Chinese Journal of Oceanology and Limnology
Vol. 33 No. 2, P. 510-524, 2015
http://dx.doi.org/10.1007/s00343-015-4106-x

Mineral distributions in surface sediments of the western South Yellow Sea: implications for sediment provenance and transportation*

LU Jian (卢健)[1, 2], LI Anchun (李安春)[1, **], HUANG Peng (黄朋)[1], LI Yan (李艳)[3]

[1] *Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China*

[2] *University of Chinese Academy of Sciences, Beijing 100049, China*

[3] *Yantai Ocean Environmental Monitoring Central Station of State Oceanic Administration, Yantai 264006, China*

Received May 4, 2014; accepted in principle Jul. 7, 2014; accepted for publication Aug. 18, 2014

© Chinese Society for Oceanology and Limnology, Science Press, and Springer-Verlag Berlin Heidelberg 2015

Abstract The South Yellow Sea (SYS) is strongly influenced by the substantial sediment loads of the Huanghe (Yellow) (including the modern Huanghe and abandoned old Huanghe subaqueous delta) and Changjiang (Yangtze) Rivers. However, the dispersal patterns of these sediments, especially in the western SYS, have not been clearly illustrated. In this study, we have analyzed clay minerals, detrital minerals, and grain sizes for 245 surface sediment samples (0–5 cm) collected from the western SYS. The clay minerals, on average, consist of 67% illite, 14% smectite, 11% chlorite, and 8% kaolinite. Clay minerals, detrital minerals, and grain size analyses of surface sediments, combined with water mass hydrology analysis, reveal that sediments in the western SYS are mainly derived from the modern Huanghe River, the abandoned subaqueous delta of the old Huanghe River, some material from the Changjiang, and coastal erosion. The clay minerals (especially illite and smectite) and quartz/feldspar ratio distribution patterns, reveal that the influence of modern Huanghe sediments can reach 35°N in the northwestern part of the study area, an influence that can be enhanced especially in winter owing to northerly winds. Conversely, sediments along the Jiangsu coast are mixed, in summer, with material from the Changjiang arriving via northward flow of Changjiang Diluted Water. The Subei Coastal Current carries the refreshed sediments northward into the western SYS. Sediment distribution and transport in the western SYS are mainly controlled by the oceanic circulation system that is primarily related to the monsoon.

Keyword: South Yellow Sea; clay mineral; Subei Coastal Current; provenance

1 INTRODUCTION

The South Yellow Sea (SYS) has been influenced by large volumes of sediment derived from the Huanghe (Yellow) and Changjiang (Yangtze) Rivers during the Holocene (Milliman et al., 1985; Ren and Shi, 1986; Qin et al., 1989; Alexander et al., 1991). Because of the complex hydrodynamic system (Su and Yuan, 2005) and wide range of sediment sources (Yang et al., 2003; Shi et al., 2012), the sediment dispersal patterns and transport paths in the SYS are not thoroughly understood.

As an important constituent of marine sediments, clay minerals are widely distributed in various types of sediments. They are sensitive indicators of geological processes and environmental change. Therefore, characteristics of clay minerals such as their compositions, assemblages, shapes and structures can help to identify sediment provenance and depositional environment (Park and Han, 1984; Lan, 2001). For example, clay mineral studies in marine surface sediments are able to indicate the provenance of the clay in the world's oceans (Griffin et al., 1968), currents in the Indian Ocean (Gingele et al., 2001), and sediment transport paths in the South

---

* Supported by the National Natural Science Foundation of China (Nos. 41076032, 41430965)

** Corresponding author: acli@qdio.ac.cn

Atlantic Ocean (Petschick et al., 1996) and South China Sea (Liu et al., 2010a, b). The study of clay minerals in the SYS began in the 1970s (Li, 1990). Subsequently, a number of studies on these clay minerals were undertaken that described the clay mineral distribution (Zhao, 1983; Shi et al., 1989; Li, 1990), discussed the sources of the fine-grained sediments in the central SYS (Park and Khim, 1992; Wei et al., 2001), and analyzed the provenance of clay minerals in the SYS (He, 1989; Song et al., 2008; Lan et al., 2011). However, restricted by technical and economic conditions, previous studies have been limited in their sample numbers, and have focused on specific areas. Moreover, inconsistencies in sample pretreatments and analytical procedures prevent the comparisons of similar studies or the compilation of their results, because abundances of clay minerals are significantly dependent on pretreatments, X-ray machine conditions, and calculation methods (Park and Khim, 1992). Also, sediment distributions can be greatly constrained by oceanographic conditions (Milliman et al., 1986); however, in some previous studies, the influence of the oceanic circulation system on sediment distribution and transport in the SYS has been underestimated or neglected.

Sediment provenance and dispersal patterns in the SYS have been discriminated using sedimentological (Milliman et al., 1989) and geochemical (Yang et al., 2003) approaches, and also numerical simulations (Chen and Zhu, 2012). However, most of these studies were primarily restricted to the eastern (Chough et al., 2004; Lim et al., 2007) and central (Shi et al., 2012) SYS. The western SYS (with water depths <50 m) have not been as involved in such studies. Annually, the Huanghe and Changjiang Rivers discharge a large volume of fluvial clastics into the sea (Milliman and Meade, 1983). During the period spanning AD 1128–1855, the Huanghe River annually discharged about 1.1×10^9 tons of suspended sediments into the Yellow Sea (Milliman et al., 1985). However, the dispersal patterns of the sediments from the Huanghe (including the current Huanghe and the abandoned old Huanghe River subaqueous delta) and Changjiang Rivers in the western SYS have not been clearly illustrated. Therefore, it is necessary to investigate the sediment provenance and transport paths in the western SYS that has been contaminated by anthropogenic activities (Hong et al., 1998).

The main objectives of this study are: (1) to discriminate sediment provenance in the western SYS based on clay mineral and detrital mineral analyses, and (2) to characterize the transport paths of major sediment sources based on combined analyses of clay minerals, detrital minerals, grain sizes, and water mass hydrology.

2 REGIONAL SETTING

The Yellow Sea is a semi-enclosed epicontinental sea surrounded by China mainland and the Korean Peninsula. The seafloor is relatively flat, and tilts to the center and southeast from the north, east, and west. The average water depth of the SYS is 46 m, with a north-south oriented trough named the Yellow Sea Trough located in the center and east with water depths of 60–80 m. Most outcrop exposed along the coast of Shandong Peninsula is bedrock, whereas there are bedrock, sandy and muddy coasts on the Jiangsu coastal plain. Southerly and southeasterly winds prevail in summer, contrasting with northerly and northeasterly winds in winter, caused by the typical East Asian monsoon (Qin et al., 1989).

The main components of the circulation system in the Yellow Sea are the Yellow Sea Warm Current (YSWC) and the coastal currents along the west and east coasts in the cold months (December–April). The YSWC extends toward the SYS with a tongue-like shape from the southwest of Cheju Island, and is distributed right from the surface to the bottom water. The Yellow Sea Coastal Current (YSCC) flows eastward along the northern coast of the Shandong Peninsula and turns southward and southwestward at the east of the Shandong Peninsula Tip. The southward branch along the 40–50 m isobaths turns southeastward near 33–32°N (Su and Yuan, 2005). Additionally, the Subei Coastal Current (SCC) along the southwest coast of the SYS flows southeastward in winter (Fig.1a). The tidal currents in the southwestern part of the SYS are hydrodynamically strong, with tidal current velocities exceeding 100 cm/s (Ding, 1985; Dong et al., 1989). The circulation in warm months (May–November) presents an almost enclosed loop owing to the Yellow Sea Cold Water (YSCW) density current (Su and Yuan, 2005). In contrast to the winter, the SCC flows northward in summer according to recent studies (Xia et al., 2006; Yuan et al., 2008; Liu and Hu, 2009; Pang et al., 2011; Wang et al., 2013). The velocities of currents and tidal currents in the SYS are listed in Table 1.

The modern Huanghe River empties into the Bohai Sea (BS) to the north of the study area, and to the south the Changjiang River discharges into the East

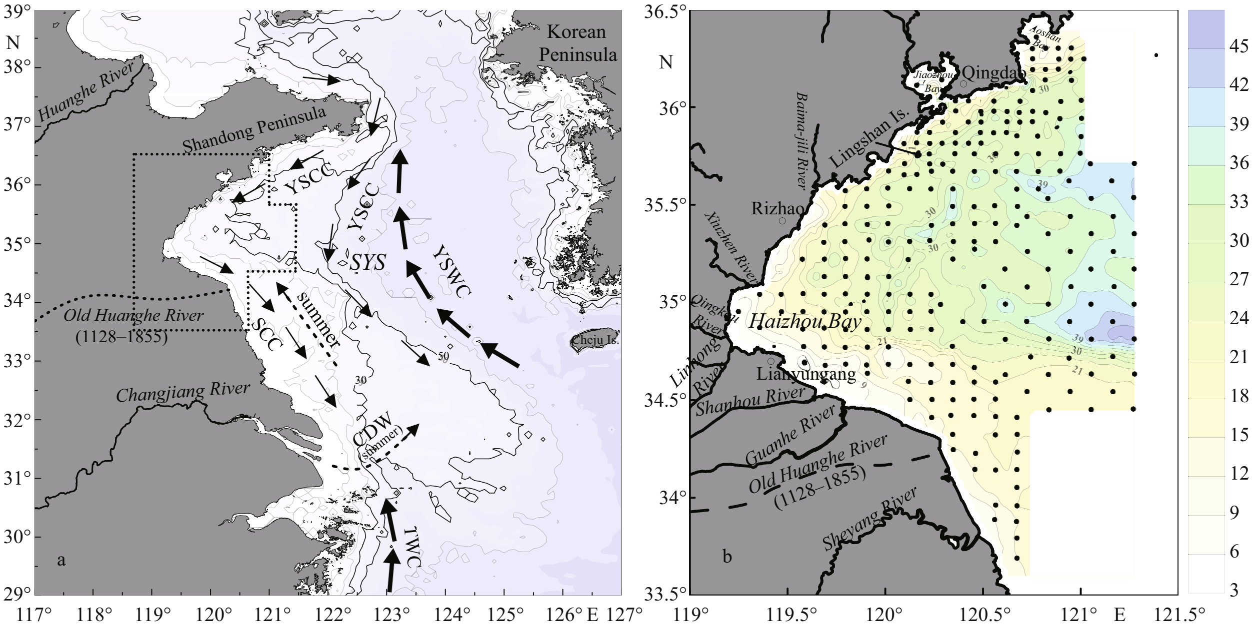

Fig.1 The circulation system in the South Yellow Sea (modified after Su, 2005) (a); spatial distribution of the sample stations and bathymetric contours (b)

Units: m. YSCC: Yellow Sea Coastal Current; YSWC: Yellow Sea Warm Current; SYS: South Yellow Sea; SCC: Subei Coastal Current; CDW: Changjiang Diluted Water; TWC: Taiwan Warm Current.

