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Features of Clay Minerals in the YSDP102 Core on the Continental Shelf of the Southeast Yellow Sea

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Abstract Ninety-eight clay mineral samples from the YSDP102 core were analyzed by *x*-ray diffractometer to study the four clay minerals: illite, chlorite, kaolinite and smectite. Twenty-eight samples had been analyzed on the laser particle-size analyzer to reveal the particle features of the sediments. Distribution of the clay minerals and the particle characteristics in the YSDP102 core show that the core experienced three different depositional periods and formed three different sedimentary intervals due to different sediment sources and different depositional environments. Features of the clay minerals and the heavy minerals in the YSDP102 core indicate that coarse-grained sediments and fine-grained sediments result from different sources. The Yellow Sea Warm Current has greatly influenced the sedimentary framework of this region since the current's formation.

Key words clay minerals; sediment sources; Yellow Sea Warm Current; depositional environment

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1 Introduction

The Yellow Sea is a semi-closed epicontinental sea with a shallow, broad seafloor with water depths from 20–80 m except the 'Yellow Sea Trough' in the south Yellow Sea with a water depth more than 80 m. The Yellow Sea Warm Current (YSWC), a ramification with high salinity and temperature branched from the Kuroshio Current, is an important hydraulic dynamic factor which controls the distribution of the water mass and the deposition of the Yellow Sea. Four cyclone-like eddies denominated as 'cold water masses' or 'cold eddies' are present on both sides of the YSWC and four muddy deposits denominated as 'cold eddy deposits' or 'cyclone eddy deposits' are in correspondence with them (Li *et al.*, 1997; Shen *et al.*, 1993) (Fig.1). The temperature of the four cold water masses is often lower than its surrounding water and the cold water mass exists for a long time within a year (Su *et al.*, 1995; Lan *et al.*, 1986).

In correspondence with the cold water mass on the east side of the YSWC, a patch of muddy deposits to the northwest of Cheju Island (33°33′–35°33′ N, 125°45′–126°15′E) in the Southeast Yellow Sea extends basically north-south and projects westward. The YSDP102 core (33°49.496′ N, 125°45.009′ E) was recovered by the Korea Institute of Energy Sources and Institute of Marine Geology in 1995 in the muddy deposits where the water depth is about 60.65 m (Fig.1). The core penetrates into a depth of 60.65 m with a

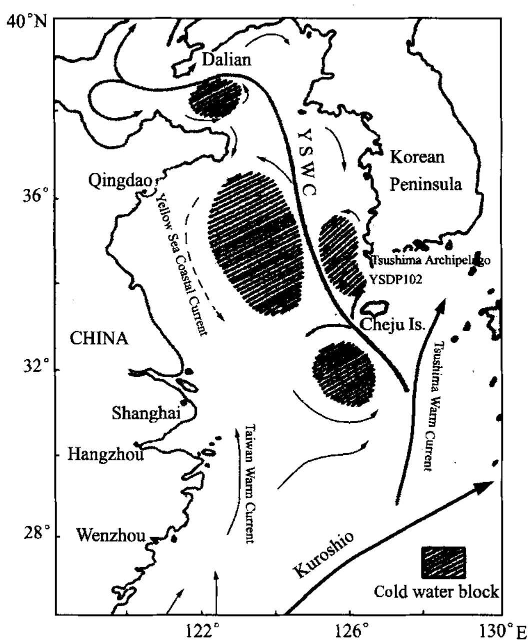

Fig.1 Current systems in the Yellow Sea and East China Sea and the location of YSDP102 core (Redrawn from Shen *et al.*, 1993)

core recovery of 55%. From the bottom of the core to 57.60 m and from 57.60 to 51.57 m are the transgressive lag sand-gravel and tidal sand ridges or 'relic' sands, respectively (Li, F. *et al.*, 1998). The sedi-

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ments from 51.57 m to the surface are muddy deposits with a mean grain size less than 5.23Φ. There is an acoustics internal reflection plane near 13.5 m in the YSDP102 core. The segment above the reflection plane is soft and abundant in water, while the segment below the reflection plane to 51.57 m has a small abundance of water but with a high hardness. The sediments above the plane have a mean grain size from 5.23Φ to 6.71Φ, while the mean grain size of the sediments below the plane to 51.57 m is from 5.93Φ to 7.33 Φ. In correspondence with the grain size, the sediments above the plane have more detrital heavy minerals than the sediments below the plane. The depositing time of the sediments from 51.57 m to the internal reflection plane is about from 6400 a B. P. to 4200 a B. P. in calender year (Li *et al.*, 2000).

