Indian Journal of Geo Marine Sciences
Vol. 48 (04), April 2019, pp. 582-589

End-member modeling analysis of tidal flat sediments grain size and their implications for sedimentary sources from Jiangsu coast, Eastern China

Longsheng Wang[1,2*], Shouyun Hu[2], Ge Yu[2], Mingming Ma[2], Xiaohui Wang[1], & Mengna Liao[2]
[1]School of Resources and Environmental Engineering, Ludong University, Yantai 264025, China
[2]State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[*][E-mail: 52wls@163.com]

Received 22 August 2017; revised 09 January 2018

Sediment grain-size distributions (GSDs) provide rich information about sedimentary sources and potentially about environmental and climatic changes. However, neither traditional descriptive statistics nor curving fitting methods are able to address this complexity fully. In this study, end-member modeling analysis (EMMA) was conducted on the GSDs of tidal flat samples from the Jiangsu coast. Based on the frequency and spatial distributions of the end members (EMs), the sedimentary sources of each EM were discussed. The results show that EM1 comprises 76.07-100% of the total grain sizes between YTJ and CM3 and represents Yangtze River as a dominant supplier. EM2 comprises 50.50% to 95.6% of the total grain sizes between DF and LSG, reflecting that the coast is the transitional zone influenced by Yellow River and Yangtze River. EM3 comprises 50.33% to 100% of the total grain sizes between GHK1 and DLG, showing Yellow River as a dominant supplier. EM4 comprises 88% to 97.53% of the total grain sizes between LD1 and LD3, reflecting that the tidal flat sediments of Liandao Island were mainly from the nearshore rock weathering. Compared to the traditional method of sediment grain size analysis, EMMA can determine the EMs and provide better explanations of the sediment provenance and regional sedimentary environment in the study area.

[**Keywords**: End-member modeling analysis; Grain size distributions; Tidal flat; Jiangsu coast]

Introduction

Sediment grain size distributions (GSDs) can provide direct information on the origin of sediments. In addition, analysis of GSDs is an effective method of evaluating sediment transport, deposition and size-selective erosion. First attempts to describe GSDs in objective terms were performed in the late 1950s. Folk and Ward described GSDs in statistical terms as mean, standard deviation, skewness and kurtosis[1]. A connection between grain-size distribution and sedimentary sources was described by several authors[2,3,4,5]. A first attempt to manually decompose GSDs was described by Curray[6] and Tanner[7]. Decomposition of GSDs by cubic spline curves was described by Sheridan et al.[8] Moreover, Sun et al.[9] described the decomposition of GSDs into Weibull distributions. Many methods for decomposition of grain-sizes are based on curvefitting, which is a relatively subjective procedure. EMMA is a popular method of characterizing GSDs. EMMA of sedimentological data gives a genetic interpretation of grain-sizes with minimal assumptions[10, 11] and was first extensively described by Weltje[12]. EMMA has also been a powerful and flexible statistic approach to identify and quantify generic sediment transport process from multimodal GSDs. Paterson and Heslop[13] developed new software called AnalySize, which incorporates new algorithms for unmixing grain size data as well a suite of standard grain size analysis and presentation tools.

Increasing dataset sizes have led to a growing popularity of multivariate statistical methods in many scientific fields, as they allow simultaneous interpretation of a set of parameters. Modern techniques for grain-size analysis based on laser diffraction result in datasets with many samples and grain-size classes, increasing the need for statistical analysis. GSDs are classically interpreted as the result of mixing of elementary populations11, 14. The common occurrence of polymodal grain-size distribution is in agreement with this assumption3 and several methods have been designed to unmix distributions[9,15]. However, these methods can only be applied using certain assumptions or pre-conditions.

Unlike multivariate statistical methods, viz., principal component analysis and factor analysis, EMMA performs simultaneous interpretation of all variables within the dataset for every sample. This allows coupling of sediment archives with natural processes instead of linear interpretation of abstract parameters as mean or median[16], since these parameters are not representative for skewed or polymodal distributions. EMMA aims to decipher the construction of several EMs combined with an indication to what extent this EM is represented in a sample. EMMA allows the unmixing of sediment populations within a set of samples. Mixing can result from different factors, viz., transport processes, source regions, and environmental conditions[17]. Therefore, one should determine whether the measured GSDs result from mixing of different sedimentary sources, size-selective dispersal, or a combination of those.

EMMA is applied in many fields of geosciences, including hydrological sciences[18], remote sensing[19], and soil geochemistry[20]. Many sedimentological researchers used EMMA to enhance interpretations of site formation processes by unmixing the measured GSDs[10,11,12,17,21]. The technique has been demonstrated to successfully extract a more robust geologically meaningful interpretation of the GSDs from deep-sea sediment cores[10,22,23,24], lake cores and surface samples[17,21,25,26], and provide an unbiased confirmation of field and proxy data used in palaeoenvironmental reconstruction.

