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Transportation and Deposition of Modern Sediments in the Southern Yellow Sea

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Based on the data obtained under the China-Korea joint project (1997-2001) and historic observations, the distribution, transportation and sedimentation of sediment in the southern Yellow Sea (SYS) are discussed, and the controversial formation mechanism of muddy sediments is also explored. The sediment transport trend analysis indicates that the net transport direction of sediment in the central SYS (a fine-grained sediment deposited area) points to 123.4°E, 35.1°N, which is a possible sedimentation center in the central SYS. The sediment transport pattern is verified by the distribution of total suspended matter (TSM) concentration and $\delta^{13}C$ values of particulate organic carbon (POC), the latter indicates that the bottom water plays a more important role than the surface water in transporting the terrigenous material to the central deep-water area of the SYS, and the Yellow Sea circulation is an important control factor for the sediment transport pattern in the SYS. The carbon isotope signals of organic matter in sediments indicate that the Shandong subaqueous delta has high sedimentation rate and the deposited sediments originate mainly from the modern Yellow River. The terrigenous sediments in deep-water area of the SYS originate mainly from the old Yellow River and the modern Yellow River, and only a small portion originates from the modern Yangtze River. The analytical results of TSM and stable carbon isotopes are further confirmed by another independent tracer of sediment source, polycyclic aromatic hydrocarbons (PAHs). Five light mineral provinces in the SYS can be identified and they indicate inhomogeneity in sources and sedimentary environment. The modern shelf sedimentary processes in the SYS are controlled by shelf dynamic factors. The muddy depositional systems are produced in the shelf low-energy environments, which are controlled by some meso-scale cyclonic eddies (cold eddies) in the central SYS and the area southwest of the Cheju Island. On the contrary, an anticyclonic muddy depositional system (warm eddy sediment) appears in the southeast of the SYS (the area northwest of the Cheju Island). In this study, we give the cyclonic and anticyclonic eddy sedimentation patterns.

Key words: The Southern Yellow Sea (SYS), Sediment Distributions and Transportation, Total Suspended Matter (TSM), Muddy Deposition

INTRODUCTION

The Yellow Sea, lying between Chinese mainland and Korea Peninsula, is a typical semi-enclosed shelf sea. Sediments in the Yellow Sea are derived mainly from Chinese mainland and secondly from Korea Peninsula. Sedimentation and sedimentary environments in the southern Yellow Sea (SYS) are controlled by marine dynamic processes and exhibit unique characteristics compared with other shelf environments. The SYS has a complex hydrodynamic system including wind, ocean wave, circulation (the Yellow Sea Warm Current (YSWC), the coastal currents and the Yellow Sea Cold Water Mass (YSCWM) etc.) and tidal currents; this system plays a direct role in the processes of transport-dispersion-deposition of materials entering the sea, and also in the erosion and remoulding of submarine sediments [*Hu*, 1984].

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In general, the SYS is a very complex sedimentary environment overlaid with various types of submarine sediments. The sediments in the SYS recorded the sedimentary dynamics characteristics and sedimentary environmental change.

Sedimentologic researches of the SYS started in 1930s with the initiative work from *Niino* [1934, 1968, 1970] and *Emery* [1968]. Since 1980s, many geological and sedimentologic investigations and researches of the Yellow Sea (especially the SYS) have conducted by Chinese and Korean scientists, and lots of valuable data have been collected [*Qin et al.*, 1989; *Zheng et al.*, 1989; *Liu et al.*, 1987; *Chough et al.*, 2000; *Lee*, 1989; *Alexander*, 1991]. But all the work is seldom involved in the relationship among sedimentary environment, dynamic factor and depositional system although it is important to illustrate sedimentary processes in the SYS.

At present, a key problem of sedimentology in the Yellow Sea to be resolved is the sedimentary process and dynamic mechanism of muddy sediments. The study on muddy sediments has become the focus of the sedimentological research of the Yellow Sea; the three patches of mud distributed in the central SYS, the area southwest of the Cheju Island and the northern Yellow Sea have been paid extensive attention in oceanographic society [*Park et al.*, 1990; *Zhao et al.*, 1991; *Gao et al.*, 1997; *Li et al.*, 1998]. Recently, another small patch of mud has been found in the southeast of the Yellow Sea (the area northwest of the Cheju Island) [*Liu et al.*, 1999; *Shen et al.*, 2000].

As to the study area and content, the previous researches are limited. Chinese scholars are often involved in the west, Korean scholars in the east of the SYS, and the comprehensive studies related to physical, chemical and biological processes of sediment formation have seldom been made. The project "China-Korea Joint Study of Sedimentary Dynamics and Paleoenvironment in the Yellow Sea" conducted from 1998 to 2001 made it possible to fully study the sediment distributions and sedimentary characteristics in the Yellow Sea on a relatively large scale.

In this paper, large amounts of data mainly from the China-Korea joint surveys and partly from the previous Chinese surveys were comprehensively analyzed, and the study area almost covers the whole SYS. Based on these data, we summarized the distribution, transport and sedimentation patterns of sediment and suspended matter, especially the distribution and dynamics process of muddy systems.

SEDIMENT DISTRIBUTION AND TRANSPORT TREND

Sediment Distribution

The sediment types of the SYS mainly include sand (S), silty sand (TS), clayey silt (YT), clay (Y), sand-silt-clay (STY), silty clay (TY) and gravel (G) (Fig. 1).

It is shown form Fig. 1 that clay is distributed in the central SYS, and silty clay, sand-silt-clay, clayey silt and/or clay sand are distributed outward in turn. A patch of fine-grained silty clay is occurred in a silty sand deposited area northwest of the Cheju Island. Gravels are sporadically distributed in the southern and the southeastern of the Yellow Sea. The contents of clay fractions in the sediments in Fig. 2 also well illustrate the seabed sediment distributions in the study area.

Transport Trend of Sediments

The method of grain size trend analysis was used to simulate the transport trend of sediments in the central SYS [*Shi et al.*, 2002].

The concept of grain size trend refers to the variation trend of horizontal distribution of sediment grain size parameters, and the grain size trend between two adjacent sites can be expressed by a vector (trend vector). In fact, the mathematic model of sediment transport trend is a model of sediment dynamics. The basic hypothesis is that the vector anisotropy of grain size trend can stand for net transport direction of sediments. In general, the changes of grain size parameters show two tendencies: (1) sediment grain size becomes finer with well sorting and negative values of *SK* and (2) sediment grain size becomes coarser with well sorting and positive values of *SK* (Gao *et al.*, 1998). Therefore, it's possible to get the resultant vector of sediment transport direction and to further get grain size trend of sediment transport by introducing grain size parameters into this model and by comparing the change trends of the grain size parameters in two adjacent samples at certain intervals.

The first step of grain size trend analysis is to compare each group of adjacent sampling sites on the sampling site grid to get all grain size trend vectors. It is easy to judge whether the two sampling sites are adjacent or not by the comparative distance Der, which is usually the largest sampling interval. If the actual interval between the two sites is less than Der,