A lot of studies about the YSDP102 core have been carried out and many reports have been published in recent years (Li *et al.*, 1997; Liu *et al.*, 1999; Wang *et al.*, 1997; Li *et al.*, 2000). But some important problems for sedimentology, *e.g.*, the source of the sediments and the depositional environment, are much controversial or remain unresolved. The clay minerals have been used to help solve many sedimentological problems such as the sources, dispersal pathways, transport agents of sediments, *etc.* by many authors (Nair *et al.*, 1982; Naidu and Mowatt, 1983; Hume and Nelson, 1986). We will use the clay minerals and other data to analyze the formation, depositional environment and sources of the sediments in the YSDP102 core.

2 Methods

Clay minerals of the samples are extracted from suspensions of the mixd solution according to the Stokes Formula and the mixed solution are made by adding the samples into beakers with 4000 mL water to make them complete suspension. The time needed for depositing was determined according to the amounts of the clays in the samples. The accumulated clay minerals were made into two types of flakes: untreated flake and oriented flake.

The clay minerals were analyzed on a D/max-rA x-ray diffractmeter with a scintillation detector, using Graphite monochromatic filter and copper Kα radiation.

The clay minerals identified by their characteristic basal reflection maxima include smectite (17Å), illite (10 and 3.3Å), kaolinite and chlorite (7 and 3.5Å). The kaolinite and chlorite were differentiated by the relative intensities of their 002 (3.67 and 3.54Å) reflections. To get a weighted percentage of the different clay minerals, a semi-quantitative technique must be used. The following peaks and the weighting factors were used: 17Å glycolated peak area for smectite; 4 times the 10Å (glycolated) for illite; and 2 times the 7Å peak area (glycolated) for kaolinite and chlorite divided in proportion to the relative areas of their 002 (3.58Å) and 004 (3.54Å) peaks respectively.

Besides the clay minerals analysis, twenty eight samples were analyzed by laser particle-size analyzer to facilitate solving many sedimentary problems, such as those related to fluid mechanics, depositional environments, *etc.*

3 Results of Clay Mineral Analysis

3.1 Suites of the Clay Mineral

Ninety-eight samples (collected according to the lithology of the core) from the YSDP102 core were analyzed by x-ray diffractometer. The clay minerals principally consist of illite, chlorite, smectite and kaolinite with probably a micro-quantity of roseite, palygorskite and sepiolite. The average content percentage of the illite, smectite, chlorite and kaolinite are 61.8%, 10.6%, 16.1% and 11.5%, respectively.

3.2 Distribution of Clay Minerals

Illite was relatively the stable one among the 4 clay minerals and its average abundance is 61.8%. The abundance of the illite in the core fluctuates from 55% to 70% except three samples with abundances less than 50%.

The abundance of the chlorite fluctuates from 8.1% to 23.7% with an average of 16.1%. According to the distribution of the chlorite and the lithology the core of the YSDP102 can be divided into three clay mineral intervals. The interval from surface to the internal reflection plane can be taken as the upper one and its abundance of chlorite fluctuates greatly from 23.7% to 11.4% with an average of 18.0% (standard deviation $\sigma = 3.16$) and a manifest decreasing trend with a slope of −0.63 (results from linear regression analysis). The interval from the internal reflection plane to 51.19 m can be regarded as the middle one in which the chlorite fluctuates from 9.9% to 21.8% with an average abundance of 15.1% ($\sigma = 2.69$) and an approximately increasing trend of slope 0.14. The interval from 51.19 m to bottom is the lower one with its chlorite content fluctuating drastically with an average abundance of 17.4% ($\sigma = 4.53$).