The tidal flats along the coast of the province of Jiangsu, China, extend in the north-west south-east direction from approximately 35°N to 32°N along the Yellow Sea (Fig. 1). The tides are semidiurnal and come both from the south-east (the Pacific) and the north-east (the Yellow Sea, in that region the tides rotate counterclockwise). The middle section of the tidal flats is sheltered by extensive offshore radial sand ridges. Investigation of the sedimentary sources for such massive depositional system have attracted much scholarly attention in the past several decades[27,28,29]. The sediments along the Jiangsu coast have been supplied by the Yellow river which had its mouth on the Jiangsu coast at Feihuanghekou from 1128 to 1855 AD. After that mouth had been abandoned for the present one in Bohai Bay, erosion of the former river mouth produced the sediments that have been, and still are, deposited on the mud flats south of the Sheyang River. Presently they are still prograding. The southern part of the coast was formed through the infilling of the paleo-Yangtze River

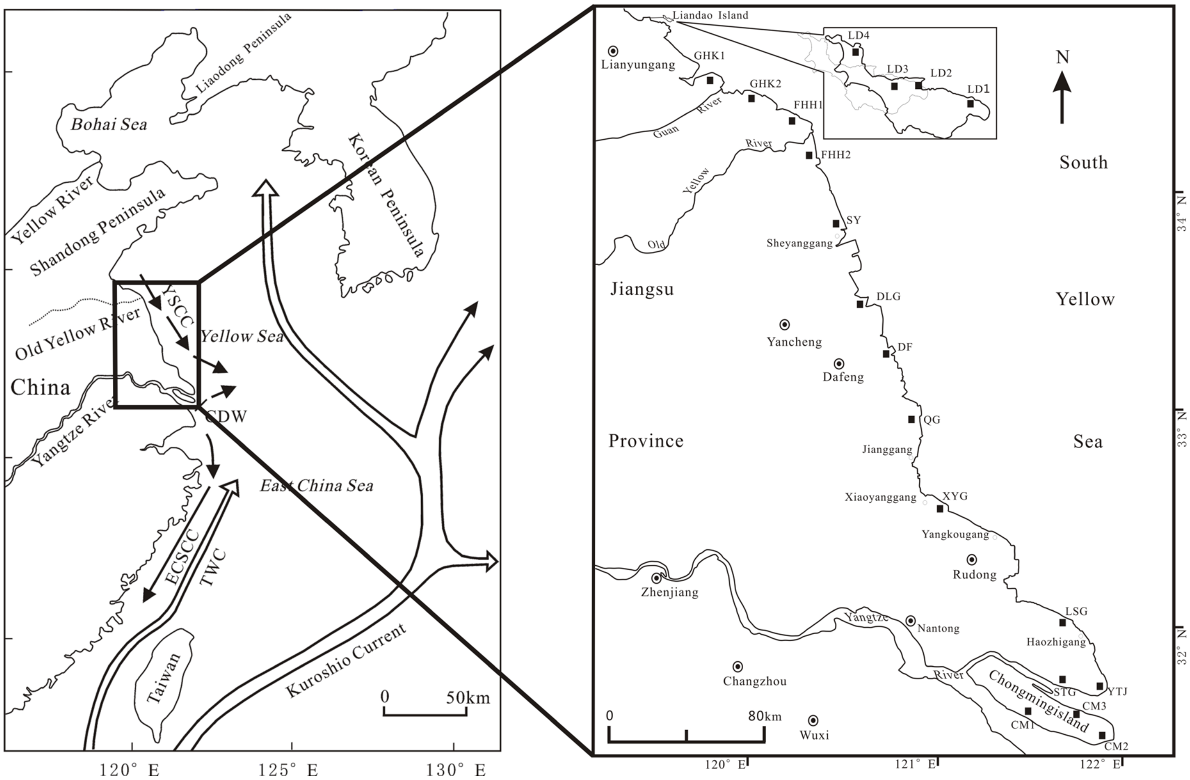

Fig. 1 — Site map showing the study region in China (left) and the study sites of tidal flat along the Jiangsu coast (right).

incised valley during the Holocene[29,30], and therefore, comprised the northern arm of the present Yangtze River delta.

