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Diatom distribution and its relationship to sediment property in the Minjiang Estuary, southeast China

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Abstract

The distribution of diatoms in surface sediments in the Minjiang Estuary, southeast China, was investigated in 2009. Total 56 species and other species belonging to 25 genera were identified, among them 11 species were dominant over 5%. Dominant species included *Actinocyclus ehrenbergii*, *Coscinodiscus curvatulus*, *C. divisus*, *C. jonesianus*, *C. radiatus*, *C. rothii*, *C. subtilis*, *Cyclotella stylorum*, *Epithemia hyndmanii*, *Hydrosera whampoensis*, and *Trachyneis aspera*. Diatom abundance varied spatially, with the absolute abundance of diatoms ranging from 13 valves/g to 11×10^4 valves/g, and averaging 2.5×10^4 valves/g. A canonical correspondence analysis (CCA) was used to explain the relationships between diatom distribution and sediment properties in the Minjiang Estuary. CCA revealed that the major elements (Fe_2O_3, Na_2O, CaO, MgO, TiO_2, SiO_2, Al_2O_3, and K_2O) were closely related to diatom abundance. Four diatom assemblages were distinguished, representing different sediment properties, which may assist late Quaternary palaeoceanographic reconstructions of the Minjiang Estuary.

Key words: diatom, surface sediment, Minjiang Estuary, canonical correspondence analysis, sediment properties

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1 Introduction

Diatoms, microscopic algae found in almost all aquatic habitats (Round et al., 1990; Dawes, 1998; Cibic et al., 2007; Krause et al., 2011), play an important role in the global biogeochemical cycle. Nelson et al. (1995) estimated that more than 40% of all primary production is attributable to diatoms. Each diatom habitat has its own characteristic diatom flora, developed under distinct environmental variables (Hendey, 1964). Diatom assemblages from surface sediments reflect physical and chemical characteristics of the river water masses in the area (Jiang et al., 2001). Using diatom assemblages as environmental variables has some advantages: (1) they have a short life span and therefore respond rapidly to environmental changes; (2) they are small, and their hard tests preserve well in sediments; (3) they are abundant and diverse; (4) they are widely distributed and almost immobile, and their ecological and taxonomy distribution is well known (Facca and Sfriso, 2007; Smol and Stoermer, 2010; Li et al., 2015). Before carrying out palaeoceanographical reconstructions using fossil diatom records, studies on diatoms from the surface sediments and their relationships with local environments are necessary (Sancetta, 1982; Jiang et al., 2005; Roubeix et al., 2008; Shen et al., 2017). In recent decades, researchers have developed methods of using diatom assemblages to monitor different envorpnmental variables in Chinese estuaries and adjacent areas (Zong et al., 2010; Lin et al., 2012; Xiao, 2013; Yu et al., 2013; Liu et al., 2015). Various studies have been carried out in the Minjiang Estuary using foraminifera (Li et al., 2015), stable isotopes (Liu et al., 2016), trace metals (Xu et al., 2014; Zhou et al., 2014), organic pollutants (Zhang et al., 2003, 2004) and phytoplankton (Zhang et al., 2011; Dai et al., 2016). So far, however, little work has been done on diatoms.

The Minjiang River is the longest river (2 959 km) in Fujian Province, southeast China. The drainage basin of the Minjiang River has an area of approximately 6.1×10^4 km^2, accounting for half of the total area of Fujian Province (Li et al., 2015). The average annual runoff is 1.75×10^3 m^3/s. Every year, an average of 6×10^9 m^3 fresh water with a sediment load of 6.56×10^6 tons is transported into the East China Sea through the Minjiang River (Liu et al., 2001; Gao et al., 2012), and about 50% of the sediment is deposited in its estuary. Sediments include chemical composites deposited in the estuary, which become one of the most important records to demonstrate the degree of interaction between land and sea as well as industrial pollution (Zhou et al., 2004). However, in comparison with some American and European estuaries, our understanding of the chemical composition of the Minjiang Estuary is limited because of the short history of research in this area (Chen et al., 2002).

Thus, the objectives of this paper were (1) to explore the diatom distribution in surface sediments of the Minjiang Estuary and (2) to distinguish diatom assemblages in different areas and discuss the factors affecting diatom preservation in the Minjiang Estuary.

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2 Materials and methods

2.1 *Study area*

The Minjiang River belongs to a subtropical monsoon climate, and the highest and lowest rainfall takes place in summer and winter, respectively. The high-flow periods are generally from April to July (average 3.2×10^3 m^3/s), and the low-flow periods are from October to March of the next year (average 0.62×10^3 m^3/s) (Yang et al., 2007). The annual average water temperature is 19.9°C with a range of 9.8–32.2°C. The Minjiang Estuary is divided into two branches (the South Channel and the North Channel) upstream of the area shown in Fig. 1. The mean width of the South Channel is 1 km, and is wider than the North Channel, which is 0.5 km wide (Zhang et al., 2015). Near the river mouth the outflow is blocked by the Langqi Island and subsequently divides into two branches. A submerged delta develops at the front of the river mouth with water depths less than 15 m (Chen et al., 1998). The Minjiang Estuary is affected by tidal currents, river runoff and waves. The tidal and river currents are the dominant forces in the region (Liu et al., 2015). The estuary is affected by formal semi-diurnal tides (Zhang et al., 2011).

2.2 *Diatom sample processing*

The sampling stations were selected and distributed along the Minjiang Estuary, southeast China, on the margin of the northwest Pacific Ocean (Fig. 1). Surficial sediment samples were collected by grab sampling in 2009 from 25 sites using the R/V *Yanping 2*.

All samples were processed at the diatom analysis laboratory in Xiamen University, and the samples were prepared according to Håkansson (1984). Carbonates and organic material were removed using 10% HCl and 30% H_2O_2, respectively; subsequent washings in distilled water were used to remove the chemicals from the solution and to produce 2 mL of concentrated diatom suspension. After complete homogenization a subsample was transferred to a cover slip and air-dried. Permanent slides were made with Canada balsam (Håkansson, 1984).

2.3 *Diatom numeration*

Diatom species were observed and identified using an Olympus BX51 optical microscope (Olympus Corporation, Tokyo, Japan) with magnification of 800× and 1 000× (oil immersion). In this study, for each sample at least 300 diatom valves were counted and identified in random transects from at least three slides. For incomplete valves, if more than half the frustule was present, the diatom was counted as a whole. Using illustrations in the literature (Jin et al., 1965, 1992; Lawson and Rushforth, 1975; Grimes and Rushforth, 1982; John, 1983; Round et al., 1990; Cheng et al., 1996, 2012; Lange-Bertalot, 2000; Witkowski, 2001; Guo, 2003; Qi and Li, 2004; Smol and Stoermer, 2010), each specimen was identified to species level or, if this was not possible, at least to genus level.