The abundance of the kaolintie fluctuates from 7.8% to 17.9%, the average being 11.6%, less than that of the smectite. According to the lithology of the core and the distribution of the kaolinite, the kaolinite has the same type of intervals as that of the chlorite. Its abundance fluctuates from 17.9% to 9% with an average of 12.4% ($\sigma = 2.21$) and an approximate decreasing trend (slope $= -0.19$) in the upper one. Kaolinite fluctuates from 8.3% to 15.5% with an average of 11.4% ($\sigma = 1.36$) in the middle interval, showing an approximately flat trend with a slope 0.05. The abundance of the kaolinite, like that of chlorite, fluctuates a bit in the lower interval with an average of

10.8% (σ = 2.22).

Smectite has a boundary plane in the core of YSDP102 approximately between 10 m and 11 m and there is very little smectite above that plane (Fig.2), the average value being only 0.26% (σ = 1.11). The smectite can still be divided into three intervals according to its distribution. The interval from surface to the internal reflection plane can be taken as the upper one. Although the smectite average value is 2.6% (σ = 6.0), the smectite just concentrates from 12 m to 13 m and almost disappears above 11 m. From the internal reflection plane to 51.19 m, the abundance of the smectite fluctuates greatly with an average of 12.5% (σ = 5.28). The abundance fluctuates vastly from 0 to 50.5% from 51.19 m to the bottom of the core with an average value of 16.5% (σ = 16.99).

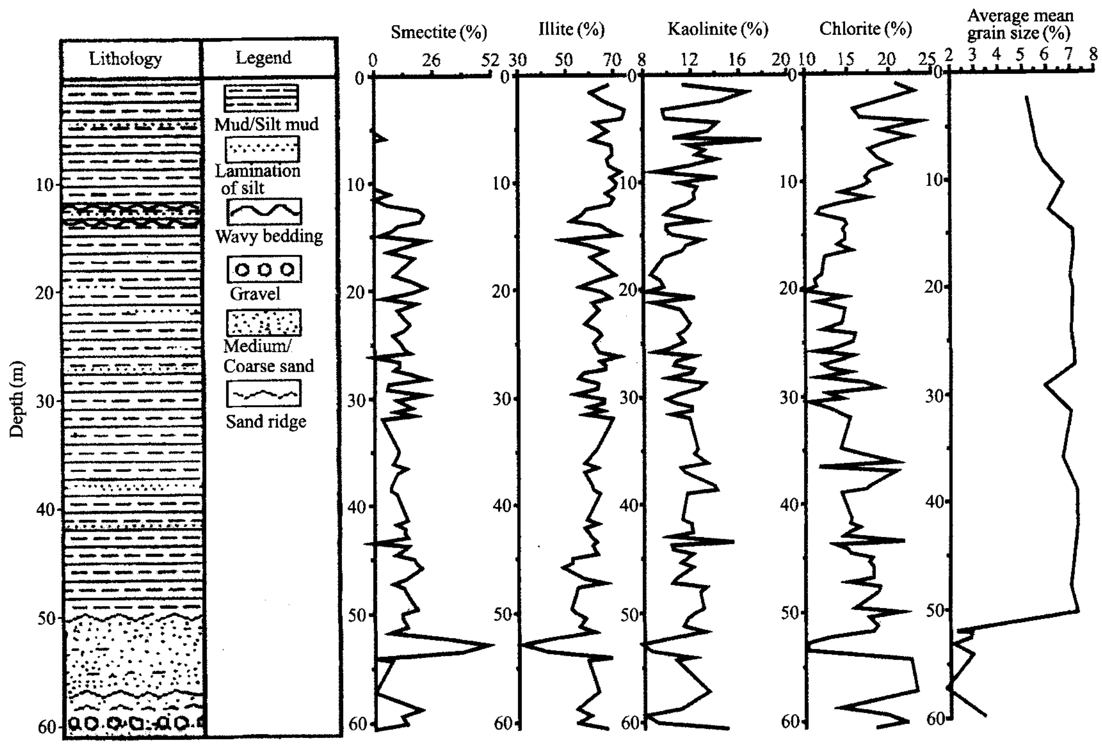

Fig.2 Graphiclog, distribution of the clay minerals and fluctuation of the mean grain size of the YSDP102 core

According to mean grain size of the sediments, the YSDP102 core can also be divided into three intervals just as the chlorite, kaolinite and smectite: from 51.19 m to bottom, the lower one with an average mean grain size of 2.6 Φ (σ = 0.6) and a line regression value of 0.04; from the internal reflection plane to 51.19 m, the middle one with an average mean grain size of 7.0 Φ (σ = 0.3) and a line regression value of 0.004; from the surface to the internal reflection plane, the upper one with an average mean grain size of 5.9 Φ (σ = 0.6) and a line regression value of 0.11.