Table 1 Current and tidal current velocities in the SYS

		Velocity (cm/s)	Data sources
Currents	YSCC (near the Shandong Peninsula Tip)	>30	(Sun, 2006)
	YSCC (south of 34°N, east of 122°E)	25	(Sun, 2006)
	YSWC	5–10	(Su and Yuan, 2005)
M_2 tidal current	West coast of SYS	20–40	(Fang, 1986)
	Subei Coast	>60	(Fang, 1986)
	Central SYS	20	(Fang, 1986)

China Sea (ECS). The modern Huanghe and Changjiang rivers annually discharge about 1.1×10^9 and 5.0×10^8 tons of suspended sediment, respectively (Milliman and Meade, 1983). About 9%–15% of the annual discharged sediment from the Huanghe River accumulates in the Yellow Sea, and two-thirds of the sediment accumulates in the Shandong subaqueous delta, with the remaining sediment spreading and accumulating in the southern part of the Yellow Sea (Alexander et al., 1991). With regard to heavy mineral and clay mineral assemblages, as well as the geochemical characteristics of surface sediments, Lan et al. (2005) pointed out that material from the Changjiang River would mainly affect areas south of 33°N in the SYS. Additionally, the southern part of the study area is located at the subaqueous delta formed by the Huanghe River between AD 1128 and 1855 (Milliman et al., 1985). There are some other small rivers including the Baima-Jili, Xiuzhen, Qingkou, Linhong, Shanhou, Guanhe and Sheyang Rivers from north to south along the west coast of the study area (Fig.1b and Table 2). The total drainage area of these rivers is about 14.8×10^3 km^2, accounting for only 1.96% of the Huanghe River drainage area, and 0.82% of the Changjiang River. The total annual water discharge of the rivers is about 14% of the Huanghe River, and 0.8% of the Changjiang River. Owing to the lack of data for the annual suspended sediment load for every river, we have had to estimate the total load. Taking the annual suspended sediment load of the Guanhe River as a reference, we calculate that the total annual suspended sediment load of the rivers along the west coast of the study area is about 3.2×10^6 tons, less than 10% of the suspended sediment load of the Huanghe River accumulating in the southern part of the Yellow Sea (more than 3.3×10^7 tons/year according to Alexander et al., 1991). This is a minor sediment discharge in the study area. Therefore, these rivers mainly affect the sediment distribution near estuaries.

The samples in this study are distributed in an area less than 50 m deep (Fig.1a), in close proximity to abundant human activities. An accurate discrimination

Table 2 Parameters of the main rivers in and around the study area

River	Length (km)	Drainage area (km^2)	Water discharge(10^8 m^3/year)	Suspended sediment Load (10^6 tons/year)	Data source
Huanghe River	5 464	$0.752×10^6$	490	1 080	Hay (1998)
Changjiang River	6 300	$1.8×10^6$	9 000	500	Hay (1998)
Baima-Jili River	72.7	$0.497×10^3$	1.69	-	a
Xiuzhen River	45	$0.396×10^3$	-	-	a
Qingkou River	64	$0.493×10^3$	-	-	a
Linhong River	175	$1.349×10^3$	-	-	a
Guanhe River	74.5	$8×10^3$	15	0.7	Liu et al. (2006b)
Sheyang River	198	$4.036×10^3$	44.35	-	Ma et al. (2010)

a: http://zh.wikipedia.org; -: no data.

of provenance and depositional environment can provide a better understanding of sediments transportation, along with the migration and diffusion of pollutants.

3 MATERIAL AND METHOD

A total of 245 surface sediment samples were collected with box or grab samplers during a series of cruises between June and November in 2008. The sampling interval is 6 km×6 km in the northwest, 10 km×10 km in the west and south, and 14 km×14 km in the east (Fig.1b). After removal of organic matter and carbonate with 10% hydrogen peroxide and 10% acetic acid, respectively, the samples were fully cleaned with distilled water. According to the Stoke's settling velocity principle, clay components smaller than 2 μm were separated out. Then the clay components were made into air-dried clay slides, and the same slides were saturated with ethylene glycol to prepare for analysis. To identify clay mineral compositions correctly, we heated some slides at 550°C for 2 h before reanalysis. Clay minerals were analyzed by X-ray diffraction (XRD) on a D8 ADVANCE diffractometer with CuKα radiation (40 kV, 40 mA). The step size was 0.02° with a step interval of 2 steps/s and a scan range between 3° and 30° (2θ).

The semi-quantitative calculation of relative clay mineral content followed the method introduced by Biscaye (1965). The position of the (001) series of basal reflections on the ethylene glycol saturation slide XRD spectrum was used for clay mineral identification (Fig.2). The integrated peak areas of four kinds of clay minerals were calculated using the software TOPAS. The three integrated peak areas, smectite (17Å) (including mixed-layers), illite (10Å), kaolinite and chlorite (7Å) on the XRD spectrum of glycolated slides, were used to estimate the relative content of the four main clay minerals, with empirical factors of 1, 4, and 2, respectively. Relative proportions of chlorite and kaolinite were obtained by calculating the peak area ratio 3.54Å/3.57Å close to 25° (2θ) on the XRD spectrum.

Furthermore, to maintain data consistency, we analyzed the clay minerals of sediment samples collected from the downstream sections of the modern Huanghe and Changjiang Rivers, following the pretreatment and calculation methods introduced above.

Grain sizes of the 245 samples were analyzed with a Cilas 940L laser particle size analyzer (0.3–2 000 μm) after separate pretreatments with 15% hydrogen peroxide and 0.25 mol/L hydrochloric acid to remove organic matter and carbonate. The light and heavy minerals in the fine-sand components (63–125 μm) were separated with heavy liquid (density of 2.80 g/cm^3, bromoform diluted with alcohol). After the mineral species were identified and counted with the microscope, the particle percentages were calculated.

The clay mineral, grain size and detrital mineral analyses were carried out in the Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences (IOCAS).

Salinity data were obtained with a SBE9 CTD (conductivity, temperature and depth sonde), and the velocities and directions of tidal currents in the SYS were collected by a ship-mounted ADCP (Acoustic Doppler Current Profiler) during the May 2009 and July 2012 Open Cruises of Chinese Offshore Oceanography Research by IOCAS, respectively.

To better classify the provenances of all the surface sediment samples, we used cluster analysis provided by the software SPSS 13.

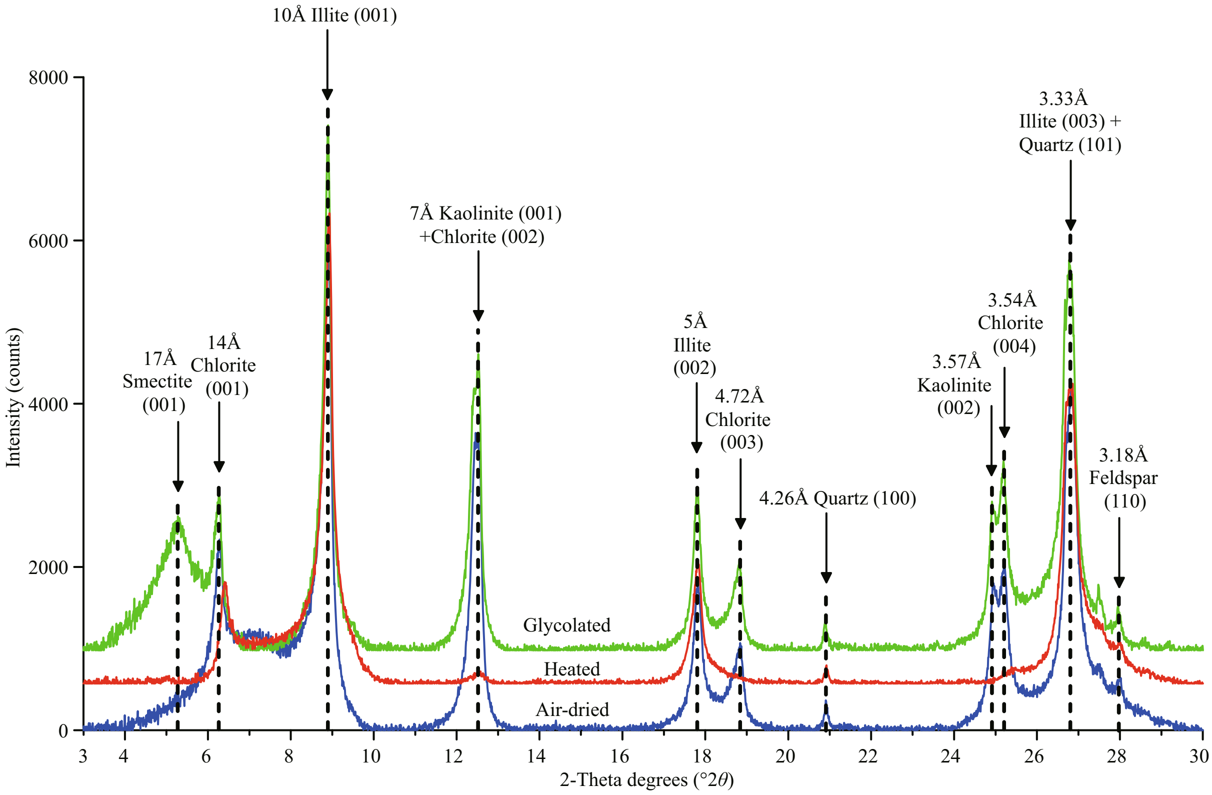

Fig.2 Multiple X-ray spectra of a typical sample from the western SYS with various treatments as indicated (air-dried, heated and glycolated)

According to Biscaye, 1965; Liu et al., 2010b.