2.4 *Environmental variable data*

For grain size analysis untreated sediments were dried, weighed, mixed with sodium hexametaphosphate and water, soaked and then wet sieved through a set of standard sieves larger than 63 μm. The dry weights were then determined with an analytical balance (resolution of 0.000 1 g) at 1Φ intervals, and

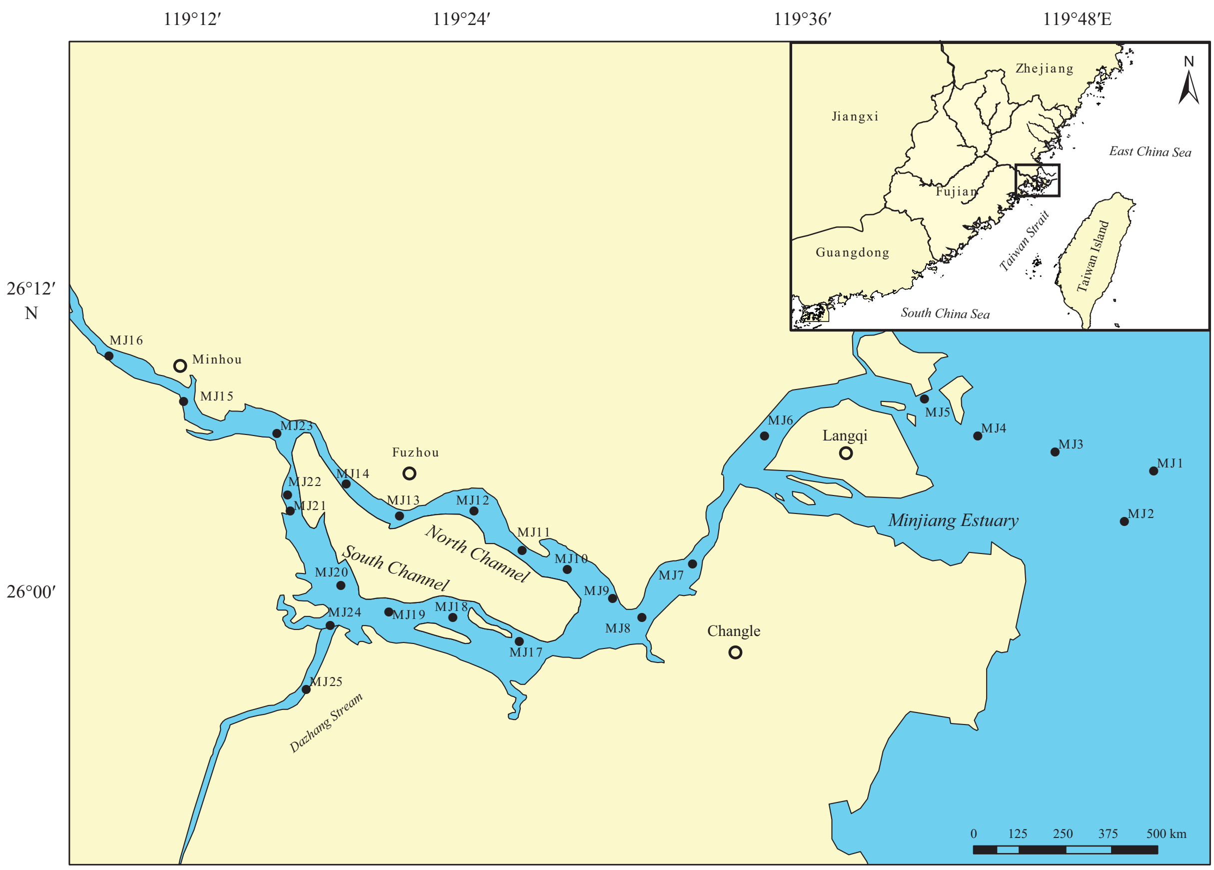

Fig. 1. Map of geographical location and diatom samples in surface sediment of the Minjiang Estuary. The upper right frame shows the study area, and the black circles the Minjiang Estuary stations.

the grains (<63 μm) were analyzed using a Mastersizer 2000 laser diffraction particle sizer (USA), with the detected sizes ranging from 0.02 to 2 000 μm. The results of grain size analysis were plotted on the Wentworth scale, and sediments classified by the Shepard triangular diagram (Wu et al., 2013; Wang et al., 2014).

The sub-samples from 25 sites were dried at 60°C, ground in an agate mill to pass through a 150 screen mesh, pressed into cakes and put into a Rigaku 100e type dispersive spectrometer (ZSX-100e) to analyze the major components: SiO_2, Al_2O_3, K_2O, Fe_2O_3, Na_2O, TiO_2, CaO and MgO. Two replicates were used for standards, analytical blanks and samples.

2.5 *Statistical analysis*

To detect the influences of environmental variables on the distribution of diatoms, CANOCO (version 4.5) was used in the numerical analysis (ter Braak and Smilauer, 2002). Several statistical methods can be used for data analysis in CANOCO, based on the characteristics of the data set (e.g., linear or non-linear methods, direct or indirect analyses) (Jiang et al., 2001). Before choosing linear or non-linear ordination methods, a detrended correspondence analysis (DCA) was used on the diatom data to determine which method was appropriate, with gradient length as the criterion (Birks, 1995; ter Braak and Smilauer, 2002). In our database, DCA showed a first gradient length of 2.839, implying a unimodal diatom distribution. Therefore, canonical correspondence analysis (CCA) was used to determine which environmental variables were most likely to explain the highest amount of variation present in our diatom database (McCune, 1997). Species data were transformed before statistical analyses, and only species with more than 2% relative abundance in at least one sample were included in further statistical analyses (Lopes et al., 2006).

3 Results

3.1 *Diatom occurrence and species distribution pattern*

Diatoms were abundant in most of the surface sediments from the Minjiang Estuary, with abundance varying spatially (Fig. 2a). The results indicated that the highest diatom abundance occurred in Sta. MJ11, reaching 11×10^4 valves/g. In contrast, the sample from MJ1, in the estuary of the Minjiang River had the lowest diatom abundance (13 valves/g). The average diatom abundance of the study area was 2.5×10^4 valves/g.