4 Discussion on the Sedimentology of the YSDP102 Core

4.1 Depositional Environment

The manifest variations among the clay minerals suites, the grain size as well as the gross content of the clays in the three intervals indicate that the sediments are controlled by different depositional environments and different sediment sources.

From 51.19 m to bottom, the content percentage of the four types of clay minerals vary drastically, *e.g.*, the standard deviation of the chlorite and the smectite in the low interval are 4.53 and 16.99, respectively.

The average content percentage of clays (7.4%) is less than those of the middle (37.2%) and upper (23.5%) intervals and the mean grain size fluctuates from 1.8 Φ to 3.4 Φ with an average value of 2.6 Φ (σ = 0.6) (Fig.2). Additionally, the sediments consist of medium-coarse grained sand with gravel laminates intercalated occasionally and the sediment colors are from brownish yellow to gray. These indicate that the sediments in the lower interval deposited in an unstable environment. This is in agreement with the depositional environment occurring during the incipient period of the post-glacial transgression. Within that period of time the hydraulic dynamic was relatively very strong and the depositional environment fluctuated drastically. This type of depositional environment caused the lithologic character of the sediments in the lower interval.

The fact that chlorite and kaolinite have approximately identical distributions in the middle interval of the YSDP102 core (with a correlation coefficient of 0.67) and both show relatively weak fluctuations, suggesting that the fine-grained sediments, in particular the clay minerals in this area during this period of time for deposition were supplied steadily, transported and deposited under a relatively weak hydraulic energy condition. This conclusion can be deduced from the data of the grain size of the sediments. The mean grain size of the sediments almost has no fluctuation with an average value of 7.0 Φ ($\sigma = 0.3$) except for the depth of 29.16 m (5.9 Φ) and with a flat trend (line regression value being 0.004). Otherwise, unstable hydraulic energy condition would make the clay minerals redistribute to form a different clay mineral suite, *i.e.*, there would be lower correlation coefficient than 0.67 between chlorite and kaolinite. Although it is reported that the sediments in this interval accumulated during the transgression (Shen *et al.*, 2000), they deposited under low hydraulic energy condition.

That chlorite, kaolinite and smectite all fluctuate drastically and the mean grain size of the sediments fluctuates a bit from 5.2 Φ to 6.7 Φ with an average value of 5.9 Φ ($\sigma = 0.6$) showing an increasing trend downwards (with the line regression value of 0.11) in the upper interval indicates that the source of the sediments or the depositional environment had changed during this period.

The core below the internal reflection plane (13.5 m) with a small abundance of water and high hardness indicates that the sediments in the middle interval deposited with a higher rate than the sediments above the reflection plane did. The average mean grain size (7.0 Φ) of the middle interval is smaller than that of the upper interval (5.9 Φ) and the upper interval has far more detrital heavy minerals than the middle interval. Additionally, the average percentage of the clays (37.2%) of the sediments in the middle interval is higher than that of the upper interval (23.5%). This indicates that the sediments in the middle interval deposited under a weaker dynamic environment than that of the upper one but deposited with a higher rate. Sediments in the middle interval attained such a thickness of about 38 m during so short a period of about 2200 a (Li *et al.*, 2000), while the sediments in the upper interval attained a thickness of only about 13.5 m during about 4200 a (Li *et al.*, 2000). Although there is an internal reflection plane near the depth of 13.5 m, the sediments in both upper and middle intervals have the same lithology on the whole. Because the sediments are all dark greenish gray and olive gray silty mud and the lithology generally is homogeneous except for the water content and the hardness. In addition, the sediments are all rich in pyrites from the middle interval to the upper interval. This indicates that the sediments in the middle and upper intervals deposited in an overall reduced environment and under a weak dynamic condition.

