Temporal and Spatial Distribution of Surface Sediment and Its Implications in the Yangtze Subaqueous Delta

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Abstract. Characteristics of sediments vary significantly temporally and spatially in the Yangtze subaqueous delta and adjacent East China Sea shelf due to complicated dynamic conditions. Magnetic properties of sediments are sensitive to hydrodynamics and provenance, and therefore can indicate sediment transportation and deposition. High-resolution surface sediments collected in different seasons and years from the Yangtze subaqueous delta and neighboring East China Sea shelf were subjected to environmental magnetic analyses. In combination with granulometric analysis, this paper discusses temporal and spatial variations of magnetic properties and their implications for indicating sediment transportation, sediment source identification, and hydrodynamic response. The results show that magnetic parameters SIRM and $\chi_{ARM}/SIRM$ suggest sediment transportation path from the Yangtze River into the East China Sea, with majority migrating to the south and southeast and then deposited to the west of 123°E, while a little fine sediment delivered to the northeast in summer. Cluster analysis demonstrates three sedimentation districts according to magnetic properties and particle size in the study area, which represent modern Yangtze sediment, late Pleistocene relict sand, and their mixture, respectively. Temporal-spatial changes in particle size of sediments suggest erosion outside the North Branch in the past few years, while opposite trend of changes on particle size of surface sediment in the adjacent area might reflect different degrees of erosion.

1. Introduction

Estuarine delta is a key area for studying land-sea interaction and source to sink process of matters. The annual global runoff and sediment transported by rivers into the sea reach 3.6×10^{13} m^3 and 2.0×10^{10} t, respectively, among which most sediment are deposited in the estuary and adjacent continental shelf, while only less than 5% are transported to the deep sea [1].

The Yangtze subaqueous delta is a typical marginal sea area affected by large river. Terrigenous sediments from the Yangtze River display a complex sedimentary distribution under the influence of regional current system including Changjiang diluted water (CDW), tidal currents, East China Sea coastal current (ECSCC), and Taiwan warm current (TWC). Formation and evolution of the Yangtze Delta since the Last Glacial Maximum [2-4], development of the Yangtze Estuary and subaqueous delta in the last
2000 years [5-7], and muddy deposits on the inner East China Sea Shelf [8,9] have been widely studied. According to previous researches, half of the Yangtze River-derived sediment spreads to the East China Sea, in which ~30% deposited in the estuarine delta [5,9-11]. Based on the distribution of surface sediment, Chen et al.[3] defined four sediment belts of the Yangtze subaqueous delta from land to sea, which are delta front with fine sand and silt, prodelta with silty clay and clayey silt, prodelta to continental shelf with sand-silt-caly, and late Pleistocene relict sand. Marked hydrodynamic and geomorphological changes have occurred in the Yangtze subaqueous delta resulted from natural and anthropogenic changes in recent decades. The decline of the Yangtze River sediment load results in slowdown of tidal flat progradation and local erosion in subaqueous delta [12-14]. Thus, sediment transportation and sedimentation features under new environmental conditions need further study.

Magnetic minerals (iron-containing oxides and sulfides generally) could reflect transportation, deposition and secondary changes of sediments, and accordingly respond sensitively to sedimentary environmental change. Thus, environmental magnetic parameters can indicate sedimentary dynamic processes [15-19]. In this paper, surface sediment collected in different periods from the Yangtze subaqueous delta and neighboring inner East China Sea shelf were subjected to magnetic and granulometric analysis to characterize their temporal and spatial distributions before discussing response of magnetic indicators to hydrodynamics, sediment transportation, and provenance.

2. Study Area and Methods

The present-day Yangtze Estuary exhibits four outlets (Figure 1), which are the North Branch, the North Channel, the North Passage and the South Passage [5,7]. The South Branch dominates water and sediment discharge since the 1950s in the Yangtze Estuary [7]. Sediment discharge of the Yangtze River decreased dramatically since the Three Gorges Dam operation in 2003, from an annual average of 470 million t/yr to 145 million t/yr [14,20]. The Yangtze subaqueous delta and adjunct inner East China Sea shelf are influenced by currents including the Changjiang diluted water (CDW), the East China Sea coastal current (ECSCC), the Yellow Sea coastal current (YSCC), the Taiwan warm current (TWC), and the Kuroshio current (KC) [21] (Figure 1a).

