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Spatial variability of surface sediment basis on geostatistical analysis in the littoral area of Yellow River delta, China

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A total of 155 surface sediment samples were collected from the littoral area of Yellow River Delta in 2007, and analyzed for texture and composition. Using geostatistic analysis, it is founded that there exist notable spatial autocorrelation of the clay and sand fractions in these samples with the autocorrelation scale being 44 km and 39 km, respectively. In comparison, the spatial autocorrelation of silt fraction is moderate, with the autocorrelation scale of 27 km. Analysis also reveals that the anisotropy of the sediment components is clear at the scale <20 km and >60 km and the distribution of the depocenters of sand fraction (i.e. content up to 40%) is very heterogeneous. Boundaries between these sedimentary units and their substratum are very sharp.

[Keywords: Geostatistical method; Semivariogram; Sand fraction, Characteristic distance, Yellow River Delta]

Introduction

Geostatistics is a method that was first proposed by Matheron[1] in 1962 involving the use of various principles and methods of statistics in geological problems. It is mainly used to study geological processes that have both structural and random characteristics in space and is particularly useful in uncertainty analysis and spatial prediction through revealing the spatial self-correlations that exist in the data. Until the late 1980s, geostatistics were mainly used to describe the spatial structure of environmental parameters and to predict the values of these parameters in non-sampled points[2]. Therefore, the geostatistical method was successfully used in sediment distribution[3].

The Yellow River is regarded as the second largest river for its high sediment discharge in the world. Over thousands of years, the lower reach of the Yellow River experienced frequent channel shifts[4], and the latest channel shift (artificial) was to the 8th section of the Qingshuigou Promontory in 1996 (Fig.1), so the delta developed toward the sea because of high sediment load.

Previous studies about the modern Yellow River Delta are mostly concerned with the changes of the river courses and the erosion-deposition characteristics of the littoral zone [5, 6,7]. Some sediment research also carried by scholars[8,9,10], however, most publications were focused on sediment properties, and they were limited to either part of the tidal flat or

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suspended sediments. Grain size parameters analysis (mean grain size, sorting coefficient and skewness) was main sediment research method in those studies, geostatistical methods was hardly used to analysis sediment characteristics of littoral area of modern Yellow River Delta.

Present study is an attempt to understand the overall spatial distributions characteristics of the seabed surface sediment of littoral area of Yellow River Delta. In order to study spatial variability of the sediment, the geostatistical methods, which are based on a semivariographic study and a Kriging interpolation for surface sediments mapping, are used in analysing sediment samples. To better understand the spatial characteristic of sediment fractions, the paper also analysed distributions characteristics combined with sedimentary environment.

Materials and Methods

The study area belong to Shandong Province and Bohai Sea, and the littoral area of the delta refers to the arc sea area, including the southern of Bohai Bay and the western Laizhou Bay. The sediments supplied the Yellow River is transported, diffused, deposit and re-suspensed under various marine hydrodynamics[11]. Howerer, the annual sediment load discharged from the Yellow River to the sea has decreased seriously because of climate change and human activities in past 50 years[12,13], as a result, the development of delta and sediment depositional systems suffered effects in a certain degree. The sea area of abandoned river mouth suffered serious erosion, and the predominant sediment around delta is poorly sorted, stratified and prone to re-suspension under the action of wave and tide[8]. The estuarine hydrodynamic processes have an important influence on sediments, especially the re–suspended fine sediments and coarse sediments in the delta area.

The average tidal range of the irregular diurnal tide zone is 0.2-1.0 m, and gradually increases westward and southward to 1.6 to 1.8 m at the innermost parts of the Bohai Bay and Laizhou Bay[14]. The tidal currents change in different seasons. The maximum current speed is around 1.4 m/s in spring while it could reach 1.8 m/s in summer because of the river discharges[11]. The surface residual current affected by monsoon generally flows to southward in winter and northward in summer.

A total of 155 surface sediment samples (the upper 5-10 cm of bed material) were obtained with grab sampling during May and July 2007 along 18 profiles (No.S1-S18 in Fig. 1). These profiles spaced out at 10 km apart covering the whole littoral zone and extending from the shore to the deeper part of the sea. At each profile 7-9 samples were taken, 2-3 samples in the shoal zone while 3 samples in the steeper and gentler slope areas, respectively. The water depths at the sampling locations ranged from 0.5 m to25 m. The location point of each sampling was poisoned by DGPS of AG122GPS Beacon machine that has an accuracy of less than 3 m.

