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Diatom assemblages in surface sediments from the South China Sea as environmental indicators*

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Abstract We studied diatom distribution from 62 samples from the uppermost 1 cm of sediment in the South China Sea (SCS), using grabs or box corers in three cruises between 2001–2007. Fifty six genera, 256 species and their varieties were identified. Dominating species included *Coscinodiscus africanus*, *Coscinodiscus nodulifer*, *Cyclotella stylorum*, *Hemidiscus cuneiformis*, *Melosira sulcata*, *Nitzschia marina*, *Roperia tesselata*, *Thalassionema nitzschioides*, *Thalassiosira excentrica*, and *Thalassiothrix longissima*. Most surface sediments in the SCS were rich in diatoms, except for a few coarse samples. Average diatom abundance in the study area was 104 607 valve/g. In terms of the abundance, ecology, and spatial distribution, seven diatom zones (Zones 1–7) were recognized. Zone 1 (northern continental shelf) is affected by warm currents, SCS northern branch of the Kuroshio, and northern coastal currents; Zone 2 (northwestern continental shelf) is affected by intense coastal currents; Zone 3 (Xisha Islands sea area) is a bathyal environment with transitional water masses; Zone 4 (sea basin) is a bathyal-to-deep sea with stable and uniform central water masses in a semi-enclosed marginal sea; Zone 5 (Nansha Islands marine area) is a pelagic environment with relatively high surface temperature; Zone 6 (northern Sunda Shelf) is a tropical shelf environment; and Zone 7 (northern Kalimantan Island shelf area) is affected by warm waters from the Indian Ocean and coastal waters. The data indicate that these diatom zones are closely related to topography, hydrodynamics, temperature, nutrients and especially the salinity. Better understanding of the relationship between diatom distribution and the oceanographic factors would help in the reconstruction of the SCS in the past.

Keyword: surface sediments; diatom assemblage zones; environmental factors; South China Sea (SCS)

1 INTRODUCTION

The South China Sea (SCS), the largest marginal sea of the western Pacific, plays a key role in climate change in East Asia, and is a natural experimental site for research into the driving forces and regional responses to global change (Zhao and Wang, 1999). Various forms of marine life in the SCS have been studied, such as foraminifera (Jian and Wang, 1997), radiolarians (Wang and Abelmann, 2002) and calcareous nannofossils (Wei et al., 1997). However, available data on diatoms are very limited.

Diatoms are microscopic algae found in almost all aquatic and most wet terrestrial habitats. Each habitat has its own chemical and physical environment and is represented by its own characteristic diatom flora. Opaline silica skeletons preserved in sediments contain paleoenvironmental information (Stoermer

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and Smol, 1999). Therefore, research on diatom assemblages in surface sediments is important for reconstructing the local environmental changes.

This research covered mainly the northern part of the SCS, spanning 3°56.61′–20°59.37′N, 108°30.68′–116°46.70′E. It was performed in a large-scale and comprehensive manner on surface sediment diatoms to identify the factors affecting their preservation and better understand how the diatom record changes with time.

2 TECTONIC SETTING

The SCS is the largest marginal sea in the world, with a surface area of approximately 3.5×10^6 km^2. The main basin extends from the equator along the northwestern coast of Borneo to approximately 23°N along the southern coast of China, and from near to 105°E along the coast of the Indochinese Peninsula to 120°E along the eastern coast of the Philippines. The deepest basin, located in the northeast, is reported as 5 000 m deep. The shelf is narrow, with area of 1.2×10^6 km^2 (Shaw and Chao, 1994), and is separated from the western Pacific to the east and the Indian Ocean to the south by a series of sills. The climate and surface-water circulation in the SCS are largely controlled by monsoons which driven by differential heating in adjacent continents and oceans (Wytki, 1961), and characterized by abnormal rain and wind patterns in summer and winter of monsoon years. The northeast and southwest monsoons change the surface-water circulation regularly, bringing in water into the SCS from the western Pacific (including probably the warm Kuroshio (Wytki, 1961) through the Bashi Strait, north of Luzon) and Indian Ocean surface water across the Sunda Shelf in summer (Wang and Abelmann, 2002).

The topography of SCS is complex. The northern or northwestern and southwestern margins are flat continental shelves, which transform to slopes from 150 m depth. The boundary between slope and basin is approximately at the 3 200 m isobath in the west, and at 3 600 m in the center. The continental slope contains submarine plateaus, troughs, and trenches. Abyssal plains are widely distributed at the bottom of the deep-sea basin, and many seamounts rise above the seabed for a few kilometers (Mao et al., 1982). Because of different effects of these water systems, temperature and salinity of the SCS are high in the south and low in the north. From North to South, average surface temperatures vary from 22.6 to 27.1°C and average salinities from 29 to 33.5.

3 MATERIAL AND METHOD

3.1 Sampling and sample processing

Diatom samples (Fig.1; Table 1) were taken from the uppermost 1-cm sediment collected with a grab or a box corer during cruises on R/Vs *Ocean-4* in 2000–2001, *Shiyan-3* in 2007, and *Yanping-2* in 2007. The sampling stations lay between 3°56.61′–20°59.37′N, 108°30.68′–116°46.70′E. The sampling depths ranged from 101 to 4 185 m. Samples were prepared according to Håkansson (1984). All the samples were treated with 10% HCl to remove calcareous matter and treated with 30% H_2O_2 (1–2 h in a water bath at 60°C) to remove organic material. Very clayey samples were washed repeatedly with distilled water in a 100-mL beaker to suspend and disperse the clay material. The supernatant was decanted off after at least 3 h, and the aliquot of the suspension was shaken, smeared on a cover slip, and dried. After the materials were completely dried, samples were mounted with Naphrax (Håkansson, 1984).

3.2 Diatom analysis

Diatoms were identified and counted with an Olympus BX-51 microscope on phase contrast at magnification of 1000×. More than 300 diatom valves were counted for each sample, and the counts were converted to percentage abundances (Lapointe, 2000; Jiang, 2001). For samples containing very few diatoms, all diatoms on the entire slide were counted. The row numbers for counting diatoms were randomly chosen for statistical purposes (Lapointe, 2000).

The absolute number of diatom valves per gram of sediment was calculated as follows: the number of valve/g=$((N\times(S/s))\times(V/v))\times1\ 000/w$: N is the number of diatom valves observed; S is the total number of rows divided per slide; s is the number of rows in which diatoms were counted; V is the total volume; v is the volume of solution placed onto cover slip; and w is the dry weight of the sample. Relative abundances of individual taxa are given as percentages (Abrantes et al., 2007).