Many researchers used different methods to differentiate the sedimentary sources of tidal flat sediments along the Jiangsu coast. Based on the clay mineral assemblages, Li et al.[28] suggested that the sediments north to Dafeng could be dominated by the Yellow River, whereas the sediments south of Rudong could be influenced by the Yangtze River, with the sediments between Dafeng and Rudong representing a mixture of the two types of sediments. Zhang et al.[32] and Wang et al.[29] used the magnetic and geochemical evidence to differentiate the sedimentary sources of the Jiangsu coast, which indicated that the tidal flat sediments of Liandao Island were mainly from the nearshore rock weathering. The Yellow River is the dominant supplier for the north of Dafeng, while the Yangtze River is the dominant supplier for the south of Rudong. The coast between Dafeng and Rudong is the transition zone influenced by both rivers. In this study, we applied the sediment grain size results of EMMA to identify sedimentary sources of tidal flat sediments along the Jiangsu coast. Compared with the routine classification method that is based on clay-silt-sand ternary diagrams, the physical meaning and spatial distributions of end members (EMs) are clearer and helpful for better understanding the sedimentation processes and transport mechanisms. We selected tidal flat samples to measure grain size, and used AnalySize Software proposed by Paterson and Heslop[13] to demonstrate the applicability of EMMA. The sedimentary sources of tidal flat sediments along the Jiangsu coast was analyzed according to the result of EMMA. These results will be useful for identifying sediment transport mechanism (traction, saltation and suspension) responsible for deposition.

Study Area

The study area of the Jiangsu coast covers an area about 3000 km2 (32°N-35°N), which is situated between the Yangtze River estuary and the Liandao Island (Fig. 1). This study area is controlled by a monsoon climate. The annual mean temperature is 14.1 °C and annual precipitation is around 1100 mm33. The tides are irregularly semidiurnal, with an average tidal range of 3.68 m[27]. The currents during the flood phase of the tide are stronger than those during the ebb. The wave height over the intertidal flat is relatively small. Waves from the north-east and south-east prevail in winter and summer, respectively, with higher wave height in winter than that in summer35.

During 1128 to 1855 AD, Huanghe river discharged into the Yellow Sea on the Jiangsu coast, resulting in rapid growth of the northern Jiangsu mud flats. In 1855, the river shifted its course to discharge into the Bohai Sea in northern China. Since then the coastline of the abandoned Huanghe River delta has been eroding. The average width of tidal flat was more than 10 km before 1978; however, it has decreased to 2.9 km, by 2008. The prograding tidal flat from land to sea typically consists of saltmarsh, mud flat and silt/sand flat[26]. The vegetation includes native species (Phragmites australis, Suaeda maritima) and introduced species (Spartina angelica and Spartina altiflora)[34]. However, Suaeda glauca Bunge and Suaeda maritime Dumort are disappearing and Spartina has become the dominant salt marsh species over the upper intertidal flat[36].

Materials and Methods

To make a systematically comparative study of the tidal flat deposits in the Jiangsu coast, a fieldwork in the study area was conducted in November 2013. A total of 19 surface samples (top 5 cm) were collected at 19 sites between Lianyungang and Chongming island. According to the actual situation, 2-5 samples were obtained at each site, and were homogenized mixed. The samples were dried at 40℃ and disaggregated before analyses.

Grain-size measurements

Visible impurities contained in each sample were eliminated and the samples were then air-dried and sieved using a 2 mm sieve. Each sample (200 mg) was placed into a beaker, after which 10 ml of 30% hydrogen peroxide was added, followed by heating. Then 10 ml of 10% hydrochloric acid was added, followed by heating until boiling. After fully injecting water, the beakers were allowed to stand for 12 hours, and subsequently, 10 ml of 0.05 M sodium hexametaphosphate solution was added. Each beaker was then placed into an ultrasonic vibrator for 5 minutes, after which the grain size of the sediment was determined. Grain size analysis of the sediment samples was conducted using a Malvern Mastersizer-S laser grain size analyzer in the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences.

Grain size results of EMMA

The sample grain size distribution of tidal flat sediments from the Jiangsu coast has a wide range (0–630 μm) (Fig. 2(a)), and the peak of the frequency distribution curve ranges from 5 to 280 μm. The samples from most of the locations are primarily composed of fine-grained sediments. Using the AnalySize Software, we calculated the squared linear correlation (R^2) and the angular distance in degrees (Theta) (Fig. 2(b), (c)) by assuming two to six EMs. If the R2 value is low and theta is high, this is an indication of a poor fit. This may be because the given EMs do not fit the data well, or that additional EMs are needed to model the data. The results show that with two EMs, the R^2 value is 0.65 and the Theta value is 32.22, indicating that two EMs cannot satisfy the fitting requirement. When three EMs are used, the R^2 value increases and the theta value decreases, which indicates that three EMs generally satisfy the requirements for most of the grain size fits. Certain local continuous multiple grain size fits are still poor, which indicates that three EMs cannot reflect all of the information that is recorded by the grain size distribution. When four EMs are used, the R^2 value is higher than 0.95 and the theta value is lower than 10, which indicates that four EMs can fit the data. By increasing the number of EMs to five, the R^2 value is 0.98 and the theta value is 6.29. By increasing the number to six, the R^2 value is 0.99 and the theta value is 4.57. Thus, increasing the number of EMs beyond four does not improve the squared linear correlation and the angular distance in degrees. Therefore, we use four EMs to conduct the EM retrieval based on the grain size data.