A total of 53, 64, and 56 surface sediment samples were obtained by box samplers from the Yangtze subaqueous delta and neighboring inner East China Sea shelf in March 2013, July 2016, and February 2017, respectively (Figure 1b). Granulometric analysis was carried out by a laser grain size analyzer (Coulter LS 13320), ranging from 0.04μm to 2000 μm. Magnetic measurements were taken using Bartington Instruments MS2B magnetic susceptibility meter, DTECH 2000 AF demagnetizer, MMPM10 pulse magnetizer, and JR6 spinner magnetometer. Magnetic parameters including magnetic susceptibility (χ), saturation isothermal remanent magnetization (SIRM), hard isothermal remanent magnetization (HIRM), S ratios (S_{100}, S_{300}), frequency-dependent susceptibility (χ_{fdep}), anhysteretic remanent magnetization susceptibility (χ_{ARM}), and the ratios χ_{ARM}/χ, χ_{ARM}/SIRM, and SIRM/χ were measured and calculated. Granulometric and magnetic measurements and calculation were followed by Ge et al. [22].

χ and SIRM reflect magnetic minerals concentration generally, especially ferrimagnetic minerals [23]. In the meanwhile, paramagnetic and diamagnetic minerals also influence χ values [23]. HIRM is an indicator for the concentration of high-coercivity minerals, such as hematite and goethite (Thompson and Oldfield, 1986). χ_{fdep} indicates grain size of magnetic minerals, which commonly increasing with concentration of fine viscous magnetic grains close to the superparamagnetic (SP)/stable single domain (SD) boundary [23]. χ_{ARM} reflects SD ferrimagnetic grains generally [24]. χ_{ARM}/SIRM and χ_{ARM}/χ are grain size indicators for ferrimagnetic minerals, negatively related to grain size [24-26]. S_{300} is a parameter reflecting the ratio of low- and high-coercivity components to total magnetic mineral assemblage, while S. \text{100} denotes the comparison of low-coercivity minerals and medium- and high-coercivity minerals [27,28].
Systat 13 software was used to perform cluster analysis (Ward method) and T-test on magnetic and particle size parameters of sediment.

3. Results and Discussion

3.1. Characteristics of Sedimentation Districts and Influencing Factors

According to the results of granulometric and magnetic analysis, characteristics of surface sediment in study area varied significantly in space. In order to illustrate spatial distribution of sediment, 10 magnetic parameters ($\chi$, SIRM, HIRM, S-100, S-300, $\chi_{ARM}$, $\chi_{ARM}/\chi$, $\chi_{ARM}/\chi_{SIRM}$, and SIRM/$\chi$) and 4 particle size parameters (median size, clay content, silt content, and sand content) were chosen as variables to conduct cluster analysis with Ward method.
Table 1. Statistics of magnetic and granulometric parameters for surface sediment, T-test significance $\alpha=0.05$