In total, 56 species and varieties of diatoms from 25 genera were identified in the study area. According to Pokras and Molfino, when the relative percentage of an individual species reaches 10%, or even 5% under certain environmental conditions, the species can be considered dominant (Pokras and Molfino, 1986). Using this criterion, we have indicated the 11 most dominant taxa in our study in Fig. 2. Among these dominant diatoms, freshwater diatoms contained *Epithemia hyndmanii* (0%–7.14%) and *Hydrosera whampoensis* (0%–7.14%). These species were mainly distributed in the downstream estuary (Figs 2j, k). The marine diatoms *Coscinodiscus curvatulus* (0%–21.45%), *C. divisus* (0%–96.50%), *C.radiatus* (0%–21.90%), *C. jonesianus* (0%–59.06%), *C. rothii* (0%–16.08%), *C. subtilis* (0%–27.27%) and *Trachyneis aspera* (0%–9.09%) were found in most of the stations (Figs 2c–h, l). Brackish-water species included *Actinocyclus ehrenbergii* (0%–7.47%) and *Cyclotella stylorum* (0%–8.90%). *A. ehrenbergii* mainly appeared in the estuary (Fig. 2b), while *C. stylorum* was abundant in the North Channel area (Fig. 2i).

3.2 *Grain size distribution of the surface sediments*

The result of grain size analysis from the sediment samples is presented in Fig. 3. The sand content ranged from 1.63% to 83.56%, with an average of 35.02%; the silt content varied from 13.86% to 76.84%, with an average of 48.11%; the clay content varied from 0.41% to 83.24%, with an average of 16.88%. The grain size data set indicated that silt and sand accounted for more than 80% of all sediments. The sediment median size varied from 0.12Φ to 2.68Φ (with an average of 1.22Φ), and the sediment sorting and skewness ranged from 0.42 to 1.81 (with an average of 0.69) and –0.39 to 0.26 (with an average of –0.05) (Table 1), respectively. Silt and clay were mainly distributed in the outer part of estuary, whereas sand and sand silt constituted the inner estuary.

3.3 *Chemical composition of the surface sediment*

Major elements found in the sediment are listed in Table 2. The SiO_2 concentrations were significantly high in the Minjiang River sediments (average 88.58%), and the minimum level was observed in front of the estuary, while the highest level was occasionally found in the upstream region. The concentration of Al_2O_3 was the second highest in the study area and varied from 3.41% to 8.06%, with an average of 5.76%. The concentrations of other six major elements varied: K_2O, 1.64%–3.49%, average 2.73%; Fe_2O_3, 0.24%–1.98%, average 0.87%; Na_2O, 0.30%–1.06%, average 0.56%; TiO_2, 0.11%–0.60%, average 0.23%; CaO, 0.15%–0.36%, average 0.20% and MgO, 0.07%–0.47%, average 0.18%. The significantly varied concentrations of major elements indicated different distribution patterns in the study area. The high concentrations of SiO_2, and low concentrations of K_2O, Fe_2O_3, Na_2O, TiO_2, CaO and MgO, were associated with enriched silicate silt and sand in the area (Gao et al., 2012).

3.4 *Canonical correspondence analysis (CCA)*

CCA revealed the relationships between diatom distribution and environmental variables; CCA outputs are given in Table 3. Monte Carlo permutation tests revealed that only nine variables (Fe_2O_3, SiO_2, CaO, Na_2O, MgO, depth, silt, clay, and sand) qualified for interpretation of the total variance in the diatom community composition (p<0.05).

The CCA based on 22 selected species and varieties of diatoms from 25 samples showed that a total of four axes explained 53.3% of the species variance. However, Axes 3 and 4 were considered to be less important to interpretation of species-environment correlations, because of low eigenvalues (Table 3). Therefore, the first two axes were selected to interpret the CCA results, explaining 21.2% and 13.9% of the variance, respectively. The species-environment correlations individually obtained for the axes were 0.857 and 0.774, respectively.

The correlation between environmental variables and the CCA axes can be inferred from Table 4. The first axis was positively correlated with depth (0.456), followed by Fe_2O_3 (0.431), silt (0.257) and other major elements (<0.198). SiO_2 (–0.192), sand (–0.189), CaO (–0.046) and clay (–0.039) were negatively correlated with Axis 1. The second axis had a positive relationship with Na_2O (0.392), CaO (0.381), Fe_2O_3 (0.377) and MgO (0.325) and a negative relationship with depth (–0.511), SiO_2 (–0.160), K_2O (–0.038) and silt (–0.032).

In the CCA diagram, the biplots of sites-environment and species-environment displayed a relationship between environmental variables and sites and species (Fig. 4). The CCA diagram for sites and environmental variables showed distribution patterns along the canonical axis (Fig. 4a). Sixteen sites were projected on the negative side of Axis 1, and nine sites (MJ2–MJ11) were projected on the positive side of Axis 1.