Results and Discussion

Grain-size distribution frequency curves

The grain-size distribution frequency curves of the sediments on the Jiangsu coast are shown in Figure 2(a). The results show the grain-size curves of the tidal flat sediments from Liandao Island are clearly dominated by sand. The tidal flat sediment between

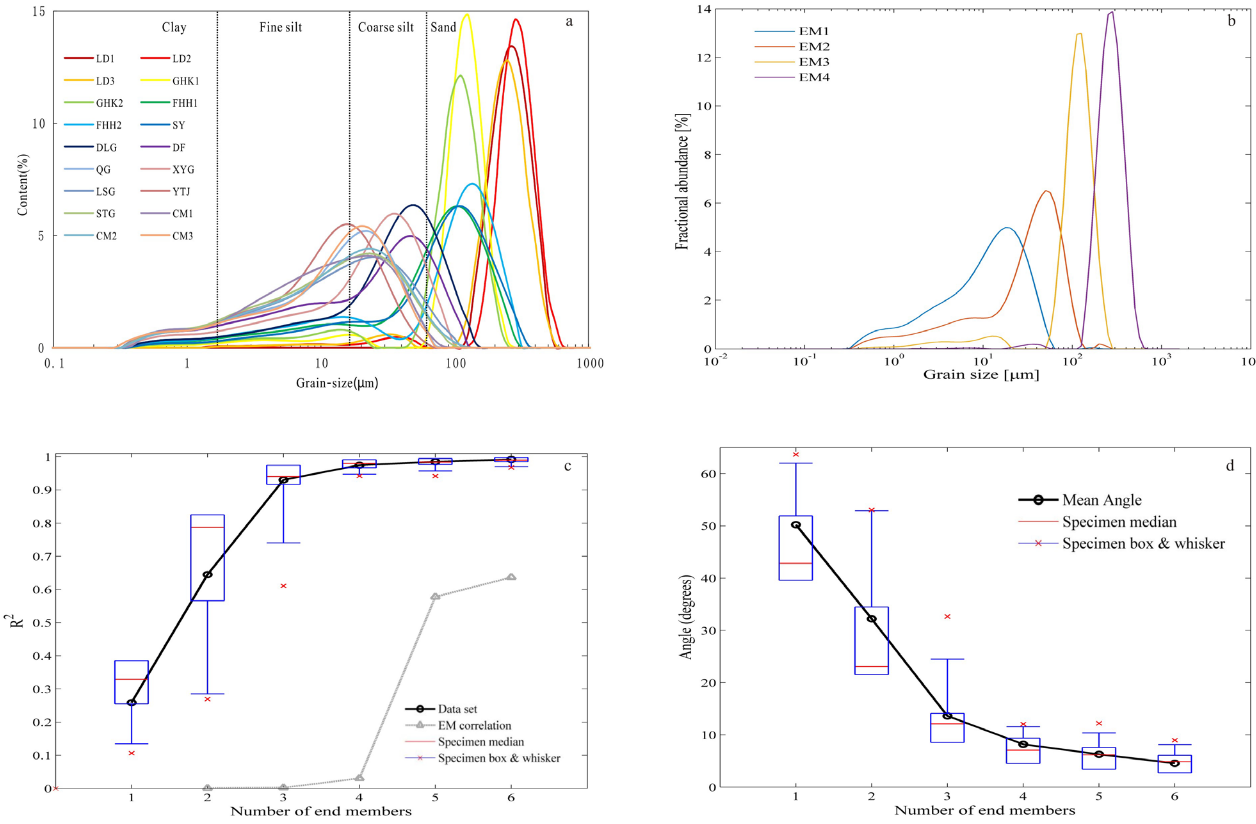

Fig. 2 — EMMA results of the tidal flat sediment grain size data from the Jiangsu coast: (a) Grain size frequency distribution of the tidal flat sediments, (b) The squared linear correlation (R2), (c) The angular distance in degrees (Theta), (d) Angular deviation goodness-of-fit statistics for various numbers of EMs.