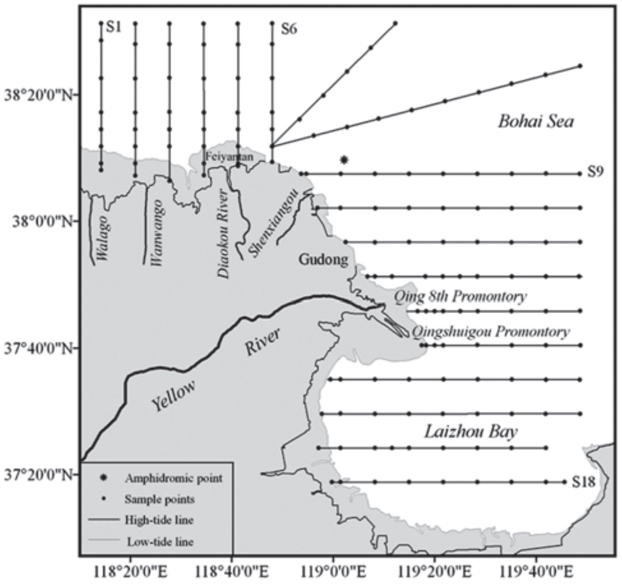

Fig. 1. Study area and locations of sediment sampling in the littoral area of Yellow River Delta.

To reduce as much as possible the analysis errors or distortion, a strict procedure was followed in laboratory analyses. Prior to grain-size analysis, organic matter was removed from the bed sediments by adding H_2O_2 (30%). Sediments were then dispersed by the addition of $(Na_3PO_3)_6$ (3.3%) and undergone subsequent ultrasonic treatment. The sediment grain size was analyzed with a Coulter-LS100Q Laser Granularity Analyzer which measures over a range of 0-11Φ. Sediments are classified according to Folk's triangular diagram method based on the ratio of the sediment components[15] with the sediment diameter > 4Φ as sand, 4Φ ~ 8Φ as silt, and <8Φ as clay.

In this study, the sand fraction of the sediment represents the regionalised variable. Regionalised phenomenon gathers all the environmental parameters influencing the spatial distribution of the sand fraction of sediment. Geostatistical procedure for this study includes several stages Including Gaussian transformation, variogram analysis, anisotropic analysis, and interpolation.

The premises of geostatistical methods is the frequency distribution of data should be close to a normal distribution. But, in the practical case of the sand fraction of sediments, the date is no-normally distributed caused many reasons, such as sampling scale that is not representative to the spatial sedimentary process scale and errors in laboratory analysis, etc. Therefore, it is necessary to transform the original data to a normally distributed data set.

Variogram is a basic tool for the estimation and mapping of regionalised variables. It reveals the random and structured aspects of spatial dispersion. The variorum $\gamma(h)$ represents the average variance between observations separated by a distance h. This value plays an important role in the description and interpretation of the structure of the spatial variability of the investigated regionalized variable[16]). so the semivariogram function is expressed as following:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z(x_i+h)-Z(x_i)]^2$$

where h is vector of separate two sampling station and called step length, $Z(x_i)$ is equal to the value at location x_i, $Z(x_i+h)$ is equal to the value at location x_i+h, $\gamma(h)$ is equal to the variogram for distance h between values $Z(x_i)$ and $Z(x_i+h)$, the $N(h)$ is equal to the number of pairs of values separated by h.

The best fitting model (Line, Spherical, Exponential, and Gauss model) and the nugget value (Co), base station values (Co+C, C as structure variance), spatial correlation (Co/Co+C) and range (Ao) are obtained through semivariance analysis. Semivariance analysis is used by statistical software GS+9.0, drawing is used by GS+9.0 and ArcGIS 9.2 software in the paper.

Spatial distribution of the surface sediments is governed by complex mechanisms which can induce spatial variability of the sediments in several ways. Description of this spatial difference is made by the study of the anisotropy which means the variation of the correlation distance for a certain sediment parameter varies in different directions[17,18,19]. To conduct an anisotropy study, there must be enough information presented, which requires a significant number of data points, usually more than 100[20,21]. Direction of the maximum continuity can be revealed from a variogram surface map. In this direction the parameter varies most moderately, and the correlation scale is the largest[19].