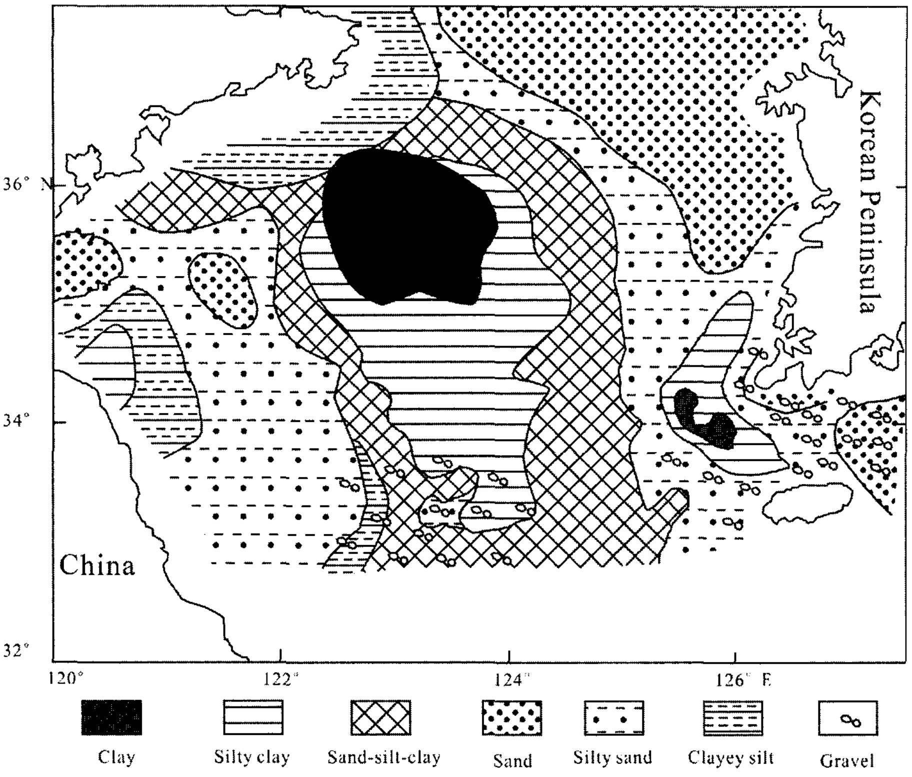

Fig. 1. Surface sediment types in the southern Yellow Sea.

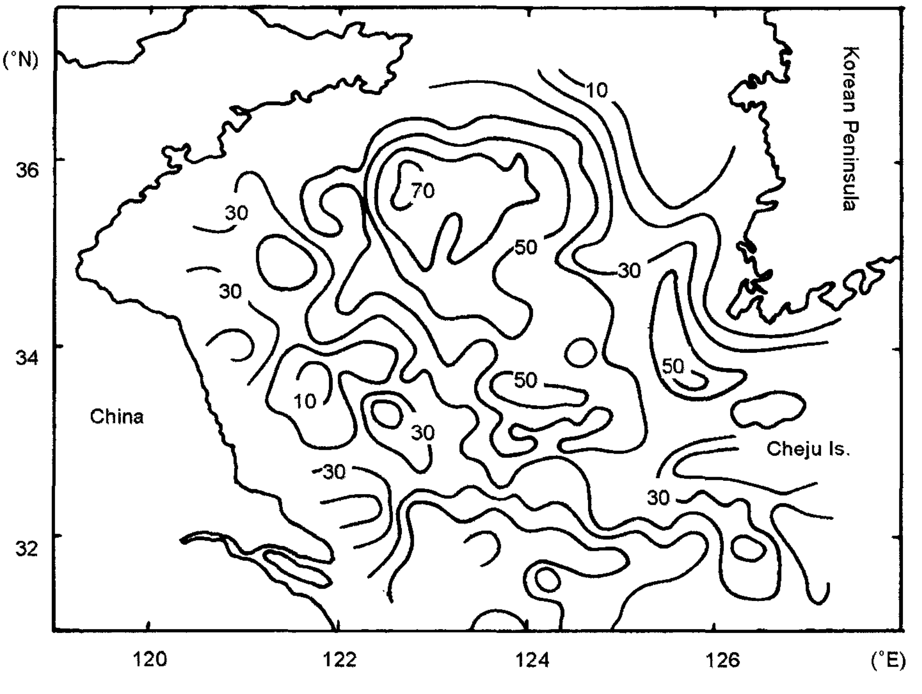

Fig. 2. Clay fraction contents of surface sediments in the southern Yellow Sea.

they could be regarded as "adjacent"; if not, they are regarded as "separate". The second step is to calculate the sum of trend vectors R (x, y) for every site. The third step is to smooth R (x, y) and eliminate the noises caused by the high-frequency variations of R (x, y). The horizontal distribution of trend vector can display net transport pattern of sediment after smoothing.

It is necessary to construct equidistant grids for sampling sites in grain size trend analysis. In this way the resultant vector can reflect sediment spatial transport and the noise can be reduced to the lowest extent. Because of the limitations of seabed topography, hydrometeorology and sampling technology, it

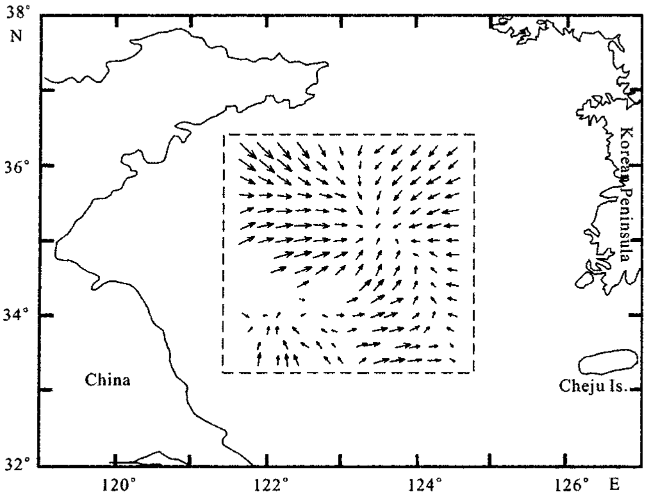

Fig. 3. The pattern of grain size trend analysis with Der=0.6.

is often difficult to get ideal equidistant grids for the sampling sites in the practice, so 165 samples were selected from large amount of surface samples to fit trend analysis in this study. The sampling density is usually 0.25°x0.2° and the smallest one is less 0.2°, but locally beyond 1°.

According to the previous results of transport trend analysis of sediment grain size in the central SYS, the values of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.5 of Der (Euclidean distance between any two sites in the geodesic coordinates) were used in turn in the analysis. When comparative distance (Der) is set to 0.6, the grain size trend map can give a better transport pattern of particles in the muddy area of the central SYS (Fig. 3). The resultant vector straightly points to the center (123.4°E, 35.1°N). This center is supposed to be the sedimentation center of the muddy area of the SYS, and the net transport direction of sediments in this region points to this sedimentation center in the central SYS.

The pattern implies that cyclonic circulation (including the YSCWM) and cold-water gyre in the central SYS control the sediment transport and deposition in the region [*Zang et al.*, 2003]. The resultant vectors of sediment transport in the southeast of the study area also indicate that there is an anticlockwise cyclonic circulation.

The pattern of transport trend of sediment in the central muddy area of the SYS verifies that the transport trend of sediment is consistent with the surface sediment types and the hydrologic data. All these evidences indicate that there is a sedimentation center in the central SYS located in the vicinity of 123.4°E, 35.1°N. The resultant vectors in the study area mostly point to this sedimentation center and the outside sediments tend to be transported towards the center. In addition, this sedimentation center is located largely in the center of the SYS Cold Water Gyre. This kind of sediment transport and deposition trend reflects the important feature of sedimentary environment in the central SYS.

It is shown from the hydrographic data that there is a cyclonic circulation all the year round in the central SYS to form the YSCWM from May to October [*Hu*, 1994; *Tang et al.*, 2000; *Zang et al.*, 2003]. In the central part of the YSCWM, there exists a cold-water gyre. Due to the joint action of cyclonic circulation and cold-water mass, a low-energy, weak dynamic sedimentary environment appears there and controls the transport trend and depositional pattern of sediments in the region to result in the centrality of sediment transport. The direction of resultant vector is southeastward and displays the characteristics of anti-clockwise gyre of cyclonic circulation and the YSCWM.

It should be pointed out that fine-grained and coarse-grained sediments have different dynamic characteristics. In marine environments, fine-grained sediments are influenced not only by hydrodynamics but also by agglomeration, so in interpreting transport trend of fine-grained sediments, agglomeration should be taken into consideration.

TOTAL SUSPENDED MATTER (TSM) AND STABLE CARBON ISOTOPES

Horizontal Distribution Characteristics of TSM Concentrations

284 suspended matter samples from 7 transects and in 5 layers in the SYS were collected for this study on the cruise in May, 1998.

The surface TSM concentration ranges from 0.66 to 13.30 mg/l with a mean value of 3.08±3.05 mg/l (Fig. 4a), which indicates the following characteristics.