The perennial cold water mass created by the YSWC, which interacts with the alongshore currents along the Korean Peninsula, has a temperature lower than that of the surrounding water (Su J. L. and Huang, 1995; Lan *et al.*, 1986). The water in the water mass changes little with outside water and presents a weaker dynamic condition. The YSDP102 core is approximately at the center of the 'cold eddy'. So it is reasonable to assume that the sediments of the middle and upper interval was controlled by the cold eddy and can be denominated as 'cold eddy deposits'.

4.2 The Genesis of the Characters of Clay Minerals in the YSDP102 Core

From 51.19 m to bottom, the smectite content in percentage is very high with an average of 16.3% and fluctuates drastically especially from 51.19 m to 53.48 m where the average content reaches the value of 28.34% while the gross percentage content of the clays is only about 7.4%. In consideration of the lithology of sediments above described, it is assumed that the clay may result from the weathering product of the basal rock rather than from terrestrial deposits, for it is almost impossible for the smectite delivered by the rivers from China and Korea to reach such an value, the smectite delivered by the rivers constituting less than 24% (Table 1).

Table 1 Relative clay mineral abundances of riverine sediments delivered to the Korean continental shelves, western-central Yellow Sea continental shelves (Park and Khim, 1990) and the average values of the clay minerals in the three intervals

Rivers	Smectite (%)	Kaolinite (%)	Chlorite (%)	Illite (%)
Han	0.7	12.5	16.8	70.0
Keum	0.1	17.0	19.3	63.7
Yeongsan	0.1	19.2	16.8	63.9
Seomjin	0.1	30.0	26.5	45.7
Nakdong	0.1	22.5	18.8	58.6
Modern Yellow	23.2	8.5	9.3	59.0
Old Yellow	24.0	8.9	8.1	59.0
Yangtze	5.5	12.7	13.9	68.0
Upper interval	2.6	12.4	28.0	67.9
Middle interval	12.5	11.4	15.1	60.8
Low interval	26.5	10.8	27.4	55.2

From the reflection plane to 51.19 m, the average values of illite, smectite, chlorite and kaolinite are 61.0%, 12.5%, 15.1% and 11.4%, respectively. It is cogent to provide other data to interpret the source of clay minerals in the mud. Another core (YSDP103 (34°29.246′N, 125°29.201′E)) was recovered in 1995 in the mud and the percentage content of the illite, cholorite, kaolinite and smectite are 63.9%, 13.8%, 14.8% and 9.1%, respectively. These data indicate that clay minerals of the mud seem to be influenced by both the Yellow River and the rivers of Korea. But clay minerals in the middle interval result mainly from the suspended sediments delivered by the Yellow River for the following reason. The sediments in the interval can reach a thickness of 38 m during such a short period of about 2200 years (Li *et al.*, 2000). However the suspended sediments delivered by the rivers from the Korean Peninsula constitute only such a small quantity that they cannot reach so large a scale within so short a period (Li, S. Q. *et al.*, 1998) (Tables 1, 2 and Fig.3). Another reason is that the so-called Chinese source for the four major clay minerals seems to be smectite-rich, kaolinite- and chlorite-poor, whereas the Korean source minerals is poor in smectite but rich in kaolinite and chlorite (Park and Khim, 1990). Additionally, although the Yellow River presently delivers its large volume of fine-grained materials into the Gulf of Bohai *i.e.*, 1080 million tons per year (Milliman and Meade, 1983), it once discharged the suspended sediments directly into the Yellow Sea (Qin and Li, 1983; Li, S. Q. *et al.*, 1998). The suspended sediments can be carried to a long distance as evidenced by the mud presently accumulating in the area to the southwest of Cheju Island which comes from the Yellow River (Milliman *et al.*, 1985) (Fig.3).