GHK1 and DLG are dominated by sand, but contain small amounts of coarse silt. The sediments between DF and LSG are dominated by coarse silt, and contain small amounts of finer silt. Compared to the sediments between DF and LSG, the tidal flat sediments between YTJ and CM3 contain larger amounts of finer silt. The results indicate that the sediments north to Dafeng (GHK1-DLG) could be dominated by the Yellow River, whereas the sediments south of Rudong (YTJ-CM3) by the Yangtze River. The coast between Dafeng and Rudong (DF-LSG) is a transitional zone influenced by both rivers. These results are consistent with the results of Zhang et al. [32] and Wang et al. [29].

Grain size frequency distributions for the EMs of the four EM solution

Each EM clearly has a dominant peak and shows a normal distribution in the grain size distribution curves of the four EMs (Fig. 2(d)). The grain size of the dominant peak increases, and the sorting improves toward finer grains to different degrees from EM1 to EM4. EM1 has a mode of 18 μm, with a majority in the coarse silt range and a small bulge in the <1 μm range. EM2 has a mode of 50 μm, with a majority in the coarse silt range, and EM3 has a mode of 110 μm, with a majority in the fine sand range. EM4 has a mode of 280 μm, with a majority in the sand range. EM3 and EM4 have secondary peaks with lower peak values in the fine-grained range.

Distributions of the relative contents of the four EMs

Table 1 shows the spatial distributions of the relative contents of the four EMs, which range from 0 to 100%.

The contents of EM1 between YTJ and CM3 are the highest. The EM1 contents between YTJ and CM3 range from 68.81% to 100% with an average of 82.86%. Based on the frequency distribution curve of the grain size, the curves of the samples between YTJ and CM3 contain two main components, finer silt and coarse silt, which are approximately equivalent to each other. Combined with the front analyses, the fine-grain characteristics of EM1 indicate that the sediments are from the Yangtze River.

The EM2 contents between DF and LSG are the highest, ranging from 50.50% to 95.6% with an average of 71.87%. Based on the frequency distribution curve of the grain size, the curves of the samples between DF and LSG contain two main components, finer silt and coarse silt. But the sorting is poorer than that of EM1. Studies have shown that the coastal sediments have the characteristics of mixed provenances of the Yangtze and Yellow River[32]. Thus, the south-west peovenance that is indicated by EM2 is mainly composed of northern Jiangsu coastal sediment from both the Yangtze River and the Yellow River.

The EM3 contents between GHK1 and DLG are the highest, ranging from 50.33% to 100% with an average of 76.43%. Based on the frequency distribution curve of the grain size, the curves of the samples between GHK1 and DLG contain two main components, coarse silt and sand. Prior to 1855, the Yellow River entered the sea along the north Jiangsu coast; however, because of hydrodynamic processes, such as tidal movements, that occurred for more than 100 years, the fine-grained clay components in the deposits were washed away and got mixed with the sand sediment in the surrounding coastal areas, which has resulted in the lack of EM1, EM2 and EM4 as well as the enrichment of EM3 in this region (Fig. 3).

The EM4 contents between LD1 and LD3 are the highest, ranging from 88% to 97.53% with an average of 94.12%. Based on the frequency distribution curve of the grain size, the curves of the samples between LD1 and LD3 show two peaks. The main peak was shown in the sand component. Main reasons are: (a) the sediments in Liandao Island are from the nearshore rock

Table 1 — Grain-size distribution of the tidal flat sediments along Jiangsu coast

Sample	Clay (0-2μm)	Finer silt (2-16μm)	Coarse silt (16-63μm)	Sand (>63μm)
LD1	0.12	1.57	2.56	95.75
LD2	0.25	2.51	5.09	92.15
LD3	0.17	2.00	3.50	94.32
GHK1	1.64	6.19	2.11	90.06
GHK2	2.22	8.95	4.12	84.70
FHH1	3.93	14.12	20.26	61.69
FHH2	4.40	17.22	10.41	67.97
SY	4.83	27.81	52.60	14.75
DLG	9.92	29.58	44.33	16.16
DF	11.01	51.95	36.88	0.16
QG	11.32	41.68	46.12	0.88
XYG	7.57	26.17	57.53	8.74
LSG	10.49	49.11	39.24	1.16
YTJ	10.14	42.39	43.48	3.99
STG	11.13	44.03	41.53	3.30
CM1	2.70	42.46	49.68	5.16
CM2	11.15	40.84	42.48	5.53
CM3	9.86	38.69	49.74	1.71

