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Modern sedimentary environments and dynamic depositional systems in the southern Yellow Sea

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Abstract **Based on analyses of more than 600 surface sediment samples together with large amounts of previous sedimentologic and hydrologic data, the characteristics of modern sedimentary environments and dynamic depositional systems in the southern Yellow Sea (SYS) are expounded, and the controversial formation mechanism of muddy sediments is also discussed. The southern Yellow Sea shelf can be divided into low-energy sedimentary environment and high-energy sedimentary environment; the low-energy sedimentary environment can be further divided into cyclonic and anticyclonic ones, and the high-energy environment is subdivided into high-energy depositional and eroded environments. In the shelf low-energy environments, there developed muddy depositional system. In the central part of the southern Yellow Sea, there deposited the cold eddy sediments under the actions of a meso-scale cyclonic eddy (cold eddy), and in the southeast of the southern Yellow Sea, an anticyclonic eddy muddy depositional system (warm eddy sediment) was formed. These two types of sediments showed evident differences in grain size, sedimentation rate, sediment thickness and mineralogical characteristics. The high-energy environments were covered with sandy sediments on seabed; they appeared mainly in the west, south and northeast of the southern Yellow Sea. In the high-energy eroded environment, large amounts of sandstone gravels were distributed on seabed. In the high-energy depositional environment, the originally deposited fine materials (including clay and fine silt) were gradually re-suspended and then transported to a low-energy area to deposit again. In this paper, the sedimentation model of cyclonic and anticyclonic types of muddy sediments is established, and a systematic interpretation for the formation cause of muddy depositional systems in the southern Yellow Sea is given.**

Keywords: southern Yellow Sea, dynamic environment, depositional system.

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The Yellow Sea, lying between China mainland and Korea Peninsula, is a typical semi-enclosed shelf sea. Sediments in the Yellow Sea are derived mainly from China mainland and secondly from Korea Peninsula. Sedimentation and sedimentary environments in the southern Yellow Sea are influenced by marine dynamic processes and exhibit unique sedimentary characteristics compared with those in other shelf seas in the world. The southern Yellow Sea has a complex hydrodynamic system including wind, wave, circulation (the Yellow Sea Warm Current (YSWC), the coastal currents and the Yellow Sea Cold Water Mass (YSCW) etc.) and tidal currents; this system plays a direct control role not only in the processes of transport-dispersion-deposition of materials entering the sea, but also in the erosion and remoulding of seabed sediments[1]. In general, the southern Yellow Sea has a very complex sedimentary environment, in which various seabed sediments have been formed (Fig. 1). The sediments have recorded the complicated sediment dynamic characteristics and changes in sedimentary environments of the southern Yellow Sea.

Researches on sediment types in the SYS started in the 1930s with the initiative work from Niino[2—4] and Emery[5]. Since the 1980s, Chinese, Korean and other scholars have conducted many investigations and researches on geology and sedimentology of the Yellow Sea (especially the southern Yellow Sea) and obtained lots of valuable data[6—15]. 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 southern Yellow Sea.

At present, a key problem of sedimentology in the Yellow Sea to be solved is the forming process and dynamic mechanism of muddy sediments. The study on muddy sediments is always a focus of the sedimentological research of the Yellow Sea; strikingly, three patches of mud distributed in the central SYS, the area to the southwest of Cheju Island and the northern Yellow Sea have been drawn to the extensive attention in oceanographic community[1,5,15—19]. Recently, another type of muddy sediment in the southeast of the Yellow Sea (northwest of Cheju Island) has been studied by many scholars[15,20—22] but no comprehensive sedimentation model has been given.

As to the study area, the above researches are mostly limited. Chinese scholars are often involved in the western part while Korean scholars in the eastern part of the southern Yellow Sea. As for the research contents, previous studies seldom give a comprehensive and full consideration to the relationships among sediment dynamics, sedimentary environment and sediment. The project "China-Korea Joint Study of Sedimentary Dynamics and Paleoenvironment in the Yellow Sea" started in 1998 made it possible to fully illustrate sedimentary characteristics and sediment distributions in the Yellow Sea. In this