For an incomplete valve, the centric diatoms were counted as representing the whole specimen if more than half of the valve was observed (including the central area). Pinnate diatoms were counted as half if only a single apex was found on the valve (Lopes, 2006). Whenever possible, each specimen was identified to species level; otherwise, it was assigned to a genus. Because of difficulties in classifying *Chaetoceros* resting spores, all of them were recorded

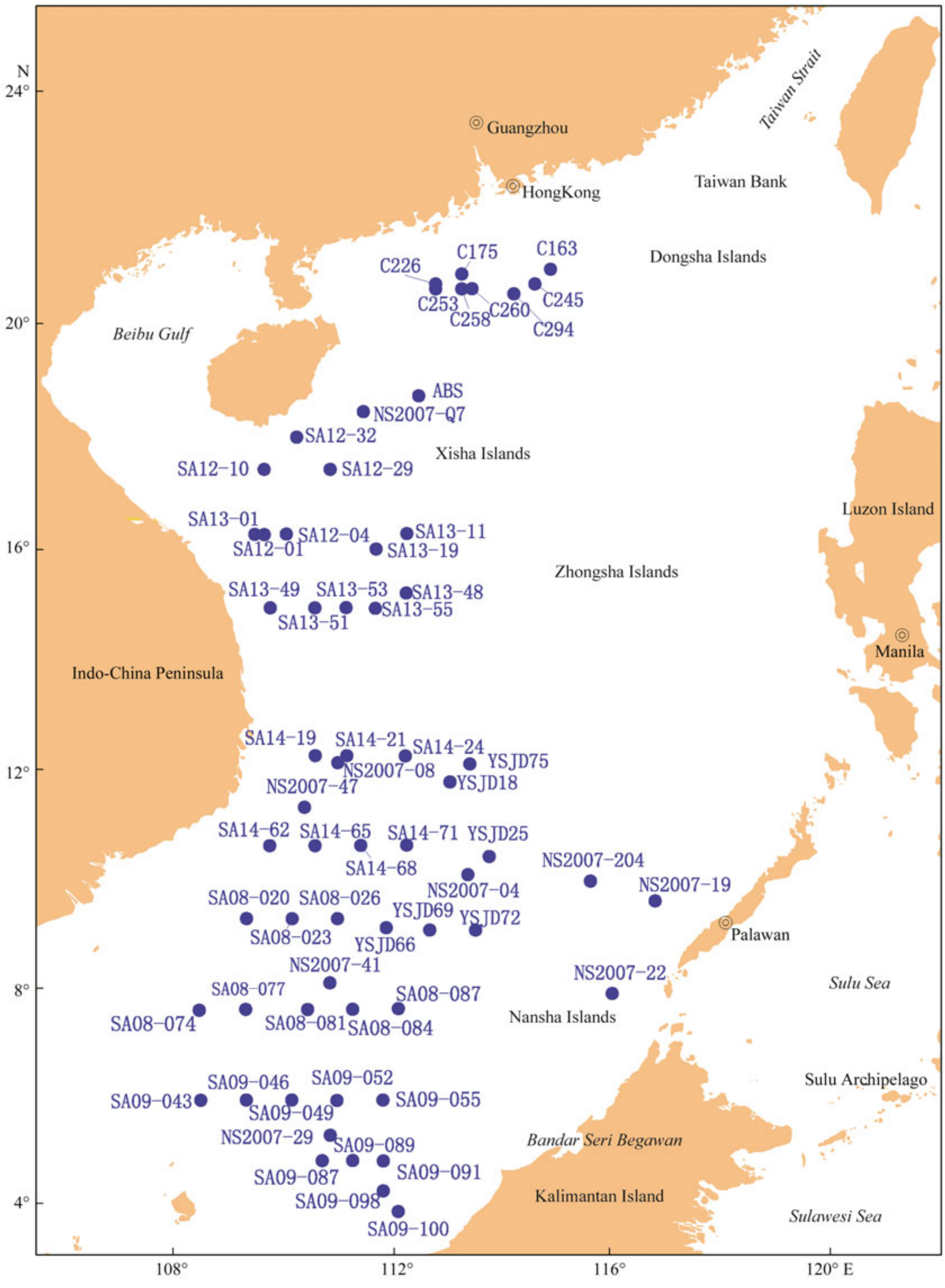

Fig.1 Locations of diatom samples in surface sediment in SCS

as spores of *Chaetoceros* (Nave et al., 2001).

Diatom taxonomy and ecological affinity information followed Jin et al. (1965, 1982, 1992), Lan et al. (1995), Schmidt (1874–1959), Hustedt (1930), Mann (1925), van Heurck (1896), Metzeltin et al. (1998) and Round et al. (1990).

3.3 Grain size analysis

Grain size and detrital mineral analyses were conducted according to the Specifications for Oceanographic Survey (No. GB/T 13909-92, National Standard of China). Subsamples for grain size

Table 1 Details of diatom samples in surface sediment in the SCS

Station	Latitude	Longitude	Depth (m)	Station	Latitude	Longitude	Depth (m)
ABS	18°41.09′	112°28.65′	471	SA09-087	04°46.09′	110°43.38′	112
C163	20°59.37′	114°52.48′	98	SA09-089	04°46.27′	111°16.58′	101
C175	20°54.05′	113°15.61′	73	SA09-091	04°45.80′	111°49.99′	114
C226	20°43.21′	112°47.13′	72	SA09-098	04°13.09′	111°49.92′	78
C245	20°43.23′	114°35.40′	100	SA09-100	03°56.61′	112°06.29′	62
C253	20°37.80′	112°47.15′	77	SA12-01	16°09.62′	109°40.12′	875
C258	20°37.87′	113°15.62′	83	SA12-04	16°10.18′	110°04.22′	1 010
C260	20°37.81′	113°26.97′	85	SA12-10	17°20.75′	109°39.97′	138
C294	20°32.47′	114°12.51′	99	SA12-29	17°20.83′	110°52.06′	1 665
NS2007-04	09°58.40′	113°22.29′	2 189	SA12-32	17°55.94′	110°15.46′	138
NS2007-08	12°00.59′	111°00.32′	2 946	SA13-01	16°09.82′	109°29.72′	635
NS2007-19	09°29.61′	116°46.70′	2 150	SA13-11	16°10.73′	112°15.65′	1 076
NS2007-204	09°51.34′	115°36.05′	1 446	SA13-19	15°53.88′	111°42.12′	1 180
NS2007-22	07°48.56′	115°59.80′	2 589	SA13-48	15°05.76′	112°15.01′	1 820
NS2007-29	05°23.02′	110°52.09′	181	SA13-49	14°49.67′	109°46.63′	377
NS2007-41	08°00.21′	110°51.68′	1 865	SA13-51	14°49.61′	110°35.35′	800
NS2007-47	11°11.93′	110°23.97′	1 609	SA13-53	14°49.90′	111°09.37′	1 565
NS2007-Q7	18°23.83′	111°28.22′	1 184	SA13-55	14°49.06′	111°41.37′	1 211
SA08-020	09°10.41′	109°20.70′	1 071	SA14-19	12°08.29′	110°35.74′	2 300
SA08-023	09°10.26′	110°10.51′	2 012	SA14-21	12°08.20′	111°10.20′	2 614
SA08-026	09°10.28′	110°59.96′	2 091	SA14-24	12°07.86′	112°13.98′	4 238
SA08-074	07°31.21′	108°30.68′	108	SA14-62	10°30.01′	109°46.04′	350
SA08-077	07°31.27′	109°19.85′	423	SA14-65	10°29.99′	110°35.47′	1 920
SA08-081	07°31.10′	110°27.46′	1 838	SA14-68	10°30.31′	111°25.46′	3 772
SA08-084	07°31.37′	111°16.51′	1 960	SA14-71	10°30.62′	112°15.46′	4 070
SA08-087	07°32.07′	112°06.43′	1 860	YSJD18	11°39.58′	113°02.77′	3 700
SA09-043	05°52.03′	108°30.75′	101	YSJD25	10°18.22′	113°45.55′	2 226
SA09-046	05°52.27′	109°20.53′	139	YSJD66	09°00.29′	111°53.24′	1 731
SA09-049	05°52.33′	110°10.13′	354	YSJD69	08°57.82′	112°40.69′	2 353
SA09-052	05°51.79′	110°59.41′	1 123	YSJD72	08°57.82′	113°30.69′	1 813
SA09-055	05°52.28′	111°49.57′	1 432	YSJD75	11°59.84′	113°24.64′	4 185

analysis were sampled, dried, weighed, mixed with sodium hexametaphosphate and water, soaked, and sieved through a 63-μm mesh. The grains retained on the sieve (>63 μm) were analyzed after being dried, and the grains passing through the mesh (<63 μm) were analyzed using a Mastersizer 2000 laser diffraction particle size analyzer (measurement range, 0.02–2 000 μm). The results of grain size analysis were plotted on the Wentworth scale, and the sediments were classified using the Shepard triangular diagram.