| Parameter                  | Group A       |                      |                      | Group B       |                      |                      | Group C       |                      |                      |
|----------------------------|---------------|----------------------|----------------------|---------------|----------------------|----------------------|---------------|----------------------|----------------------|
|                            | Minimum | Maximum | Mean±SD* | T value | Minimum | Maximum | Mean±SD* | T value | Minimum | Maximum | Mean±SD* | T value |
| $\chi$ ($10^{-8}$ m$^3$ kg$^{-1}$) |          |          |          |          |          |          |          |          |          |          |          |          |
| Winter                     | 52      | 112      | 67±17    | 0.433   | 43      | 99      | 62±15    | 1.501   | 23      | 71      | 46±15    | 1.919   |
| Summer                     | 45      | 87       | 65±12    | 1.124   | 39      | 85      | 56±13    | 2.159   | 23      | 44      | 38±6     | 4.620   |
| SIRM ($10^{6}$ Am$^2$ kg$^{-1}$) |          |          |          |          |          |          |          |          |          |          |          |          |
| Winter                     | 108     | 543      | 360±117  | 0.509   | 17      | 313     | 178±82   | -0.118  | 105     | 292     | 177±52   | 2.178   |
| Summer                     | 114     | 510      | 343±94   | 0.700   | 17      | 468     | 181±82   | 0.792   | 119     | 186     | 145±19   | 0.715   |
| HIRM ($10^{5}$ Am$^2$ kg$^{-1}$) |          |          |          |          |          |          |          |          |          |          |          |          |
| Winter                     | 84      | 93       | 87±2     | -0.205  | 85      | 94      | 90±2     | 0.694   | 74      | 91      | 88±5     | 0.825   |
| Summer                     | 85      | 93       | 87±2     | 0.173   | 93      | 100     | 96±2     | 1.288   | 86      | 96      | 94±2     | 0.825   |
| $S_{100}$ (%)               | 0.40    | 6.71     | 3.7±1.88 | -0.825  | 0       | 7.00    | 2.0±1.64 | 0.490   | 0       | 6.30    | 1.4±1.55 | 0.465   |
| $S_{300}$ (%)               | 1.28    | 6.03     | 4.1±1.45 | 0.51    | 3.55    | 1.8±0.69 | 0.26    | 2.76    | 1.2±0.75 | 0.136   |
| $X_{0.5}$ (%)               | 0.95    | 8.36     | 5.5±2.36 | 0.462   | 1.57    | 7.60    | 3.2±1.63 | -0.875  | 2.09    | 8.35    | 4.7±2.01 | 0.236   |
| $X_{0.5}$ ($10^{6}$ m$^3$ kg$^{-1}$) |          |          |          |          |          |          |          |          |          |          |          |          |
| Winter                     | 101     | 517      | 324±102  | 0.618   | 96      | 397     | 194±83   | -0.068  | 59      | 297     | 203±64   | 1.510   |
| Summer                     | 112     | 514      | 324±106  | 0.568   | 82      | 303     | 196±62   | 0.624   | 103     | 253     | 171±43   | 1.510   |
| $SIRM/X$                   | 1.18    | 7.32     | 5.2±1.79 | 0.462   | 1.36    | 8.30    | 3.6±1.46 | 3.30    | 7.49    | 4.5±1.36 | 0.236   |
| $X_{0.5}$/SIRM ($10^{5}$ m A$^{-1}$) |          |          |          |          |          |          |          |          |          |          |          |          |
| Winter                     | 17      | 82       | 56±19    | 0.041   | 21      | 85      | 44±19    | -1.557  | 28      | 114     | 65±22    | -1.298  |
| Summer                     | 19      | 77       | 56±16    | 0.173   | 18      | 87      | 53±17    | -1.298  | 49      | 117     | 76±19    | -1.298  |
| SIRM/\chi ($\times\times$ m A$^{-1}$) |          |          |          |          |          |          |          |          |          |          |          |          |
| Winter                     | 4.70    | 11.70    | 9.5±1.99 | 0.870   | 4.54    | 10.53   | 7.4±1.58 | 0.567   | 5.33    | 10.35   | 7.15±1.52 | 2.591   |
| Summer                     | 6.20    | 10.52    | 9.0±1.38 | 0.870   | 4.20    | 12.89   | 7.1±2.00 | 0.567   | 5.33    | 7.11    | 6.0±0.63 | 2.591   |
| Median size (μm)           | 5       | 279      | 56±88    | 0.816   | 5       | 287     | 154±105  | 2.131   | 5       | 173     | 106±63   | 0.776   |
| Clay (%)                   | 1       | 44       | 24±11    | 0.001   | 2       | 40      | 13±11    | -1.283  | 7       | 39      | 17±10    | -0.127  |
|                            | 3       | 33       | 24±7     | 0.001   | 2       | 38      | 16±8     | 0.001   | 8       | 34      | 17±8     | 0.001   |
|        | Silt (%) | Sand (%) |
|--------|----------|----------|
|        | winter   | summer   | winter | summer   |
|        | 271      | 97       | 95     | 89       |
|        | 49±22    | 27±32    | 20±24  | 20±24    |
|        | -1.149   | 0.822    | 4.92   | 4.92     |
|        | 4±67     | 0±94     | 2±92   | 2±92     |
|        | 67±16    | 67±16    | 67±16  | 67±16    |
|        | 31±14    | 31±14    | 31±14  | 31±14    |
|        | 29±16    | 29±16    | 29±16  | 29±16    |

