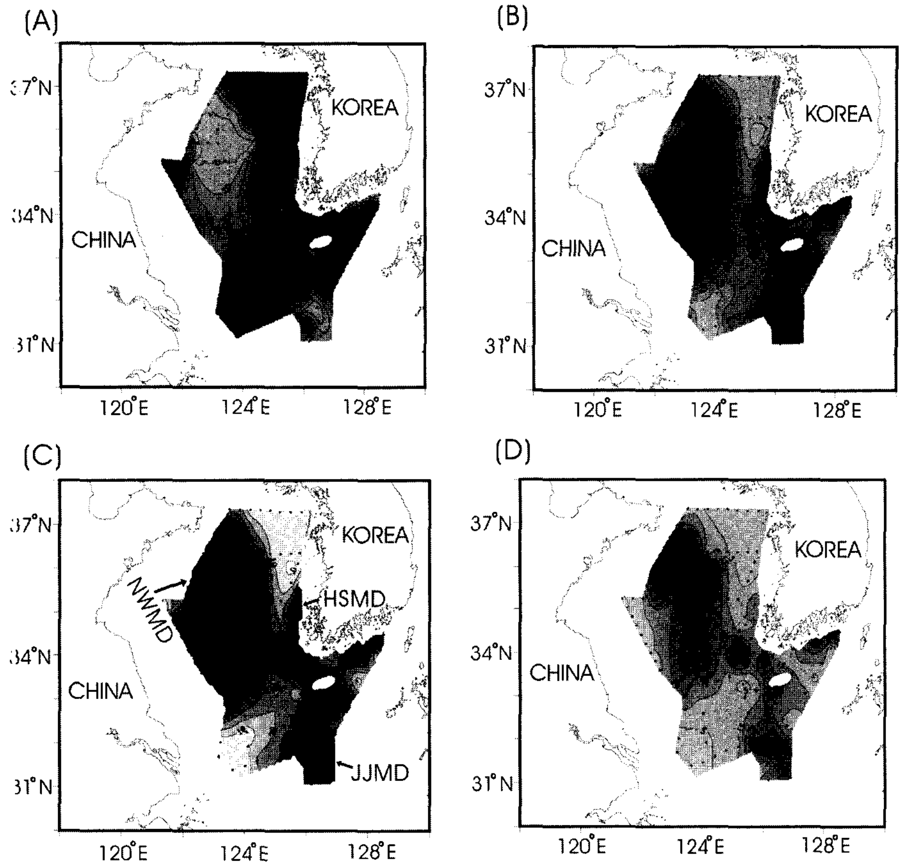

Fig. 3. Map of the study area showing the pathy distribution of grain size in surface sediments. (A) sand, (B) silt, (C) clay, (D) silt and clay.

(Shi *et al.*, 2000).

Only sand, silt and clay particles in the total sediment sizes are selected and drawn in Figs. 3A and 3B. The distribution of sands (Fig. 3A) shows clearly that high percentage of sands exists in the northeastern part of Yellow Sea and this distribution is narrowed toward the south. Sand rarely exists in the northwestern part of Yellow Sea. The mechanisms of the very fine grain particles in the central Yellow Sea are already discussed in the above. The high percentages of silt content are found in the south of NWMD and in HSMD and JJMD (Fig. 3C). The widespread distribution of sands and muddy sands is found in the eastern part of middle Yellow Sea. And the transportation direction of these sediments shows a tendency to the south. The southern boundary of sands is slightly the south of 35.5° N, and the western limit is about 123°E to 124° E. Sand deposits in the southeastern part of Yellow Sea are identified subtlely in the position of 35.0°N-35.5°N and about 121.54°E from this study area (Figs. 2D and 3A). These sands might be originated from the old Huanghe River during the time of either 821 yrs BP to 454 yrs BP or 454 yrs BP to 145 yrs BP, or both which are discharged directly to the Yellow Sea when the course of Huanghe River was changed from the Bohai Bay to the Yellow Sea in the last 4,000 yrs BP. These coarse sediments are not still actively moving and reworking (Liu *et al.*, 1989).

Clay content of surface sediments is shown that the depocenter of clay particles in the northwestern Yellow Sea which is the south of Shandong Peninsula (Fig. 3C). This zone is corresponded with the weakest point of Ms tides. The depocenter of clay particles are believed to be resulted from anticlockwise eddy. The distribution of combined silt and clay contents is shown in the bottom of Fig. 3D. The distribution pattern of silt-clay content is similar to that of the detailed sediment types classified by Yi (Fig. 2D). It shows that sediment dynamics are more complicated in the southwestern Korean coasts and adjacent to Jeju Island. In this area, at least 6 isolated mud packages are recognized including the coastal mudbelt in the South of Korea. The muddy sands by Folk's classification are found neighboring sand deposits, while the sandy muds are adjacent to the mud distribution (Fig. 2C). These characteristics indicate muddy sands and sandy muds are the mixture zone by sand and mud areas. As the mechanisms and complex position of NWMD, HSMD and JJMD formation in the Yellow Sea are explained above, the interaction of coarse and fine sediments results in the mixture zone of two extreme grain particles.