4 RESULT

4.1 Bottom sediment types

Six main types of sediments in SCS were classified according to grain size (Medium-fine Sand, Fine Sand, Silty Sand, Sandy Silt, Silt, and Clayey Silt). They were distributed in an obvious zonation. Coarse-grained sediments of sand or silty sand were mainly distributed in the southwest Sunda shelf, the Mekong River mouth, and the northern part of the SCS, as well as some local

Table 2 Diatom abundance in surface sediments in SCS

Station	Abundance (valve/g)	Station	Abundance (valve/g)
ABS	508	SA09-087	264
C163	186	SA09-089	71
C175	638	SA09-091	2 578
C226	3 764	SA09-098	155 556
C245	653	SA09-100	137 221
C253	2 112	SA12-01	41 027
C258	663	SA12-04	24 482
C260	634	SA12-10	3 123
C294	224	SA12-29	177 222
NS2007-04	354 656	SA12-32	3 000
NS2007-08	219 975	SA13-01	3 121
NS2007-19	335 510	SA13-11	39 047
NS2007-204	122 714	SA13-19	68 627
NS2007-22	44 938	SA13-48	146 410
NS2007-29	1 289	SA13-49	2 273
NS2007-41	63 448	SA13-51	97 008
NS2007-47	129 512	SA13-53	196 244
NS2007-Q7	58 667	SA13-55	70 398
SA08-020	35 148	SA14-19	23 162
SA08-023	342 238	SA14-21	152 906
SA08-026	214 391	SA14-24	32 242
SA08-074	79	SA14-62	4 792
SA08-077	969	SA14-65	163 009
SA08-081	219 459	SA14-68	217 333
SA08-084	251 169	SA14-71	154 277
SA08-087	94 582	YSJD18	623 438
SA09-043	264	YSJD25	313 462
SA09-046	84	YSJD66	409 574
SA09-049	2 578	YSJD69	377 778
SA09-052	155 556	YSJD72	90 022
SA09-055	137 221	YSJD75	249 873

reefs in the Nansha undersea plateau district; fine-grained silts were mainly distributed from the continental slope to the deep-sea basin. Fine-grained sediments were mainly distributed in the central basin, the eastern part of the Indo-China Peninsula and the Nansha Islands. In general, grain size of surface sediment samples was coarse, but varied greatly in some areas. Silt content was over 50% in most stations, 40% in Station SA14-19 only, 30% in a few stations in the sea basin and in southeastern Indochina (e.g., NS2007-22, SA08-20, SA08-26, and SA13-53) and 20%–30% in many other stations. Clay content was very low, indicating strong hydrodynamics in the SCS.

4.2 Absolute abundance in surface sediments

Most surface sediments in the SCS contained a significant number of diatoms, and only few samples with coarse granularity contained a small number of diatoms. Difference in distribution of diatom abundance was significant (Table 2). For example, diatom abundance in Station SA09-089 on the continental shelf was only 71 valve/g, whereas that Station YSJD18 in southern sea basin was 623 438 valve/g. The average diatom abundance of the study area was 104 607 valve/g.

Diatom abundance tended to increase from shelf to basin (Table 3). The most southern parts of the study area, north of the Kalimantan, are in insular outer shelf with silty sand sediments. Here, the average abundance of diatoms was 291 valve/g, the lowest in the study area. In the southwestern part of the study area on the shallow areas of Sunda Shelf and northern continental shelf, sediments were coarser, mostly silty and medium–fine-grained sands; diatom species were few, with low average abundances of 352 and 907 valve/g, respectively. In the outer shelf and slope (the northwestern part of the study area) sediments were fine-grained clay silt. Here, the average diatom abundance increased to 3 124 valve/g. The areas off southeastern Hainan Island and Xisha Islands are parts of the continental slope at depths of 500–1 800 m. Sediments here were mainly fine-grained and the distribution of diatoms was patchy: ~100 000 valve/g in deeper stations and ~5 000 valve/g in shallower stations; on average, 83 606 valve/g. In the Nansha basin area, sediment was clayey silt and average diatom abundance was 197 239 valve/g. In the islands, reefs, and seamounts between the north and south basins in the Nansha Islands, where sediment grain size varied greatly, the abundance was 210 000 valve/g.

4.3 Distribution of dominant diatom species

In total, 256 species and varieties of diatoms from 56 genera were identified. According to Pokras et al. (1986), a particular species is considered dominant when its relative percentage reaches 10%, or 5% if bearing certain environmental implications. Therefore, the 10 most dominant species in this case were *Coscinodiscus africanus*, *Coscinodiscus nodulifer*, *Cyclotella stylorum*, *Hemidiscus*

Table 3 Diatom abundance and sediment types in different topography of surface sediments of SCS

Different topography	Stations	Average abundance (valve/g)	Sediment types
North of Kalimantan	SA09-087, SA09-089, SA09-091, SA09-098, SA09-100	291	Silty sandy
Sunda Shelf, shallower area	NS2007-29, SA08-074, SA09-043, SA09-046, SA09-087, SA09-089, SA09-091, SA09-098	352	Medium-fine sand, fine sand, filty sandy
Northern continental shelf	C163, C175, C226, C245, C253, C258, C260, C294	907	Medium-fine sand, fine sand, filty sandy
Outer shelf and slope of the northwestern	SA12-10, SA12-32, SA13-01, SA13-49	3 124	Clayey silt
Southeastern Hainan Island and Xisha Islands waters	ABS, NS2007-Q7, SA12-01, SA12-04, SA12-29, SA13-11, SA13-19, SA13-48, SA13-51, SA13-53, SA13-55	83 606	Clayey silt
Nansha basin	NS2007-04, NS2007-08, NS2007-204, NS2007-47, SA14-19,SA14-21, SA14-24, SA14-62,SA14-65, SA14-68, SA14-71,YSJD18, YSJD25, YSJD75	197 239	Clayey silt
In the islands, reefs, and seamounts between the north and south basins in the Nansha Islands	NS2007-19, NS2007-22, NS2007-41, SA08-081, SA08-084, SA08-087, SA09-052, SA09-055, YSJD69, YSJD72	210 000	Silt, flayey silt

cuneiformis, *Melosira sulcata*, *Nitzschia marina*, *Roperia tesselata*, *Thalassionema nitzschioides*, *Thalassiosira excentrica*, and *Thalassiothrix longissima* (Plate I and Plate II). Detailed descriptions of these species are as follows:

(1) *Coscinodiscus africanus* Janisch ex A.Schmidt 1878 is a thermophilic species (Lan, 1995), more abundant in the southern region of the SCS, and concentrated in the area 7°48.56′–9°58.40′N, 113°22.29′–116°46.70′E. Its abundance accounted for 0.9%–5.6% of all species in the Xisha Islands area. *C. africanus* abundance was the lowest (0%–2.5%) in the northern regions of the SCS and Sunda Shelf, which are easily affected by coastal currents because of the shallow depth. The species was not detected in the northwestern continental shelf (shallow water area) and northern Kalimantan Island shelf. Previous studies have shown that this species is widely distributed in the western Pacific (5°N–4°S) and eastern Pacific (15°N–7°S) (Jousé et al., 1969, 1971), as well as in the areas of inflow of the warm Kuroshio in the East China Sea (Jin, 1980).