4 RESULT

Sand content ranges between 0 and 90.86% (average 23.50%), with higher values in the central part and lower values in the northern and southern parts of the study area (Fig.3a). In contrast, the silt content, ranging from 6.20% to 86.36% (average 53.34%) has the reverse distribution with lower values in the central part while the northern and southern parts are characterized by silt contents greater than 50% (Fig.3b). The clay content is between 1.22% and 59.62%, with an average of 23.16% (Fig. 3c). The area between Qingdao and Lingshan Island as well as Haizhou Bay are defined by clay contents exceeding 20%, whereas the clay content ranges from 20% to ≥50% in the abandoned old Huanghe River subaqueous delta. A tongue-like distribution of high clay content occurs in the northeastern study area off Qingdao coast. With the exception of some patches with a content in excess of 15%, the clay content in the other regions is less than 10%.

The clay minerals are composed of illite (average 67%), smectite (14%), chlorite (11%), and kaolinite (8%).

Illite (average 67%) dominates the four clay minerals, with a range of concentrations between 57% and 77% (Fig.4a). The northwestern part of the study area located between the coasts of Qingdao and Rizhao, and the estuaries of the Shanhou and Guanhe rivers in Haizhou Bay present a relatively high illite content (>67%). In contrast, the abandoned old Huanghe River subaqueous delta presents a medium illite content (about 65%). Except for these two areas, most of the study area has illite contents <65%.

Smectite content (average 14%) ranges from 7% to 24% (Fig.4b), and the spatial distribution can be divided into three parts by the 14% contour. A relatively low smectite content (<14%) is observed in the northwest off the Qingdao and Rizhao coasts and in the south off the abandoned old Huanghe River subaqueous delta. In contrast, higher smectite content (>14%) occurs in the middle of the study area. The distribution characteristics of smectite are opposite to those of illite, such that high concentrations of smectite correspond to low concentrations of illite at the same locations. Therefore, there is a negative correlation between illite and smectite contents (Fig.5).

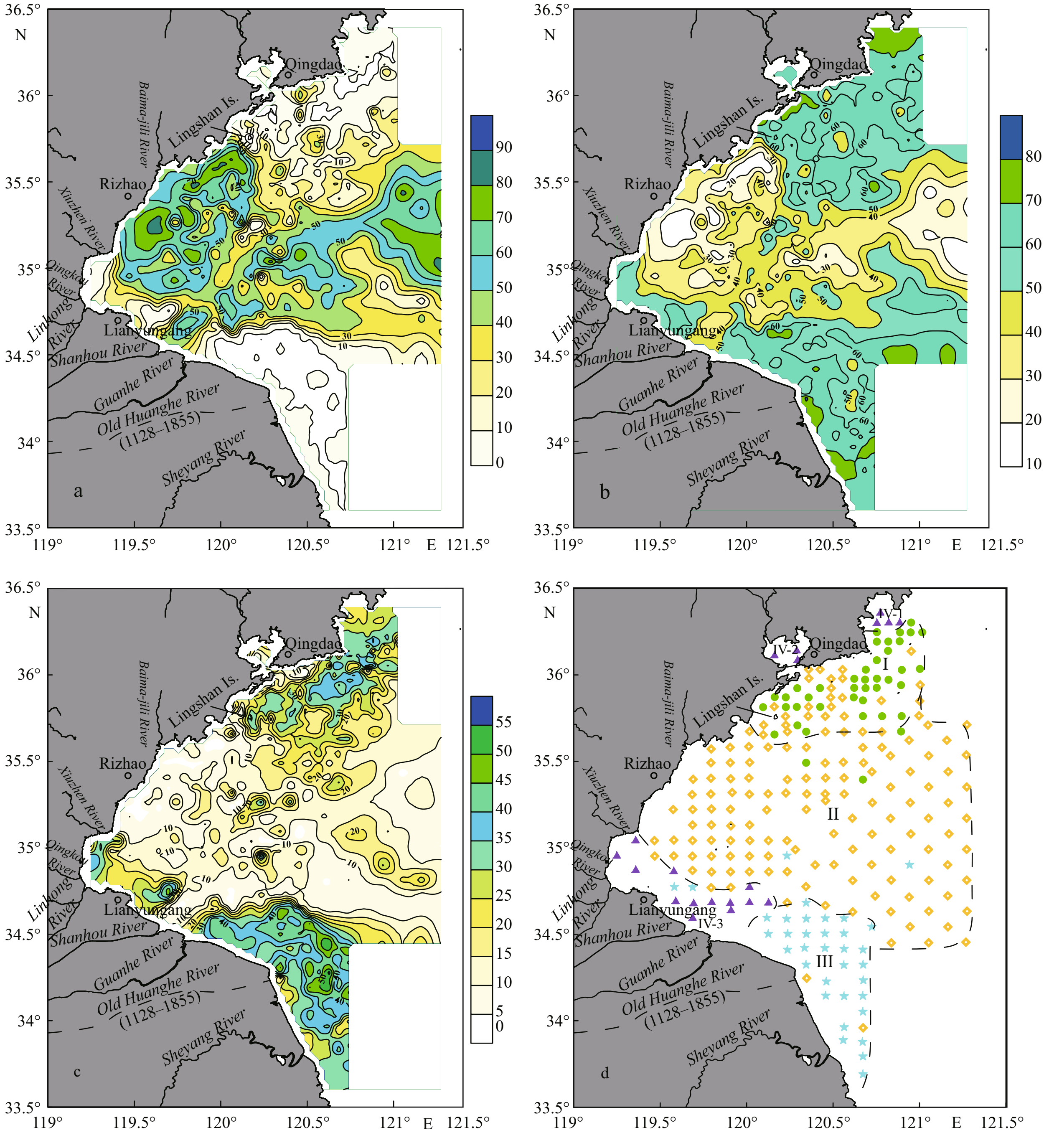

Fig.3 (a) Sand content (%), (b) silt content (%), (c) clay content (%), (d) cluster analysis results of clay minerals

I: northern zone; II: central zone; III: southern zone; IV-1: Aoshan Bay; IV-2: Jiaozhou Bay; IV-3: Haizhou Bay.

Kaolinite (average 8%) is the lowest in the study area with a content range between 5% and 12% (Fig.4c). The kaolinite content in the northern region is mostly less than 8% and it displays an uneven distribution, while in the southern region it is more than 8%.

Chlorite contents vary from 8% to 17% (average 11%) in the study area (Fig.4d). The regions of highest content (>13%) occur around Lingshan Island and the offshore areas of Rizhao and the southeastern area. The low content mainly occurs in the central part of the study area.

Results of clay mineral cluster analysis show that surface sediment samples in the study area can be clustered into four main zones (Fig.3d), a northern zone (I), central zone (II), southern zone (III), and bays (IV). Furthermore, the fourth zone (IV) could be subdivided into three zones, Aoshan Bay (IV-1),