(1) There is a tonguelike isopleth of 2.0 mg/l extending to the NEE off the Yangtze River estuary, and the TSM concentration decreasing from about 4 mg/l to less than 1 mg/l indicates the main diffusion direction of the Yangtze River diluted water and the TSM concentration near 123°E off the Yangtze River estuary has a value (2.07-2.67 mg/l) lower than that on its both sides, indicating a possible effect of the branch of the Taiwan Warm Current occurring in the

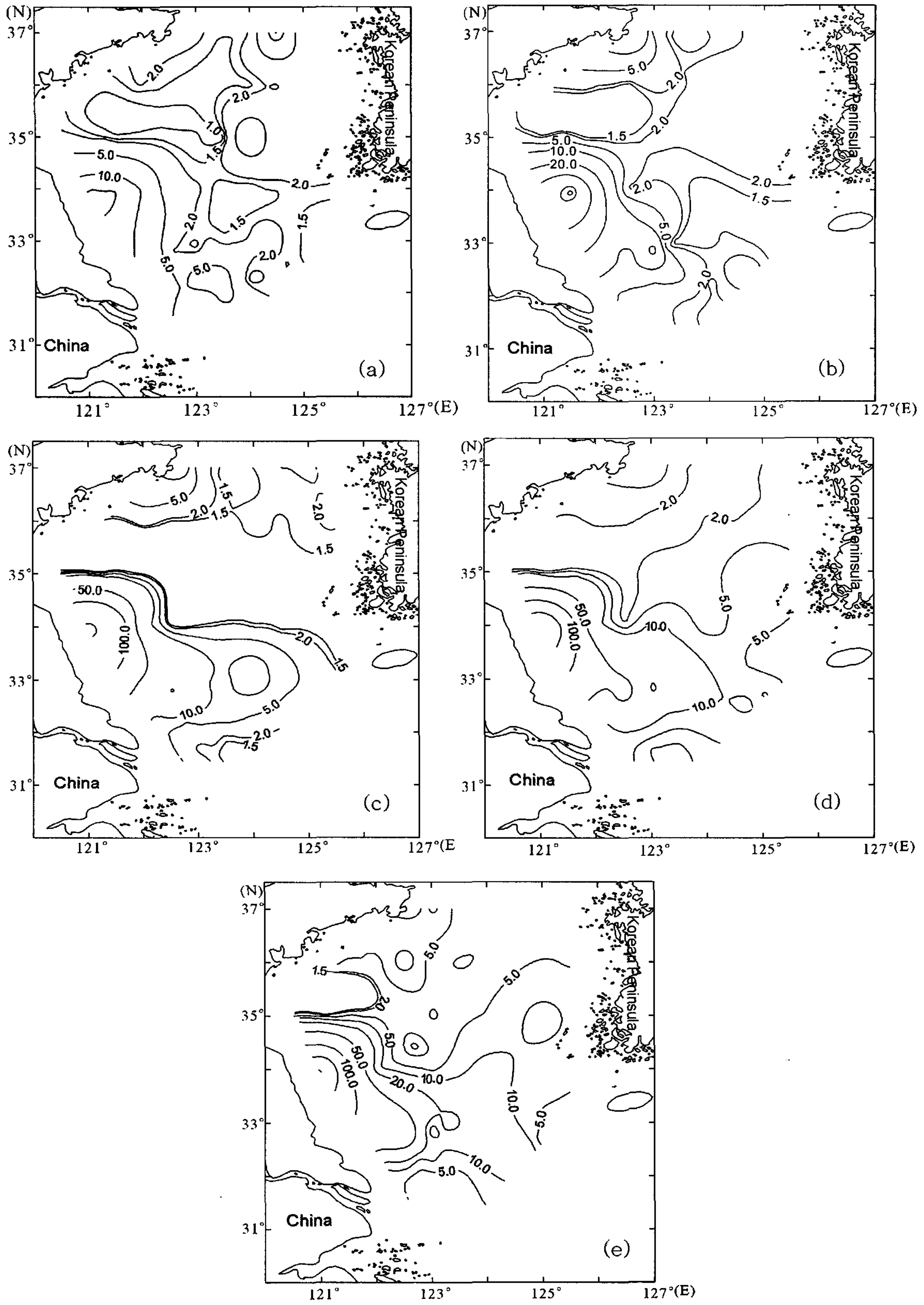

Fig. 4. Distribution of TSM concentration (mg/l) in the southern Yellow Sea in spring. (a) Surface layer; (b) subsurface layer; (c) intermediate layer; (d) lower layer; (e) bottom layer.

boundary area of the Yellow Sea and the East China Sea [*Hu*, 1984].

(2) There are isopleths parallel to the Subei coastline, the TSM concentration in these areas is high, and its TSM concentration decreases rapidly from 13 mg/l to less than 2 mg/l with increasing water depth and distance off the shoreline.

(3) There are isopleths of 2.0 and 1.5 mg/l parallel to the shoreline southeast of Shandong Peninsula, which is a manifestation of material coming from the modern Yellow River.

(4) The water bloom in spring brings about a uniform cloud-like TSM distribution in the deep-water area and results in high TSM concentrations of more than 10 mg/l especially in the asea east of Chengshan Cape and in the central Yellow Sea.

(5) There is a lower TSM concentration tonguelike isopleth of 1.5 mg/l extending to the NNW in the southeast corner of the survey area, which may be related to the influence of the Yellow Sea Warm Current, a branch of Tsushima Warm Current.

The TSM concentration in the subsurface layer ranges from 0.86 to 43.53 mg/l with a mean value of 5.11±8.26 mg/l (Fig. 4b), being higher than that in the surface layer. The reason for this is that spring is a high reproducing season for phytoplankton in this region, and the subsurface layer provides abundant nutrients and illumination for the growth and reproduction of phytoplankton. In general, the distribution characteristics of TSM concentration in the subsurface layer are similar to those in the surface layer. There is a high value area south of the old Yellow River estuary in Subei area and the maximum is over 40 mg/l and higher than that in the surface layer. Another high value area appears in the area southeast of Shandong Peninsula. Similar to the surface layer, the lower TSM concentration also appears in the southeast of the survey area, but its extent is larger in the subsurface layer than in the surface layer.

The TSM concentration in the intermediate layer (Fig. 4c) ranges from 1.15 to 205.25 mg/l with a mean value of 11.43±34.02 mg/l being higher than those in the surface and subsurface layers. If some abnormally high concentrations (>100 mg/l) in the shallow water area of Subei area are omitted, the mean value in the intermediate layer is 5.19 mg/l and similar to that in the subsurface layer, indicating that the intermediate layer is also one of high reproducing layers for marine phytoplankton. The high value region of the intermediate layer is located in the area south of the old Yellow River estuary of Subei area. The second high value region is defined by an isopleth of 5 mg/dm^3 and extends northeastward from the Yangtze River estuary to the area near 33.5°N, 125°E. The third high value region is located in the area southeast of Shandong Peninsula possibly due to resuspension of sediments.

The TSM concentration in the lower layer is in the range of 0.74~20.35 mg/l (not including a shallow water region south of the old Yellow River estuary of Subei area). The mean value is 5.03±4.22 mg/l (Fig. 4d) and is slightly lower than that in the intermediate layer, which is due to that reproduction of phytoplankton in the lower layer decreases with illumination, and the resuspended seabed sediments might not reach this layer.

The TSM concentration in the bottom layer ranges from 1.28 to 209.44 mg/l with a mean value of 15.05±33.09 mg/l (Fig. 4e), which is the highest in the water column and seems to be related to seabed sediment resuspension caused by tidal current and wave. In the bottom layer, the highest value of TSM concentration appears in the area south of the old Yellow River estuary of Subei area. Another high value area is defined by the isopleth of 10mg/l extending northeastward from the front edge of Yangtze River subaqueous delta (124°E-124°45'E) to the area north of 34°N, which might be the main route for material transport from the Yangtze River to the central deep-water area of the Yellow Sea.