Kriging interpolation method is one of the main parts of the geostatistical analysis and an unbiased optimal estimation of the regionalised variables in a limited area, based on the variogram theory and structural analysis. For the Kriging method to be effective the variagram analysis needs to show the existence of the spatial correlation of regionalised variables. Kriging method can be used to interpolate values at un-sampled locations based on the original data set of the regionalized variables and the structural features of the variogram. The process of interpolation is similar to the weighted moving average, and the weight value is determined by the spatial data analysis.

Results and Discussion

Spatial variability of sand fraction

Different sized sediments are usually transported in different ways under different hydrodynamic conditions. The location where coarse material is found in the spatial distribution of sediments usually indicate the strong local hydrodynamic conditions and erosion environment, thus the analysis of coarse particle distribution is an effective way to understand coastal erosion and its related landform features.

In the present study the statistical distribution of sand fraction in the sediments is represented using 10 size bands with a typical frequency histogram as shown in Fig. 2a. The histogram reveals several characteristics of the distribution of the sand fraction in the study area. Sand content in the surface sediments varies between 0 and 94.8%. The histogram of sand fraction (Fig. 2a) shows a great heterogeneity and that only a small number of samples have high sand content. 63 samples among 155 show sand content higher than the mean value of the studied area (27.1%) and only 27 samples have a sand content higher than 50%.This heterogeneity also indicates the low content of two percentage classes (70-80% and >90%). The juxtaposition of these classes underlines the existence of intensely coarsening sedimentary areas, marked by a very sharp boundary.

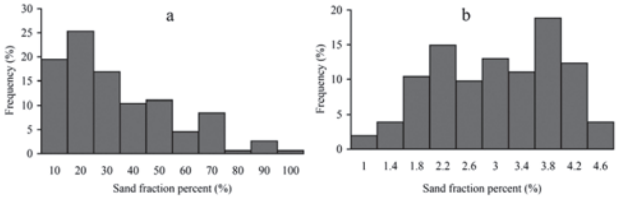

Figure 2. a. Histogram of the sand fraction content of the sediment samples; b. Histogram of logarithmic transformation of the sand fraction content of the sediment samples.

The frequency of the sand fraction showns obvious positive skew distribution, so data of sand frequency needed to be transformed to normal distribution. The frequency distribution of the transformed data (Fig. 2b) is seen to be close to normality. The transformed variable, noted as S_T (transformed sand fraction) is used for the geostatistical analysis.

As the semivariance curve of S_T data (Fig. 3) does not continuous increase over the study area after transformation, andthere is no discernable trend in the transformed data, therefore, it permits the use of geostatistic tools without some other transformation[22]. The higher base station values (Co+C) means the higher spatial heterogeneity of the system. Smaller distance, similarity is spatial correlation is bigger within range (Ao). The ratio of Co and Co+C, indicates the degree of spatial correlation of the system variable. When the value is less than 25%, it means the spatial correlation of the variable is notable; when the value is between 25 -75%, the spatial correlation of the variable is moderate; when the value is greater than 75%, the spatial correlation of the variable is weak.

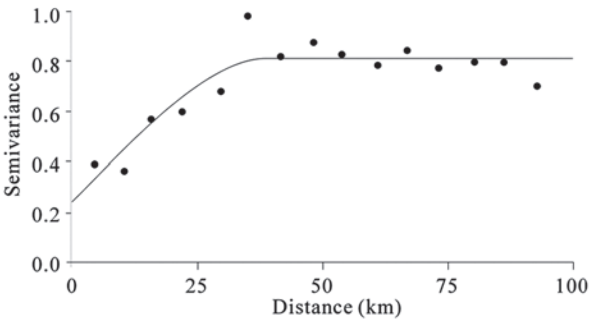

Figure 3. Semivariogram with a fitted parametric model (solid line) of ST.

This semivariogram shows a nugget value (Co) of 0.23 (Fig. 3), which characterises sharp variations in the amount of sand fraction over a short distance. These variations could be the result of either artificial or natural factors, because they could originate from analytical errors or underlying morphological structure[23]. There is no explanation that could be given for this nugget effect. The nugget effect of the semivariogram highlights the sharp transition between the sandy units and their silt substratum. It also reveals the existence of morphological phenomena with dimensions lower than the average sampling distance (8000 m).