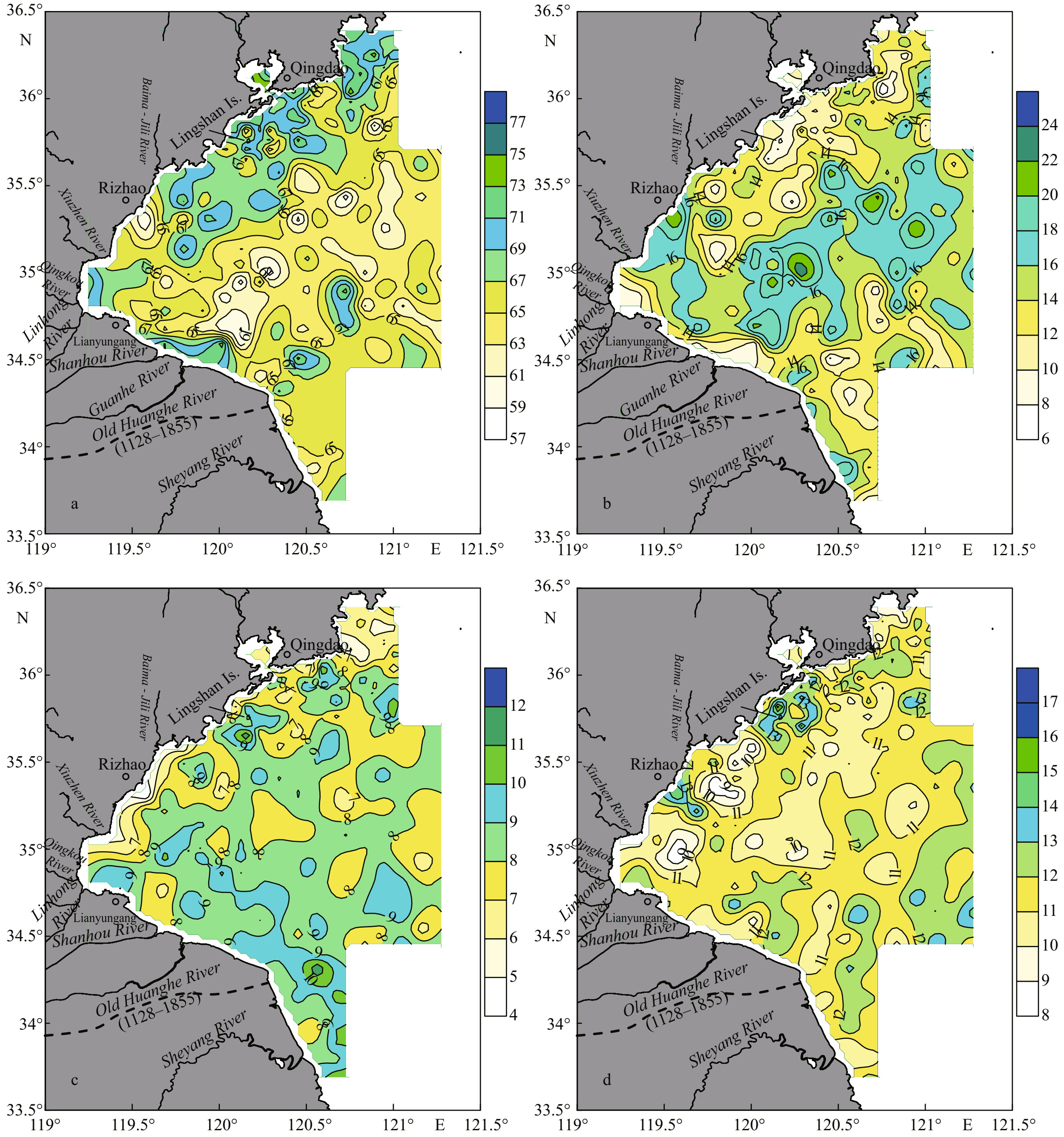

Fig.4 Spatial distribution of clay mineral contents (%) in the western SYS

a. Illite; b. smectite; c. kaolinite; d. chlorite.

Jiaozhou Bay (IV-2), and Haizhou Bay (IV-3).

The clay mineral assemblages of the four zones are listed in Table 3.

5 DISCUSSION

5.1 Provenance analysis

Previous studies have indicated that the main sediment sources in the western SYS are terrigenous materials derived from modern Huanghe sediments and carried by YSCC, substances resuspended and carried from the abandoned old Huanghe River subaqueous delta (Qin et al., 1989), and material from the Changjiang (Lee and Chough, 1989; Wei et al., 2001; Lan et al., 2005; Lan et al., 2011). Other materials, such as authigenic minerals and aerosol materials, are only a minor component (Shi et al., 2012).

As the results show (Table 3), smectite contents

Table 3 Clay mineral assemblages of the four zones, Huanghe and Changjiang Rivers

Zones	Clay content (%)	Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Illite/Smectite	Kaolinite/Chlorite
I (41)	32.39	13	68	8	12	5.70	0.66
II (149)	12.56	15	66	8	11	4.84	0.73
III (35)	37.12	13	66	9	12	5.27	0.78
IV-1 (4)	23.49	13	70	6	10	5.45	0.63
IV-2 (3)	24.12	10	73	7	10	7.88	0.64
IV-3 (13)	16.37	15	65	8	12	4.66	0.72
Western SYS	0.28–59.62	7–24	57–77	5–12	8–17	2.41–10.41	0.45–1.07
	21.46	14	67	8	11	5.09	0.72
Huanghe (19)	-	26	56	8	11	2.19	0.74
Changjiang (5)	-	7	71	7	14	10.83	0.53

Number in the parentheses represent sample numbers.

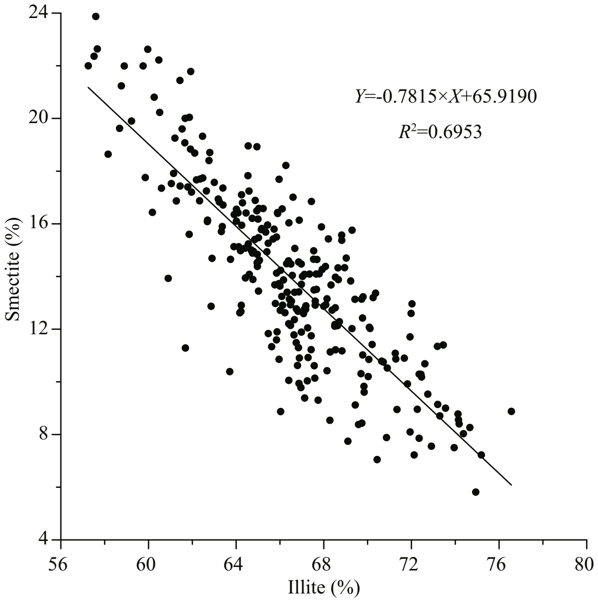

Fig.5 Relationship between illite and smectite contents (%)

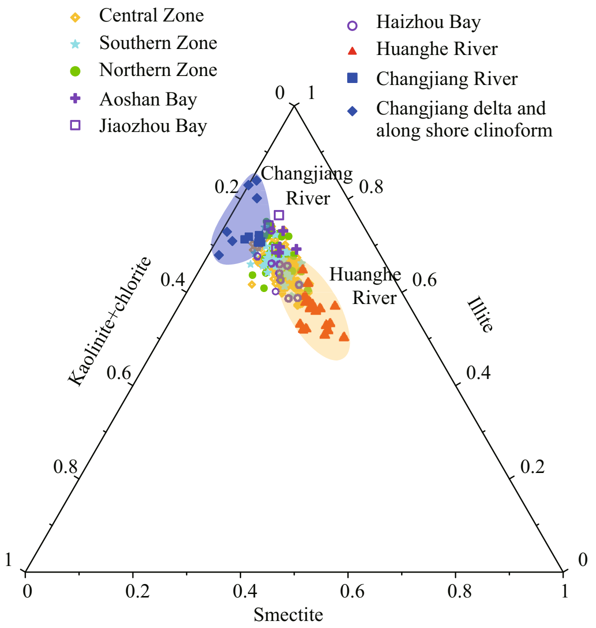

Fig.6 Ternary diagram of clay minerals smectite, illite, and kaolinite+chlorite

vary from 7% to 24%. This is clearly determined by the smectite contents of the sources (modern Huanghe River=26%, Changjiang River=7%), which is consistent with previous studies. Because of the addition of material from the Changjiang and other sediment sources, smectite content in the western SYS has been diluted.

We plotted a ternary diagram with smectite, illite and kaolinite+chlorite as end members to discriminate the provenance of clay minerals in the western SYS (Fig.6). Additionally, some surface sediment samples from the along-shelf clinoform in the East China Sea, which is derived from the Changjiang River (Liu et al., 2006a), are added in the diagram. The ternary diagram indicates that the composition of clay mineral assemblages in the western SYS lies between those of the modern Huanghe and Changjiang Rivers.

Because of the various possible clay mineral assemblages, the illite/smectite and kaolinite/chlorite ratios in modern Huanghe sediments are significantly different from those of the Changjiang River. Fan et al. (2001) suggested that the illite/smectite ratios in modern Huanghe sediments characteristically exceed 8, whereas, at the Changjiang River, the ratio is <6. In our results, the illite/smectite ratios range from 2.41 to 10.41, with an average value of 5.09 (Table 3). This indicates that the sediment sources are derived from the modern Huanghe and Changjiang Rivers (Fig.7a).

The different characteristics of clay mineral assemblages in the modern Huanghe and Changjiang

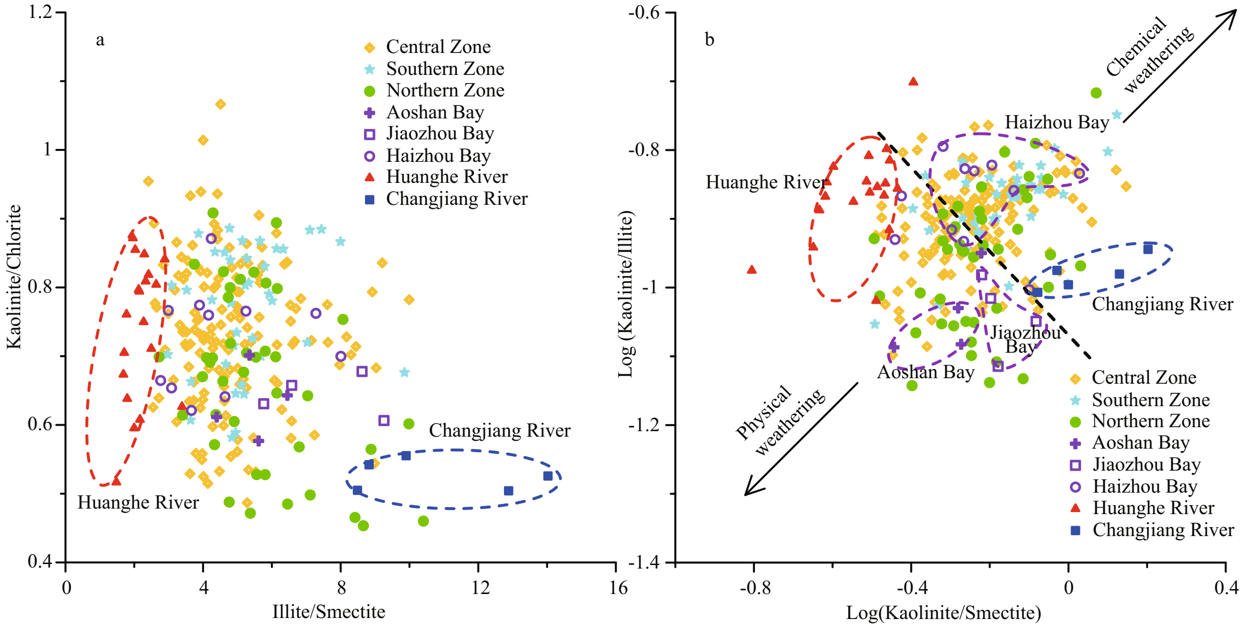

Fig.7 Correlation diagrams between illite/smectite and kaolinite/chlorite(a); log ratios transformed from kaolinite, smectite and illite (b)