The horizontal TSM distribution trends in the five layers are basically similar to each other. Compared with the circulation pattern in the Yellow Sea [*Hu*, 1984], the TSM distributions are found to have a close relation with the circulation. It is obvious that the Yellow Sea circulation is a main transporting force and controlling factor for TSM in the Yellow Sea although the TSM concentration is locally influenced by tidal current and wave. This conclusion is coincident with the NOAA satellite remote sensing image [*Sun et al.*, 2000], namely, the distribution characteristics of the surface TSM in the Yellow Sea and the East China Sea are dependent on the interaction of different currents in these regions. The representative TSM isopleths of 2 mg/l, 5 mg/l and 10 mg/l in the surface, intermediate and bottom layers extending northeastward from the Subei Shoal and the Yangtze River estuary may be caused by the confluence of the southward Yellow Sea Coastal Current and the northeastward branch of Taiwan Warm Current, and the two currents result in the main channel for transporting the old Yellow River material at the Subei Shoal and the modern Yangtze River material to the central deep-water area in the SYS. After entering the SYS, parts of the modern Yellow River material are carried southeastward by the Lubei coastal current deposits on the Shandong subaqueous delta and the others are continuously transported southward.

Horizontal Distribution Characteristics of POC $\delta^{13}C$ in TSM

The particulate organic matter (POM) in TSM is composed of living and non-living organisms, and they can be formed *in situ* or transported from other places by currents. Many literatures have shown that the particulate organic carbon (POC) $\delta^{13}C$ value is an important source tracer for terrigenous and planktonic particles. The stable isotope compositions of POC in the 5 layers were determined and their material source indicating significances are discussed as follows.

The distribution of surface POC $\delta^{13}C$ is described below (Fig. 5a). There is an isopleth of -26‰ off Chengshan Cape at the east end of Shandong Peninsula extending southwestward along the coastline. In the waters southeast of Shandong Peninsula, the TSM concentrations are higher, but its POC $\delta^{13}C$ is the lowest in the survey area, exhibiting an obvious feature of the modern Yellow River materials (which have an annual average value of -26.5‰) [*Cai*, 1994]. This is an isotopic evidence that sediment on the Shandong subaqueous delta is derived from the modern Yellow River. The grain size trend analysis of the sediments north of Shandong Peninsula (in the northern Yellow Sea) indicates that the modern Yellow River materials are transported to the east or northeast to form a channel for transporting the modern Yellow River material to the SYS [*Cheng and Gao*, 2000]. There is a high value area of POC $\delta^{13}C$ (-19.7‰) off the Yangtze River estuary, which is coincident with the surface POC $\delta^{13}C$ value (-19.7‰) obtained on the cruise of June 1980 at Station 06 in Sino-USA joint investigation [*Tan et al.*, 1991]. This is inferred as an isotope evidence of planktonic creature influenced by the branch of Taiwan Warm Current [*Cai et al.*, 1999]. Also, an isopleth of -26‰ appears in the area east of 125°E at Transect 36°N, indicating certain effect of terrigenous material from Korean rivers.

The POC $\delta^{13}C$ distribution in the bottom layer is basically similar to that in the surface layer (Fig. 5e), it also exhibits higher values of -19.3‰ and -20.4‰ off Yangtze River estuary and reflects the influence of plankton from Taiwan Warm Current off the Yangtze River estuary. However, considerable differences exist in other areas compared with the surface POC $\delta^{13}C$ distribution. The bottom POC $\delta^{13}C$ distributions have two remarkable features: (1) there is a set of the most negative tongue like $\delta^{13}C$ isopleth (-27‰~-25‰) near Chengshan Cape east of Shandong Peninsula extending seaward to the southeast, which is consistent with the extending direction of Shandong subaqueous delta. It is shown from the evidence of stable isotopes that the main materials source to develop the Shandong subaqueous delta nowadays is the modern Yellow River; (2) the trend of -25‰ isopleth is basically similar to that of 10 mg/dm^3 isopleth of TSM, which is consistent with the route of the Yellow Sea circulation [*Hu*, 1984; *Liu et al.*, 1987]. This further confirms that the Yellow Sea circulation is main transporting force of terrigenous materials from the inshore area to the central area of the Yellow Sea. The main reason for the differences between the surface and bottom POC $\delta^{13}C$ value distributions may be due to the more intense resuspension of seabed sediments in the bottom layer and the considerable difference in organic materials generated *in situ* at different depths. Taking chlorophylla concentration as a rough measure of living organism, we have found that the distribution of chlorophyll-*a* in the water column is relatively uniform in shallow water area, whereas a low-high-low distribution pattern appears in the deep-water area. That is to say, the chlorophyll-*a* concentration is lower in the surface and bottom layers, but higher in the subsurface and intermediate layers, suggesting a smaller influence of living organism in the bottom layer. Furthermore, the bottom TSM concentration is the highest in the water column, so it is suggested that the bottom layer can well reflect the transport condition of terrigenous material in the SYS.

The POC $\delta^{13}C$ distribution in the lower layer (Fig. 5d) is roughly similar to that in the bottom layer, and the following three phenomena are still apparent: (1) the distribution east of Chenshan Cape indicates the transporting route of terrigenous material from the Yellow River; (2) it also indicates the influence of marine material composed of plankton carried by a branch of Taiwan Warm Current off the Yangtze River estuary; (3) the Yellow Sea circulation transports the terrigenous material to the deep-water area

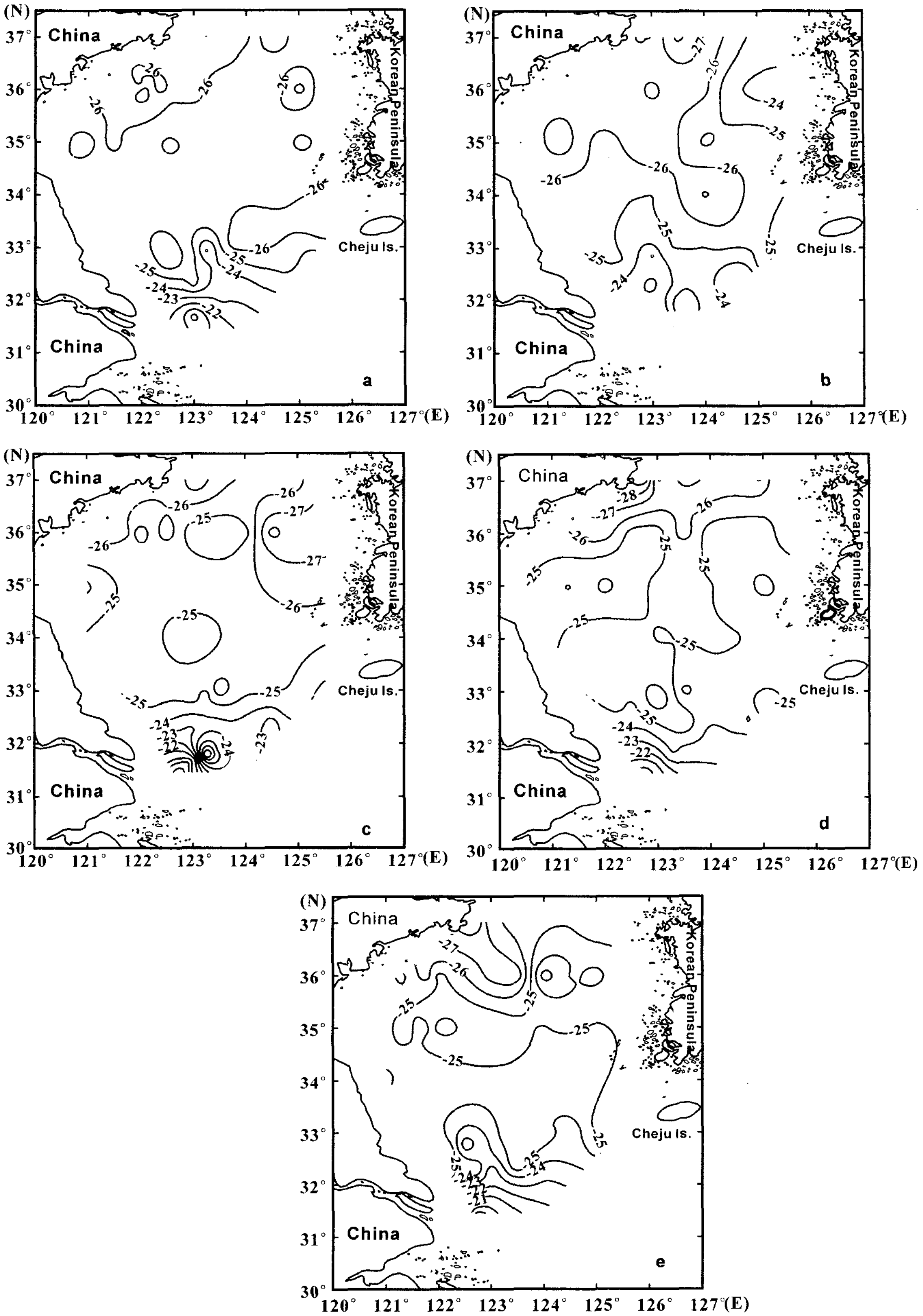

Fig. 5. Horizontal distribution of POC $\delta^{13}C$ value (‰) in TSM. (a) Surface layer; (b) subsurface layer; (c) intermediate layer; (d) lower layer; (e) bottom layer.

in the SYS. It is shown from this survey results that terrigenous materials are mainly derived from the modern and old Yellow River, while the material from the Yangtze River is relatively small.