Especially, the muddy sands in the eastern part of Yellow Sea (toward the Korean coasts) show the banding shape along the sand deposits. These sand deposits in the eastern Yellow Sea are believed to be originated from the fluvial sediments of the Han and Keum rivers of the Korean Peninsula. It is not surprising that the sand deposits in the eastern Yellow Sea can be distributed broadly due to the relatively steep slope and the main channel system in comparison with the gentle slope of the western Yellow Sea. In the southern part of eastern Yellow Sea, some offshore sand ridges are reported by Wells (1988). The sediment source of these submerged sand ridges is originally from the Yeongsan River, but the sediment discharge is not either in a great amount or the equal amounts compared to that of the Han and Keum rivers. Next to the muddy sands, the sandy muds are also formed as a banding shape in the eastern boundary and eventually faced HSMD in the western coast of Korean Peninsula. This banding shape of sandy muds is widened to the south and occupied completely about 34^0 N where HSMD is disappeared.

A certain direction of sediment transportation is shown in Figs. 2D and 3A. The sands in the eastern Yellow Sea seem to be moved to the west. Martin *et al.* (1993) reported that the sediments from the Huanghe River affect very little directly to the Yellow Sea. The distribution of sands is resulted in the banding shape of muddy sands and sandy muds which are also transported to the west. Also, the sand deposits in the eastern Yellow Sea seem to be transported to the south along the Korean coasts. This transportation pattern is well matched with the coarsening upward sequences of core sediments.

The mud deposits in the southeastern Yellow Sea (Hucksand Island in the southwestern part of Korean coasts) are also pushed to the west and confronted with the southern transportation of sands. The mud patch in the western part of Yellow Sea is a tendency to be transported to the southeast and southwest slightly. The northern part of mud patch is coarsened at present, which might be affected by the western movement of coarse sediment from the east (Korean coast) and removal and depletion of fine sediments. At present, sediment supply, especially suspended sediments, from Han, Keum, Mangyung, Dongjin and Youngsan rivers are limited and/or completely blocked by the artificial seawall and seaport construction. Especially, Saemankeun-seawall will be completed within a few years and almost 90% of sediment discharge of Mangyung and Dongjin rivers will be controlled and blocked by this seawall.

The southern transportation of mud patch in the western Yellow Sea has two directions: one is toward obliquely the west, while the other is directed straightly to the south. To the west, the mud patch is protruded which is the result of recent transportation. This pattern is also identified from the core sediments. These muds in the western area of Yellow Sea are not deposited in the sedimentary sequences. This mud pattern is shown in more detail from Fig. 2D. That is, clay is transported to the west and south. This trend is slowly switched to the southwest where clay is changed to silty clay, silt-clay, clayey silt, sandy-silty clay, and sandy-silty clay. These sediment patterns are eventually confronted by the western movement of sand, clayey silty sand, clayey silt-sand, silty-clayey sand, and silty clayey sand. Therefore, sandy silt-clay, clayey-sandy silt and silty clay-sand are in the middle of the above two groups of sediment types.

In the western Yellow Sea, again, the clay patch (NWMD) has several directions of movement, at least four to five directions. Therefore, the directions of silty clay adjacent to the clay patch in the western Yellow Sea are the west, the south and the northwest. In this clay patch, the weight percentage of clay ranges over 95 wt.% of total sediment sample. And the rest of percentage (0-5 wt.%) is purely silt in this case. Among a total of 72 sample stations, 4 stations are identified as in the category of silt-clay: one is the west side of the Shandong Peninsula with 3.9 wt.% sand, 49.2 wt.% silt and 47.0 wt.% clay.

Another three stations are located in the middle of Yellow Sea where the protrusion of mud patch was recognized (Figs. 2D and 3C). Among the three stations, the western side of two stations in the north contains silt of 43.7 wt.% and clay of 56.3 wt.%. This percentage is changed to silt of 44.1 wt.% and clay of 56.0 wt.% in the eastern side of another station, showing the slight increase in silt and decrease in clay to the east, indicating the coarsening toward the east. These two stations do not contain sands at all. And, one station in the southwestern side from the three stations is composed of 3.9 wt.% sand, 46.1 wt.% silt and 50.0 wt.% clay. Among the three stations, the shortest distance between the station in the north and that in the south is about 30 km, while the distance between two stations in the north is about 18 km. In these short distances, the influence of grain sizes in silt-clay is well recognized. To the west, clay is dominated, while, to the east, silt is increased and eventually changed to sand and to the south, sand is included while clay is decreased. Instead, silt is much higher than the other two stations in the north in which the relatively coarse materials are moved to the north in this area. Some characteristics of clay distribution are as follows: The coarse sediments relative to clay are transported toward the north, while the sand and sand-related sediments originated from the old Huanghe Deltas are much narrower by the southwestern invasion of clay. The west and south movements of clay are found in the middle part of Yellow Sea (Fig. 3C). The cyclone eddy (anticlockwise circle) is recognized from the distributions of sand, clay and mud (Fig. 3) as well as the detailed sediment types in Fig. 2D. This cyclonic sediment movement in this area is well correlated with the cyclonic eddy recognized from the water properties and circulations. Therefore, the sediment transportation on the sea-floor is deeply related to the circulation and current pattern of water column.