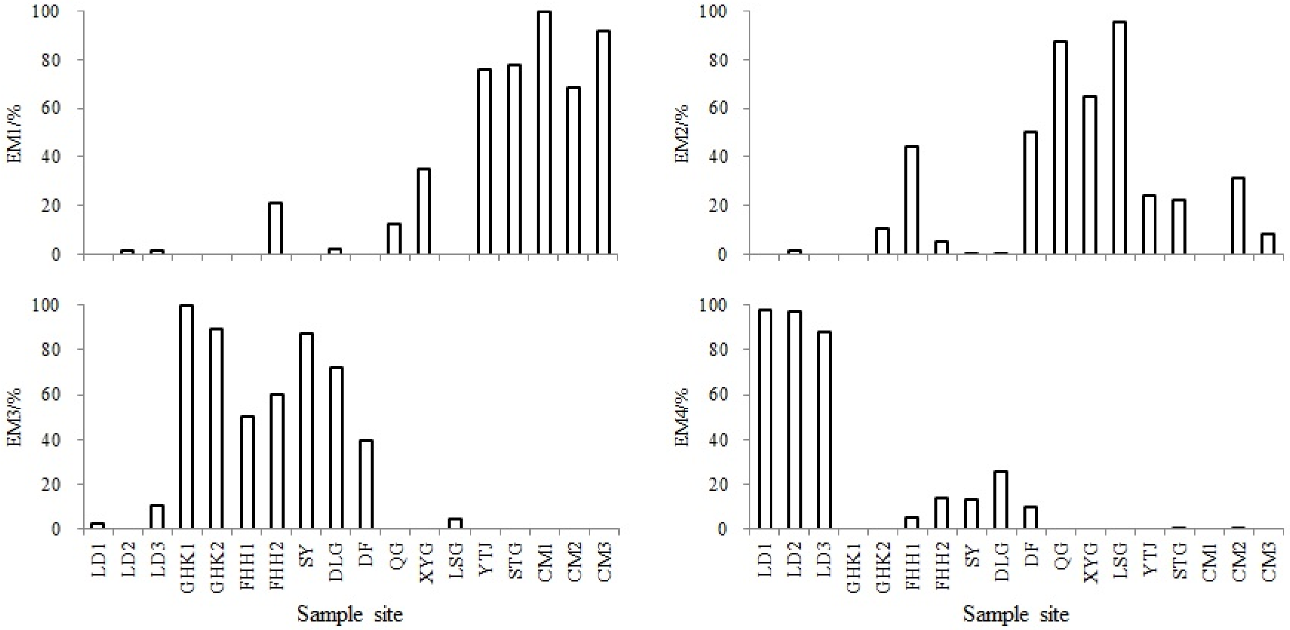

Fig. 3 — Spatial distributions of the relative contents of the four EMs of the tidal flat sediments along Jiangsu coast.

weathering and (b) Sediments have not been transported for a long distance, and deposited nearby after weathering, which led to the sediments being coarse.

Advantages of studying sedimentary sources by using the EMMA.

Factors that generate modern sedimentary patterns include sedimentary sources and hydrodynamics, which are referred to as dynamic populations by Weltje and Prins[10]. Sediments from different sedimentary sources have specific grain size distribution characteristics, such as normal distribution and Weibull distribution, due to long-term alteration by the dynamic environments[9]. Although sediments from different provenance regions have different grain size characteristics, their grain size frequency distribution curves usually overlap; thus, certain grain size generally cannot be used to determine sources.

Using EMMA to analyze sediment grain sizes, we can retrieve grain size data for sediments that were formed and affected by multiple dynamic populations and decompose EM frequency distribution curves and spatial distributions of the relative contents that represent different sedimentary sources and hydrodynamic environments. Then this information can be used to assess the physical meaning of the dynamic populations that are represented by different EMs by combining information about the local dynamic sedimentary environment. Thus, this method avoids the problems that are associated with using incorrect or incomplete information by directly using the sediment grain size type or content. In addition, the map of the sediment distribution that is obtained from the EMMA is more continuous than that obtained from the Shepard and Folk sediment classification diagram and better demonstrates the effects and processes of changes due to sediment transport and deposition in the region. Compared with the routine classification method that is based on clay-silt-sand ternary diagrams, the map distributions of different EMs are more accurate and can better represent the ranges and internal structures of different sedimentary regions. This method is particularly useful for areas from different sources, such as Jiangsu coast, whose boundaries are difficult to distinguish by using traditional methods. The decomposed EM contents can accurately represent the ranges and variations of the Yangtze River and Yellow River; thus, this method is better for determining their provenance and sedimentary dynamics. EMMA requires less sample numbers than grain size trend analysis does, and the inconsistency in the sedimentary transport vectors that is obtained from grain size trend analyses with different parameters never happens by using EMMA. In addition, EMMA is more robust; the location and grain size characteristics of this region can still be obtained through EMMA even when few sample numbers are available from the relict sedimentary region.