(2) *Coscinodiscus nodulifer* A. Schmidt 1886 is a thermophilic species (Lan, 1995). It was the most abundant and widely distributed species, found in all stations. However, its distribution was uneven, generally greater than 10% in every station with a peak value 62.5% in Station SA09-46. Its relative abundance was high in the deep-sea area of Nansha basin, ranging from 16.3%–50.6%, and in the Xisha area (28.8%–51.7%). In addition, it accounted for 12.5%–36.4% of all diatoms in the northern Kalimantan Island shelf area. Its abundance was relatively low in the northern continental shelf shallow sea area, northwestern continental shelf, and northern Sunda Shelf (1.9%–21.4%, 0.7%–19%, and 4.6%–62.5%, respectively).

(3) *Cyclotella stylorum* Brightwell 1860 is a eurythermal and coastal species (Lan, 1995), found mainly in the northwestern continental shelf, comprising 42%–73.1% of the total in that area. In other marine areas, it was relatively less abundant, accounting for 0%–7.1% in the neritic area of the northern continental shelf, for 0.4%–11.8% on the northern Sunda continental shelf and for 0.2%–7.1% in the Nansha basins. It was even less abundant in Xisha Islands region, being absent in some stations, while it reached 10.2% in only one station. This species was nearly undetectable in the northern Kalimantan Island shelf area.

(4) *Hemidiscus cuneiformis* Wallich 1860 is a thermophilic species (Lan, 1995) distributed throughout the whole survey area. It comprised 1.5%–11.8% of the total species in the northern continental shelf, 0%–1% in the northwestern continental shelf, 0.6%–4.6% in Nansha Islands, 1.3%–13% in Xisha Islands and 0.8%–18.2% in the northern Kalimantan Island shelf area (excepting Station SA09-100).

(5) *Melosira sulcata* (Ehr.) Kützing 1844 is a eurythermal and coastal species (Lan, 1995). It was the second most abundant species in the SCS next to *C. nodulifer*, except at several stations (SA09-046, SA09-087, SA09-089, SA09-091, and SA09-098) on

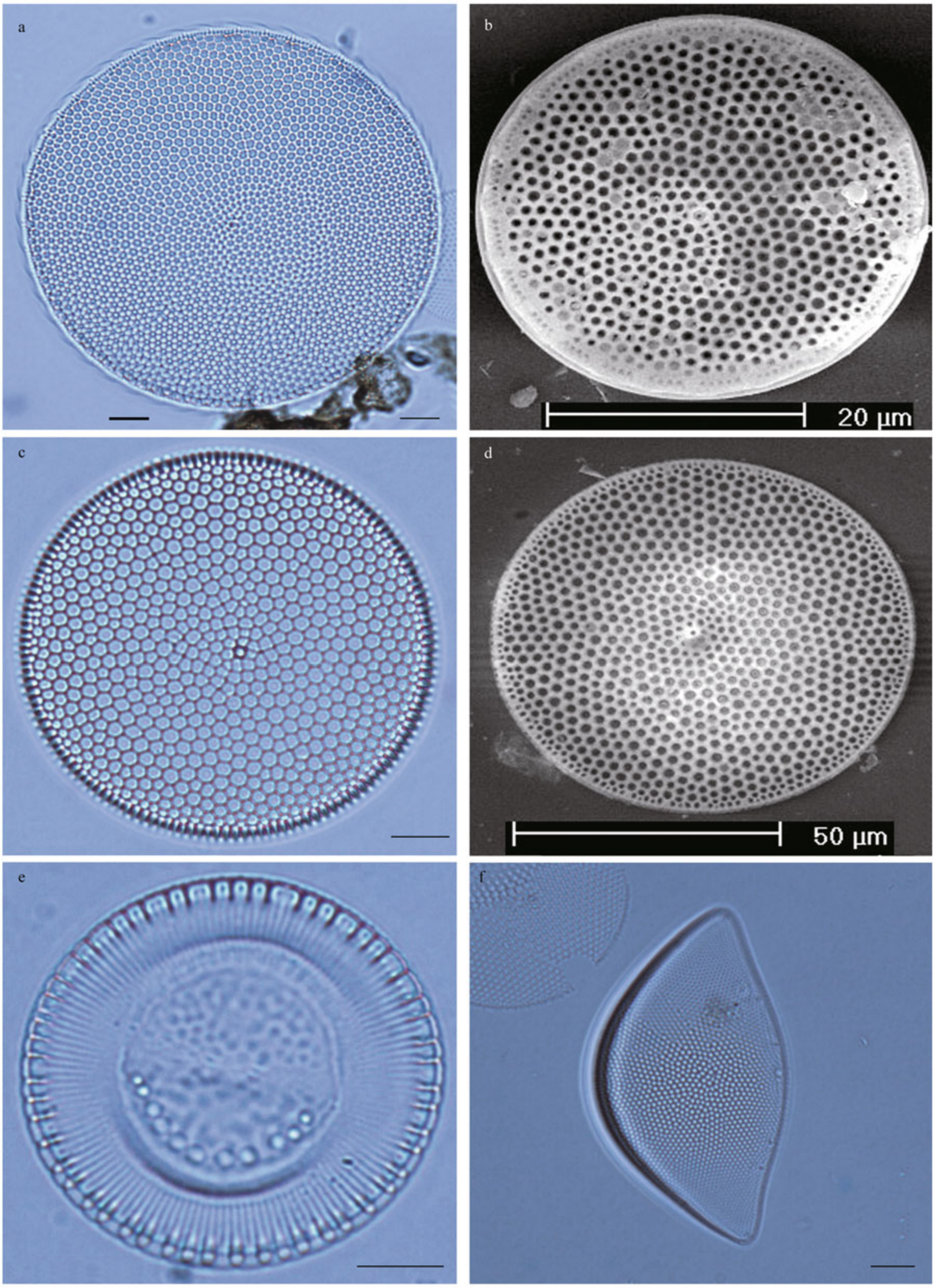

Plate I Dominant diatom species in surface sediments from SCS

a. *Coscinodiscus africanus* (LM); b. *Coscinodiscus africanus* (SEM); c. *Coscinodiscus nodulifer* (LM); d. *Coscinodiscus nodulifer* (SEM); e. *Cyclotella stylorum*; f. *Hemidiscus cuneiformis*. (Scale bars: a, c, e, f=10 µm)