However, the distribution pattern of silt percentage is much different in the western Yellow Sea (Fig. 2D). As we know, silts are much dynamic and the easiest particles to be transported by energy because there is no character of flocculation as like clay particles. Also, these non-flocculation particles can be the smallest particles of sediments for the movement. Three places for high amount of silts are recognized: the area adjacent to the Shandong Peninsula, the surrounding area of Hucksan Island and the middle west of Yellow Sea (about 35°N and 122.5°E - 123°E). The coarse and fine sediments in the middle Yellow Sea, which are pushing and pushed each other, might be related to the distribution pattern of silt (Fig. 2D). Silt seems to be moved to the northeast and eventually to the north. This center of silts in the southwestern Yellow Sea is affected by another cyclonic gyre of water circulation. Also, silts adjacent to the old Huanghe coarse sediments (mostly sands) are transported to the northwest and southwest which prevent the eastern expansion of the old Huanghe coarse sediments. However, these silts (located in about 34°N and 123°E) are transported to the west by the coarse sediments, which are provided from the eastern Yellow Sea (the western part of Korean coasts).

On the other hand, silts in the Hucksand Island area are expanded to the west and restricted by the eastern expansion of sands. The strong front of water mass exists in this area. As a result, two different sediment types are countered each other in this frontal zone, showing that the typical water properties affect the sediment distribution on the sea-floor.

It has been already known that some major and minor element contents are correlated with grain-size distribution. Elements which are strong relationship with grain-size particles are Al, Ti, Fe, Mg, Li, Sc, V, Zn, Co and Cu. Elements of Mo, Ca, Ba and Sr shows no correlation with mean grain size. In this paper, grain-size-dependent on major and minor elements are presented for comparing with the distribution of different grain-size sediments (Fig. 4). Fe and Mg elements are major rock-forming elements, and the amounts of these are well correlated with grain-size of sediments (Figs. 5A and 5B). Minor elements of Co, Zn, Cu and V are also well correlated with grain-size distribution (Figs. 5C and 5D). On the other hand, the element of Cu and V is more or less correlated selectively with clay-dominated particles. These elements are well represented responding to the grain-size particles. Therefore, these elements can be used as a checking-marker for transportation and dynamics of sediments in the Yellow Sea.

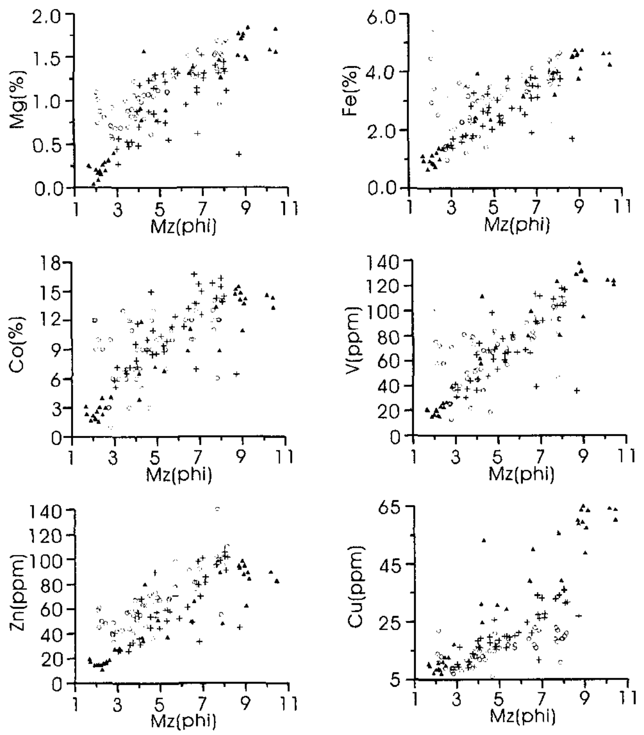

Fig. 4. Graphs of mean grain size (phi) versus geochemical elements (Mg, Fe, Co, V, Zn and Cu) showing the good correlation.