The distributions of the subsurface and intermediate POC $\delta^{13}C$ value (Figs. 5b and 5c) are quite different from those in other three layers. The reason is that the massive reproduction of plankton in photic zone greatly increases the percentage of plankton in POC. However, the influences of material from the Yellow River east of Chengshan Cape and plankton carried by the branch of Taiwan Warm Current off the Yangtze River estuary still exist in the two layers.

$\delta^{13}C$ Distribution Characteristics of Total Organic Matter in Surface Sediments

The distribution of TSM $\delta^{13}C$ values in the water column can be used to trace transport processes of suspended matter in seawater, while $\delta^{13}C$ values of the surface sediments may reflect the relative ratio of terrestrial to marine material in sedimentary processes. The results of stable organic carbon isotope $\delta^{13}C$ in surface sediments of the SYS are showed in Fig. 6, and four apparent characteristics can be summarized: (1) sediments in Shandong subaqueous delta exhibit the most negative $\delta^{13}C$ values in the whole survey area and the $\delta^{13}C$ isopleth increases southeastward gradually from -28‰ to -23‰, the sedimentation rates in this area are the highest (3.4-8.6 mm/a) in the survey area because the Yellow River provides abundant fine particulate matter [*Alexander et al.*, 1991]; (2) another area with ^{13}C depletion in the surface sediments is near the old Yellow River estuary, and sedimentation and resuspension of sediments from the old Yellow River alternatively take place in Subei Shoal and the sediments are transported by the Yellow Sea circulation to the central deep-water area of the SYS; (3) plankton carried by the branch of Taiwan Warm Current with high-temperature and high-salinity influences the $\delta^{13}C$ of sediments at Transect F off the Yangtze River estuary. The $\delta^{13}C$ value tends to increase with increasing distance off the Yangtze River estuary, indicating the addition of ^{13}C-enriched material in the neighbourhood of 122°45'E and 124°30'E. It may provide a clue for explaining the phenomenon that the sediment at the frontier of secondary subaqueous terrace (124°E -124°30'E) is coarse and the bottom TSM concentration is relatively high, which is due to the flocculation of dissolved material in the Yangtze River diluted water after meeting with the high-temperature and high-salinity branch of Taiwan Warm Current rather than due to the sediment resuspension; (4) an isopleth of -25‰ appears in the northeast corner of the survey area and indicates the influence of materials from the Korean rivers.

The terrigenous percentage in deposited organic matter can be estimated based on the organic carbon $\delta^{13}C$ values in sediments using a simple bivariate

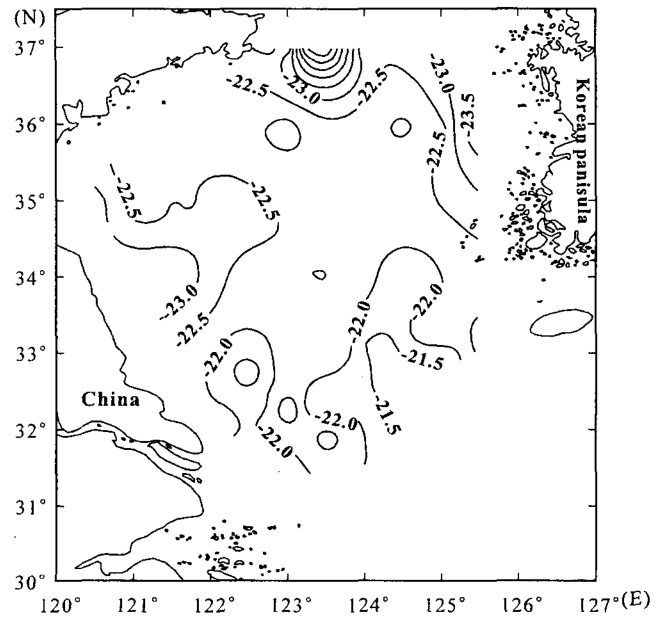

Fig. 6. The distribution of $\delta^{13}C$ values (‰) in the surface sediments.

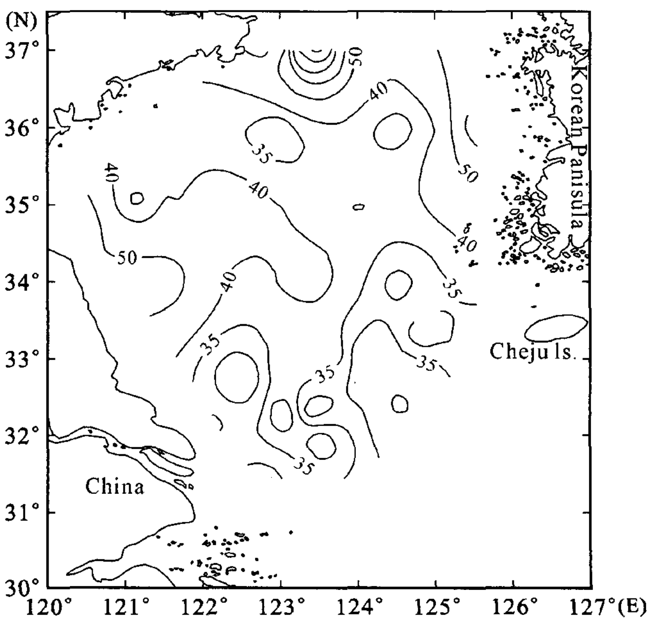

Fig. 7. Terrigenous percentage of sedimentary organic matter (%).

mixed model [*Cai et al.,* 1988], and the result is shown in Fig. 7. The isopleths clearly indicate that the higher values of terrigenous organic matter were observed mainly in the waters of the Shandong subaqueous delta and Subei Shoal. Sediments in the central deep-water area in the SYS are isotopically heavier, and correspond to the lowest sedimentation rate (~1 mm/a) [*Alexander et al.,* 1991].

PAHs distribution characteristics in surface sediments

Polycyclic aromatic hydrocarbons (PAHs) are a kind of important organic geochemistry molecular indicator. PAHs in the SYS are mainly those products originating from incomplete combustion of fossil fuel, so they are also an independent indicator of terrigenous material in ocean. The concentrations of ΣPAHs in surface sediments of the SYS range from 19.9 to 381 *n*g/g [*Li,* 2000]. Compared with those in other shallow sea or bay, e.g., 5967 *n*g/g in Tokyo Harbor [*Yu,* 1988] and 1798 *n*g/g in the western Mediterranean Sea [*Lipiatou et al.,* 1991], ΣPAHs content of the surface sediments in the SYS is relatively low, indicating that this area is not seriously polluted and basically in a natural state.