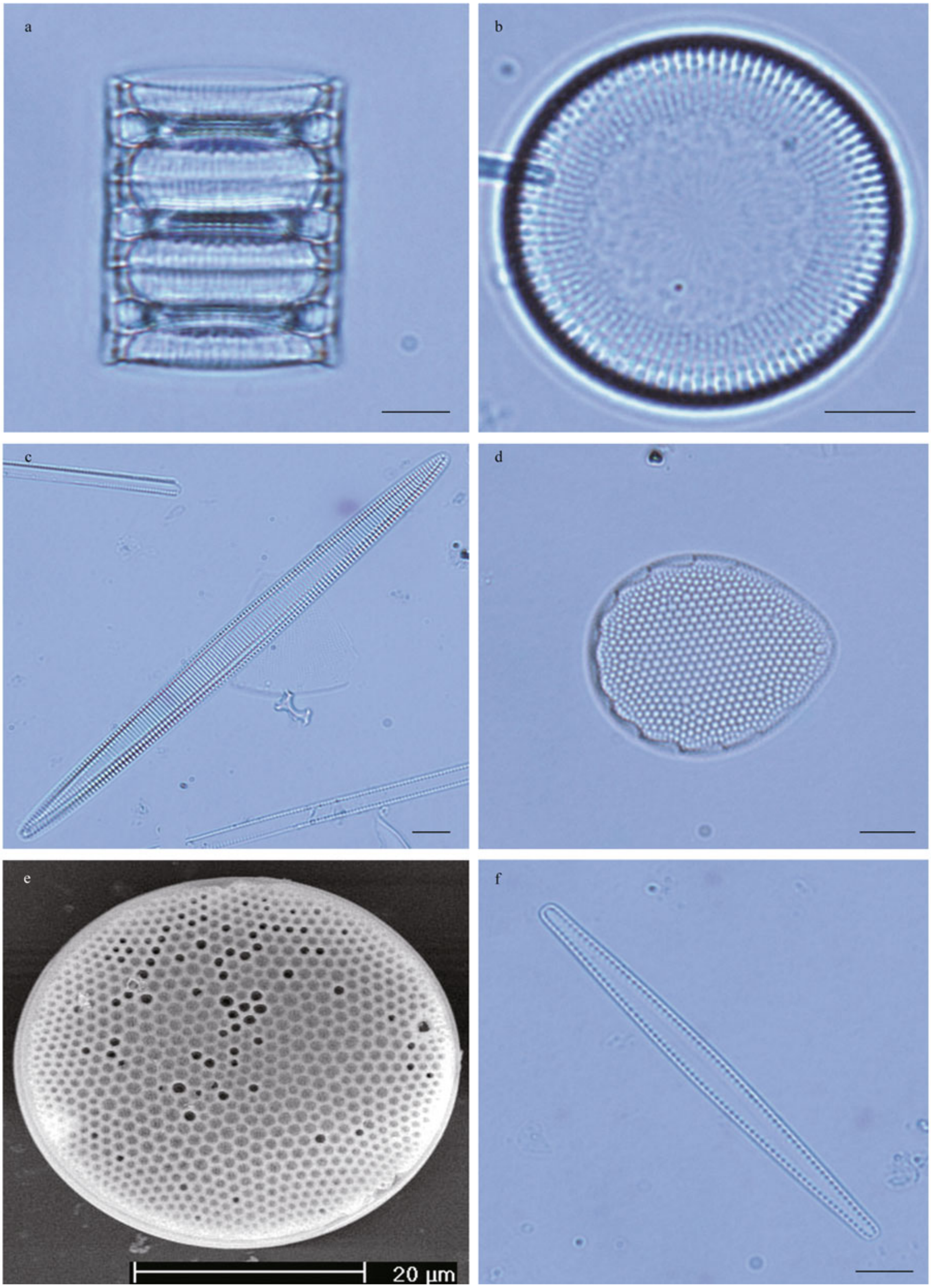

Plate II Dominant diatom species in surface sediments from SCS

a. *Melosira sulcata* (girdle view); b. *Melosira sulcata* (valve view); c. *Nitzschia marina*; d. *Roperia tesselata* (LM); e. *Roperia tesselata* (SEM); f. *Thalassionema nitzschioides*. (Scale bars: a, b, c, d, f=10 μm)

Table 4 Autecology of the dominant diatom species in the SCS

Species	Ecological implication		
	Jin et al. (1965, 1982, 1992)	Wang et al. (1985)	The present study
C. africanus	Warm-water species	Thermophilic species	Thermophilic species
C. nodulifer	Warm-water species	Thermophilic species	Thermophilic species
C. stylorum	Cosmopolitan species		Eurythermal and coastal species
H. cuneiformis	Warm-water species	Thermophilic species	Thermophilic species
M. sulcata	Cosmopolitan species		Eurythermal and coastal species
N. marina	Warm-water species	Thermophilic species	Thermophilic species
R. tesselata	Warm-water species		Warm-water species
T. nitzschioides	Cosmopolitan species	Water species	Eurythermal species
T. excentrica	Cosmopolitan species		Eurythermal species
T. longissima	Cosmopolitan species		Eurythermal species

the Sunda Shelf and the northern Kalimantan Island shelf area. It accounted for 5.7%–35.3% of the species in the northern continental shelf and 0.7%–19% of those in the northwestern continental shelf. In deep-sea areas, the abundance varied considerably: 1.6%–13.8% in the Xisha area, 0.6%–11% in the Nansha sea basin and 0.8%–8.4% in the Nansha Islands.

(6) *Nitzschia marina* Grunow 1880 is a thermophilic species (Lan, 1995) which varied greatly in SCS: 0.2%–4% in deep sea areas, scarce or absent in neritic areas such as the Sunda and north Kalimantan Island Shelves. It was also scarce in the northern continental shelf and absent in the northwestern continental shelf.

(7) *Roperia tesselata* (Rop.) Grunow 1881, a thermophilic species (Lan, 1995) similar to *N. marina*, distributed in deep-sea areas of the SCS. It was highly concentrated in the Nansha area, accounting for 3%–9.8% of the species, and 1.4%–7.8% in the Xisha area. Its abundance was low on the continental shelf area, such as in the northern mainland (0%–7.1%), sporadic in some parts of the northwestern continental shelf, and it was missing in all the northern Kalimantan Island shelf area.

(8) *Thalassionema nitzschioides* (Rop.) Grunow 1880, a eurythermal species (Lan, 1995), was mainly seen in the Nansha Islands (average 2%) and Xisha Islands (1.5%) areas and was rare in the neritic area of the continental shelf.

(9) *Thalassiosira excentrica* (Ehr.) Cleve 1904, a eurythermal species (Lan, 1995) was distributed mainly in the Nansha (1.4%–8.6%) and Xisha (1.1%–6.8%) areas. Only a small amount of this species was found in neritic area of the continental shelf. Its distribution was similar to that of *T. longissima* and *R. tesselata*, being mainly seen in deep-sea areas.

(10) *Thalassiothrix longissima* Cleve et Grunow 1880, is a eurythermal species (Lan, 1995) concentrated and distributed in all stations in Nansha area at 0.7%–11.8% relative abundance. It was common in the Xisha area (0.6%–11.2%), and found in two deep stations in the Sunda Shelf, in one station in the northwestern continental shelf, but not found in the northern continental shelf.

In summary, *C. nodulifer* was the dominant diatom species being widely distributed at over 10% relative abundance throughout the survey area. Other dominant species tended to be concentrated in certain sea areas. This difference provides a basis for combination partitioning.

4.4 Autecology of the dominant diatom species in the SCS

The dominant diatoms in the SCS and the ecological implications reported previously and this study are listed in Table 4.

4.5 Patterns of diatom assemblage distribution

Diatom assemblages in the study area could be divided into seven zones from north to south in terms of percentage and spatial distribution of dominant species, and the members of thermophilic, warm water, eurythermal, or coastal species (Fig.2).