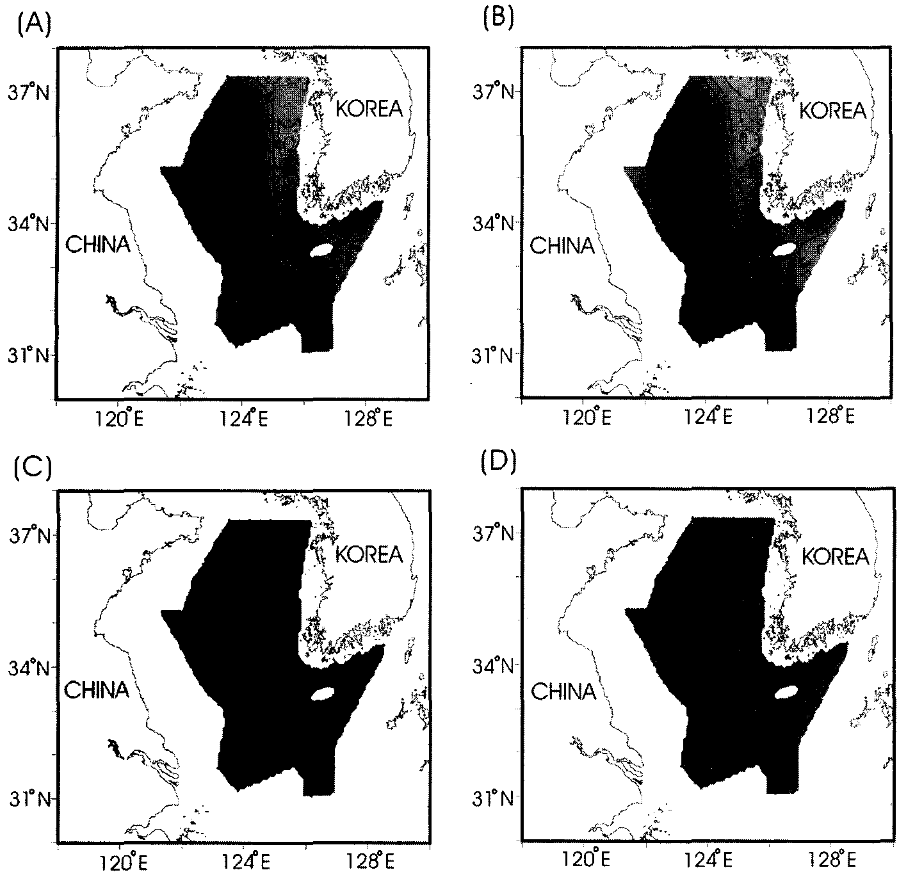

Fig. 5. Map of the study area showing the pathy distribution of geochemical elements in surface sediments. (A) Mg, (B) Fe, (C) Cu, (D) V.

Core Sedimetary Stratigraphy

Seven cores across A1-line in the northest part of study area show the very distinctive grain-size distribution (Figs. 1B and 6A). Sedimentary sequences on the western part (toward Shandong Peninsula of China) of this section contains mainly clayey silt. On the other hand, sediment deposits across the eastern part (toward Gyunggi Bay of Korea) of line is mostly composed of sands. Among 7 cores, the grain-sizes are sharply changed between cores 98YS-A06 and 98YS-A07. The grain-sizes in core 98YS-A06 deposits are sands, while those in core 98YS-A07 are clayey silt to silty clayey sand. The area between these two core locations is the boundary between Chinese-influenced sediments and Korean-influenced sediments.

Core 86YS-A06 is located in 37°20'N and 124°10' E, while core 98YS-A07 is located in 37°20'N and 123°50'E. The colliding zone of sediment transport trend is about 124°E in this latitude. Sediment transport trend analysis by Shi *et al.* (2001) indicates that about 123°20'E is the colliding zone of sediment transport from both the east and the west. Frequency distribution of grain-sizes shows that mostly sands are dominated on the surface of stations A06 and A07 (Fig. 7) As mentioned above, these two stations are the areas of sharp changes of grain-sizes.

Grain-size distribution of eleven cores along B1-line of approximately 36°20'N is partly similar to that of cores along the above cross-section (A1-line) except the boundary of sharp grain-size changes is slightly shifted to the east due to the position of NWMD. The boundary area of sediment mixture zone is located at approximately 124°30'E, to 123°50'E. Therefore, the colliding zone of sediment transport trend is about 124°20'E in this latitude.

Frequency distribution of grain sizes for stations B05, B07 and B013 represents that extreme grain-size changes from sand-dominated particles of station B05 in the east (from the Korean coasts), via bimodal particle distribution in station B07 to clay-dominated particle in station B013 in the west (the Chinese coasts). Unbalanced but bimode-to-be frequency distribution of grain-sizes can be recognized in station B05, indicating the mixture of two energy regimes and two sedimentary dynamic histories.

On the C1-line core profile, NWMD is still part of locations of cores 99YS-C06 to 99YS-C10. Bio-