Table 2 Annual river discharge of water and sediments from Korea, China and sea currents to the Yellow Sea (Park *et al.*, 1990; Gao *et al.*, 1996; Yang *et al.*, 2003)

River and current	Water (km^3a^{-1})	Sediment (ta^{-1})
Yellow	49×10^9	1.08×10^9
Yangtze	900×10^9	4.78×10^8
Aprock	28×10^9	4.8×10^6
Han	25×10^9	
Keum	7×10^9	5.62×10^6
Yeongsan	2×10^9	$<1\times10^6$
YSWC		About 10^6

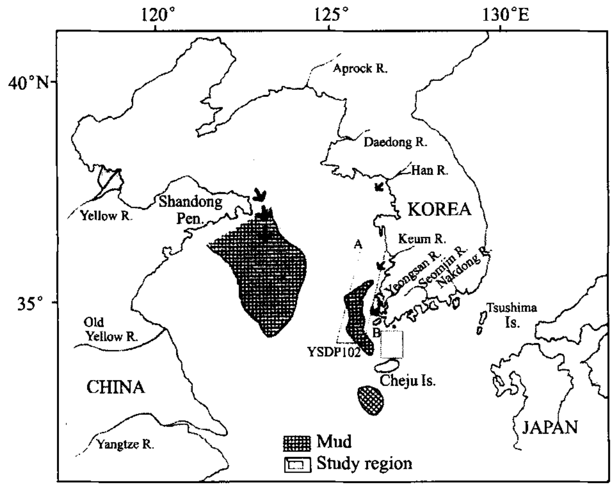

Fig.3 Possible dispersal pattern of the recent fine-grained sediments associated with the four major minerals on the Yellow Sea continental shelves and study regions
Arrows only represent the dispersal direction of the fine-grained sediments (Redrawn from Park and Khim (1990)).

From the internal-reflection plane to surface, smectite percentage value is very low, and the substance even almost disappears from the surface to 12 m. The average values of illite, chlorite and kaolinite are 67.0%, 18.0% and 12.4%, respectively, which are consistent with the clay mineral analysis data of the surficial sediments in this area (A region: illite 69.1%; chlorite 16.1%; kaolinite 13.9%; smectite 0.8%) as given in Fig.3 by Park and Khim (1990) who used the same analysis methods as this paper. Not only do the content percentages of the clay minerals in the upper interval change much, the gross content of the clays in the sediments also changes from 37.2% in the middle interval to 23.5% in the upper interval. This consequence comes from two factors: one is the depositional environment and the another is the source of the sediments, which will be discussed below.

The sediments from 51.19 m to the surface in the YSDP102 core have been influenced by the YSWC (Li *et al.*, 2000). The YSWC divides the Yellow Sea into two parts from south to north and a cyclonic (anticlockwise) eddy in the west of the YSWC occurs due to the interaction between the YSWC and the Yellow Sea Currents along the Chinese coast, while the interaction between YSWC and the currents along the Korean coast causes the clockwise circulation in the east of Yellow Sea (Su, J. L. and Huang, 1995) (Fig.1). The anticyclonic eddy (clockwise) to the northwest of the Cheju Island is an important part of the clockwise circulation. Not only does the eddy have a characteristic anticyclonic circumferential circulation, there is also a vertical circulation in the center with a distinct double-gyre structure. The upper layer water in the center of the structure is downwelling while the lower layer water in the center is upwelling; the upper layer gyre is smaller and weaker than the lower one (Su, Y. S. and Su, 1995). Therefore the bottom current velocity is often larger than the threshold for the initial motion of the fine-grained sediments (Shen *et al.*, 2000) which can be resuspended and redeposited.