Zone 1: *Melosira sulcata* — *Coscinodiscus nodulifer* — *Pyxidicula weyprechtii* — *Diploneis crabro*— *Hemidiscus cuneiformis* (northern continental shelf)

This zone contained a very diverse diatom assemblage, with 46 species (mostly benthic) with

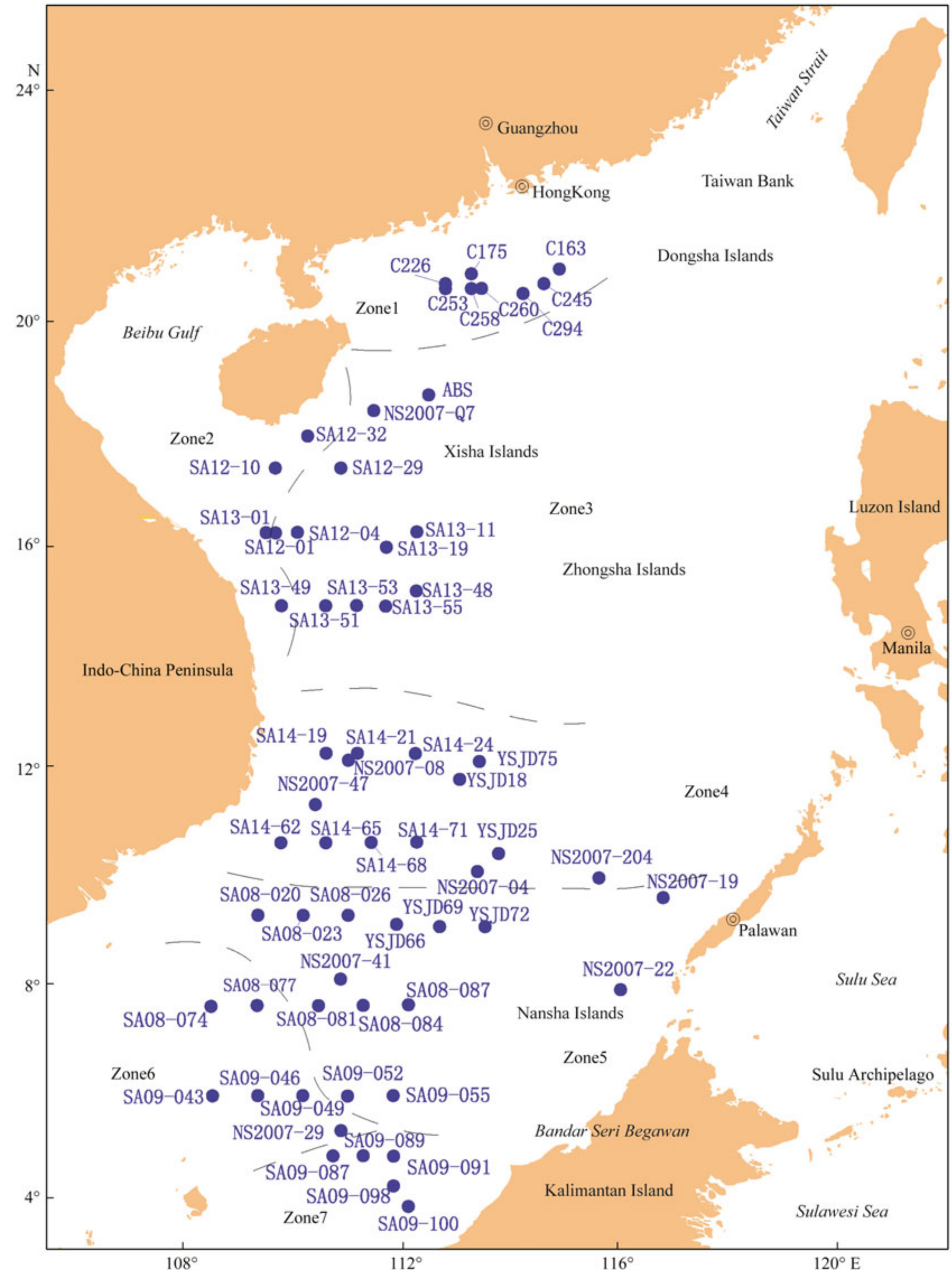

Fig.2 Diatom assemblages in the surface sediments of the SCS

relative abundance greater than 1%. *M*. *sulcata* accounted for 5.7%–35.3% of the assemblage; *C*. *nodulifer* for 9%–21.4%; *P*. *weyprechtii* Grunow, a eurythermal and coastal species, for 1.9%–19.1%; *Diploneis crabro* Ehrenberg, also a eurythermal and coastal species, for 0%–13.2%. Furthermore, *H*. *cuneiformis* accounted for 1.5%–11.8% of the total in the zone; *C*. *radiatus* Ehrenberg, a warm-water species, comprised 0%–11.3%; and *R*. *tesselata*, another warm-water species, comprised 0%–7%. A number of other eurythermal and coastal species, such as *Ditylum brightwellii* (West) Grunow, *Surirella fluminensis* Grunow, *C*. *stylorum* Brightwell, *Actinoptychus undulatus* (Bailey) Ralfs, and

Trachyneis antillarum Cleve, were also identified.

The high percentage of eurythermal to warm-water species indicated that this zone, located in the shallow shelf area of the northern South China Sea, was mostly affected by warm currents of the SCS, while the high percentage of coastal species indicating the influence of the northern coastal flow. Several freshwater *Concentricystes* spp. of various temperature preferences were also detected, indicating that the environment of this zone is also influenced by freshwater masses.

Zone 2: *Cyclotella stylorum—Melosira sulcata—Coscinodiscus nodulifer—Pyxidicula weyprechtii* (northwest continental shelf)

The average diatom abundance was greater than that of the northern continental shelf, ranging 3 123–2 273 valve/g and quite evenly distributed. There were less diatom species than in the neritic area in the northern continental shelf. Only 14 species reached 1% relative abundance. *C. stylorum* was the dominant species, reaching 73.1% (highest content in the study area) at Station SA12-32 near Hainan Island. Its lowest abundance was 42%. The second most dominant species was *M. sulcata*, accounting for 9.8%–18.4%. *C. nodulifer* accounted for 10%, and *P. weyprechtii* accounted for 2%–2.9%.

Zone 2 was located in the northwestern South China Sea, near the outer shelf and upper continental slope edge of the Indo-china Peninsula at depths of 138–635 m. The dominant species being coastal diatoms indicates that this zone is mainly affected by coastal-flow.

Zone 3: *Coscinodiscus nodulifer — Thalassiothrix longissoma— Roperia tesselata — Coscinodiscus radiatus* (Xisha area)

Zone 3 was highly enriched with diatoms with abundance range of 24 482–196 244 valve/g and average of 83 606 valve/g. The abundance tended to increase with increasing water depth. For example, in deeper stations (SA12-29, SA13-48, and SA13-53), the abundance was around 100 000 valve/g, while in shallow ones, it was around ~5 000 valve/g. Zone 3 was rich in a diverse assemblage of diatoms, with 32 comprising >1%. The dominant species, *C. nodulifer*, accounted for 28.8%–47.1%; thermophilic *R. tesselata* 1.4%–7.8%; and warm-water species *C. radiatus* 2.7%–8.3%. Furthermore, warm-water species *T. pacifica* accounts for 0.6%–6.6%; thermophilic *H. cuneiformis*, *C. africanus*, and *N. marina* for 1.3%–13%, 0%–5.6%, and 0%–3.6%, respectively; eurythermal species *T. nitzschioides* for 0.4%–2.5%.