sediments are dependent on distinctive climate types (Yang, 1988; Fan et al., 2001) and geological backgrounds (Yang and Li, 1999; Fan et al., 2001). About 90% of the Huanghe sediment come from loess deposits, which are widely distributed in the central reaches of the Huanghe River, where loess deposits suffer intense physical weathering (Chen et al., 1984; Ren and Shi, 1986). In comparison, the sediments in the Changjiang drainage basin have complex sources. Paleozoic carbonate rocks, acidic metamorphic rocks, and Quaternary clastic sediments dominate the upper, middle and lower reaches, respectively (Qu and Yan, 1990; Zhang et al., 1990; Yang et al., 2000). In contrast with the Huanghe River, strong chemical weathering happens in the Changjiang drainage basin (Chen et al., 1984).

To eliminate the constant-sum constraint, a bivariate plot (Fig.7b) of log ratios transformed from kaolinite to smectite and illite is used to illustrate the extent of weathering (Vital et al., 1999). From the plot (Fig.7b), we can see that chemical weathering in the Changjiang drainage basin is stronger than that in the Huanghe basin, in accordance with the weathering conditions in the two river basins.

The clay minerals in the northern zone (I) are mainly derived from modern Huanghe sediments carried by the YSCC (Fig.1a) along the south coast of the Shandong Peninsula (Qin et al., 1989). Martin et al. (1993) pointed out that the influence of modern Huanghe sediments on the Yellow Sea was mostly limited to north of 36°N. However, fine-grained sediments, especially clay-sized particles, can be advected over a long distance before removal from the water mass, so they can settle far away from their original sources (Martin et al., 1993; Gingele et al., 2001). During the process of alongshore transport (Fig.1a), the YSCC can interact with local waves, tides and upwellings (Yang and Liu, 2007), so the addition of coastal erosion and resuspended sediments probably increased the illite content, while lowering the smectite content (Fig.4a, b). So the strip of lower smectite content in the northwestern part of the study area can represent the region of influence of modern Huanghe sediments. From the smectite content distribution (Fig.4b), observe that to the north of 35°N, the western SYS is mainly influenced by modern Huanghe sediments (Fig.3d). In winter, the influence of modern Huanghe sediments can be enhanced owing to the prevailing northerly winds. Moreover, the strip of higher smectite content in Haizhou Bay indicates that the YSCC (along the south coast of Shandong Peninsula) cannot connect with the SCC in winter (Fig.1a).

The central zone (II), with a lower clay content of about 12% (Table 3), is mainly composed of relict sediments (Wu, 1981; Wang, 1982; Liu, 1987). The relict sediments were deposited on the continental shelves during and immediately after the latest glacial stage of the Pleistocene, and as such are not related to their present environments (Emery, 1968). The relict sediments experienced strong hydrodynamic sorting at the time of lower glacial-period sea levels, and fine-grained sediments were removed (Wang, 1982). As a result, the clay content is low there, especially under the condition of a lack of any supplementary material. Additionally, the ancient Huanghe River delta was formed in the western SYS in the late Pleistocene (Li et al., 1993), so the higher smectite content in the central zone (II) (Fig.4b) may reflect the original clay mineral compositions of pure Huanghe sediments. The western part of the central zone (II), just offshore from Rizhao, which is dominated by strong hydrodynamic conditions (probably strong tidal currents or waves) (Lü, 1982), is now in an erosional environment where clay minerals cannot accumulate.

The southern zone (III) covers the region of the abandoned old Huanghe River subaqueous delta (Milliman et al., 1985), which is governed by strong tidal currents and waves (Ding, 1985; Liu et al., 1989). The surface sediments of the subaqueous delta are mainly composed of silty mud and muddy silt (Yuan and Chen, 1984), so from our results, the sediment types are classified as silt and mud (Folk et al., 1970). Under the influence of strong hydrodynamic conditions, about (0.5–1.0)×10^9 tons of suspended sediment are produced near the abandoned old Huanghe delta mouth annually (DeMaster et al., 1985; Saito and Yang, 1994). Clay minerals in the southern zone (III) mainly come from the abandoned old Huanghe River subaqueous delta sediments. Compared with the modern Huanghe River, the clay mineral assemblages of the abandoned old subaqueous delta present different characteristics (Fig.6 southern zone (III) compared with Huanghe River). Moreover, the chemical weathering reflected from the clay minerals of the abandoned old Huanghe River subaqueous delta is stronger than that of modern river (Fig.7b southern zone (III) compared with the Huanghe River). After the Huanghe River channel shifted back into the Bohai Sea in AD 1855, the abandoned old Huanghe River subaqueous delta underwent reworking because of the strong hydrodynamic conditions of tidal currents and waves (Yuan and Chen, 1984; Liu et al., 2013).

The clay minerals in the bays (Aoshan Bay (IV-1), Jiaozhou Bay (IV-2), and Haizhou Bay (IV-3)) mostly originate from coastal erosions, resuspended sediment and discharge from small nearby rivers (Gao et al., 1982; Zhao et al., 1983). So they present a different clay mineral assemblage (Fig.6). The chemical weathering in Aoshan, Jiaozhou, and Haizhou bays presents an increasing trend from north to south (Fig.7b), which indicates a different supply of sediment sources.

5.2 Sediment transport mechanism in the western SYS

Numerical studies and in-situ observations indicate that tidal currents dominate sediment resuspension, transport, and deposition in the Yellow Sea (Dong et al., 1989; Lee and Chu, 2001; Lu et al., 2011). By analyzing the clay mineralogy of surface sediments, one can track the transport pathway of suspended particles (Zöllmer and Irion, 1993). As discussed above, modern Huanghe sediments are carried by the YSCC and influence the northwestern part of the study area. Additionally, from the diagrams of clay mineral assemblages (Figs.6, 7), we find that material from the Changjiang can also influence the western SYS, but how do these substances influence the western SYS?

Changjiang Diluted Water (CDW) is found in the vicinity of Changjiang estuary and Hangzhou Bay. It is composed of a mixture of fresh water (mainly from the Changjiang and Qiantang Rivers) and seawater. Generally, an isohaline of 30 has been defined as the CDW boundary, which can spread to the southwest of the SYS and connect to the SCC (Sun, 2006). Based on the distribution of maximum bottom stresses associated with the dominant M_2 and M_4 currents, Milliman et al. (1985) pointed out that the maximum bottom stress north of the Changjiang was directed northwestward, meaning that fine-grained material could be retained within the coastal region. From May to July, southerly and southeasterly winds are prevalent in the SYS (Qin et al., 1989), and surface currents flow in a predominantly northward direction (Pang et al., 2011). Therefore, about 0.34×10^8 tons of suspended sediments (including some Changjiang material) are transported from the East China Sea (ECS) to the SYS through the 32°N section in spring and summer (Pang et al., 2003). A clay mineralogy study shows that south of Jianggang (32°40′N), intertidal flat sediments were greatly influenced by sediments from the Changjiang River (Ren and Shi, 1986). A numerical simulation of tidal elevations and currents in the Yellow Sea showed that some of the Changjiang substances could be transported northward just offshore from the northern Jiangsu coast (Zhu and Chang, 2000); a MODIS satellite observation indicated that the northward expansion of the CDW in summer could refresh the Subei coasts with Changjiang sediments (Yuan et al., 2008). Based on the Empirical Orthogonal Function and freshwater flux analysis, Wu et al. (2014) found that a portion of the Changjiang plume spread northward along the Jiangsu Coast in both summer and autumn seasons. In our results, the spatial distribution of salinity in May 2009 (Fig.8a) also reveals northeastward and northward spread of CDW, which can be confirmed by the tidal current directions measured by ship-mounted ADCP (Fig.8b) and numerical simulations of surface tidal currents in July (Fig.8c). The CDW can connect with the SCC, therefore the sediment on Subei coasts can be redistributed and mixed with Changjiang substances.

Subei Coastal Water (SCW) is a mixture of fresh water (mainly from the Guanhe River, Jiangsu Irrigation Channel, Sheyang River and some other rivers along the northern Jiangsu coast) and seawater. Because of a flat seafloor and a shallow water depth, the horizontal distribution of the SCW is wide, and because of the strong hydrodynamic conditions along the Jiangsu coast, the SCW is found almost the whole way from the surface to the seabed (Sun, 2006). As described previously in the Regional Setting section, the SCC flows northward in summer, which can be further confirmed by the tidal current directions measured by ship-mounted ADCP (Fig.8b), and the drift path of *Enteromorpha prolifera* outbreak in the summer of 2008 (Hu et al., 2010).