The semivariogram also shows a cyclicity characterized by the presence of undulations after the distance where the curve reaches a Co+C and the undulations attenuate gradually. This cyclicity shows the existence of small groups of sandy sedimentary structures which are of different sizes. The attenuation generally demonstrates the variability in the distance between these sandy groups and the fact that different sedimentary units are superposed.

The number of analysed samples is sufficient (N=155) for a study of isotropy on the study area.

This omnidirectional technique gives more precise results for the direction of a possible anisotropy than those obtained with experimental semivariograms. The variogram surface map built from the transformed data S_T is shown in Fig. 4. It shows a clear anisotropy, with the maximum continuity observed in the direction of azimuth 100°. It underlines anisotropy at the scale of the Yellow River Delta, oriented in a NW-SE direction, which corresponds to the strongest gradients of sediment coarsening.

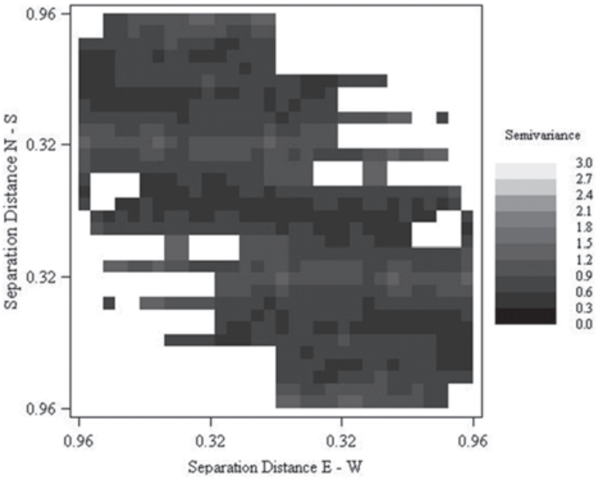

Figure 4. Variogram surface map for ST.

The choice of the interpolation method is governed by the information supported by the data set. In this study, one of the most important results, from the semivariogram analysis, is the distribution of small sandy structures separated by different distances. As a consequence, the interpolation must be performed to visualise these sedimentary units. Ordinary Kriging is particularly adapted to this kind of study.

4.2 Sand origin analysis

Two types of sandy units are distinguished in the study area: the coarsening of surface sediments due to erosion; and the on-site accumulation of terrigenous sediment due to sharply reduced sediment-carrying capacity when river met the sea.

Since 1976 when the Yellow River course diverted to the Qingshui channel, sediment sources of the northern deltaic coast reduced or even was completely cut off, the coast retreated due to erosion from Shenxian Ditch to Wanwan Ditch. Where the sediment was principally river-borne silt, its compactness was poor because of rapid accumulation by Yellow River, and sediments were subject to re-suspension into the water under combined actions of wave and current. After the Yellow River diverted, the protruding part of underwater accumulation was most subject to erosion, experiencing a transformation from deposition into erosion[24]. According to calculation, the area shallower than 6.5 m of water depth is a strong dynamic zone, combined sediment stir by waves and sediment transport by tidal current. Therefore sediment carrying capacity is large and the nearshore zone suffered from intensive erosion[25]. To sum up, the area with high sand content in the northeast littoral zone of the delta is the result of bed sediment coarsening due to erosion by combined waves and tidal current.

The littoral area along Laizhou Bay was less influenced by the water and sediment from Yellow River, where the surface sediment could be affected by the role of short source rivers. The sediment discharge into the sea from Xiaoqing River has declined rapidly due to the construction of reservoir upstream and reduced rainfall in recent years. Fig.5