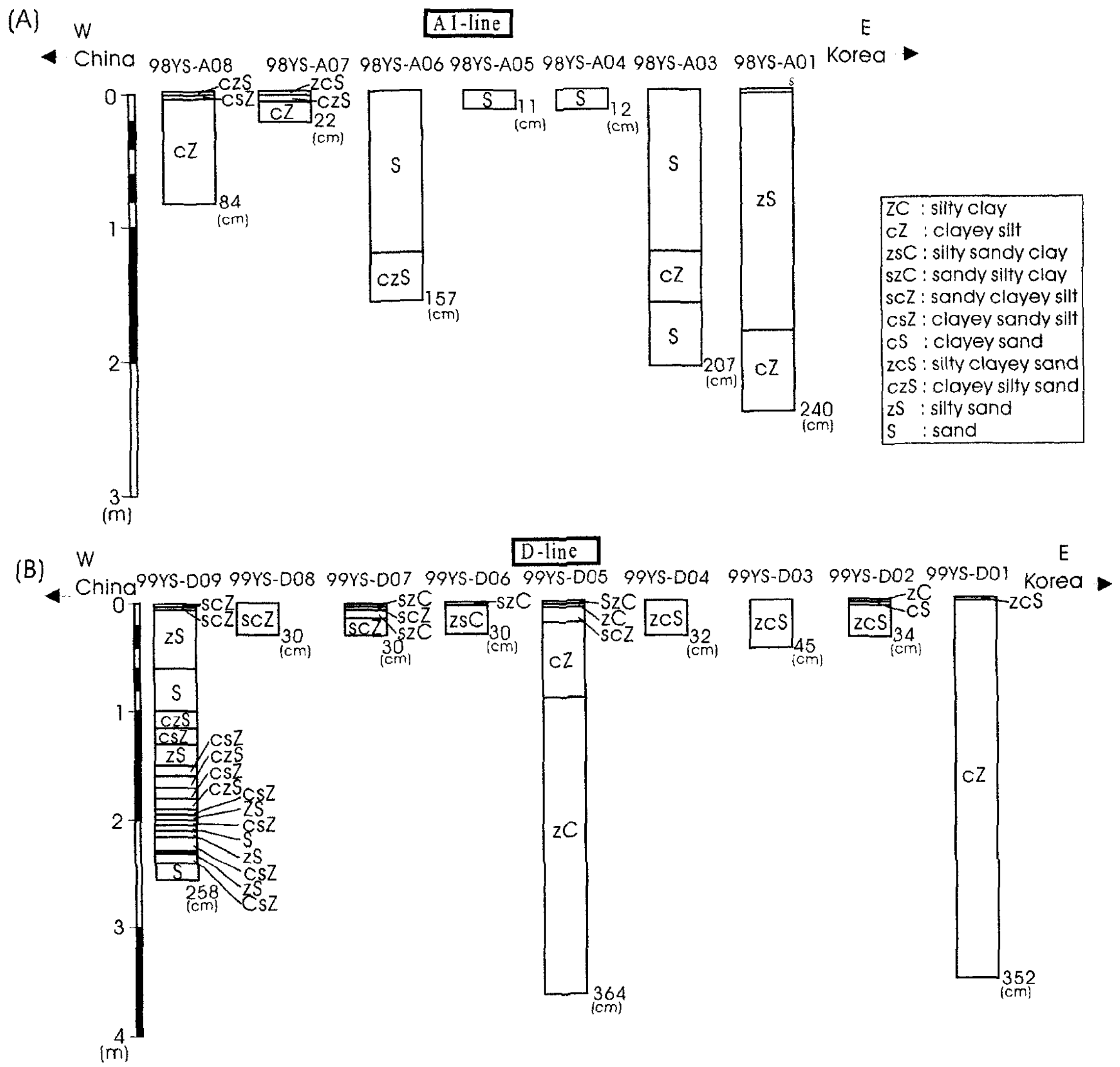

Fig. 6. Vertical profiles of grain size (Yi's classification) from core sediments of the Yellow Sea. (A) A1-line, (B) D-line.

mode frequency distribution of grain-sizes is also found in stations C08 and C09 which is the same position of cores 99YS-C08 and C09.

Nine cores on D-line (approximately between 33°N and 34°N) are analyzed (Fig. 9). Among 9 cores, three are piston cores and other 6 cores are collected from multi-corer. Grain-size distribution in core 99YS-D09 which is the closest to the Chinese coasts is the coarsest among 9 cores. In this core, sand and muddy sand deposits are alternated. Using detailed grain-size classification, it is shown that mainly sand- and silt-dominated deposits are alternated at least 20 times in this core. In the D1-line, the colliding zone of sediment transport might be located between cores 99YS-D04 and 99YS-D05. However, fine sedimentary sequences of core 99YS-D05 might be old clay and silt sediments in which Shi *et al.* (2000) mentioned. The latitudes of stations D04 and D05 are 123°40'E and 124°E. Sedimentary sequence in the easternmost station, core 99YS-D01, is part of HSMD. Except the very topmost sediments, grain particles of this deposit are silt-dominated ones. The area between cores 99YS-D02 and 99YS-D04 contains sand-dominated sediments. The area between cores 99YS-D05 and 99YS-D08 contains silt- and clay-dominated sediments. In the westernmost station, grain particles in core 99YS-D09 are mostly coarse materials. Frequency distribution of grain-sizes for stations D02, D03 and D06 represents fine sediments are dominated but bimodal pattern of grain-size distribution is also shown in station D03 and D06 (Fig. 6B).