In the CCA scatter diagram, the diatom species were projec-

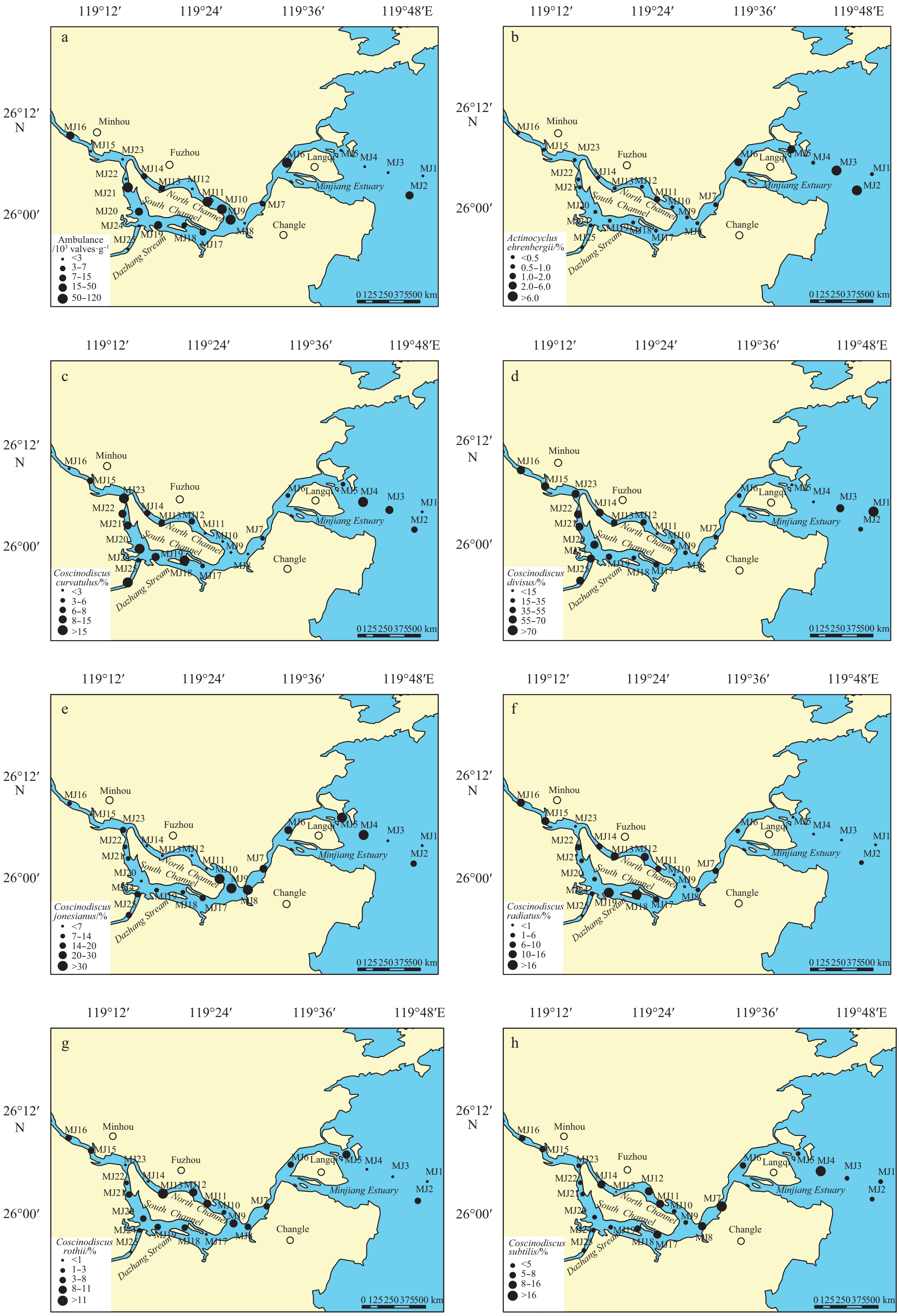
119°12′
119°24′
119°36′
119°48′E
26°12′ N
26°00′
a
b
c
d
e
f
g
h
Minhou
Fuzhou
Langqi
Changle
Minjiang Estuary
North Channel
South Channel
Dazhang Stream
MJ1
MJ2
MJ3
MJ4
MJ5
MJ6
MJ7
MJ8
MJ9
MJ10
MJ11
MJ12
MJ13
MJ14
MJ15
MJ16
MJ17
MJ18
MJ19
MJ20
MJ21
MJ22
MJ23
MJ24
MJ25
0 125 250 375 500 km
Ambulance /10³ valves·g⁻¹
<3
3–7
7–15
15–50
50–120
Actinocyclus ehrenbergii/%
<0.5
0.5–1.0
1.0–2.0
2.0–6.0
>6.0
Coscinodiscus curvatulus/%
<3
3–6
6–8
8–15
>15
Coscinodiscus divisus/%
<15
15–35
35–55
55–70
>70
Coscinodiscus jonesianus/%
<7
7–14
14–20
20–30
>30
Coscinodiscus radiatus/%
<1
1–6
6–10
10–16
>16
Coscinodiscus rothii/%
<1
1–3
3–8
8–11
>11
Coscinodiscus subtilis/%
<5
5–8
8–16
>16

Fig. 2

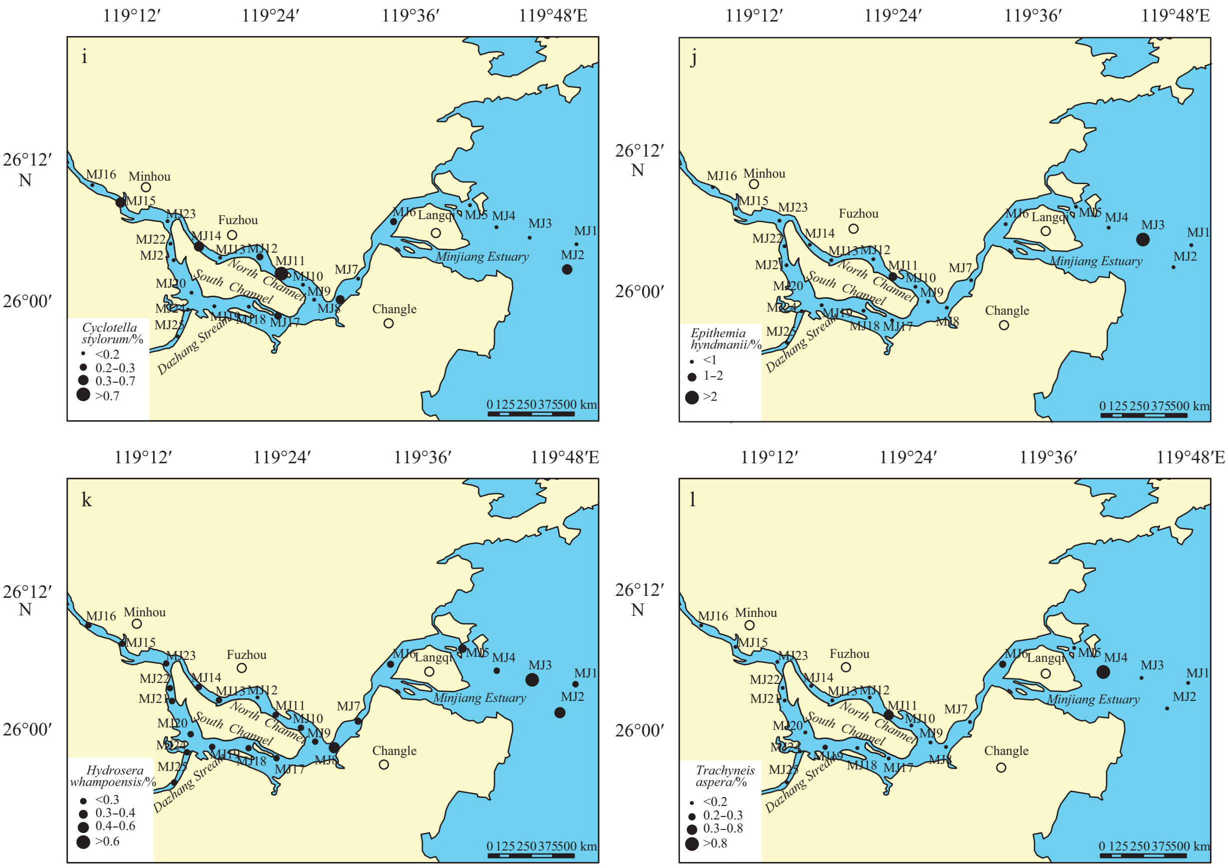

Fig. 2. Maps show the spatial distribution patterns of abundance and dominant diatom taxes across the Minjiang Estuary. a. Abundance (valves/g), b. *Actinocyclus ehrenbergii*, c. *Coscinodiscus curvatulus*, d. *Coscinodiscus divisus*, e. *Coscinodiscus jonesianus*, f. *Coscinodiscus radiatus*, g. *Coscinodiscus rothii*, h. *Coscinodiscus subtilis*, i. *Cyclotella stylorum*, j. *Epithemia hyndmanii*, k. *Hydrosera whampoensis*, and l. *Trachyneis aspera*.