It is shown from Fig. 8 that the distribution of PAHs concentration in surface sediments in the SYS is characterized by higher value in the west and lower value in the east. The highest value of 381.3 *n*g/g in this region appears at stations east of Chengshan Cape and characterizes the modern Yellow River material carried by Lubei coastal current. This is completely in agreement with the dispersion of the modern Yellow River material shown by POC $\delta^{13}C$ isopleth of -26‰. ΣPAHs isopleth of 750 *n*g/g in the northern Yellow Sea is parallel to the north shoreline of Shandong Peninsula, which provides a direct evidence for the above conclusion based on POC $\delta^{13}C$ values. ΣPAHs isopleths of the surface sediments along the Subei coast are parallel to the shoreline and ΣPAHs values gradually decrease seaward from 300 ng/g to 100 *n*g/g. The isopleth of 100 *n*g/g takes a shape similar to the bottom TSM isopleth of 10 mg/dm^3, and has a trend approximate to the organic carbon $\delta^{13}C$ isopleth of -25‰ in surface sediments. This consistency between ΣPAHs values, $\delta^{13}C$ value and the Yellow Sea circulation indicates that the dispersion of terrigenous material to the central region of the Yellow Sea is closely related to the Yellow Sea circulation.

LIGHT MINERAL ASSEMBLAGE

The distributions for percentages and assemblages of light minerals were compiled on the basis of 222 samples from the SYS. Five mineral provinces can be identified (Fig. 9), and they are I-northern mineral province of the SYS, II-mixed mineral province, III-mid-east mineral province, IV-eastern of Yangtze River

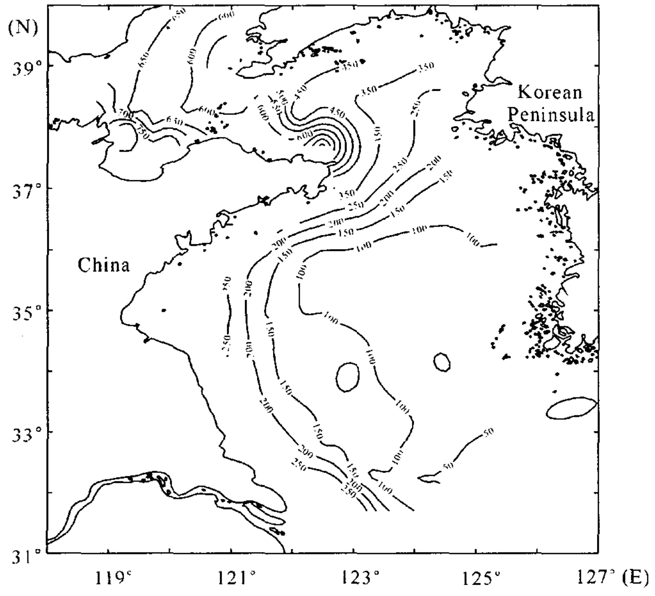

Fig. 8. Distribution of ΣPAHs concentration of surface sediments in the southern Yellow Sea (after Li, 2000).

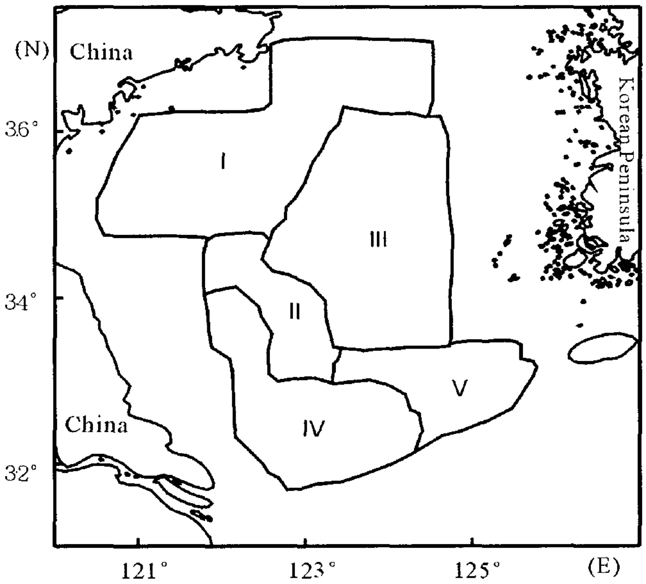

Fig. 9. Light mineral assemblage provinces in the southern Yellow Sea.

estuary province, and V-southeastern mineral province. I-northern mineral province, mineral assemblage: quartz-plagioclase-potash feldspar; II-mixed mineral province, mineral assemblage: plagioclase-potash feldspar-quartz; III-mid-east mineral province, mineral assemblage: potash feldspar-quartz; IV-easterm of the Yangtze River estuary province, mineral assemblage: quartz-plagioclase; V-southeastern mineral province, mineral assemblage: quartz-plagioclase.

Northern Mineral Province (I)

The water depth is in the range of 20~70 m. This province has high contents of light mineral and low contents of potash feldspar, plagioclase and iron-stained quartz, its contents of weathered detritus, calcite, and southern minerals are the lowest in the five provinces. Content of quartz is the highest among five provinces, so the dominant mineral is quartz. Mineral assemblage is quartz-plagioclase-potash feldspar. The high content of potash feldspar is consistent with the high potash feldspar content of the Yellow River source, so the sediment in this province originates mainly from the Yellow River.

Mixed Mineral Province (II)

The water depth is in the range of 20~70 m, its distribution range is largely similar to that of the small circulation, and the bottom sediment is just clayey silt. This province is well correlated with provinces III and IV, because province II is the transitional area between province III and IV. The ratio of plagioclase to quartz is the highest (0.62) and the content of quartz is the lowest among five provinces. Contents of iron-stained quartz, calcite and weathered detritus are high. Mineral assemblage is plagioclase-potash feldspar-quartz, the diagnostic mineral is calcite, and material source is complicated because sources of the Yangtze River, the Yellow River and *insitu* sediment all affect this province. The modern sedimentation might have considerable influence on the light mineral deposit because of the high feldspar to quartz ratio.

Mid-east Mineral Province (III)

The water depth is in the range of 70~100 m. This province is located in the mid-east of the SYS, and is controlled mainly by the YSWC. Sedimentary types are variable with a north-south distribution. The sediments on the west side are clayey silt and those on the east side are sand-silt-clay. Mean contents of plagioclase and iron-stained quartz are lower comparing with other provinces. Calcite content is also lower whereas schistose mineral, potash feldspar and feldspar contents are the highest among five provinces. Mineral assemblage is potash feldspar - quartz. Diagnostic mineral is schistose mineral. Material source derives mainly from sediment of the Yellow River.

Eastern of the Yangtze River estuary Province (IV)

The water depth is in the range of 10~60 m. The main current systems are the Yangtze River diluted water in summer and the Yellow Sea Coastal Current in winter. Submarine terrain is gentle. Sediment type in the south is silty sand and fine sand, while in the northward extension is clayey silt. The content of weathered detritus is the highest among five provinces, and that of quartz is medium, those of calcite (2.15%) and iron-stained quartz (7.60%) are very high, that of schistose mineral is lower and that of potash feldspar is the lowest among five provinces. Mineral assemblage is quartz-plagioclase. Diagnostic mineral is calcite and iron-stained quartz. Material source derives mainly from sediment of the Yangtze River.

Southeastern Mineral Province (V)

The water depth is in the range of 60~100 m. The current system is complex with the YSWC diverging from the Tsushima Warm Current here, and the Yangtze River diluted water has little influence on this province. The sediment types in this province include clayey silt, silty clay and clayey sand, and the bottom terrain is gentle because this province is located in the Yellow Sea trough. Ratio of feldspar to quartz is the lowest among five provinces. It have low contents of feldspar and calcite, and has high content of quartz and medium content of iron-stained quartz. The assemblage is quartz-plagioclase, and the diagnostic mineral is iron-stained quartz. Light minerals of the SYS and the northern East China Sea have certain influence on the mineral distributions in this province, so the mineral content and distribution of this province are similar to those of the area east of the Yangtze River estuary and the northern part of SYS. The sediments in this province may be affected by the Yangtze River diluted water to a certain extent.

SHELF LOW-ENERGY SEDIMENTARY ENVIRONMENTS AND MUDDY DEPOSITION

The SYS shelf can be divided into two distinctive sedimentary environments, i.e., low-energy and high-energy sedimentary environments; and the low-energy environment can further be divided into cyclonic and anticyclonic ones.