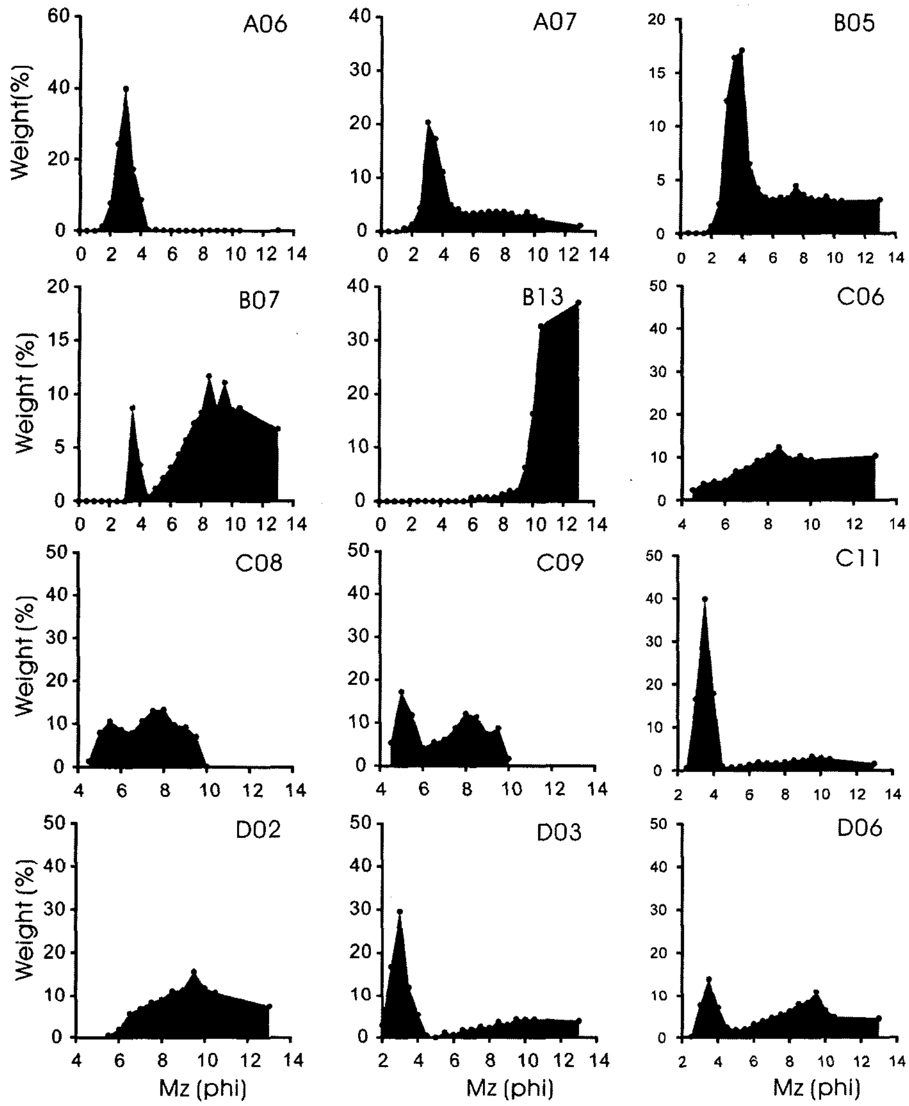

Fig. 7. Graphs of mean grain size (phi) in surface sediments of the Yellow Sea.

Shallow Seismic Stratigraphy

Seismic stratigraphic sequences from chirp sonar in the Yellow Sea can be divided into at least three units. They are the Holocene, Pleistocene and Pre-Pleistocene sedimentary sequences. Seismic profile in Fig. 8A is collected from northeastern part of Yellow Sea. This profile crosses from the west, i.e., close to China to the east, i.e., to Korea. The present erosional channel is shown while several cross-bedded channel-filled deposits are found in the right side of this profile. These channels were formed during the Pleistocene glacial period. At least two sequential units are found in the Holocene Epoch. On the left, irregular and cut-off sediment layers by erosion are recognized. Many sand waves are shown on the sea-floor. The depth of the sea-floor on this profile is approximately between 50 and 60 m.

On the other hand, the flat transparent reflection on the seismic profile in Fig. 8B is the area of NWMD which is composed of homogeneous, slightly semi-consolidated dominant clay deposit. This transparent unit is the Holocene deposit by cyclonic eddy in the Central Yellow Sea. The water depth is about 65 m in average and the seawater temperature is very cold (the coldest one is about 6°C) even during the summer season. Two additional seismic units are recognized below the transparent Holocene unit. Theses units are also flat but strong reflection than the Holocene unit. The lowest layer of these units seems to be multiple but the reflection lines are slightly different indicating that they had two distinctive environmental changes in the Pleistocene.

Well-developed sand-ridges are found in the northeastern part of mid-Yellow Sea (Fig. 8C). This seismic profile crosses from the northwest to the southeast.