*SD: Standard Deviation

Figure 2. Spatial distribution of surface sediment in (a) winter and (b) summer. Circle, diamond, and triangle represent Groups A, B, and C, respectively, black lines show boundaries among groups.
As the results of cluster analysis, sediments in winter (201303) and summer (201607) were both divided into three components, A, B, and C, with spatial distribution shown in Figure 2. Statistics of magnetic and particle size parameters of each component are shown in Table 1. T-test results for corresponding components in winter and summer (Table 1) demonstrated that main granulometric and magnetic parameters ($\chi$, SIRM, $S_{300}$, SIRM/$\chi$, and median size) of corresponding components in two seasons show no significant difference under the 95% confidence interval, indicating little influence of seasons on sediment characteristics of three components. Thus, sediment collected in summer was taken to discuss the characteristics of sedimentation districts and influencing factors.

Despite few samples in Groups B and C, $S_{100}$ and $S_{300}$ values are higher than 80% and 90%, respectively, which indicates ferrimagnetic minerals are dominant in magnetic minerals of surface sediment in study area. Group A sediments are mainly located in the outer estuary to the south of Chongming Island, with an east boundary by the 30 m isobath, while few are found in the north. Particle size of Group A sediment is generally fine, in which clayey silt dominates. The average of median size is 36 μm, ranging from 7 to 236 μm. Actually, the average particle size of Group A is from 7 to 36 μm, with an average of 13 μm, despite two samples in the north. $\chi$, SIRM, HIRM, $\chi_{50}$%, $\chi_{ARM}$, $\chi_{ARM}/\chi$, and SIRM/$\chi$ have highest mean values in Group A, suggesting highest contents and finest particle size of magnetic minerals (both ferrimagnetic and antiferromagnetic minerals). Group C sediments lie on the southeast area, which is generally deeper than 50 m. Group C sediments are predominant by sand and silty sand, with median size ranging from 6 to 190 μm and an average of 88 μm. Lowest $\chi$, SIRM, and HIRM values imply lack of magnetic minerals in Group C sediments. Group B sediments are distributed between Groups A and C and in the area to the north of 31°N. Sand, silty sand, and clayey silt are found in Group C sediments, resulting in particle size varying greatly, with median size of 6-280 μm and an average of 92 μm. $\chi$ and SIRM values between Groups A and C sediments reveals that magnetic mineral contents in Group B sediments are between A and C. Low values of $\chi_{50}$%, $\chi_{ARM}$, $\chi_{ARM}/\chi$, and SIRM/$\chi$ suggests coarse magnetic mineral particles in Groups B and C. Finer magnetic mineral particles are concentrated in finer sediments, and vice versa.