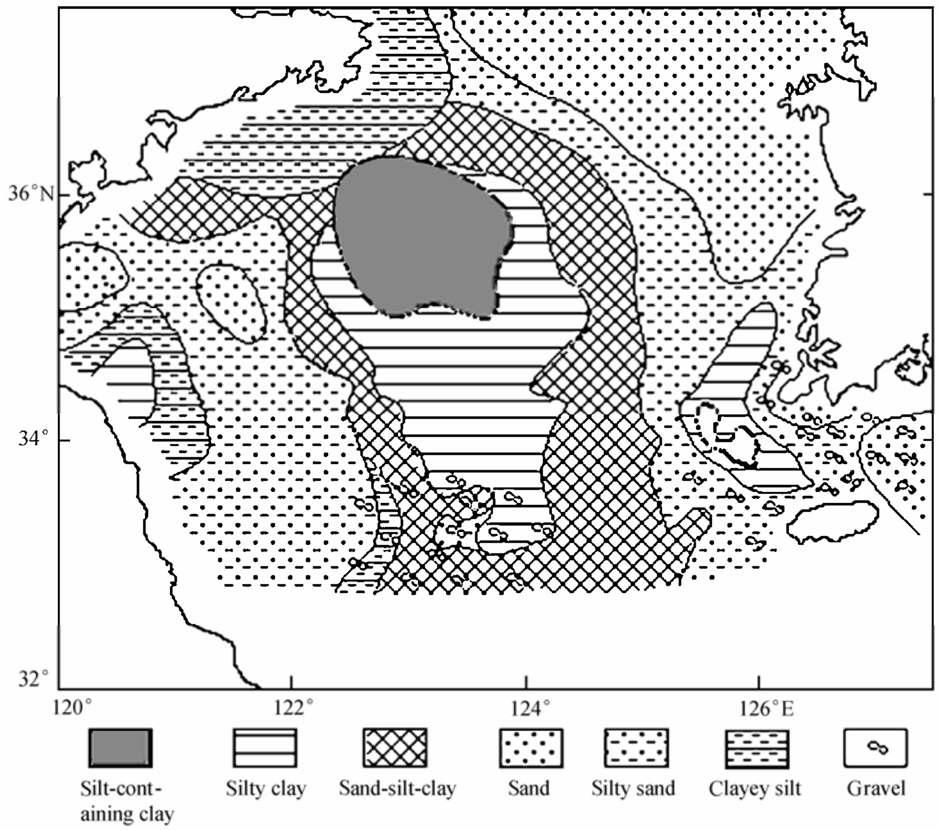

Fig. 1. Surface sediment types in the southern Yellow Sea.

study, the data obtained from China-Korea joint investigation and other Chinese cruises were used to fully discuss the distribution pattern of surface sediments and dynamic sedimentary systems in the southern Yellow Sea, with emphasis on the depositional systems which were formed under the actions of the Yellow Sea Warm Current and some secondary circulations. This study gave a relatively comprehensive and systematic consideration to sedimentary processes, especially the formation mechanism of muddy depositional systems in the southern Yellow Sea.

1 Materials and methods

More than 600 sediment samples were obtained by First Institute of Oceanography, State Oceanic Administration in May of 1998 and October of 1998. Among them, suspended matter sampling and current measurement were conducted at 70 stations in the cruise of May 1998. The seabed sediment samples were taken using box sampler and grab sampler, and the suspended matter samples were collected using GCC4-1 reversing water bottles at five pre-determined depths. The currents were measured using ADCP.

Grain size of sediments was analyzed using a GSL-101B laser grain-size analyzer. Heavy minerals were separated by tribromidemethane and then examined under a microscope to calculate the heavy mineral contents. Furthermore, more than 800 historical data of sediment, suspended matter and hydrology were collected.

2 Shelf low-energy sedimentary environments and depositional systems

The southern Yellow Sea shelf can be divided into two kinds of 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. There are deposition and erosion activities occurring in the high-energy environment. In different environments, there developed different depositional systems with their own characteristics.

(i) Characteristics of shelf low-energy environments. Continental shelf area is generally shallow water area with strong activities of tide, wave and current, so it is an area of more active hydrodynamics. However, in the area occupied by a meso-scale eddy on the shelf of the southern Yellow Sea, there appears a special low-energy environment. It is shown from the grain size data of surface sediments that the central part of the southern Yellow Sea has a fine-grained sediment (silty clay) distribution area, in which sediments have a mean grain size of 8.7ϕ and contain over 70% of clay fraction. This patchy muddy sediment area corresponds to the central area of the Yellow Sea Cold Water Mass, and the grain size of sediment in the area increases outward (Figs. 1 and 2), which indicates that muddy area is located in a low-energy environment, i.e., the circulation environment of the Yellow Sea Cold Water Mass. The low-energy environments were also found in the area southwest and northwest of Cheju Island.