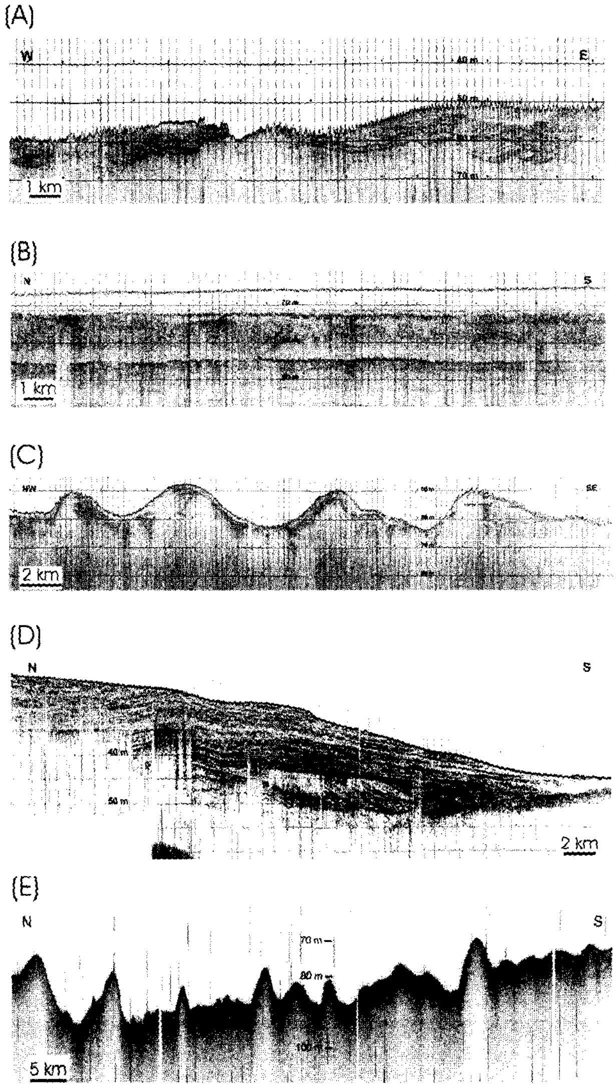

Fig. 8. Chirp profiles of the study area. (A) Channel-filled deposits and small present channels, sand waves in the northwestern Yellow Sea, (B) Homogeneous mud sequences underlained by the other Pleistocene flat homogeneous sequences, (C) Well-developed large-scale sand-ridges on the mid-western Yellow Sea, (D) Thick Holocene silt-dominated deposits underlain by the lower deposits which are also underlain by the Pleistocene erosional surface, (E) major channel is composed of a series of smaller channels.

The average width and depth of these sand-ridges is about 2 to 4 km and about 10 to 20 m, respectively. This kind of large-scale sand-ridges can be formed by strong and daily tidal movement in the sand-rich areas. The dominant tidal direction is from the east to the west on the basis of the lee- and stoss-side of sand-ridges. These repeated sand-ridges are smaller and less well-formed to the west and eventually changed to the non-depositional and irregular small channels (it is not shown in this profile).

The water depth of these sand-ridges is approximately 45 to 65 m. Four large sand-ridges are recognizable on this seismic profile. Among them, the crest of sand-ridges on the most left side (the northwest) seems to be disturbed, and a few sand waves are recognized on the crest. A lot of sand waves are found in the southeast side on the most right side. These sand waves exist on the flat sea-floor, but formed on the sand-ridges. The well-developed sand waves are formed on the stoss-side of sand-ridges on the most right side of profile. The crest of this sand-ridge has a certain deformed structure but it is difficult to identify on this profile.

Thick deposits along the N-S seismic profile are formed on the slope sea-floor (Fig. 8D). The Pleistonce erosional surface is shown on the left-hand side of seismic profile (in the south), while the acoustic boundary of Pleistocene is not shown on the right-hand side of profile (in the north) due to gas-filled section. However, it is identifiable from the left part of profile that at least two Holocene units are formed. One is the steep bedding form, probably the channel-filled deposits, while the upper unit is parallel bedding with a slight slope toward the south. These thick silt-dominated deposits are formed adjacent to the HSMD. The water depth of sea-floor in this seismic profile is about 25 to 45 m. The thickest Holocene deposits in this profile are about 15 to 20 m.

The largest channel system in the Yellow Sea is the long north-south direction of channels in the middle of Yellow Sea. Actually the position of the main channels is slightly toward east. The water depth of this main channel is approximately 70 to 80 m. The deepest major channels, about more than 120 m in water depth with the east-west direction, exist adjacent to Jeju Island and are connected to the north-south. The N-S seismic profile in Fig. 8E shows that a lot of series of channels exists in the main channel system. The water depth of these channels is about 70 to 90 m. The valley of some channels is composed of the sedimentary depositional structures. However, the overall morphology of channel sea-floor shows non-deposition and/or erosion, indicating strong energy regimes.

CONCLUSIONS

1. The 116 surface sediments are analyzed the grain size and geochemical elements and show the well-distributed pattern of sediment transportation pattern.

2. The distribution of two types of sediment characteristics, the weight percentage of sands, silts,

muds, clays, and mean grain-size contain the specific pattern of sediment transport.

3. The cyclonic movement of surface sediments in the central and southwestern part of Yellow Sea is well matched with the anticlockwise gyre of water properties. Therefore, the concept of one way sediment transportation in the Yellow Sea must be corrected because the bottom sediments are strongly affected by the water systems such as water properties, currents and meteorological factors.

4. The fine sediments (including the mudbelt deposits) in the surrounding area of Hucksan Island are formed also by the strong front of water properties. This mud patch exists adjacent to the coarse sediments such as sands and muddy sands which are explained clearly by the block of strong water front zone.