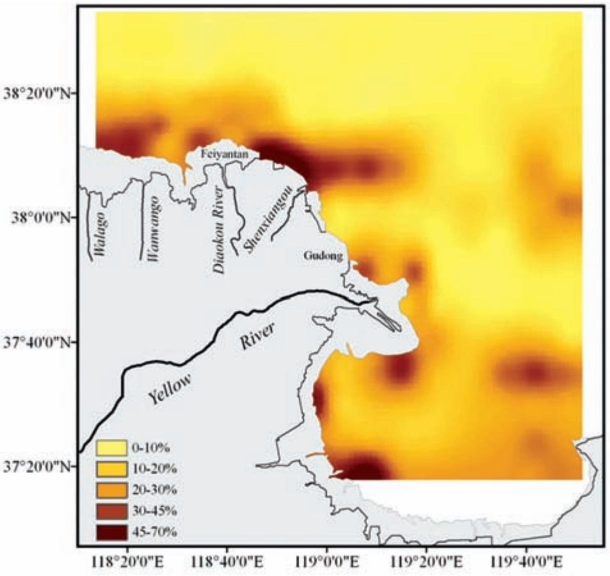

Figure 5. Spatial distribution of the sand fraction in the study area

shows that there exists an obvious high sand content area near the mouth of Xiaoqing River. This result coincides with the study results of coastal erosion in this area. Based on the analysis of the water depth data, Feng *et al*. (2006)[26] concluded that the area within 5m isobath near Xiaoqing River mouth displayed clear erosion. The area of sediment coarsening in this study is exactly located within the area.

4.3 Semivariogram analysis of sediments

Silt had the highest content among the various components of surface sediments in the littoral area of Yellow River Delta (Table 1), which reflected the silty feature of sediments. The coefficients of variance differ rather notably in three components of sediment, in which the coefficients of variance of clay and sand are 0.65 and 0.86 respectively, while the coefficient of variance of silt content is only 0.26 which indicated that silt has more uniform spatial distribution. Skewness and kurtosis reflect statistic distribution forms of sediment sample data, i.e. deviation extent from the normal distribution of various components of all data sampling points. Their physical meaning differs from that of skewness and kurtosis in size parameters for a single sediment sample. According to statistical distribution forms of measured data, all component contents showed different degree of skewed distribution. This is because the effects of sorting and transport by wave and tidal current, and the data of partial sampling points obviously differ from other sampling points, so that the sample data attain specific values.

Table 2 is the theoretical semivariogram models and corresponding parameters of different surface sediment components. The best fitting model of clay content is an exponential model, while the best models far both silt and sand contents are spherical model. The values of Co/(Co+C) of clay and sand are both less than that of silt, which indicates that the spatial autocorrelations of clay and sand are both stronger than that of silt. This difference is related to the dominant factors controlling spatial variability of each component. Because of light quality, clay mainly is transported in suspension under hydrodynamic actions[27] therefore the dominant factor controlling its spatial variability is tidal current. Sand component is of larger grain size and hard to be transported in long distance under hydrodynamic actions, and its spatial variability is largely controlled by regional geological background conditions and the sorting and transport of tidal current for fine sediments. Because geological background conditions and tidal current action are relatively stable, and largely responsible for the spatial variability of clay and sand in a continuous or periodic way, the two sediment components show significant spatial autocorrelation. While silt, its size ranges between clay and sand, is easy to initiate movement and motion also easy to settle, and mainly transports in a bed-load or saltation way. This makes the control factors of its spatial variation have not only cyclical factors of waves and tidal current, but also human factors such as shipping, breeding disturbance. Because the human factors are of strong randomness, disturb the periodic functions of waves and tidal current, thus increases the uncertainty of spatial variability. Consequently the spatial autocorrelation of silt decreased.

The range value (Ao) indicates the range of sediment spatial autocorrelation. Within the range,

Table 1—Descriptive statistics of different surface sediment components

Sediment components	Percentage (%) Min	Max	Average	Standard Deviation	Variation Coefficient	Skewness	Kurtosis
Clay	0.01	36.17	14.47	9.40	0.65	0.11	1.86
Silt	4.68	78.97	58.71	15.48	0.26	-1.50	5.13
Sand	0.39	94.75	26.83	23.09	0.86	0.97	3.20

Table 2—Theoretical semivariogram models and corresponding parameters of different surface sediment components

Sediment components	Theoretical model	C_O	C_O+C	$C_O/(C_O+C)$	Ao (km)
Clay	Exponential model	0.137	0.361	0.38	39
Silt	Spherical model	0.928	1.857	0.50	27
Sand	Spherical model	0.234	0.817	0.29	44

the more near are sample points, the more similar the content of same components. When spacing greater than the range value, the two sample points are not related. As shown in Table 2, the spatial autocorrelation range of sand component is maximum, up to 44 km; the spatial autocorrelation ranges of clay and silt components are 39 km and 27 km respectively. Silt component exhibits relatively small range value, likely affected by random factors such as human activities[28].