Characteristics of Shelf Low-energy Environment

In the area occupied by a meso-scale eddy on the shelf of the SYS, there exhibits a special low-energy environment. The grain size data of surface sediments show that there is a patch of fine-grained sediment in the central part of the SYS, in which sediments have a mean grain size of 8.7ϕ and contain over 70% of clay fraction. This patchy muddy area corresponds to the central area of the YSCWM. The grain size of sediment in the area increases outwards (Figs. 1 and 2) and indicates that the muddy area is in a low-energy environment, i.e., an environment occupied by the YSCWM. Two other low-energy environments were also found in the areas southwest and northwest of the Cheju Island.

The YSWC has a high temperature and divides the SYS into two parts from south to north, and interacts with the Yellow Sea Coastal Current and the Korean Coastal Current. Generally, a cyclonic eddy (cold eddy, anti-clockwise) is formed in the area west of the warm current and constitutes a relatively big circulation system; the Cold Water Mass Circulation System in the central part of the SYS is a good example for this case. The cold water mass behaves like a cyclonic eddy with a marginal maximum current speed of only 5 cm/s, which indicates that the area has a relatively weak hydrodynamic condition. Numerical simulation of tidal currents also shows that this area is a weak zone of tidal current. A clockwise circulation east of the YSWC is constructed by an anticyclonic eddy and the Korean Coastal Current. The anticyclonic eddy northwest of the Cheju Island has a vertical double-ring structure, in which there are a strong downwelling in the upper water of the central area and a weak upwelling in the lower water, so the characteristics of this anticyclonic eddy is evidently different from those of the vertical double-ring structure of the YSCWM [*Sun*, 1995]. Compared with the latter, the anticyclonic eddy has small size and strong hydrodynamic condition.

Muddy Sediments and Their Formation Dynamic Processes

Under long-term actions of eddy in the low-energy environment on the SYS shelf, fine-grained mud of sitly clay deposited and formed a muddy depositional system. Due to the differences in the eddy characteristics, especially in characters of cyclonic and anticyclonic eddies, the formed sediments in different depositional systems are different.

Cyclonic Eddy Muddy Sediment

The three muddy areas in the central SYS, southwest of the Cheju Island and in the west of the northern Yellow Sea correspond to three cyclonic eddies and belong to cyclonic eddy sediment area. In general, cyclonic eddy sediments have relatively wide distributions and construct main body of the muddy depositional system. The central muddy sediment area in the SYS is the largest one among the three muddy areas, but its thickness in the center is less than 3 m; sediments in the area have mean size of 8.5ϕ; they contain plentiful pyrite, and ^{14}C dating age of its bottom sediment is about 5,550 yr BP [*Liu et al.*, 1987].

Based on the dynamic investigation on sediments on the bottom with large gradient southwest of the Cheju Island, *Hu* (1994) pointed out that the cyclonic eddy played a decisive role in generating the muddy sediments. He also calculated the average horizontal divergences in different layers using the observed data and confirmed that the central eddy area consisted of a divergent area in the upper 50 m seawater depths and a convergent area below the 50 m depths. Suspended matters near seabed were transported to the eddy center by the convergent water and then accumulated on the seafloor to form the muddy sediments.

Anticyclonic Eddy Sediment

The anticyclonic eddy sediment is distributed in a small patch in the southeast of the Yellow Sea, and its dimension is much smaller than that of cyclonic eddy muddy sediment. A relatively big anticyclonic eddy sediment area is located to the northwest of the Cheju Island. The sediments are dark gray, 13.5~20 m thick, and composed mainly of fine-grained clay minerals with a mean size of 6-7ϕ; they contain lots of organism-like pyrite. The bottom of this muddy sediment system at 13.5 m below seabed was inferred to be about 5,689 yr old by using the ^{14}C dating data from Hole YSDP102 [*Liu*, 1999]. Below the muddy layer in the area northwest of the Cheju Island, *Shen* (2000) found that there was another eroded muddy layer, and the distribution area of the eroded muddy layer was larger than that of the upper one, so it would be exposed on seabed in the area uncovered by the anticyclonic eddy sediments. Some differences between the sedimentary dynamics during the formation age of the eroded muddy layer and at present were found (some sedimentary dynamics were found different in the formation of the eroded muddy layer from those at present), i.e., the eroded muddy layer was not the product of modern sedimentary dynamic environment but was formed in a certain period before the occurrence of modern sedimentary environment. Under the actions of modern hydrodynamics, the originally formed muddy sediments were eroded and transported.

The anticyclonic eddy sediment in the area northwest of the Cheju Island was formed by a double-ring structure consisting mainly of anticyclonic circulation. Because the anticyclonic eddy in the upper seawater is characteristic of high-pressure eddy, it caused suspended matter including plankton organism in the adjoining area to continuously converge to the eddy center, and then to be transported to seabed in the downwelling process. The lower-layer seawater was in upward motion, but its energy is smaller than that of downwelling, so the suspended matter gradually deposited on seafloor and eventually formed 20 m thick sediments [*Ky*, 1993]. Compared with the cyclonic eddy environment, the anticyclonic eddy environment has stronger sedimentary dynamic characteristics.

Comparison Between Cyclonic Eddy Sediment and Anticyclonic Eddy Sediment

The similarities between cyclonic and anticyclonic eddy sediments are summarized as follows: their main compositions are alike and both of them consist mainly of clay minerals; they contain plentiful pyrite in detrital minerals; the depositional bodies are distributed in the circular shape and sediments have homogenous structure and high water contents. Differences between them mainly lie in the thickness, sediment grain size and sedimentation rate. It is shown from the comparison between the cyclonic eddy sediment (in the central SYS) and the anticyclonic eddy sediment (in the southeast of SYS) that the former has weaker sedimentary dynamics and stronger reducing characteristic than the latter, and the former is composed of finer material and contains higher pyrite content; the former has lower sedimentation rate but larger distribution area than the latter.

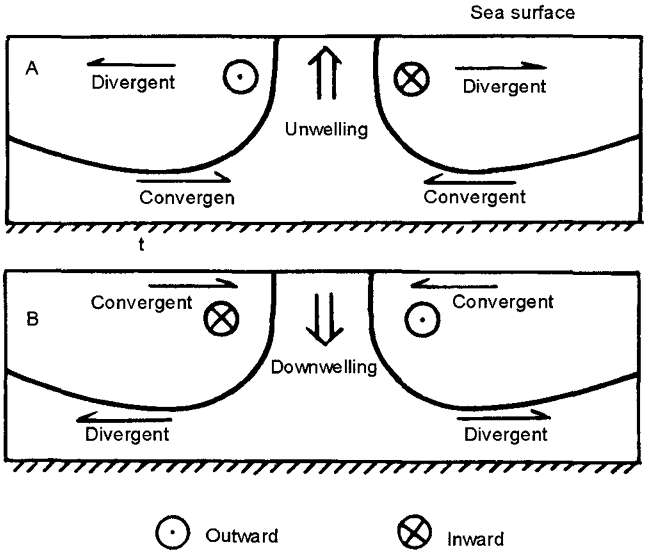

Fig. 10. Sedimentation patterns of (a) cyclonic and (b) anticyclonic eddies.

On the basis of the above analyses, the sedimentary patterns of cyclonic and anticyclonic eddies are shown in Fig. 10 [*Shi et al.*, 2003].

CONCLUSIONS

(1) The analysis of transport trend of sediment indicates that the net transport direction in fine-grained sediment deposited area in the central SYS points to point of 123.4°E, 35.1°N, which is possibly the sedimentation center, and sediments have trend to be transported toward this sedimentation center. The depositional pattern in the Yellow Sea is controlled by cyclonic circulation (including the YSCWM) and the cold-water gyre.

(2) The main sediment transport pattern in the SYS was obtained by analyzing the distribution characteristics of TSM concentration and POC $\delta^{13}C$ values. It was confirmed from the pattern that the bottom layer plays a more important role than the surface one in the process to transport the terrigenous material to the central deep-water area of the SYS. The Yellow Sea circulation is an important control factor for determining the sediment transport pattern in the SYS.