The above discussion indicates that the sediments in the interval can be assumed to be mainly from the west of the Yellow Sea, *i.e.*, main part from the Yellow River and minor part from the rivers on the Korean Peninsula. On the other hand, coarse-grained sediments also appear in this region, because the ESR dates for the quartz in the mud are about between 18 000 a and 70000 a B. P. (Li, F. *et al.*, 1998) while the C^{14} dates for the foram in the mud are younger than 6400 a B. P. (Li *et al.*, 2000). This indicates that the mixture of fine-grained and coarse-grained sediments in this region appeared before the formation of the 'cold eddy' rather than being transported there by the action of the 'cold eddy'. The 'cold eddy' appeared in keeping with the formation of the YSWC when the sea level reached a certain height. The previously deposited fine-grained sediments could be resuspended by the circulation of the 'cold eddy' and deposited in the center of the 'cold eddy' again. The fine-grained sediments could deposit rapidly due to the weaker circulation during this period of about 2200 years (Li *et al.*, 2000). The weaker circulation can also be inferred from the grain size of the sediments and the gross content percentage of the clays. Of course, the YSWC can carry a large amount of fine-grained sediments here to deposit (Sun and Huang, 2000; Lin, 1992) after the formation of the YSWC. So the sediments can reach such a scale of about 38 m in thickness during so short a period due to the weaker circulation and sufficient sediment supply as its source. It is obvious that the circulation has been winnowing the fine-grained sediments from the mixed sediments to redeposit because the mud is solitary and surrounded by fine-coarse grained sandy sediments. In addition, the mud over the tidal sand ridges is in a higher position than the surrounding tidal sand ridges and there is no hiatus between the mud and the underling tidal sand ridges except that the mud overlaps the old stratum locally with unconformity.

The sediments in the upper interval from the internal reflection plane to surface, about 13 m in thickness, experienced about 4200 a (Li *et al.*, 2000). The sediments in the middle interval had been formed when the sediments in the upper interval began to deposit. It is almost impossible for the sediments from the west of the Yellow Sea to be transported here to deposit when sea level reaces a certain height (Fig.3). It is reasonable to assume that the sediments in this interval mainly come from those delivered by the rivers on the Korean Peninsula, because the clay suites in this interval are in correspondence with those rivers (Table 2). Meanwhile a large amount of fine-grained sediments (approximately in the order of $10^6 t\,a^{-1}$ (Gao *et al.*, 1996)) can be carried by the YSWC to the Yellow Sea along the southwest coast of the Korean Peninsula (Sun *et al.*, 2000; Lin, 1992). The sediments in this interval reach such a thickness of about 13 m during so long a period of time of about 4200 a (Li *et al.*, 2000) due to the relatively insufficient supply of the sediments (compared with that of the middle interval). By the way, during this period of time the intensified dynamic force of the YSWC is assumed to result from the rising of the sea level and whereby the circulation of the 'cold eddy' is intensified. These made the fine-grained sediments deposit slowly and be rich in water compared with that of the middle interval.

5 Summary

(1) Clay minerals or fine-grained sediments in the three intervals result from different sources. The sediments of the low interval are mainly in-situ formation. The sediments of the middle interval result from the sediments delivered by the Yellow River in China and the rivers on the Korean Peninsula before the formation of the YSWC while the sediments of the upper one mainly result from the sediments delivered by the rivers on the Korean Peninsula besides a part from the sediments carried by the YSWC. Of course the sediments in the middle interval were formed through winnowing by the circulation of the 'cold eddy' from the previous deposited mixture of fine and coarse-grained sediments from both sides of the Yellow Sea while the upper interval were formed from the sedi-ments delivered by the rivers on the Korean Peninsula and the YSWC.

(2) Although the sediments of the upper interval is soft and rich in water while the sediments of the middle one is hard with relatively little water, the sediments in both layers are controlled by the 'cold eddy'. The variation of depositional environment and source of sediments leads to the difference between the two intervals. The sediments in the middle interval deposited under a weaker dynamical condition with sufficient sediment supply whereas the sediments in the upper one deposited under a relatively stronger dynamical condition with relatively insufficient sediment.

(3) The heavy minerals and the clay minerals result from different sources. The heavy minerals of the YSDP102 core are mainly in-situ formation (Jiang *et al.*, 2000) while the fine grained sediments or the clay minerals result from different sources in the three intervals of the YSDP102 core.

(4) It is unreasonable to just consider water content, grain size and hardness of the sediments as indexes of the 'cold eddy' deposits. Other indexes such as hydrological condition, lithology and ingredients of the sediments, *etc.*, should be considered too.

(5) The formation of the YSWC has greatly influenced the sedimentary framework not only in this area but also the whole Yellow Sea, the sedimentology in this area is very different before and after the formation of the Yellow Sea Warm Current.

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