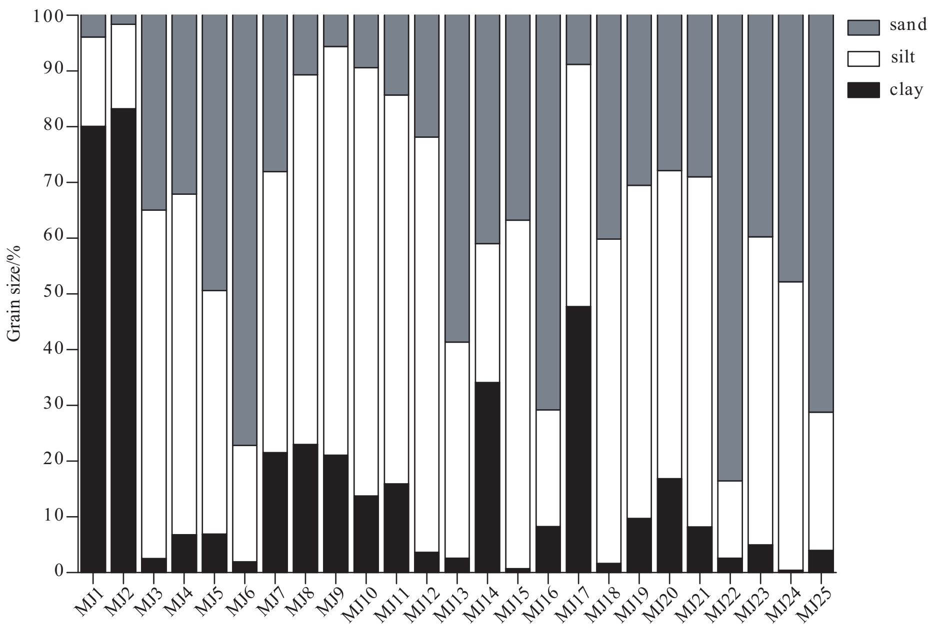

Fig. 3. Distribution of grain size in the Minjiang Estuary.

ted according to their relationship with the environmental variables in the ordination diagram (Fig. 4b). Species projection in the direction of the environmental arrow indicated a positive correlation, while species projection in the opposite direction indicated a negative correlation (Li et al., 2015). The result showed that most diatoms were negatively related to the major elements,

Table 1. Grain size in surface sediment of the Minjiang Estuary

Site	Median size/Φ	Sorting	Skewness	Site	Median size/Φ	Sorting	Skewness
MJ1	2.68	0.76	–0.02	MJ15	1.07	0.43	–0.15
MJ2	2.46	0.55	–0.03	MJ16	0.12	1.28	–0.22
MJ3	1.15	0.61	–0.19	MJ17	1.99	0.63	–0.03
MJ4	1.19	0.69	–0.16	MJ18	1.08	0.45	–0.07
MJ5	0.98	0.75	–0.03	MJ19	1.26	0.61	–0.01
MJ6	0.56	0.73	0.05	MJ20	1.36	0.71	0.00
MJ7	1.44	0.89	0.04	MJ21	1.26	0.59	–0.05
MJ8	1.66	0.68	0.09	MJ22	0.36	0.63	–0.05
MJ9	1.82	0.54	0.26	MJ23	0.94	0.70	–0.39
MJ10	1.61	0.50	0.14	MJ24	0.98	0.42	–0.14
MJ11	1.59	0.58	0.07	MJ25	0.62	0.64	0.10
MJ12	1.26	0.47	–0.17	Min	0.12	0.42	–0.39
MJ13	0.83	0.56	–0.08	Max	2.68	1.81	0.26
MJ14	0.19	1.81	–0.28	Average	1.22	0.69	–0.05

Table 2. Major elements in surface sediment of the Minjiang Estuary

Site	Depth/m	SiO_2/%	Al_2O_3/%	K_2O/%	Fe_2O_3/%	Na_2O/%	TiO_2/%	CaO/%	MgO/%
MJ1	7.5	82.36	8.06	3.18	1.98	1.00	0.60	0.36	0.47
MJ2	7.0	83.90	7.14	3.12	1.79	0.95	0.56	0.32	0.43
MJ3	7.0	87.97	5.26	2.69	1.52	0.67	0.19	0.22	0.26
MJ4	8.0	88.21	5.38	2.69	1.35	0.64	0.19	0.24	0.20
MJ5	10.0	89.35	5.13	2.54	1.15	0.57	0.17	0.16	0.15
MJ6	14.0	91.79	4.06	2.03	0.78	0.42	0.13	0.15	0.09
MJ7	25.0	88.21	5.89	2.80	1.05	0.49	0.27	0.20	0.19
MJ8	23.0	87.52	6.51	3.21	0.78	0.52	0.25	0.19	0.19
MJ9	7.0	86.32	6.34	3.53	0.68	0.48	0.20	0.18	0.19
MJ10	9.2	85.71	7.39	3.49	0.95	0.55	0.25	0.20	0.23
MJ11	9.8	85.48	7.48	3.41	1.05	0.56	0.25	0.21	0.24
MJ12	8.0	88.91	5.84	3.03	0.53	0.46	0.16	0.16	0.13
MJ13	8.9	91.73	4.40	2.36	0.33	0.36	0.13	0.15	0.08
MJ14	3.9	89.13	5.50	2.67	0.90	0.58	0.23	0.22	0.12
MJ15	9.0	90.92	4.89	2.65	0.25	0.47	0.13	0.15	0.10
MJ16	12.8	92.49	3.84	1.64	0.55	0.31	0.14	0.19	0.11
MJ17	9.2	84.81	7.60	3.36	1.30	0.53	0.38	0.25	0.27
MJ18	16.0	90.89	4.95	2.52	0.36	0.43	0.16	0.16	0.10
MJ19	4.9	89.70	5.40	2.68	0.60	0.41	0.22	0.18	0.14
MJ20	6.3	87.57	6.53	3.25	0.71	0.48	0.21	0.18	0.18
MJ21	2.9	88.98	5.84	2.95	0.58	0.44	0.19	0.18	0.14
MJ22	1.4	93.73	3.41	1.72	0.24	0.30	0.11	0.15	0.07
MJ23	3.5	91.67	4.44	2.24	0.40	0.38	0.18	0.18	0.10
MJ24	1.9	87.71	6.41	2.47	1.00	0.78	0.20	0.23	0.17
MJ25	1.9	87.15	6.88	2.75	0.84	1.06	0.19	0.23	0.17
Min	1.4	82.36	3.41	1.64	0.24	0.3	0.11	0.15	0.07
Max	25	93.73	8.06	3.49	1.98	1.06	0.6	0.36	0.47
Average	8.7	88.58	5.76	2.73	0.87	0.56	0.23	0.2	0.18

except for species such as *A. undulatus*, *Coscinodiscus argus*, *C. radiatus*, *C. jonesianus*, *C. rothii*, *C. subtilis* and *Cyclotella stylorum*, which had a positive correlation with major elements (SiO_2 and K_2O), depth, sand and silt.