Conclusion

Using EMMA of tidal flat sediments grain size from Jiangsu coast, we retrieved four EMs that indicate different sedimentary sources. EM1 reflected Yangtze River is the dominant supplier south with a grain size mode of 18 μm. EM2 reflected the coast is the transition zone influenced by Yangtze River. EM2 has a mode of 50 μm. EM3 reflected Yellow River is the dominant supplier. The grain size mode is 110 μm. EM4 reflected that the tidal flat sediments of Liandao Island are mainly from nearshore rock weathering. The grain size mode is 280 μm. These results provide a quantitative index to assess the response of the provenance and dynamic sedimentary environment to the grain size of the sediments. Compared with divisions that are made based on the sediment types or content of sediments in previous studies, this study generated well-resolved EM boundaries and distinct internal structural details, and the results are more reasonable and reliable.

Compared with the traditional methods of studying dynamic sedimentary environments that directly use data of sediment grain size types or contents, our study shows that EMMA can distinguish multiple EMs that directly reflect the sedimentary sources. These EMs have better correlations with sedimentary sources; therefore, they can better indicate the local sedimentary environments and provide additional theoretical and practical benefits.

Acknowledgement

This research was supported financially by the National Natural Science Foundation of China (No. 41702185, No. 41572152, No. 41272378), the Open Research Fund of the State Key Laboratory of Estuarine and Coastal Research (NO. SKLEC-KF201801), the Natural Science Foundation of Shandong Province (NO. ZR2018PD005); the Chinese Academy of Sciences Visiting Professorship for Senior International Scientists (NO. 2012T1Z0004, 131432WGZJTPYJY20150002); and the Talent Foundation of Ludong University (NO. LB2017017).

References

1 Folk, R.F., Ward, W.C., Brazis River bar, a study in the significance of grain-size parameters. Journal of Sedimentary Petrology, 27: (1957), 3-26.

2 Middleton, G.V., Hydraulic interpretation of sand size distributions. Journal of Geology, 84(1976), 405-426.

3 Ashley, G.M., Interpretation of polymodal sediments. Journal of Geology, 86: (1978), 411-421.

4 Bagnold, R.A., Barndorff-Nielsen, O., The pattern of natural distributions. Sedimentology, 27: (1980), 199-207.

5 Swapan, K.M., Ramkrishma, M., Analysis of sedimentation in connection to grain size and shear stress at lower reach of Rupnarayan river, West Bengal, India. Indian Journal of Geo-marine Sciences, 45: (2016), 1128-1137.

6 Curray, J.R., Tracing sediment masses by grain-size modes. Report of the Twenty First Session Norden, International Geological Congress, 22: (1960), 119-130.

7 Tanner, W.F., Modification of sediment size distributions. Journal of Sedimentary Petrology, 34: (1964), 156-164.

8 Sheridan, M.F., Wohletz, K.H., Dehn, J., Discrimination of grain-size subpopulations in pyroclastic deposits. Geology, 15: (1987), 367-370.

9 Sun, D., Bloemendal, J., Rea, D.K., Vandenberghe, J., Jiang, F., An, Z., Su, R., Grain-size distribution function of polymodal sediments in hydraulic and Aeolian environments, and numerical partitioning of the sedimentary components. Sedimentary Geology, 152: (2002), 263-277

10 Weltje, G., and Prins, M., Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics, Sedimentary Geology, 162: (2003), 39-62.

11 Weltje, G., and Prins, M., Genetically meaningful decomposition of grain-size distributions, Sedimentary Geology, 202: (2007), 409-24.

12 Weltje, G. J., End-member modeling of compositional data: numerical-statistical algorithms for solving the explicit mixing problem, Mathematical Geology, 29: (1997), 503-49.

13 Paterson, G.A., and Heslop, D., New methods for unmixing sediment grain size data. Geochemistry Geophysics Geosystems, 16: (2015), 4494-4506.

14 Doeglas, D.J., Interpretation of the results of mechanical analysis. Journal of Sedimentary Petrology, 16 (1946), 19-40.

15 Orpin, A.R., Woolfe, K.J., Unmixing relationships as a method of deriving a semi-quantitative terrigenous sediment budget, central Great Barrier Reef lagoon, Australia. Sedimentary Geology, 129: (1999), 25-35.

16 Hughes, M.K., Guiot, J., Ammann, C.M., An Emerging Paradigm: Process-Based Climate Reconstructions. PAGES news, 18: (2010), 87-89.

17 Dietze, E., Hartmann, K., Diekmann, B., IJmker, J., Lehmkuhl, F., Opitz, S., Stauch, G., Wünnemann, B., Borchers, A., An end-member algorithm for deciphering modern detrital processes from lake sediments of Lake Donggi Cona, NE Tibetan Plateau, China. Sedimentary Geology, 243: (2012), 169-180.