5. Geochemical elements such as Al, Ti, Fe, Mg, Li, Sc, V, Zn, Co and Cu in the surface sediments are well-dependent on and correlated with the grain-size distribution in the sediments. These elements can be used for sediment transport marker for the Yellow Sea sediments.

6. Many sedimentary characteristics and structures from the seismic profiles are found such as small erosional/nondepositional channels, sand-ridges and sand-waves, Pleistocene-channel-filled deposits, a series of channels in the N-S major channel system, and thick Holocene sediment package, indicating that more complex sedimentary history exists in the Yellow Sea.

7. Both sedimentological and geophysical data show that the sediment transport boundary exhibits approximately 123°E to 124°E in the Yellow Sea.

ACKNOWLEDGEMENTS

The financial support is from Ministry of Maritime and Fishery Affairs (MOMAF) of Korean Government. This work was supported by "Korea-China Joint Study of Sedimentary Dynamics and Paleoenvironments in the Yellow Sea" and "Restoration of the Eastern Marginal Environment of the Yellow Sea". The authors thank all R/V Eardo cruise members and Mrs. B.C. Kum, S. Jang and others for field and laboratory work. We also thank Dr. X. Shi (FIO of SOA) for cooperation.

REFERENCES

Cho, Y.G., C.B. Lee and M.S. Choi, 1999. Geochemistry of surface sediments off the southern and western coasts of Korea. Mar. Geol., **159**: 111–129.

Chough, S.K., J.W. Kim, S.H. Lee, Y.J. Shinn, J.H. Jin, M.C. Suh and J.S. Lee, 2002. High-resolution acoustic characteristics of epicontinental sea deposits, central-eastern Yellow Sea. Mar. Geol., **188**: 317–331.

Folk R.L., 1968. Petrology of sedimentary rocks. Univ. of Texas Press, 170 pp.

Lee, H.J. and S.K. Chough, 1989. Sediment distribution, dispersal and budget in the Yellow Sea, Mar. Geol., **87**: 195–205.

Liu, Z., Y. Tang, Y. Huang. and Q. Zhang, 1989. Tidal current ridges in the southwestern Yellow Sea. J. Sediment. Petrol., **59**: 432–437.

Martin, J.M., J. Zhang, M.C. Shi and Q. Zhou, 1992. Active flu of the Hanghe (Yellow River) sediment to the west Pacific ocean. Neth J. Sea Res., **31**: 243–254.

Milliman, J.D., Y. Qin and Y.A. Park, 1989. Sediments and sedimentary processes in the Yellow and East China Seas. In: Sedimentary Facies in the Active Plate Margin, edityed by Taira, A. and F. Masuda, pp. 233–249.

Milliman, J.D., R.C. Beardsley, Z.S. Yang, and R. Limeburner, 1985. Modern Huanghe-derived muds on the outer shelf of the East China Sea: Identification and potential transport mechanism. Conti. Shelf Res., **4**: 175–188.

Niino, H. and K.O. Emery, 1961. Sediments of shallow portions of East China Sea and South China Sea. Geol. Soc. Am. Bull., **72**: 731–761.

Park, Y.A. and B.K. Khim, 1992. Origin and dispersal of recent clay minerals in the Yellow Sea. Mar. Geol. **104**: 205–213.

Oh, I.S. and D.E. Lee, 1998. Tides and tidal currents of the Yellow and East China Seas during the last 13,000 years. J. Korean Soc. Oceanogr. **33**: 137–145.

Saito, Y. and Z. Yang, 1995. Historical changes of the Huanghe (Yellow River) and its impact on the sediment budget of the East China Sea, Proceedings of the Int'l Symposium on Global fluxes on carbon and its related substances in the coastal seas-ocean-atmosphere system, Sapporo, Nov. 14–17, 1994, Science and Technology Agency of Japan.

Shepard, F.P., K.O. Emery and H.R. Gould, 1949. Distribution of sediments on East Aisatic continental shelf. Allan Hancoc Found, Occasional Paper 9, 64 pp.

Shi, X., Y. Liu, H. Zhang, Z. Chen, H. Ren, and H. Wang, 2001. Distribution and transport of modern sediments in the southern Yellow Sea. Proceedings of 2nd China-Korea Symposium on Sedimentary Dynamics and Paleoenvironmental Changes in the Yellow Sea, Qingdao, pp. 105–119.

Wells, J.T., 1988. Distribution of suspended sediment in the Korea Strait and southeastern Yellow Sea: onset of winter monsoons. Mar. Geol., **83**: 273–284.

Yang, Z., Y. Saito, Z. Guo, Q. Cui, 1995, Distal mud area as a material sink in the East China Sea.

Yi, Hi-Il., 2000. Distribution and transport pattern of surface sediments in the Yellow Sea. In: Proceedings of 1st Korea-China symposium on Sedimentary Processes and Depositional Environments, edited by Yi, H.I and X. Shi, Ansan, pp. 161–178.

Zhao, Y.Y., M.C. Yan and R.H. Jiang, 1995. Abundance of chemical elements in continental shelf sediment of China. Geo-Mar. Lett. **15**: 71–76.

Manuscript received October 15, 2003
Revision accepted February 15, 2004
Editorial handling: Fangli Qiao