The YSWC has a high water temperature[1] 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 a warm current and constitutes a comparatively big circulation system; an example for this case is the Cold Water Mass Circulation System in the central part of the southern Yellow Sea. The cold water mass behaves like a cyclonic eddy with a marginal current speed of only 5 cm/s, which indicates that this area is an environment with a relatively weak hydrodynamic condition. Numerical simulation of tidal currents also showed that the cold water mass circulation area is a weak zone of tidal current[23]. A clockwise circulation east of the Yellow Sea Warm Current is constructed by an anticyclonic eddy and the Korean Coastal Current. The anticyclonic eddy northwest of Cheju Island has a vertical double-ring structure, in which the lower part is a cyclonic circulation; 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 Yellow Sea Cold Water Mass[24]. Compared with the latter, the anticyclonic eddy has small size and strong hydrodynamic condition.

Multi-year hydrological data show that the cyclonic eddy (cold eddy) has an annual mean bottom water temperature of less than 8℃ (24 year mean)[20] and an observed mean seabed sediment Eh value of −30 mV—−150 mV[22], which indicates that the cold eddy bottom area is in a reducing environment. Redox characteristics of the anticyclonic eddy sediment remain to be further studied.

(ii) Muddy depositional system and its formation dynamic processes. Under long-term actions of eddy in the low-energy environment on the southern Yellow Sea shelf, fine-grained mud of silty clay deposited and formed muddy depositional system. Due to the differences in the eddy characteristics, especially in characteristics of cyclonic and anticyclonic eddies, the filled sediments in different depositional systems are different.

(1) Cyclonic eddy muddy sediment. These three muddy areas in the central SYS, the area southwest of Cheju Island and in the west of the northern Yellow Sea correspond to three cyclonic eddies and belong to cyclonic eddy sediments. In general, cyclonic eddy sediments have relatively wide distributions and construct the main body of the muddy depositional system. The central muddy sediment area in the SYS is the largest one among these three muddy areas, but its thickness in the center is less than 3 m; sediments in the area have mean size of 8.5ϕ, color of gray-green and over 60% of water content; they contain plentiful pyrite, homogenous composition and texture, and ^{14}C dating age of its bottom sediment is about 5550 aBP[8].

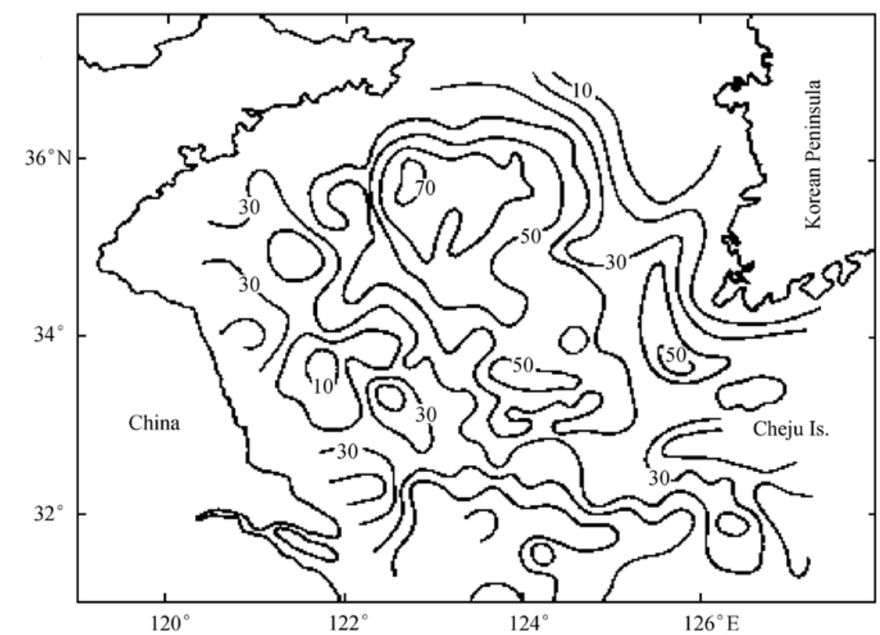

Fig. 2. Clay fraction contents of surface sediments in the southern Yellow Sea.

Based on the dynamic investigation on sediments on the bottom with large gradient southwest of Cheju Island, Hu[1] 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 depth. 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.

(2) 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 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 and have 50.3% of water content; they are homogenous in structure and have characteristics of acoustically transparent layer[20,25]. The bottom of this muddy sediment system at 13.5 m below seabed was inferred to be about 5689 a old by using the ^{14}C dating data from Hole YSDP102[21]. Below the muddy layer in the area northwest of Cheju Island, Shen[22] 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 the 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 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[20]. Compared with the cyclonic eddy environment, the anticyclonic eddy environment has stronger sedimentary dynamic characteristics.

(3) 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 they both 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 (Table 1).