In the larger spatial scale, the natural process which is often in a different direction control the spatial variability of regional variables, and make the spatial variation showed distinct directional characteristics. In order to analyze the directional characteristics of spatial variability of different surface sediment components in the study area, the semivariances in the two orthogonal groups of E90°, S180° and NE45°, SE135° were calculated, and their anisotropy ratios K(h) also computed. The anisotropy ratio may describe the anisotropic structure of regionalized variables. If the anisotropy ratio is equal or near to 1, the variable in all direction changes converges, i.e. isotropy or anisotropy.

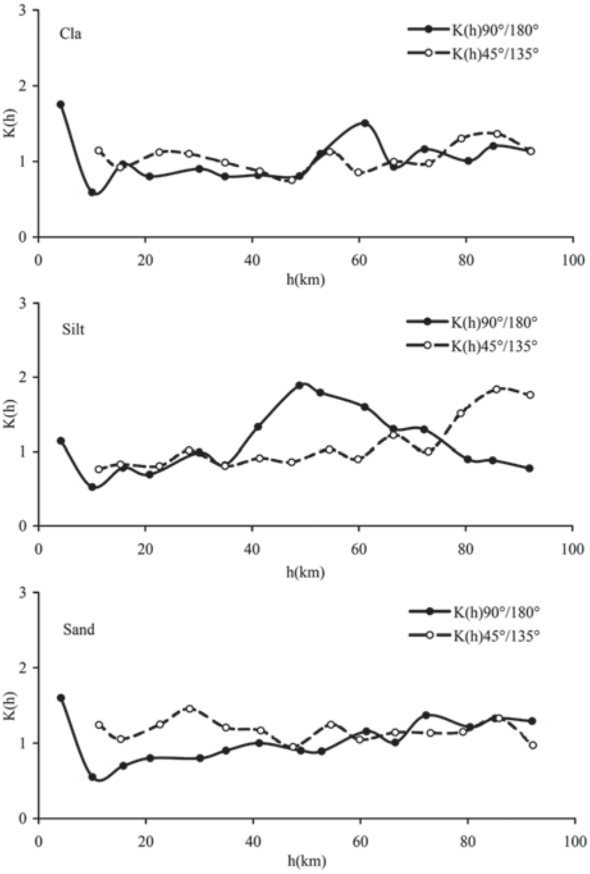

Figure 6. Ratios of anisotropic semivarigram of different surface sediment components.

As shown in Fig.6, the anisotropy ratio K(h) of each surface sediment component in the study area changes greater in 90°/180° than 45°/135°, overall. In the scale of 20 to 60 km, the spatial variation of sediment exhibited clear isotropy, while in the scales less than 20 km and larger than 60 km, it showed anisotropy, and appeared more obvious in the orthogonal directions of E90° and S180°. This is due to that in the west of amphidromic point the maximum flood-tidal current points to west by north and the maximum ebb-tidal current directs to east by south slightly; in the south of amphidromic point the maximum flood-tidal current directs to south and ebb-tidal current directs to north. Different sized sediments were sorted and transported by tidal currents in flood and ebb directions[29], which caused different sediment components to show different trends along current directions. In the orthogonal directions of NE45° and SE135°, waves played a significant role it disturbing surface. The prevailing wave direction in the study area is NE with a frequency of 10.3%, and secondarily prevailing wave direction is SE with a frequency 8%; strong waves are mainly from NNE to ENE, especially