Dolomite is the characteristic mineral of Changjiang sediments, with an average dolomite content of about 26%, much higher than that of the modern Huanghe sediments (average 4%) or the dolomite content in the abandoned old Huanghe River subaqueous delta (about 10%) (Chen, 1989). According to the different dolomite contents in these three sediments, which include the addition of Changjiang sediments, we conclude that the dolomite content in the abandoned old Huanghe River subaqueous delta has been increased; this is consistent with the results deduced from clay mineral assemblages (Figs.6, 7) that the abandoned old Huanghe River subaqueous delta has been reworked (AD 1855 to present) after the northward migration of the Huanghe River. Under the influence of Coriolis force, the drift path of the SCC continuously deflects to the right. From the results of heavy mineral identification, the narrow east-west corridor in dolomite spatial distribution (Fig.9a) could represent a northward transport pathway for sediments from the abandoned old Huanghe River subaqueous delta and some of the material from the Changjiang,

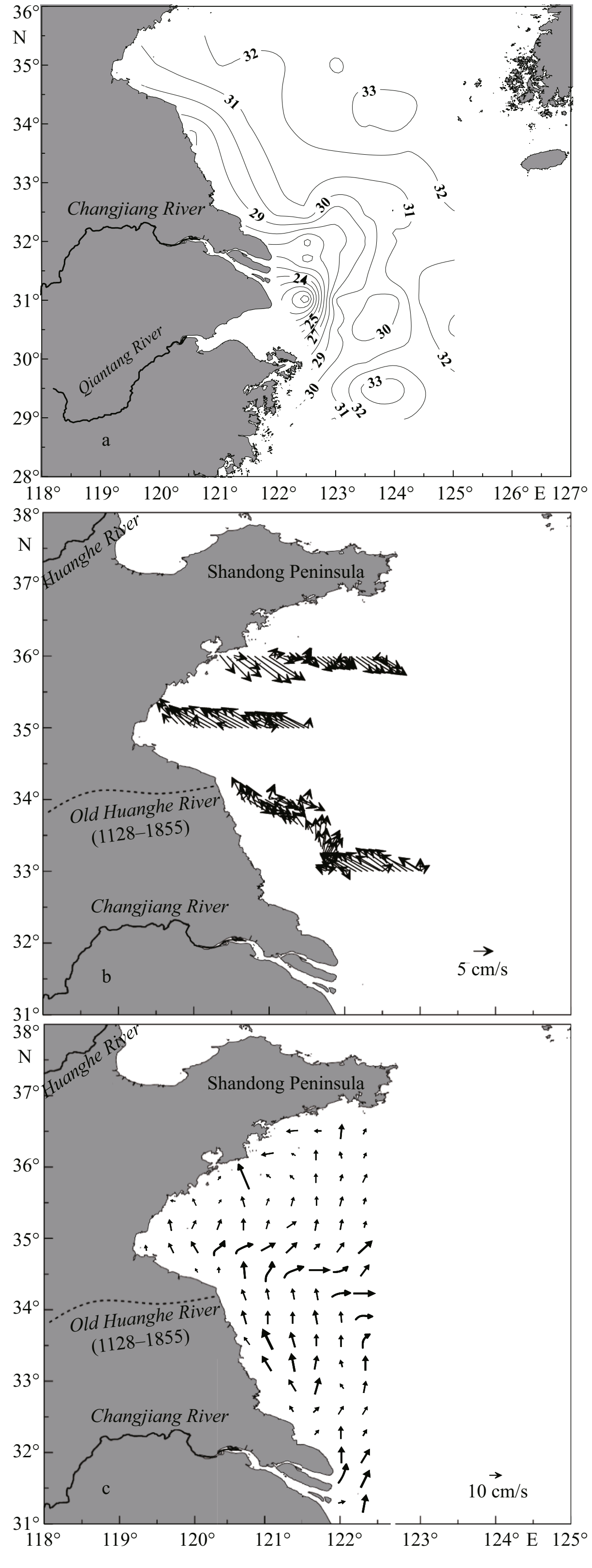

Fig.8 Surface seawater salinity spatial distribution in May 2009 (a); velocity of the 17-m-deep layer measured by ship-mounted ADCP in July 2012 (b); monthly mean currents in the July surface layer (c) (modified after Bian, 2013)

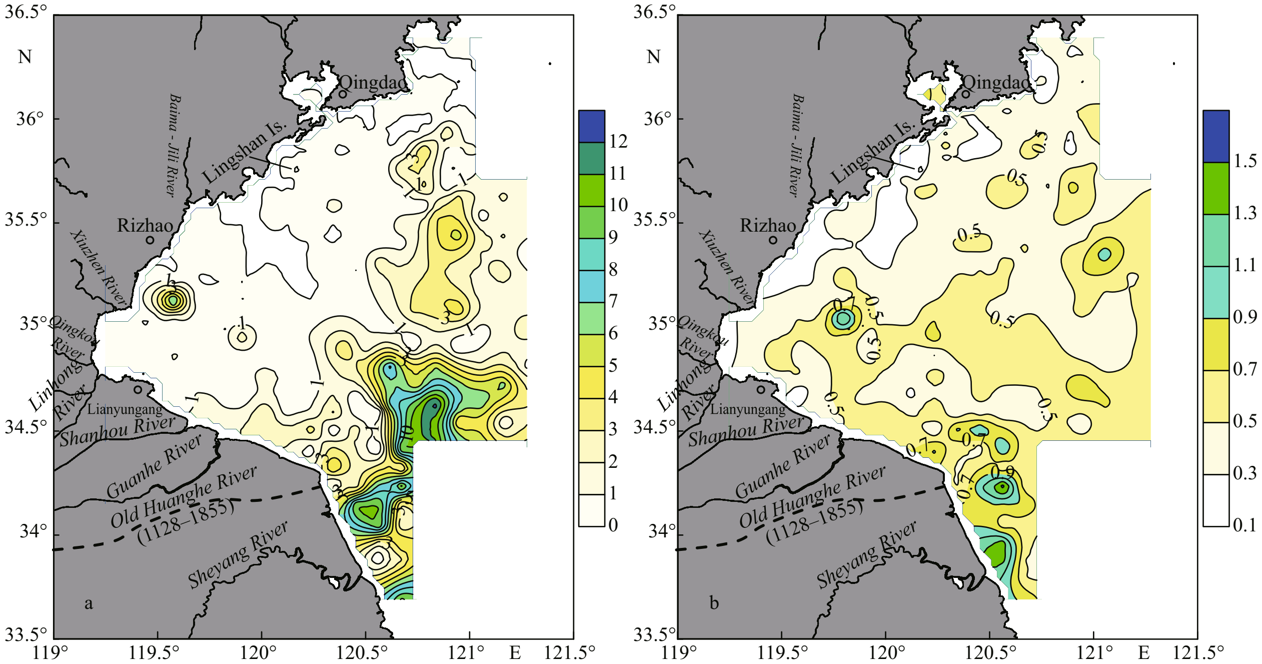

Fig.9 Spatial distribution of dolomite content (%) (a); quartz/feldspar ratio (b)

which are carried by the SCC in summer. Moreover, based on the distribution of mercury in surface sediments (He et al., 2009), one can find a similar south-to-north trend (Fig.9a). Because clay minerals can adsorb Hg^{2+} and other heavy metal ions in the water (Tang et al., 2002), and the mercury content of surface sediments in the Changjiang estuary (average 0.048 mg/kg, Xu et al., 1982) is higher than that in the SYS (average 0.022 mg/kg, He et al., 2009), the mercury distribution probably indicates the transport of clay minerals from Changjiang sediments.

The quartz/feldspar ratio (including K-feldspar and plagioclase) can be used as an index to discriminate the weathering intensity and provenance of sediments (Kuhn and Diekmann, 2002). The study of quartz/feldspar ratios in sediments from the Huanghe and Changjiang rivers shows that the quartz/feldspar ratios of Changjiang River sediment are significantly higher than those of the Huanghe River. This indicates that the chemical weathering in the Changjiang drainage basin is stronger than that in the Huanghe basin (Yang et al., 2008). Our results show that the spatial distribution of quartz/feldspar ratios presents a northward extended tongue shape in the southern study area (Fig.9b), which corresponds with the northward spread of suspended material from the Changjiang, in agreement with the conclusion deduced from dolomite content distribution (Fig.9a). Furthermore, the lower quartz/feldspar ratio distribution in the northwestern part of the study area further supports the delimitation of modern Huanghe sediment influence concluded from clay minerals.

Therefore, based on detrital mineral distribution patterns (Fig.9), together with water mass hydrology analysis, one can see that in summer, under the influence of SCC, materials derived from the Changjiang can be carried northward into the western SYS. Based on the distribution of dolomite, the region of influence of Changjiang can reach as far as the area off the Qingdao coast, (Fig.9a). This conclusion can be confirmed by measured tidal current directions (Fig.8b) and numerical simulation results (Fig.8c).

6 CONCLUSION

Analyses of clay minerals, detrital minerals and grain sizes in 245 surface sediment samples have been conducted in the western SYS to determine sediment provenance and transport paths. Combined with water mass hydrology analysis, we studied sediment transport mechanisms in the western SYS, and explained how Huanghe and Changjiang sediments have influenced the study area.

Results show that the clay mineral assemblage consists dominantly of illite (average 67%), with lesser amounts of smectite (14%), chlorite (11%), and kaolinite (8%). Sediments in the western SYS are mainly from the modern Huanghe River, the abandoned old Huanghe River subaqueous delta, some fraction of material from the Changjiang River, and coastal erosion. However, some input from small coastal rivers may be locally important for sediment distributions.