3 Shelf high-energy sedimentary environments and depositional systems

(ⅰ) Characteristic of shelf high-energy sedimentary environment in the southern Yellow Sea. There are relatively strong tidal currents, coastal currents and storm surges in the east and south of the southern Yellow Sea and the sea area off Subei Shoal[13,23], and these three areas are high-energy environments with widely distributed sandy sediments. It is shown from the calculated M_2 tide results that the above-mentioned sandy sediment areas are fine sediment eroded areas[23]. Under co-actions of strong current, storm surge, wave and shelf front, the fine-grained bottom sediments (including clay and silt) are constantly transported to other areas, i.e. the seabed surface sediments are continuously eroded and

Table 1 Comparison between characteristics of cyclonic eddy sediment and anticyclonic eddy sediment

	Mean size/ϕ	Central thickness/m	Pyrite (% in grains)	Circulation characteristic	Bottom temperature/℃	Eh/mV
Cyclonic sediments (the central southern Yellow Sea)	8.5	2.8	>80	cyclonic type	<8	−15 — −90
Cyclonic sediments (Area southwest of Cheju Island)	8	3	>80	cyclonic type	6—8	
Anticyclonic sediments (area northwest of the Cheju Island)	6—7	13.5	<5	anticyclonic type		

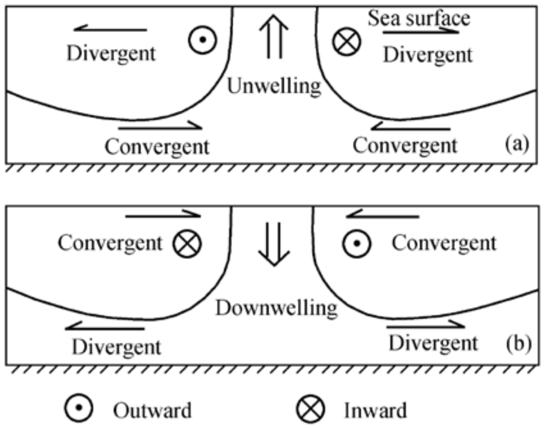

Fig. 3. Sedimentation patterns of (a) cyclonic and (b) anticyclonic eddies.

only remain coarse-grained sediments composed mainly of sand. This phenomenon reflects the characteristics of high-energy eroded area and indicates that the seabed sediment distributions coincide with the sedimentary dynamics. The surface sediments near Subei Shoal contain a large amount of Tertiary sandstone gravels[26,27], their weathered products are likely to become an important material source of adjacent areas.

(ii) High-energy environment depositional system and material characteristics

(1) Depositional system of high-energy environment. It is shown from the grain size composition distributions of surface sediments in the SYS that the grain size gradually increases with increasing distance off the central silty clay facies area, and sediment types are clay silt, silt, and fine sand etc. in turn (Fig. 2), which are evidently due to the increasing hydrodynamics. Corresponding to the high-energy areas, sandy sediments were developed in the east and south of the southern Yellow Sea and the sea area off Subei Shoal to form the sandy depositional systems; and the outer zone with the highest contents of fine sand is a high-energy eroded area. A part of fine-grained sediments eroded off in the high-energy environment area was transported to the low-energy environment and deposited there.