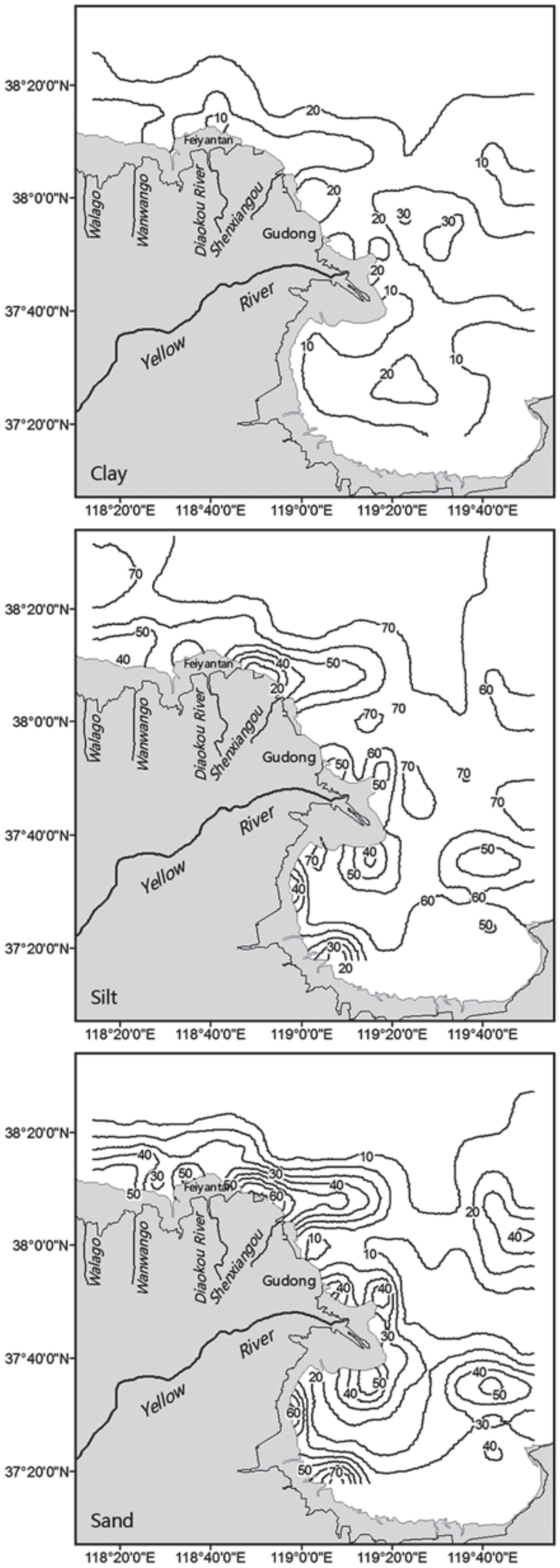

Figure 7. Distributions of sediment fractions in the littoral area of Yellow River Delta

in the strongest NE. The effect of waves performs in the relatively small scale, and offsets somewhat the differentiation of tidal current at this scale. The content variation of sediment components is larger in the direction of NE45° than SE135°. This is due to the prevailing and strong wave directions are all NE, thus the sorting variation of sediments in the direction is very significant. In addition, the variation of sand content is larger along the west to the east than in the north-south direction, which maybe due to that the terrigenous sediment discharged by Yellow River rapidly accumulated on the way. Clay content also various in a similar way, which is due to fine sediment was transported in suspension a far distance, and gradually accumulated along with weakened runoff, thus formed obvious variation distribution along the west to the east, the result is consistent to sediment distribution[31].

Conclusion

Geostatistical analysis methods is used to quantitatively analyze the space variability characteristics of littoral surface sediments from a macroscopic view, and the relationship between space variation pattern of sediment properties and sedimentary environment conditions is established by this method, therefore, it could reveal littoral sediment spatial distribution and sediment dynamic processes at different scales.

The spatial distribution of sand fraction showed obvious variability in W-E direction after semivariance ananlysis in the littoral area of the Yellow River Delta. The high content areas of sand fraction display a patch shape distribution with unequal space and various sizes. These high value areas are mainly distributed in the nearshore west mouth of Shenxian Ditch (the northeastern Yellow River Delta), the bayhead of Laizhou Bay, the old mouth of Qingshui Ditch, current mouth, and the offshore Wanwan Ditch mouth. The Semivariogram analysis shows that the sand and clay of surface sediment in the littoral area of Yellow River Delta have strong space autocorrelation due to the effect of structural factors of topographic condition, wave and current, their ranges reached 44 km and 39 km respectively; silt displayed moderate space autocorrelation due to its dynamic characteristics apt to incipient motion and settlement and artificial disturbance, its range was 27 km. The isotropic variation scale of three components (sand, silt and clay) ranged about between 20 and 60 km due to differences of hydraulic characteristics and main control factors of spatial variability for each component, and two groups of perpendicular directions S180° and E90° appeared to be clearly different.

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