The CCA results showed the relationships between the chemical composition and samples, as well as the percentage and geographical distribution of the diatom samples in the Minjiang Estuary. The diatom at the sampling sites could be distinguished into four assemblages (Fig. 4a). The assemblages were mapped according to the sampling sites, displaying a clear spatial geographic variation (Fig. 5). The sites in the estuary (MJ1–MJ5) belonged to Assemblage I. The downstream sites from MJ6 to MJ8 were dominated by Assemblage II. Assemblage III comprised the upper and middle stream of the Minjiang River, including the North Channel area (MJ9–MJ17). Assemblage IV, with eight sites, mainly occurred in the South Channel area.

4 Discussion

This study examined diatom distribution in surface sediments from the Minjiang Estuary. Changes in the abundance and types of diatoms indicated that environmental variations exist in this estuary.

Table 3. Summary of canonical correspondence analysis results from diatom assemblages

	Axis				Total inertia
	1	2	3	4	
Eigenvalues	0.212	0.139	0.107	0.075	1.736
Species-environment correlations	0.857	0.774	0.871	0.604	
Cumulative percentage variance					
of species data	12.2	20.2	26.4	30.7	
of species-environment relation	32.3	53.5	69.9	81.2	
Sum of all eigenvalues					1.736
Sum of all Canonical eigenvalues					0.656

Table 4. Correlation between the first and second canonical correspondence analysis axes and 12 selected environmental variables

Variables	Axis 1	Axis 2
SiO_2	−0.192	−0.160
Al_2O_3	0.073	0.018
K_2O	0.198	−0.038
Fe_2O_3	0.431	0.377
Na_2O	0.086	0.392
TiO_2	0.007	0.116
CaO	−0.046	0.381
MgO	0.189	0.325
Depth	0.456	−0.511
Clay	−0.039	0.028
Silt	0.257	−0.032
Sand	−0.189	−0.000

4.1 *Influence of the sedimentary environment*

In previous studies, high phytoplankton diversity and abundance usually occurred in surface seawater adjacent to the Minjiang Estuary. This was attributed to the effect of river input, which decreases salinity, increases the nutrient levels and provides diverse habitat for diatoms (Lin et al., 2012; Xiao, 2013; Dai et al., 2016). However, the spatial pattern of diatom abundance in the surface sediment differed from that of the surface seawater, with lower abundance in the Minjiang Estuary (Lapointe, 2000; Xu et al., 2014). The inconsistent spatial pattern of diatom abundance in the surface sediment and upper water column can be related to the sedimentary environment of the Minjiang Estuary.

The deposition rates in the Minjiang Estuary varied significantly, with a range of 0.79–3.34 cm/a, and average values of 1.97 cm/a (Shi et al., 2010). Ye et al. (2002) researched the tidal current speeds in the inner shelf of Zhejiang Provine and Fujian Province were 0.26 m/s. During the intense winter monsoon, sediments from the Changjiang River (Yangtze River) can reach the Minjiang Estuary, which increase deposition rate in the study area (Liu et al., 2007; Xu et al., 2014). The rate of deposition is important as it can influence the geographic distribution of diatoms, and a high deposition rate will increase the burial speed and dilute diatom abundance during the preservation process (Milliman et al., 1985; Xu et al., 2009; Liu et al., 2015). Sediment grain size is another important factor affecting the pattern of diatom distribution. In general, sandy silt and muddy sand have been found to be better than sand in preserving diatoms (Jesus et

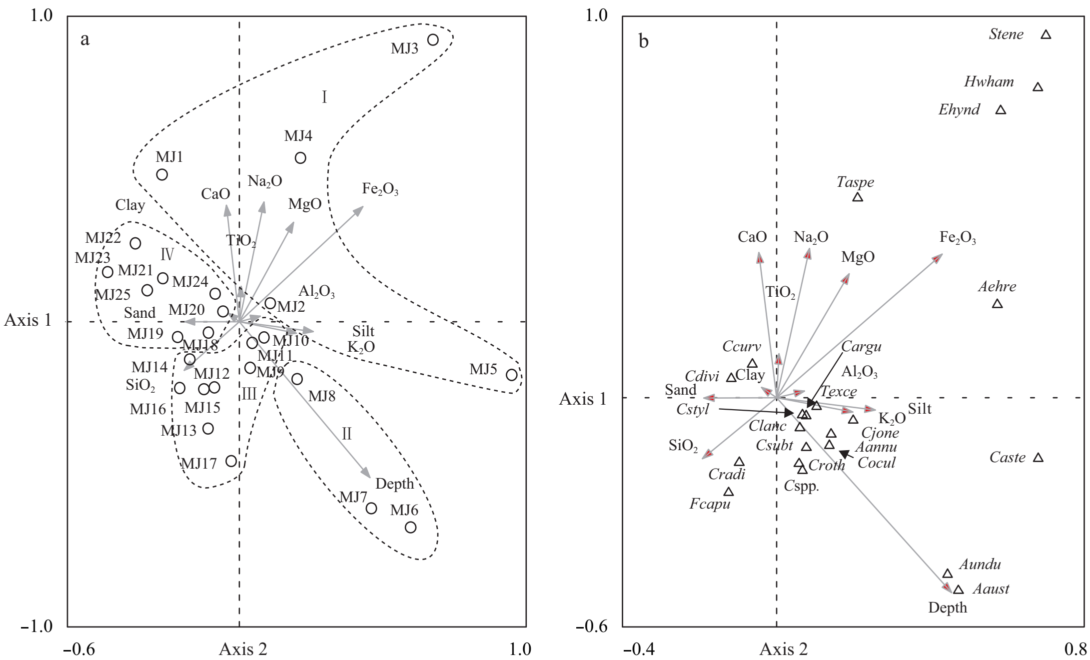

Fig. 4. Canonical correspondence analysis biplot of environmental variables and sites (a) and species (b). a. Four diatom assemblages were plotted in the Minjiang Estuary (I, II, III, and IV). b. Only relative abundance greater than 5% was displayed in the map. Abbreviations: *Aehre* represents *Actinocyclus ehrenbergii*, *Aannu Actinoptychus annulatus*, *Aaust Actinoptychus australis*, *Aundu Actinoptychus undulates*, *Cargu Coscinodiscus argus*, *Caste Coscinodiscus asteromphalus*, *Ccurv Coscinodiscus curvatulus*, *Cdivi Coscinodiscus divisus*, *Cjone Coscinodiscus jonesianus*, *Cocul Coscinodiscus oculatus*, *Cradi Coscinodiscus radiates*, *Croth Coscinodiscus rothii*, Cspp *Coscinodiscus* spp., *Csubt Coscinodiscus subtilis*, *Cstyl Cyclotella stylorum*, *Clanc Cymbella lanceolata*, *Ehynd Epithemia hyndmanii*, *Fcapu Fragilaria capusina*, *Hwham Hydrosera whampoensis*, *Stene Surirella tenera*, *Texce Thalassiosira excentrica*, and *Taspe Trachyneis aspera*.