Significant differences in magnetic and particle size parameters of the three groups sediments reflect the influence of hydrodynamic sorting and provenance. Group A sediments with fine grain size and high content of magnetic minerals match modern Yangtze River-derived sediments. Huge amounts of sediment are transported from the Yangtze River to the East China Sea annually, with a large portion deposited in the subaqueous delta and continental shelf. Net residual current of runoff and tide weakens gradually toward to the sea, leading to weaker hydrodynamic conditions. In the meanwhile, increase of water depth reduces wave stirred sand. Thus, coarse-grained sediments are settled firstly, while fine-grained ones continues to be transported to the sea, resulting in fining trend of particle size from the estuary to the sea. Sediments mainly composed of clayey silt are deposited in Group A area, which is the modern deposition center of the Yangtze subaqueous delta. Group C sediments with coarse grains and low content of magnetic minerals imply the source of relict sand. Relict sand deposited on the East China Sea shelf during the late Pleistocene with low sea level has low magnetic mineral content and coarse grains. Modern Yangtze River-derived sediments and relict sand can be effectively identified by combination of magnetic and granulometric parameters due to their significant differences. Group B sediments are located in the transition area of Groups A and C and show magnetic and granulometric values between Groups A and C, which suggests a mixture of Groups A and C sediments. As weakening of hydrodynamics and deepening of water depth, most silt particles in the Yangtze River-derived sediments settle down in Group A area, while finer particles continued to spread to the inner East China shelf and deposit on relict sand. The inference is supported by the frequency distribution of sediment (Figure 3). The frequency distribution curves of Group A sediments exhibit single-peak type, with a peak at 10-30 μm. The frequency distribution curves of Group C sediments are dominated by a major peak at 100-300 μm with a minor
peak at 1-10 μm. However, Group B sediments shows double peaks at 1-20 μm and 100-400 μm, respectively on frequency distribution curves, with the peak of fine grains decrease gradually along transportation path. The variations on frequency distribution curves of the three groups agree with transportation and deposition process of fine-grained sediments. Group B sediments show a mixing feature of Groups A and C, and the sediment from the Yangtze River is getting finer with increasing distance.

Figure 3. Grain size frequency distribution curves of surface sediment, with orange line for winter and red for summer.
3.2. Seasonal Variations of Sediment Distribution and Its Implication on Hydrodynamic Transportation

Although sediments in the same districts show no significant differences in seasons, the range of districts varies significantly (Figure 2). The boundary between Groups A and B is relatively stable, with farthest around 123°E, indicating that a majority of the modern Yangtze River-derived sediments are settled down to the west of this boundary, and few extremely fine particles spread farther. However, the boundary between Groups B and C moves from 123°15′E in winter to 123°30′E in summer. Seaward advancement of Group B area in summer reveals that more modern Yangtze River-derived sediments has been transported to the farther shelf than that in winter, which is probably driven by seasonal variations of hydrodynamic conditions in study area. Flow and sediment fluxes in the Yangtze River Basin exhibit obviously seasonal variations, with flow and sand loads at Datong Station account for 70.8% and 81.4%, respectively during flood season of the year [29], while tidal current in the Yangtze Estuary is relatively stable. Larger runoff results in a stronger residual current to the sea in summer, as well as a stronger sediment carrying capacity correspondingly. In addition, larger sediment flux in summer also ensures sufficient sediment supply. Thus, there will be more sediment transported to farther shelf in summer, which is consistent with farther east boundary between Groups B and C in summer.

The ECSCC, including Jiangsu coastal current (JCC) and Zhejiang-Fujian coastal current (ZFCC), performs significant seasonal changes. With influence of southeast monsoon in summer, the northward ZFCC along coast joins to the Yangtze runoff, forming the northeastward CDW. In the opposite, the JCC merged with sharply decreased runoff flow southward through Zhoushan Islands along coast under the influence of strong north winds in winter, which can pass through the Taiwan Strait and enter the South China Sea farthest. Sediments in both seasons show trends of decreasing SIRM and increasing \( \chi_{ARM}/SIRM \) towards south and southeast (Figure 4), indicating the transportation path of sediment [30,31]. Yangtze River-derived sediment spread and deposit along south and southeast mainly, forming the mud depositional area in the inner East China Sea shelf by the ECSCC and runoff. In addition, decreasing SIRM and increasing \( \chi_{ARM}/SIRM \) towards northeast are found in summer (Figure 4b and 4d), suggesting a northeast transportation path in summer. Sediments in the northeastern part of study area have low magnetic mineral content and high content of fine particle components, which could be resulted from transportation of fine sediment from the Yangtze River. Notably, sediment from the Huanghe River and abandoned Huanghe river delta is a potential source for sediments in the northern part of study area. Therefore, provenance identification of sediments with mixed characteristics of particle size and magnetic parameters needs further analysis combined with mineralogical and geochemical methods.
3.3. Variations in Sediment Particle Size and Its Implication on Erosion