(3) The carbon isotope signals of organic matter in sediments indicate that the Shandong subaqueous delta has high sedimentation rate and the materials originate mainly from the modern Yellow River. In

the deep-water area of the SYS, the terrigenous sediments originate mainly from the old Yellow River and the modern Yellow River, and only a small portion of them originates from the modern Yangtze River. The analytical results of TSM and stable carbon isotopes are further confirmed by PAHs, another independent tracer of sediment source.

(4) 5 light mineral provinces in the SYS can be identified, and they are (I) northern mineral province, the sediment originates dominantly from the Yellow River; (II) mixed mineral province, the sediment derives from the Yellow River and Yangtze River; (III) mid-east mineral province, the sediment derives mainly from the Yellow River and a part of sediment derives from Yangtze River; (IV) eastern of Yangtze River estuary province, the sediment derives dominantly from Yangtze River; and (V) Southeastern mineral province, sediment is affected by the relict sediment and modern sediment of the Yangtze River.

(5) The modern shelf sedimentary processes in the SYS are controlled by shelf dynamic factors. The shelf low-energy environments produced some muddy depositional systems. Controlled by meso-scale cyclonic eddies (cold eddies), two cold eddy depositional systems were formed in the central SYS and the area southwest of the Cheju Island. Also, an anticyclonic muddy depositional system (warm eddy sediment) was formed in the southeast of the SYS (the area northwest of the Cheju Island). In this study, the sedimentation patterns of the cyclonic eddy and anticyclonic eddy have been given.

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REFERENCES

Alexander, C.R., D. J., Demaster and C.A., Nittrouer, 1991. Sediment accumulation in a modern epicontinental-shelf setting: The Yellow Sea, *Marine Geology*, **98**: 51–72..

Cai, D.L., 1994. Geochemistry studies on organic carbon isotope of the Huanghe River (Yellow River) estuary. *Science in China*. Series B, **37**(8): 1001–1015.

Cai, D.L., F.C. Tan and J.M., Edmond, 1988. Source and transport of particulate organic carbon in the Amazon River and Estuary, *Estuarine, Coastal and Shelf Science*, **26**: 1–14.

Cai, D.L., X.H. Mao and Y.B., Han, 1999. $^{13}C/^{14}C$ ratios applied in marine ecology system trophic level study----the primary research in marine plant isotope composition and affecting factors, *Oceanologia et Limnologia Sinica* (in Chinese), **30**(3): 306–314.

Cheng, P. and S., Gao, 2000. Marine sedimentary size characteristics and net transportation trend in the west of the northern Yellow Sea, *Oceanologia et Limnologia Sinica* (in Chinese), **31**(6): 604–615.

Chough, S.K., H.J. Lee and S. H. Yoon, 2000. Marine Geology of Korea Seas, Elsevier.

Emery, K.O., and H. Niino, 1968. Stratum and prospect of oil in the East China Sea and Korea Strait, *CCOP Technical Bulletin*, **1**: 13–27.

Gao, S., and M. Collins, 1998. Sediment grain size trend and marine sediment dynamics, *Chinese Scientific Foundation* (in Chinese), **12**(4): 241–246.

Gao, S., Y.A. Park, and Y.Y. Zhao, 1997. Transport and resuspension of fine-grained sediments over the southeastern Yellow Sea. In: Proceedings of the Korea-China International Seminar on Holocene and Late Pleistocene Environments in the Yellow Sea Basin, Nov. 20-22, 1996. Seoul: Seoul National University Press, 83–98.

Hu, D.X. 1994. Some striking features of circulation in Huanghai Sea and East China Sea. In: Zhou D, eds. Oceanology of China Sea, **1**: 27–38.

Hu, D.X., 1984. Upwelling and sedimentation dynamics, *Chin. J. Oceano. Limnol*, **2**(1): 12–19.

Ky, B.H., and J.K. Oh, 1993. Acoustic facies in the western South Sea, Korea, *The Journal of the Oceanological Society of Korea*, **28**(5): 313–322.

Lee, H.J., 1989. Sediment distribution, dispersion and budget in the Yellow Sea, *Marine Geology*, **87**: 195–205.

Li, B., 2000. The distribution of polycyclic aromatic hydrocarbons and n-alkanes in the sediments of Yellow Sea and Bohai Sea (in Chinese), Ocean University of Qingdao Master Thesis.

Li, S.Q., J. Liu, et al., 1998. Sedimentary sequence and environmental evolution in the east of the southern Yellow Sea, *Chinese Since Bulletin* (in Chinese), **43**(8): 876–880.

Lipiatou E., and A.A. Saliot, 1991. Fluxes and transport of anthropogenic and natural polycyclic aromatic hydrocarbons in the western Mediterranean Sea, *Marine Chemistry*, **32**: 51–71.

Liu, J., S.Q. Li, and S.J. Wang, 1999. Sea level changes and formation of the Yellow Sea Warm Current since the last deglaciation, *Marine Geology Quaternary Geology* (in Chinese), **19**(1): 13–24.

Liu, M.H., S.Y. Wu, and Y.J. Wang, 1987. Late Quaternary Geology of the Yellow Sea (in Chinese), Beijing: Ocean Press.

Niino, H., 1934. On the fossil locality at sea bottom of Korean Strait, *Geog. Soc.*, **9**(12): 33–34.

Niino, H., 1970. Probe the treasure-house of the East China Sea, *Ocean Age*, **11**: 40–48.

Niino, H., and K.O. Emery, 1968. Continental shelf sediments off northern Asia, *Sed. Petrol.*, **36**: 152–161.

Park, Y.A., B.K. Kim, and S.C. Park, 1990. Origin and distribution patterns of muddy deposits in the Yellow Sea. In: Proceedings of the First International Conference on Asian Marine Geology, Shanghai, September 7–10.

Qin, Y.S., Y.Y. Zhao, and L.R. Chen, 1989. Geology of the Yellow Sea (in Chinese), Beijing: Ocean Press.

Shen, S.X., H.J. Yu, and F.G. Zhang, 2000. Anticyclonic eddy sediment northwest of the Cheju Island, *Oceanologia Limnologia Sinica* (in Chinese), **31**(2): 215–220.

Shi, X. F., C.F. Chen, Y.G. Liu, et al., 2002. Trend analysis of sediment grain size and sedimentary process in the central southern Yellow Sea, *Chinese Science Bulletin*, **47**(14): 1202–1207.

Shi, X.F., S.X. Shen, H.I. Yi, Z.H. Chen, et al., 2003. Modern sedimentary environments and dynamic depositional systems in the southern Yellow Sea, *Chinese Science Bulletin*, **48**(Supp.): 1–7.

Su, J.L., and D.J. Huang, 1995. Circulation structure of the Yellow Sea Cold Water Mass, *Oceanologia et Limnologia Sinicia* (in Chinese), **26**(Supp.): 1–7.

Sun, X.G., M. Fang, and W. Huang, 2000. The time and space variations of suspended matter transportation in the Yellow Sea and East China Sea shelf regions, *Oceanologia Limnologia Sinica* (in Chinese), **31**(6): 581–587.

Tan, F.C., D.L. Cai, and J.M. Edmond, 1991. Carbon isotope geochemistry of the Changjiang estuary, *Estuarine, Coastal and Shelf Science*, **32**: 395–403.

Tang, Y.X., E.M. Zou, and H.J. Lee, 2000. Characteristics of circulation in the southern Yellow Sea, *Acta Oceanologia Sinica* (in Chinese), **22**(1): 1–16.

Yu, S., 1988. Studies on pollution behavior in Tokyo Bay and estuary surface sediments, *Marine Environment Science* (in Chinese), **7**(4): 10–16.

Zang, J.Y., Y.X. Tang, and E.M. Zou, et al., 2003. Analysis of Yellow Sea circulation, *Chinese Science Bulletin*, **48**(Supp): 12–20.

Zhao, Y.Y., F.Y. Li, C.Y. Qin, et al., 1991. On source and origin of the mud in the SYS. *Geochemistry* (in Chinese), **2**: 112–116.

Zheng, G.Y., 1989. Quaternary Stratigraphic Correlation of the SYS (in Chinese), Beijing: Science Press.

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