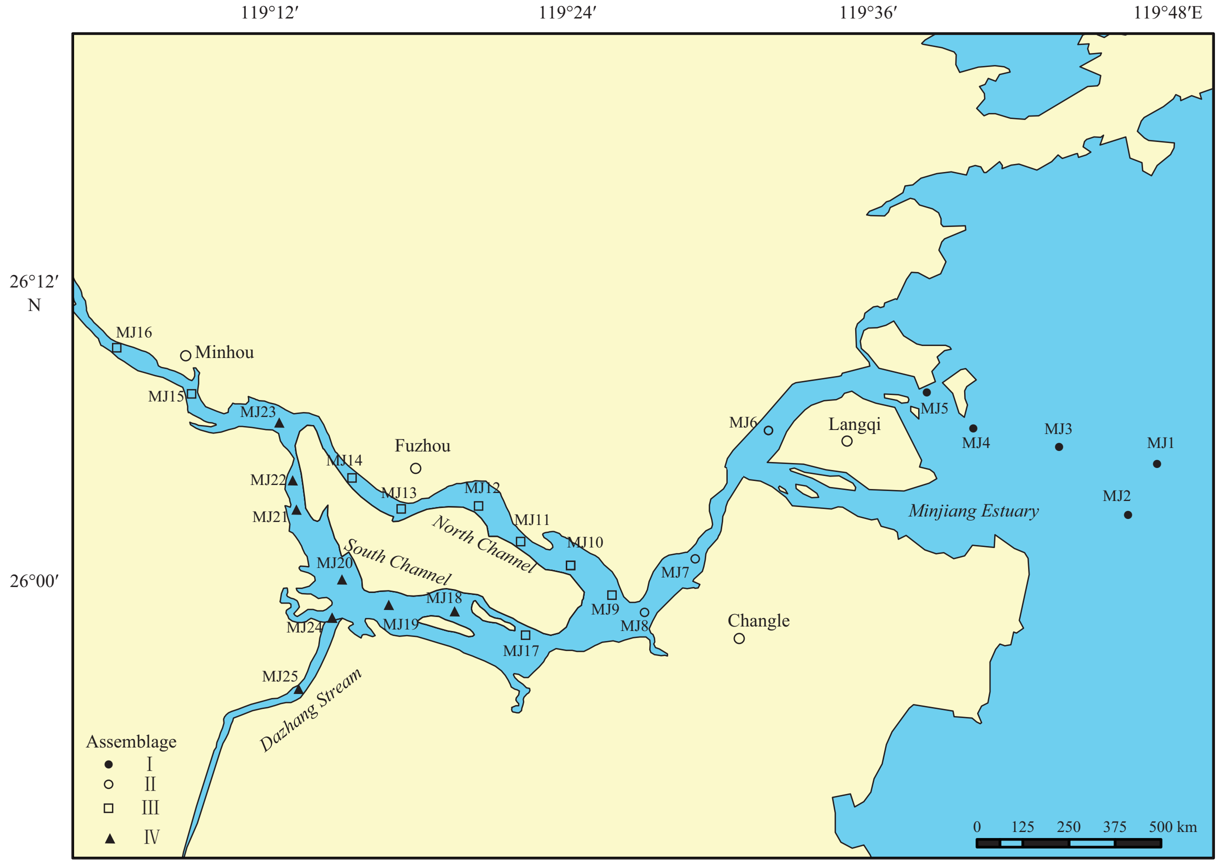

Fig. 5. Distribution of diatom assemblages I, II, III and IV in the Minjiang Estuary. Black circles represent Assemblage I, hollow circles Assemblage II, black square Assemblage III, and black triangle Assemblage IV.

Table 5. Correlation matrix of the 12 environment variables from canonical correspondence analysis

	Depth	SiO_2	Al_2O_3	K_2O	Fe_2O_3	Na_2O	TiO_2	CaO	MgO	Clay	Silt	Sand
Depth	1.000											
SiO_2	–0.050	1.000										
Al_2O_3	0.050	**–0.961**	1.000									
K_2O	0.166	**–0.834**	**0.889**	1.000								
Fe_2O_3	0.037	**–0.834**	0.660	0.484	1.000							
Na_2O	–0.214	–0.749	0.676	0.408	0.744	1.000						
TiO_2	0.065	**–0.833**	0.724	0.540	**0.803**	0.642	1.000					
CaO	–0.127	**–0.810**	0.675	0.404	**0.873**	**0.802**	**0.899**	1.000				
MgO	0.037	**–0.904**	0.771	0.603	**0.911**	0.732	**0.937**	**0.915**	1.000			
Clay	0.070	–0.731	0.619	0.463	0.721	0.540	**0.963**	**0.831**	**0.850**	1.000		
Silt	0.235	–0.015	0.119	0.428	–0.221	–0.315	–0.357	–0.401	–0.216	–0.475	1.000	
Sand	–0.283	0.775	–0.751	**–0.865**	–0.554	–0.281	–0.686	–0.508	–0.693	–0.618	–0.398	1.000

Note: The bolds highlight environmental variables with others. The numbers indicate either strong positive or negative correlation if a threshold value of 0.8 or –0.8 was exceeded (Esper et al., 2010).

al., 2006; Méléder et al., 2007). In the estuary, hydrodynamics are controlled by runoff and waves; sediment tends to be coarse, consisting of sand, or silt and sand. At Sites MJ3–MJ6, the sand fraction accounted for more than 60% by weight, and diatom species and abundance were low. In the estuary, we identified 26 species and varieties of diatoms, with absolute abundance of diatoms ranging from 16 to 78 356 valves/g, and averaging 19 670 valves/g. However, at some sites such as MJ1 and MJ2, the coastal current dominated particle transport, and the sediment was relatively fine, consisting of clay or silty clay. Diatom species and abundance were high, especially at Sta. MJ2, which had an abundance of 49 906 valves/g. In the inner estuary the sediment was fine, and diatom numbers were relatively high. Therefore, the distribution of sediment grain size is clearly a critical factor controlling the variation in diatom content.