Clay mineral content (illite and smectite) and quartz/feldspar ratio distribution patterns reveal that the influence of modern Huanghe sediments can reach as far as 35°N in the northwestern part of the study area, and the influence can be especially enhanced in winter because of the northerly winds. In summer, the sediments on the Jiangsu coast can be mixed with material from the Changjiang by the northward flow of CDW, and then the SCC carries the refreshed sediments northward into the western SYS. Material from the Changjiang can even influence areas as far away as off the coast of Qingdao, based on observations of dolomite distribution.

Sediment distribution and transport paths in the western SYS are primarily controlled by the oceanic circulation system (coastal currents, tidal currents, diluted water and waves), which in this region is intimately related to the monsoon. Oceanic circulation patterns vary with the season, so related changes in sediment distribution need further study in the future.

7 ACKNOWLEDGMENT

We thank the 2009 and 2012 Open Cruises of Chinese Offshore Oceanography Research by IOCAS that supplied the data for this work. We are also grateful to the crew from the 2008 Cruise. We express our thanks to Dr. WAN Shiming at IOCAS and other anonymous reviewers for their constructive advice on earlier versions of this paper.

References

Alexander C R, DeMaster D J, Nittrouer C A. 1991. Sediment accumulation in a modern epicontinental-shelf setting: the Yellow Sea. *Marine Geology*, **98**(1): 51-72.

Bian C W, Jiang W S, Greatbatch R J. 2013. An exploratory model study of sediment transport sources and deposits in the Bohai Sea, Yellow Sea, and East China Sea. *Journal of Geophysical Research*: *Oceans*, **118**(11): 5 908-5 923.

Biscaye P E. 1965. Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. *Geological Society of America Bulletin*, **76**(7): 803-832.

Chen J S, Li Y H, Le J X, Wang D C. 1984. The effects of physical and chemical erosion in Chinese rivers. *Chinese Science Bulletin*, **29**(15): 932-936. (in Chinese with English abstract)

Chen L R. 1989. A study on mineral assemblages in sediments of the Bohai Sea, the Huanghai Sea and the East China Sea. *Marine Sciences*, (2): 1-8. (in Chinese with English abstract)

Chen Q Q, Zhu Y R. 2012. Holocene evolution of bottom sediment distribution on the continental shelves of the Bohai Sea, Yellow Sea and East China Sea. *Sedimentary Geology*, **273-274**: 58-72.

Chough S K, Lee H J, Chun S S, Shinn Y J. 2004. Depositional processes of late Quaternary sediments in the Yellow Sea: a review. *Geosciences Journal*, **8**(2): 211-264.

DeMaster D J, McKee B A, Nittrouer C A, Qian J C, Cheng G D. 1985. Rates of sediment accumulation and particle reworking based on radiochemical measurements from continental shelf deposits in the East China Sea. *Continental Shelf Research*, **4**(1): 143-158.

Ding W L. 1985. The characteristics of the tides and tidal currents in the Bohai and the Yellow Seas. *Studia Marine Sinica*, **27**: 27-40. (in Chinese with English abstract)

Dong L X, Su J L, Wang K S. 1989. Tide current in the Yellow Sea and its relationship with sediment transport. *Acta Oceanol*. *Sinica*, **11**(1): 102-114. (in Chinese with English abstract)

Emery K O. 1968. Relict sediments on continental shelves of world. *AAPG Bulletin*, **52**(3): 445-464.

Fan D J, Yang Z S, Mao D, Guo Z G. 2001. Clay minerals and geochemistry of the sediments from the Changjiang and Yellow Rivers. *Marine Geology and Quaternary Geology*, **21**(4): 7-12. (in Chinese with English abstract)

Fang G H. 1986. Tide and tidal current charts for the marginal seas adjacent to China. *Chinese Journal of Oceanology and Limnology*, **4**(1): 1-16.

Folk R L, Andrews P B, Lewis D W. 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. *New Zealand Journal of Geology and Geophysics*, **13**(4): 937-968.

Gao L, Zhao Y Y, Zhao S L, Zheng T M, Gou S M. 1982. Studies on the sediment characteristic and its movement along the south coast of the Haizhou Bay. *Oceanologia et Limnologia Sinica*, **13**(6): 496-509.

Gingele F X, De Deckker P, Hillenbrand C D. 2001. Clay mineral distribution in surface sediments between Indonesia and NW Australia-source and transport by ocean currents. *Marine Geology*, **179**(3-4): 135-146.

Griffin J J, Windom H, Goldberg E D. 1968. The distribution of clay minerals in the World Ocean. *Deep Sea Research and Oceanographic Abstracts*, **15**(4): 433-459.

Hay W W. 1998. Detrital sediment fluxes from continents to oceans. *Chemical Geology*, **145**(3-4): 287-323.

He L B. 1989. Distribution of clay minerals in China Seas and their adjacent area. *Science in China* (*Series B*), (1): 75-83. (in Chinese)

He Z P, Song J M, Zhang N X, Zhang P, Xu Y Y. 2009. Variation characteristics and ecological risk of heavy metals in the south Yellow Sea surface sediments. *Environmental Monitoring and Assessment*, **157**(1-4): 515-528.

Hong G-H, Suk H K, Chang S C. 1998. Contamination in the Yellow Sea proper: a review. *Oceanographic Literature Review*, **45**(3).

Hu C M, Li D Q, Chen C S, Ge J Z, Muller-Karger F E, Liu J P, Yu F, He M X. 2010. On the recurrent *Ulva prolifera* blooms in the Yellow Sea and East China Sea. *Journal of Geophysical Research*: *Oceans*, **115(C5)**: C05017, http://dx.doi.org/10.1029/2009JC005561.

Kuhn G, Diekmann B. 2002. Late Quaternary variability of ocean circulation in the southeastern South Atlantic inferred from the terrigenous sediment record of a drift deposit in the southern Cape Basin (ODP Site 1089). *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, **182**(3): 287-303.

Lan X H, Zhang X H, Zhang Z X. 2005. Material sources and transportation of sediments in the southern Yellow Sea. *Transaction of Oceanology and Limnology*, (4): 53-60. (in Chinese with English abstract)

Lan X H, Zhang X J, Liu X B, Li R H, Zhang Z X. 2011. Distribution pattern of clay minerals in surface sediments of South Yellow Sea and their provenance. *Marine Geology & Quaternary Geology*, **31**(3): 11-16. (in Chinese with English abstract)

Lan X H. 2001. Compositional features of clay minerals in marine sediments and paleoenvironmental significance. *Marine Geology Letters*, **17**(1): 5-7. (in Chinese)

Lee H J, Chough S K. 1989. Sediment distribution, dispersal and budget in the Yellow Sea. *Marine Geology*, **87**(2-4): 195-205.

Lee H J, Chu Y S. 2001. Origin of inner-shelf mud deposit in the southeastern Yellow Sea: Huksan Mud Belt. *Journal of Sedimentary Research*, **71**(1): 144-154.

Li F, Jiang X H, Song H R. 1993. Influence of the Huanghe and Changjiang Rivers sediment loads on South Yellow Sea Sedimentation since late Pleistocene. *Studia Marine Sinica*, **34**: 61-72. (in Chinese with English abstract)

Li G G. 1990. Composition, distribution and geological significance of clay minerals in surface sediments of China Seas. *Acta Oceanologica Sinica*, **12**(4): 470-479. (in Chinese)

Lim D I, Choi J Y, Jung H S, Rho K C, Ahn K S. 2007. Recent sediment accumulation and origin of shelf mud deposits in the Yellow and East China Seas. *Progress in Oceanography*, **73**(2): 145-159.

Liu J G, Chen M H, Chen Z, Yan W. 2010a. Clay mineral distribution in surface sediments of the South China Sea and its significance for in sediment sources and transport. *Chinese Journal of Oceanology and Limnology*, **28**(2): 407-415.

Liu J P, Li A C, Xu K H, Velozzi D M, Yang Z S, Milliman J D, DeMaster D J. 2006a. Sedimentary features of the Yangtze River-derived along-shelf clinoform deposit in the East China Sea. *Continental Shelf Research*, **26**(17-18): 2 141-2 156.

Liu J, Kong X H, Saito Y, Liu J P, Yang Z S, Wen C. 2013. Subaqueous deltaic formation of the Old Yellow River (AD 1128-1855) on the western South Yellow Sea. *Marine Geology*, **344**: 19-33.

Liu W Y, Lou F, Yu Z Y. 2006b. Analysis of river channel scour and silting evolution and natural condition of navigation channel in the Guanhe River Estuary area. *Coastal Engineering*, **25**(3): 14-21. (in Chinese with English abstract)

Liu X Q. 1987. Relict sediments in China continental shelf. *Marine Geology & Quaternary Geology*, **7**(1): 1-14. (in Chinese with English abstract)

Liu Z F, Colin C, Li X J, Zhao Y L, Tuo S, Chen Z, Siringan F P, Liu J T, Huang C Y, You C F, Huang K F. 2010b. Clay mineral distribution in surface sediments of the northeastern South China Sea and surrounding fluvial drainage basins: Source and transport. *Marine Geology*, **277**(1-4): 48-60.

Liu Z L, Hu D X. 2009. Preliminary study on the Huanghai Sea coastal current and its relationship with local wind in summer. *Acta Oceanologica Sinica*, **31**(2): 1-7. (in Chinese with English abstract)

Liu Z X, Huang Y C, Zhang Q N. 1989. Tidal current ridges in the southwestern Yellow Sea. *Journal of Sedimentary Research*, **59**(3): 432-437.

Lu J, Qiao F L, Wang X H, Wang Y G, Teng Y, Xia C S. 2011. A numerical study of transport dynamics and seasonal variability of the Yellow River sediment in the Bohai and Yellow seas. *Estuarine*, *Coastal and Shelf Science*, **95**(1): 39-51.