Along with a decrease of the eurythermal and coastal species, thermophilic and warm-water species increased significantly in the zone 3, indicating the effect of northern currents in the southwestern region of the SCS, and the water mass invasion from the southern region of the SCS. Zone 3 is in a bathyal environment with transitional water masses and covers the Xisha area with an extension to the southeastern region of the Hainan Island at water depth 800–1 800 m. The substrate was clayey silt.

Zone 4: *Coscinodiscus nodulifer — Roperia tesselata — Thalassiothrix longissoma* (sea basin)

The maximum, minimum, and average abundances in this zone were 623 438, 4792, and 197 239 valve/g, respectively. The number of diatom species was large, with 42 species having content greater than 1%. Thermophilic species were dominant, of which *C. nodulifer* and *R. tesselata* accounted for 26.3%–49.4% and 3%–8.2%, respectively. Eurythermal species *T. longissima* accounted for 0.2%–11.8%. In addition, thermophilic *C. africanus*, *H. cuneiformis*, and *N. marina* accounted for 0%–4.3%, 0.7%–4% and 0.3%–4%, respectively; warm-water species *C. radiatus* and *T. pacifica* accounted for 0%–6.4% and 1.7%–5%, respectively; eurythermal *T. excentrica* accounted for 1.7%–6.4%; and eurythermal and coastal species *M. sulcata*, *Actinocyclus ehrenbergii*, *C. striata*, and *C. stylorum* accounted for 0.6%–11%, 0.8%–5.3%, 0.9%–5% and 0%–7.1%, respectively.

The diatom assemblages in this zone indicate the influences of warm currents. Zone 4 is in bathyal to abyssal environment, with stable and uniform central water masses. Depth is generally greater than 2 000 m, except for stations east of the Indochinese Peninsula and Station NS2007-204 (9°51.34′E, 115°36.05′N) at 1 446 m deep. Overall, Zone 4 is deeper in the eastern waters and shallower in the western. The deepest station was at 4 238 m. The substrate types are complex. In the abyssal plain, grain size was fine and the sediment was clay silt; in the islands southeast of the Nansha Islands, the sediment was silt.

Zone 5: *Coscinodiscus nodulifer—Thalassiosira excentrica—Roperia tesselata* (Nansha Islands area)

Diatom abundance was high, with maximum, minimum, and average values of 377 778, 35 148, and 210 000 valve/g, respectively. Thermophilic species were dominant, with the most abundant being *C. nodulifer* (16.3%–50.6%). Abundances ranged between 3%–13.4% for eurythermal *T. excentrica* and 3%–9.8% for thermophilic *R. tesselata*. Other species in Zone 5 included: thermophilic *C. africanus* (1.4%–8.1%), *H. cuneiformis* (0.6%–4.6%), and *N. marina* (0.5%–3.5%); warm-water species *T. pacifica* (1.5%–6%), *C. radiatus*, and *T. sackettii* (0.8%–3.9%); eurythermal *T. longissima* (0%–8.6%) and *T. nitzschioides* (0%–4.6%); eurythermal-coastal species *M. sulcata* (0.8%–8.4%) and *C. stylorum* (0.4%–5.8%). The high diatom abundance suggested nutrient input into the SCS. These could be surface inputs by rivers in the islands of Kalimantan, by the Sulu waters running through the Balabac Strait, or by upwelling of intermediate and deep-water masses driven by southwest monsoon. Zone 5 is a warmer pelagic zone covering the Nansha Islands at water depths of 1 071–2 589 m. Substrate was clayey silt.

Zone 6: *Coscinodiscus nodulifer* — *Melosira sulcata* — *Cyclotella stylorum* (Northern Sunda Shelf)

Overall, diatom abundance was low; the highest, lowest, and average levels were 2 578, 79, and 879 valve/g, respectively. Thermophilic *C. nodulifer*, as a dominant species, accounted for 4.6%–62.5% of the total assemblage, whereas eurythermal-coastal species *M. sulcata* and *C. stylorum* accounted for 9% and 5%, respectively. Other species included warm-water species *H. cuneiformis* (0.5%–3.1%) and *R. tesselata* (0%–10.9%) and eurythermal species *T. simonsenii* (0%–7%) and *D. brightwellii* (0%–9.4%).

In Zone 6, tropical and subtropical pelagic species diminished, while coastal species increased, which was significantly different from other zones and indicates the influence of the coastal flow. Zone 6 is in a tropical shelf environment and is distributed in the northern Sunda Shelf southwest of the SCS, at water depths 100–400 m. Zone 6 is largely affected by geographical and meteorological factors, due to its shallow nature; an example is the mixture of diluted coastal water masses from the Mekong River (whose estuary is located northwest of this zone) and the water masses from the open sea.

Zone 7: *Coscinodiscus nodulifer* — *Trachyneis antillarum* — *Hemidiscus cuneiformsi* (north of Kalimantan Island Shelf areas)

Zone 7 had 24 diatom species accounting for over 1% abundance. Tropical oceanic and coastal species were dominant, the most abundant being thermophilic *C. nodulifer* (12.5%–36.4%). Brackish species *T. antillarum* accounted for 1%–27.3%, and thermophilic *H. cuneiformis* accounted for 5.9%–18.2%. Other species included eurythermal *T. simonsenii* (0%–12.5%), warm-water species *C. radiatus* (0%–25%), eurythermal-coastal *Podosira stelliger* and *Campylodiscus ralfsii* (0%–9.1%) and thermophilic *N. marina* (0%–11.8%). *Concentricystes* spp. was detected at all stations of Zone 7. Zone 7 is located north of the Kalimantan insular outer shelf at water depths of 62–114 m with silty sand substrate. It featured the lowest diatom abundance of the study area, with an average of 291 valve/g (range 71 to 1 094 valve/g). This diatom assemblage represented an environment affected by warm waters from Indian Ocean and coastal waters. The presence of *Concentricystes* spp. shows that Zone 7 is affected by freshwater from the Rajang River and the Balaam River in Kalimantan Island.

5 DISCUSSION

As shown above, the diatom distribution in the SCS is affected by various marine environmental conditions. However, previous studies on the relationship between diatom distribution and ambient conditions have yielded very different conclusions. Wang et al. (1988) believed that diatom assemblages in surface sediments in the northern SCS are related closely to temperature, salinity, depth and currents etc. Zhan (1987) demonstrated a close relationship between diatom quantity and environmental factors such as landforms and ocean currents, and also the source of material and sediment velocity etc. Liu et al. (1984) believed that the number and types of sedimentary diatoms are affected by factors such as geology, geomorphology, hydrodynamics, temperature, salinity, and nutrients. We believe that the main factors in this case are seabed topography, hydrodynamics, temperature, salinity, and nutrients.

5.1 Seabed topography

The results show that the distribution of diatom abundance is closely related to depth and topography. Station SA09-089 (4°46.27′N, 111°16.58′E) in the Sunda Shelf, yielded the lowest regional value of diatom abundance at 71 valve/g only, while Station YSJD18 (11°39.58′N, 113°2.77′E) in a 3 700 m basin produced the highest one at 623 438 valve/g. Moreover, Zone 7 in the southernmost part of the study area, or the northern periphery of the Kalimantan Island shelf featured the lowest average abundance of 291 valve/g. In Zone 6 (in the southwestern shallow area of the Sunda Shelf) and Zone 1 (in the northern continental shelf) the average abundances were 352 and 907 valve/g, respectively.