Comparing spatial distributions of sediment particle size in winter and summer, there is a fining trend of sediment in subaqueous delta outside the North Branch. Content of <16 μm fraction increases, while >63 μm fraction decreases (Figure 5). In order to eliminate the impact of seasonal variations, particle size of sediment retrieved in February 2017 was taken to compare with that in March 2013. In 2013, particle size distribution outside the Yangtze Estuary was relatively uniform from south to north, while significant difference occurred in 2017, with a gap outside the North Branch. In the gap area, sediment became finer in 2017 with increasing <16 μm fraction content. However, to the south and north sides of the gap, sediment became coarser with decline <16 μm fraction content and increasing >63 μm fraction content. Yang et al. [14] demonstrated that the area outside the North Branch has been eroded in recent decades due to a dramatic drop in sediment supply from the basin, leading to coursing grain size. Particle size changes of sediment caused by erosion have different performances in different regions, which depend on the characteristics of underlying sediment and the degree of erosion. Thus, opposite changes exhibit in granularity of sediment in adjacent areas subjected to erosion. Generally, fine-grained sediment is easy to
sustain and firstly eroded, resulting in coarser sediment in-situ. Then coarse-grained sediment will be
taken away with stronger hydrodynamics. Eventually, the compacted and consolidated clay layer may
appear by sustained erosion, showing finer particle size of in-situ sediment.

Figure 5. Temporal and spatial variations of <16 μm and >63 μm fraction contents of surface sediment, (a)
<16 μm fraction in 2013, (b) <16 μm fraction in 2016, (c) <16 μm fraction in 2017, (d) >63 μm fraction in
2013, (e) >63 μm fraction in 2016, (f) >63 μm fraction in 2017.

4. Conclusions
Three groups of sediment with varied spatial and temporal distribution are identified based on magnetic
and granulometric analysis on surface sediments obtained from the Yangtze subaqueous delta and adjacent
inner East China Sea shelf. The influence factors including hydrodynamic sorting and sediment source are
discussed. The conclusions are as followed.

(1) Surface sediment in the Yangtze subaqueous delta and adjacent inner East China Sea shelf are
dominated by modern Yangtze River-derived sediment and late Pleistocene relict sand, with the former
mainly located in the modern deposition center of the Yangtze subaqueous delta and the latter lying on the
continental shelf. Three groups (A, C, and B) of sediment identified based on magnetic and granulometric
parameters represent modern Yangtze River-derived sediment, late Pleistocene relict sand, and their
mixture, respectively.

(2) The zoning of sedimentary environment in study area reflects hydrodynamic transportation of
sediment, indicated by magnetic parameters. Decreasing SIRM and increasing $\chi_{ARM}/SIRM$ values along
the south and southeast out of estuary reflects the south and southeast path of Yangtze River-derived
sediment migration, with a northeast transportation in summer additionally. Modern Yangtze River-
derived sediment are mostly deposited to the west of 123°E, which is the boundary of Groups A and B in
both seasons. The boundary of Groups B and C lies farther east in summer (123°30′E) compared to winter (123°15′E), indicating farther transportation of fine particles in the Yangtze River-derived sediment in summer.

(3) Erosion usually leads to changes in particle size of sediments, which performs differently in different areas, depending on the characteristics of underlying sediments and the degree of erosion. Spatial and temporal variations in particle size distribution of surface sediments in study area indicate erosion outside the North Branch in past few years. Grain size of surface sediment in adjacent areas shows opposite changes, which may reflect different degrees of erosion outside the North Branch.

Acknowledgements
This study was supported in part by Zhejiang Natural Science Foundation (LQ19D060001) and China Postdoctoral Science Foundation (2019M652147). Data and samples were collected on board of R/V “Runjiang 1” implementing the open research cruise (NORC2013-03, NORC2016-03, NORC2017-03) supported by NSFC Shiptime Sharing Project (41249903, 41549903, 41649903).

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