Lü Y N. 1982. Distribution and provenance of heavy minerals in Rizhao nearshore sediments, Shandong. *Periodical of Shandong College of Oceanography*, **12**(3): 43-52. (in Chinese with English abstract)

Ma H R, Chen J F, Cui Y, Zhao J, Ma S S, Yang F. 2010. Analysis of water quality and assessment of major pollutants input to the sea from the Guan River and Sheyang River. *Progress in Fishery Sciences*, **31**(3): 92-99. (in Chinese with English abstract)

Martin J M, Zhang J, Shi M C, Zhou Q. 1993. Actual flux of the Huanghe (Yellow River) sediment to the Western Pacific Ocean. *Netherlands Journal of Sea Research*, **31**(3): 243-254.

Milliman J D, Beardsley R C, Yang Z S, Limeburner R. 1985. Modern Huanghe-derived muds on the outer shelf of the East China Sea: identification and potential transport mechanisms. *Continental Shelf Research*, **4**(1-2): 175-188.

Milliman J D, Li F, Zhao Y Y, Zheng T M, Limeburner R. 1986. Suspended matter regime in the Yellow Sea. *Progress in Oceanography*, **17**(3): 215-227.

Milliman J D, Meade R H. 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology*, **91**(1): 1-21.

Milliman J D, Qin Y S, Park Y A. 1989. Sediments and sedimentary processes in the Yellow and East China Seas. *Sedimentary Facies in the Active Plate Margin*, 233-249.

Pang C G, Bai X Z, Hu D X. 2003. Numerical study of water and suspended matter exchange between the Yellow Sea and the East China Sea. *Chinese Journal of Oceanology and Limnology*, **21**(3): 214-221.

Pang C G, Yu W, Yang Y, Han D X. 2011. An improved method for evaluating the seasonal variability of total suspended sediment flux field in the Yellow and East China Seas. *International Journal of Sediment Research*, **26**(1): 1-14.

Park B K, Han S J. 1984. The distribution of clay minerals in recent sediments of the Korea Strait. *Sedimentary Geology*, **41**(2-4): 173-184.

Park Y A, Khim B K. 1992. Origin and dispersal of recent clay minerals in the Yellow Sea. *Marine Geology*, **104**(1-4): 205-213.

Petschick R, Kuhn G, Gingele F. 1996. Clay mineral distribution in surface sediments of the South Atlantic: sources, transport, and relation to oceanography. *Marine Geology*, **130**(3-4): 203-229.

Qin Y S, Zhao Y Y, Chen L R, Zhao S L. 1989. The Yellow Sea Geology. China Ocean Press, Beijing, China. p.1-135. (in Chinese)

Qu C, Yan R. 1990. Chemical composition and factors controlling suspended matter in three major Chinese rivers. *Science of the Total Environment*, **97**: 335-346.

Ren M E, Shi Y L. 1986. Sediment discharge of the Yellow River (China) and its effect on the sedimentation of the Bohai and the Yellow Sea. *Continental Shelf Research*, **6**(6): 785-810.

Saito Y, Yang Z S. 1994. Historical change of the Huanghe (Yellow River) and its impact on the sediment budget of the East China Sea, Proceedings of International Symposium on Global Fluxes of Carbon and Its Related Substances in the Coastal-Ocean-Atmosphere System. Sapporo, Japan: Hokkaido University. p.7-12.

Shi X F, Liu Y G, Chen Z H, Wei J W, Ge S L. 2012. Origin, transport processes and distribution pattern of modern sediments in the Yellow Sea. Sediments, Morphology and Sedimentary Processes on Continental Shelves: Advances in Technologies, Research and Applications (Special Publication 44 of the IAS), **44**: 321-350.

Shi Y M, Li K Y, Yang H L. 1989. Distributary characteristic of clay mineral in the South Huanghai Sea. *Marine Sciences*, (3): 32-37. (in Chinese with English abstract)

Song Z J, Zhang Z X, Yu J F, Liu X B. 2008. Study on Distribution and material sources of clay minerals in surface sediments of the Southern Yellow Sea. *Journal of Shandong University of Science and Technology* (*Natural Science*), **27**(3): 1-4. (in Chinese with English abstract)

Su J L, Yuan Y L. 2005. Hydrology in China Seas. China Ocean Press, Beijing, China. p.192-206. (in Chinese)

Sun X P. 2006. China Marginal and Regional Seas. China Ocean Press, Beijing, China. p.107-293. (in Chinese)

Tang Y J, Jia J Y, Xie X D. 2002. Environment significance of clay minerals. *Earth Science Frontiers*, **9**(2): 337-344. (in Chinese with English abstract)

Vital H, Stattegger K, Garbe-Schonberg C-D. 1999. Composition and trace-element geochemistry of detrital clay and heavy-mineral suites of the lowermost Amazon River: a provenance study. *Journal of Sedimentary Research*, **69**(3): 563-575.

Wang B, Li Y, Yuan D L. 2013. Effects of topography on the sub-tidal circulation in the southwestern Huanghai Sea (Yellow Sea) in summer. *Acta Oceanologica Sinica*, **32**(3): 1-9.

Wang Z Y. 1982. Discussion on the characteristics and origin of the relict sand of western South Yellow Sea. *Marine Geological Research*, **2**(3): 63-70. (in Chinese with English abstract)

Wei J W, Shi X F, Xin C Y, Zhang H P. 2001. The distribution characteristic of clay mineral in the South Yellow Sea and its implications. *Chinese Science Bulletin*, **46**(S1): 30-33. (in Chinese with English abstract)

Wu H, Shen J, Zhu J R, Zhang J, Li L. 2014. Characteristics of the Changjiang plume and its extension along the Jiangsu Coast. *Continental Shelf Research*, **76**: 108-123.

Wu S Y. 1981. A comprehensive study of the sedimentary characteristics of the Huanghai Sea. *Acta Oceanologica Sinica*, **3**(3): 460-471. (in Chinese with English abstract)

Xia C S, Qiao F L, Yang Y Z, Ma J, Yuan Y L. 2006. Three-dimensional structure of the summertime circulation in the Yellow Sea from a wave-tide-circulation coupled model. *J. Geophys. Res.*, **111**(C11): C11S03, http://dx.doi.org/10.1029/2005jc003218.

Xu K C, Huang S L, Wu L Q. 1982. Studies of heavy metals in the estuarine sediments of the Changjiang River. *Acta Oceanologica Sinica*, **4**(4): 440-449. (in Chinese with English abstract)

Yang S Y, Jung H S, Lim D I, Li C X. 2003. A review on the provenance discrimination of sediments in the Yellow Sea. *Earth-Science Reviews*, **63**(1-2): 93-120.

Yang S Y, Li C X, Zhu J C, Zhang W L. 2000. Provenance indicator of chemical fingerprint of magnetite from the Yangtze River and the Yellow River sediments. *Geochimica*, **29**(5): 480-484. (in Chinese with English abstract)

Yang S Y, Li C X. 1999. Characteristic element compositions of the Yangtze and the Yellow River sediments and their geological background. *Marine Geology and Quaternary Geology*, **19**: 19-26. (in Chinese with English abstract)

Yang Z S, Liu J P. 2007. A unique Yellow River-derived distal subaqueous delta in the Yellow Sea. *Marine Geology*, **240**(1-4): 169-176.

Yang Z S, Zhao X H, Qiao S Q, Li Y H, Fan D J. 2008. Feldspar/quartz(F/Q) Ratios as a chemical weathering intensity indicator in different grain size-fractions of sediments from the Changjiang and Huanghe Rivers to the seas. *Journal of Ocean University of China* (*Natural Science*), **38**(2): 244-250. (in Chinese with English abstract)

Yang Z S. 1988. Mineralogical assemblages and chemical characteristics of clays from sediments of the Huanghe, Changjiang, Zhujiang Rivers and the relationship to the climate environment in their sediment source areas. *Oceanaologia et Limnologia Sinica*, **19**(4): 336-346. (in Chinese with English abstract)

Yuan D L, Zhu J R, Li C Y, Hu D X. 2008. Cross-shelf circulation in the Yellow and East China Seas indicated by MODIS satellite observations. *Journal of Marine Systems*, **70**(1-2): 134-149.

Yuan Y R, Chen Q. 1984. Sediments and sedimentary facies of the abandoned Yellow River underwater delta in the South Yellow Sea. *Marine Geology & Quaternary Geology*, **4**(4): 35-43. (in Chinese with English abstract)

Zhang J, Huang W W, Liu M G, Zhou Q. 1990. Drainage basin weathering and major element transport of two large Chinese rivers (Huanghe and Changjiang). *Journal of Geophysical Research*: *Oceans* (*1978-2012*), **95**(C8): 13 277-13 288.

Zhao Q J. 1983. A study of the clay minerals in the Huanghai Sea sediment. *Marine Science Bulletin*, **2**(6): 48-56. (in Chinese with English abstract)

Zhao Q Y, Li J F, Duan W M, Shen Y L, Zhai S K. 1983. The chemical features of nearshore sediment from Lingshan Bay to Haizhou Bay along the Shandong Peninsula. *Journal of Shandong College of Oceanology*, **13**(3): 30-44. (in Chinese with English abstract)

Zhu Y, Chang R. 2000. Preliminary study of the dynamic origin of the distribution pattern of bottom sediments on the continental shelves of the Bohai Sea, Yellow Sea and East China Sea. *Estuarine*, *Coastal and Shelf Science*, **51**(5): 663-680.

Zöllmer V, Irion G. 1993. Clay mineral and heavy metal distributions in the northeastern North Sea. *Marine Geology*, **111**(3-4): 223-230.