In the external shelf and slope (Zone 2) in the northwest of the study area, the average abundance was 3 124 valve/g. In the slopes of the southeast region of the Hainan Island and Xisha Islands waters (Zone 3) in water depth of 500–1 800 m, the distribution was patchy: about 100 000 valve/g at deeper stations and about 5 000 valve/g at shallower stations. In the Nansha Islands (Zone 5), a bathyal area ranging from 1 071 to 2 589 m in depth, average diatom abundance was very high at 210 000 valve/g.

The flat abyssal plains of the Nansha basin (Zone 4) are in the center of modern sedimentation in the SCS. The Nansha Island Basin, in particular, was rich with various diatoms at average abundance of 197 239 valve/g. Although some stations, including SA14-24, were located at the deposition center of the basin, no high abundance was found there due to the input of volcanic materials from adjacent volcanic eruptions. The areas around seamounts that are distributed east-west in the central basin and the Nansha Islands are characterized by complicated seabed topography, varying water depth, and varying diatom abundance.

5.2 Effects of hydrodynamics

Tiny diatom cells are easily carried out by currents and barely stored in the sediment. For example, in Station NS2007-34, in the shelf areas of the Mekong estuary, sand content was 100% and no diatoms were found. This may explain why diatom valves were found in finer sediments with grain sizes <60 μm (Chen, 2005), indicating that sandy sediments are unfavorable for diatom preservation. Under strong hydrodynamic conditions, diatom valves could be carried for a great distance and hardly deposited. Moreover, sediments could be scoured somewhat. For example, currents passing through the vicinity of the Sunda Shelf are often strong and most valves could be moved away with the currents. Sediments left in-situ after scouring would be coarse particles, and only a few valves would be deposited. Low clay content found at Stations SA09-43 (1.44%), SA09-46 (4.97%) and SA09-89 (9.01%) indicates strong hydrodynamics.

The sea basin is conducive to sediment accumulation because it is located in a low-lying area where currents, particularly bottom currents, are slow. The area of the Xisha Islands is also conducive to deposition. In the southern waters of Xisha Islands, a strong southwesterly forms due to the winter monsoon, but it weakens as it is blocked by islands in the western part of the study area. A counterclockwise circulation is formed with the confluence of the southward currents in the northern gulf. Therefore, diatom content becomes higher in this area, as seen at Station SA13-48. In addition, the Nansha Islands have distinct circulation characteristics controlled by the prevailing monsoon. During the northeastern monsoon period, the western part of the study area would experience a basin-wide cyclonic circulation, whereas in the southeastern part, an anti-cyclonic circulation may form. During the southwestern monsoon period, on the other hand, the upper circulation around the Nansha Islands is controlled by an anti-cyclonic circulation, resulting in upwelling in a horizontal scale of approximately 400 km (Su, 2005). The concentration of diatoms in this area was the highest of the region, with an average of 210 000 valve/g.

5.3 Effects of hydrological and climatic conditions

The number and variety of diatom species in sediment are affected not only by geological geomorphology and hydrodynamics but also by temperature, salinity, and nutrients (Liu et al., 1984). The SCS is typical of tropical and subtropical marine climates. Local hydrological data show that the annual average temperature is 22.6°C in the most northern area of the SCS and 28.5°C in the most southern area, warming progressively southwards. In comparison with the division of sedimentary diatoms by Jousé et al. (1971) in the Pacific Ocean, the diatoms in the SCS could be divided into northern species, subtropical species, tropical species, and equatorial species with thermophilic properties. In the SCS, the northern species include *T. longissima* and *C. stylorum*; subtropical species include *C. radiatus*, *T. nitzschioides*, *Pseudoeunotia doliolus* (Wall.) Grunow, and *R. tesselata*; tropical species include *C. crenulatus*, *C. nodulifer*, *H. cuneiformis*, *T. oestrupii*, *R. bergonii*, and *N. marina* and equatorial species include *C. africanus*, *Asteromphalus imbricatus* Wallich, *Triceratium cinnamomeum* Greville, and *Asterolampra marylandica*. These species are main varieties seen throughout the SCS, and follow the trends of atmospheric and water temperatures, changing with latitude.

Salinity is one of the most important factors affecting diatom distribution, because different taxa adapt differently to salinity. Accordingly, diatoms have been divided into freshwater, brackish, and marine classes (Wang, 1985). The distribution of diatoms in the SCS is consistent with salinity variation. Surface-water salinity is significantly different between coastal and offshore areas. Generally, the salinity in coastal areas is low (30 to 33) and varies with seasonal changes, whereas that in offshore waters outside the coastal area is high (>34), making them uninhabitable for some freshwater species. Few freshwater diatoms, such as *Cymbella aspera* (Ehr.) Cleve, were found in the northern continental shelf waters (Zone 1). The amount of *Concentricystes* spp. found in the northern Kalimantan Island shelf area (Zone 7) was also low: these species can only enter the sea from rivers. Coastal currents affect Zones 1, 2, and 6, so the proportions of coastal oligohalabous species, such as *M. sulcata* and *C. stylorum*, were higher. Conversely, euryhaline planktonic diatoms were the dominant species in the deep-sea areas of Zones 3–5.

5.4 Effects of other factors

Deposition rate also affects the number and variety of diatoms (Liu et al., 1984). For example, the deep-sea clay that deposits in the central basin of the SCS, which exceeds 4 000 m in depth, is similar to oceanic red clay. The deposition rate of the deep-sea clay is 3 cm per Ma or so, which is one order of magnitude higher than that of oceanic red clay (Wang, 1995). Jousé et al. (1971) reported that the lowest diatom abundance in Pacific Ocean surface sediments was 4 million valve/g and that the highest could reach hundreds of millions. The highest abundance recorded in the SCS was only 623 438 valve/g. This large difference is due to the higher deposition rate in the SCS compared with the Pacific Ocean.

In summary, seabed topography, hydrodynamics, temperature, salinity mainly, and nutrients affect the number and variety of diatoms in sediments of the SCS. Their combined effects determine the distribution of diatoms.

6 CONCLUSION

(1) Most fine-grained surface sediments in the SCS contained a large number of diatoms, with much fewer diatoms in coarse sediments. Diatom abundance varied greatly in space. The average diatom abundance was 104 607 valve/g over the whole area. Diatom abundance tended to increase from shelf to basin.

(2) The SCS is rich with diatom species. In total, 256 species and varieties from 56 genera were identified in the present study. The 10 most dominant species are *C. africanus*, *C. nodulifer*, *C. stylorum*, *H. cuneiformis*, *M. sulcata*, *N. marina*, *R. tesselata*, *T. nitzschioides*, *T. excentrica*, and *T. longissima*.

(3) Diatom assemblage zonation reflects different oceanographic conditions at a regional scale: Zone 1 (northern continental shelf) represents an environment affected by warm currents, SCS northern branch of the Kuroshio Current and northern coastal currents; Zone 2 (northwestern continental shelf) is affected by intense coastal currents; Zone 3 (Xisha area) is a bathyal environment with transitional water masses; Zone 4 (sea basin) is a bathyal-to-deep sea environment with stable and uniform central water masses belonging to a semi-enclosed marginal sea; Zone 5 (Nansha Islands area) is a pelagic environment with higher surface temperature; Zone 6 (Northern Sunda Shelf) is a tropical shelf environment; and Zone 7 (northern Kalimantan Island shelf area) is affected by warm waters from the Indian Ocean and coastal waters. These zones could be of great importance in future paleoceanographic studies.

(4) The main factors that affect the distribution of sedimentary diatoms are seabed topography, hydrodynamics, temperature, salinity, and nutrients.

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