18 Christopherson, N., Neal, C., Hooper, R.P., Vogt, R.D., Andersen, S., Modelling streamwater chemistry as a mixture of soilwater end-members—a step towards second-generation acidification models. Journal of Hydrology, 116: (1990), 307-320

19 Gong, G.C., Liu, K.K., Pai, S.C., Prediction of nitrate concentration from two end member mixing in the southern East China Sea. Continental Shelf Research, 15: (1995), 827-842.

20 Emmanuel, S., Erel, Y., Matthews, A., Teutsch, N., A preliminary mixing model for Fe isotopes in soils. Chemical Geology, 222: (2005), 23-34.

21 Dietze, E., Wünnemann, B., Hartmann, K., Diekmann, B., Jin,

H., Stauch, G., Yang, S., and Lehmkuhl, F., Early to mid-Holocene lake high-stand sediments at Lake Donggi Cona, northeastern Tibetan Plateau, China, Quaternary Research, 79: (2013), 325-36.

22 Prins, M. A., Bouwer, L. M., Beets, C. J., Troelstra, S. R., Weltje, G. J., Kruk, R. W., Kuijpers, A., and Vroon, P. Z., Ocean circulation and iceberg discharge in the glacial North Atlantic: inferences from unmixing of sediment size distributions, Geology, 30: (2002), 555-8.

23 Stuut, J.B.W., Prins, M. A., Schneider, R. R., Weltje, G. J., Jansen, J. H. F., and Postma, G., A 300-kyr record of aridity from grain-size distributions of sediments on Walvis Ridge, SE Atlantic, Marine Geology, 180: (2002), 221-233.

24 Holz, C., Stuut, J. W., and Henrich, R., Terrigenous sedimentation processes along the continental margin off NW Africa: implications from grain-size analysis of seabed sediments, Sedimentology, 51: (2004), 1145-1154.

25 Zhang, X.D., Zhai, S.K., Xu, S.M., Application of grain size end-member modeling to the shelf near the estuary of Changjiang River in China. Acta Oceanolog Sin, 28: (2006), 159-166. (in Chinese with English abstract)

26 Zhang, X.D., Ji, Y., Yang, Z.S., Wang, Z.B., Liu, D.S., Jia, P.M., End member inversion of surface sediment grain size in the South Yellow Sea and its implications for dynamic sedimentary environments. Science China: Earth Sciences, 59: (2016), 258-267.

27 Ren, M.E., Report on a Comprehensive Survey of Coastal and Tidal Flat Resources along Jiangsu Coastal Zone. (China Ocean Press, Beijing) 1986, pp. 517. (in Chinese)

28 Li, C.X., Zhang, J.Q., Fan, D.D. and Deng, B., Holocene Regression and the tidal radial sand ridge system formation in Jiangsu Coastal zone, East China. Marine Geology, 173: (2001), 97-120.

29 Wang, L.S., Hu, S.Y., Yu, G., Ma, M.M., Liao, M.N., Comparative study on magnetic minerals of tidal flat deposits from different sediment sources in Jiangsu coast, Eastern China. Studia Geophysica et Geodaetica. 61: (2017), 1-18.

30 Yan, Q.S., Xu, S.Y., Holocene Deposits and Geomorphological Processes on the Northern Plain of the Jiangsu Province. (Shanghai Scientific and Technological Literature Publishing House, Shanghai) 1993, pp. 83. (in Chinese)

31 Li, C.X., Wang, P.X., Late Quaternary Stratigraphy of the Changjiang Delta. (China Science Press, Beijing) 1998, pp. 222. (in Chinese)

32 Zhang, W.G., Ma, H.L., Ye, L.P., Dong, C.Y., Yu, L.Z., Feng, H., Magnetic and geochemical evidence of Yellow and Yangtze River influence on tidal flat deposits in northern Jiangsu Plain, China. Marine Geology, 319: (2012), 47-56.

33 Yang, J.H., Sedimentation on intertidal mudflats near Wanggang of Dafeng, Jiangsu Province. M.Sc. Thesis, Nanjing University, China. 1986. (in Chinese)

34 Wang, X., Ke, X., Grain-size characteristics of the extant tidal flat sediments along the Jiangsu coast, China. Sedimentary Geology, 112: (1997), 105-122.

35 Wang, Y., The environment and resource of radial sand ridge field in the South Yellow Sea. (Ocean Press) 2014, pp. 1-55. (in Chinese)

36 Chung, C.H., Zhuo, R.Z., Xu, G.W., Creation of Spartina plantations for reclaiming Dongtai, China, tidal flats and offshore sands. Ecological Engineering, 23: (2004), 135-150.