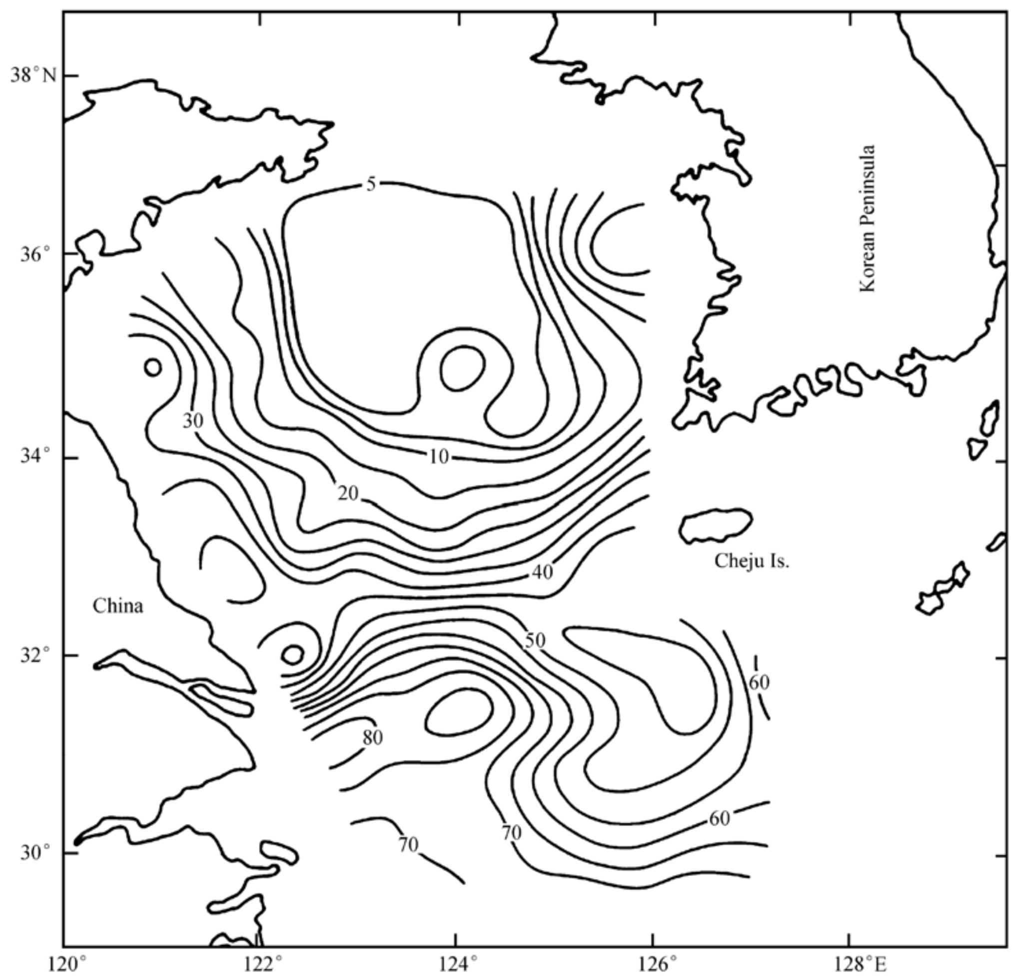

Fig. 4. Sand fraction contents in surface sediments of the southern Yellow Sea.

(2) Characteristics of suspended matter in high-energy environment. There is a special issue on the observed data of suspended matter in seawater in the SYS that total amount of suspended matter in seawater is far greater than total amount of sediment discharged by rivers[28]. Therefore, we can infer that a considerable part of suspended matter in the SYS is derived from the bottom sediment. The satellite remote sensing data also showed that the amount of suspended matter especially in the bottom seawater in the eroded area in the southern Yellow Sea was higher than that in the adjoining area[29]. Furthermore, the concentrations of suspended matter were often in the range of 100—500 mg/L, which is closely related to the seabed erosion, especially to the actions of storm-induced wave. Noncombustible component amounts to 70%—90% in suspended matter, which indicates that the suspended matter is not seawater organism[13,30]. Therefore, this area is the most active eroded zone in the southern Yellow Sea. In addition, as a source area of sediment, this area plays a nonnegligible role in forming the sediments in the southern Yellow Sea and the northern East China Sea.

(3) Characteristic of sandstone gravels and their forming environment. A great amount of sandstone gravels were collected during the towed net surveys and they are mainly distributed in 33°20′—32°30′N, 123°30′—124°30′E with a total area of up to 10000 km^2(Fig. 1). Based on incomplete statistics, gravel samples were obtained from more than 300 stations[26,27]. In general, the surface of gravel has a great amount of organism burrows. The gravels are generally composed of glauconite while there often contain large amounts of *foraminifera*, *Ostracoda* and *bivalvia* fossils in their marine facies layers. As viewed from sedimentation dynamics, the big size and distribution concentration of sandstone gravel both reflect a unique sedimentary dynamic environment, that is, the shelf eroded environment.

4 Conclusions

The modern shelf sedimentary processes in the southern Yellow Sea are controlled by shelf dynamic factors including coastal currents, waves, tidal currents, the Yellow Sea Warm Current, cyclonic eddies and anticyclonic eddies. Based on the sediment dynamic characteristics, the southern Yellow Sea shelf can be divided into low-energy (weak dynamic condition) and high-energy (strong dynamic condition) environments.

The shelf low-energy environments produced muddy depositional systems. Controlled by meso-scale cyclonic eddies (cold eddies), the cold eddy depositional systems were formed in the central southern Yellow Sea and the area southwest of Cheju Island. However, an anticyclonic muddy depositional system (warm eddy sediment) was formed in the southeast of the southern Yellow Sea (the area northwest of Cheju Island). In this study, the sedimentation patterns for cyclonic eddy and anticyclonic eddy types are given.

The shelf high-energy environments produced sandy sediments, the originally deposited fine-grained material (including clay and fine silt) was gradually resuspended and transported to the low-energy area to deposit there. In the high-energy environment, a large amount of sandstone gravels are distributed as a result of erosion.

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