4.2 *Diatom assemblages and their environmental significance*

Diatom Assemblage I comprised 14 genera and 28 diatom species; the diatom abundance ranged from 13 valves/g to 49 906 valves/g and average abundance was 10 048 valves/g. The assemblage was characterized by *C. asteromphalus* (0%–11.7%), *C. curvatulus* (0%–18.18%), *C. divisus* (7.17%–57.14%), *C. jonesianus*

(0%–58.11%) and *C. subtilis* (0%–27.27%). These dominant diatoms are marine and coastal species (Guo, 2003), and their distribution showed that this assemblage was strongly affected by the China Coastal Currents system. The assemblage also contained the freshwater species *E. hyndmanii* (0%–7.14%) and *H. whampoensis* (0%–7.14%), mainly distributed in MJ2 and MJ3 (Fig. 2), suggesting that the assemblage was affected by fresh water from the Minjiang River.

Samples from Assemblage II comprised 13 genera and 24 diatom species. Diatom abundance was higher than in Assemblage I, and varied from 544 valves/g to 78 356 valves/g; average abundance was 28 518 valves/g. The dominant diatoms mainly comprised marine and coastal species of *C. jonesianus* (28.70%–59.06%), *C. divisus* (15.79%–27.73%), *C. subtilis* (7.20%–23.19%), *C. radiatus* (5.33%–7.83%), *C. rothii* (4.09%–6.40%), *A. ehrenbergii* (0%–5.33%) and *C. curvatulus* (0%–5.33%), respectively. The dominant species being marine and coastal diatoms indicated that the oceanic and coastal water had a strong influence on this assemblage.

Assemblage III comprised 21 genera and 48 diatom species. Abundance ranged from 143 valves/g to 11 4886 valves/g, and the average value was 39 309 valves/g. The relative abundance of the dominant diatoms *C. divisus* and *C. jonesianus* accounted for 14.40%–67.14% and 0.47%–53.44% of the assemblage, respectively; the marine species *C. rothii*, *C. radiatus* and *C. subtilis* accounted for 0%–16.08%, 0.22%–15.54% and 3.66%–15.85%, respectively. Thalassiosira excentrica and Coscinodiscus argus, both cosmopolitan species (Guo, 2003), accounted for 0%–3.66% and 0%–2.36%, respectively. There was also a large number of coastal species (such as *C. stylorum*, *C. striata* and *P. sulcata*) in Assemblage III, which may have been affected by the shallow water depth. The samples from Assemblage III had positive SiO_2 values (Fig. 4a), suggesting that they were located in an area with a relatively high SiO_2 content.

Assemblage IV had few diatom species than Assemblage III, and only 8 genera and 16 diatom species were found. Diatom abundance ranged from 239 valves/g to 87 904 valves/g, and the average value was 15 698 valves/g. The relative abundance of the dominant diatoms *C. divisus*, *C. curvatulus* and *C. jonesianus* accounted for 31.72%–68.87%, 3.97%–21.45% and 6.34%–16.56% of the assemblage, respectively. The marine species *C. subtilis*, *C. radiatus* and *C. rothii* accounted for 0%–7.55%, 0%–21.90% and 0%–6.34%, respectively.

Samples from Assemblage IV had a positive correlation with sand, indicating that they were situated to coarse particles, and negative values with depth, suggesting they were characterized by shallow water depth (Fig. 4a).

4.3 *Relationships between diatom and sediment properties*

Diatoms have long been used as powerful and reliable environmental indicators (Smol and Stoermer, 2010). In this study, the spatial distribution of four diatom assemblages indicated significant environmental difference in the Minjiang River. The CCA results revealed that Fe_2O_3, Na_2O, CaO, MgO and TiO_2 were highly negative to large diatom species; however, SiO_2, Al_2O_3 and K_2O had a positive correlation with most diatom species (Fig. 4b). The Fe_2O_3, Na_2O, CaO, MgO, and TiO_2 concentrations were low at most stations; in contrast, the concentrations of SiO_2, Al_2O_3 and K_2O were high throughout the study area (Table 2). The results showed that the diatom assemblages were insensitive to a selected environmental factor until it exceeded a critical standard.

Major element chemistry can also be related to sediment property (Meybeck and Helmer, 1989). SiO_2 had positive correlation with sand, while Al_2O_3 and Fe_2O_3 presented positive correlation with silt, suggesting that SiO_2 levels increased in coarse particles, and Al_2O_3 and Fe_2O_3 levels were higher in finer sediments (Roquin and Zeegers, 1987; Ottesen et al., 1989; Vital and Stattegger, 2000). Diagenetic elements such as Al and Fe, the major components of silica minerals, are the products of rock weathering (Xie and Yin, 1993; Yamanaka et al., 2010; Zhou et al., 2014), and these elements were clearly controlled by grain size in Minjiang River sediment. The fine sediments (such as silt and clay) usually had high Al_2O_3 and Fe_2O_3 contents (Table 2). The strong positively correlation of K_2O, TiO_2, CaO, and MgO with Al_2O_3 and Fe_2O_3 (Table 5), suggested that these components might originate from human activities, and weathering, and be transferred by colloidal and mineral particulates (Gibbs, 1994; Zhao and Yan, 1994; Peng et al., 2003; Zhou et al., 2014).

There were few diatoms from stations with lower concentrations of major elements because of fresh water input, such as Sites MJ1, MJ2 and MJ3 (Fig. 2, Table 2). Fresh water input changed physical and biochemistry factors (temperature, salinity, hydrodynamics and other nutrient parameters) (Boltovskoy and Wright, 1976; Murray, 2006; Li et al., 2015), and then strongly affected diatom community structure in the coastal marine environment.

5 Conclusions

(1) Total 56 species and varieties of diatoms from 25 genera were identified from 25 samples. The absolute abundance of diatoms ranged from 13 valves/g to 11×10^4 valves/g, with an average of 2.5×10^4 valves/g.

(2) Sediment properties influenced the distribution of diatoms. When sediments were fine, the diatom abundance was relatively high. CCA revealed that the major elements (Fe_2O_3, Na_2O, CaO, MgO, TiO_2, SiO_2, Al_2O_3, and K_2O) had a close relationship with diatoms. Fresh water input can affect diatom community structure in the coastal marine environment.

(3) Four diatom assemblages have been identified, representing different sediment properties. Assemblage I (estuary area) was strongly affected by the China Coastal Current and fresh water from the Minjiang River. Assemblage II (downstream area) was affected by oceanic and coastal water. Assemblage III (upper and North Channel area) was influenced by shallow water and a relatively high SiO_2 content. Assemblage IV (South Channel area) was associated with coarse particles and shallow water depth. Diatom assemblages can therefore be important in late Quaternary palaeoceanographic reconstructions of the Minjiang Estuary.

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