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ScienceDirect
Progress in Natural Science 19 (2009) 1413–1418
Progress in Natural Science
www.elsevier.com/locate/pnsc

Short communication

Diatoms from the southwestern continental slope, South China Sea, and their paleoenvironmental significance since the last glacial times

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Received 24 October 2008; received in revised form 18 November 2008; accepted 8 March 2009

Abstract

A quantitative study was undertaken on diatoms from cores (SA08-34) obtained from the southwestern continental slope of the South China Sea (SCS). A total of 165 diatom species belonging to 45 genera were identified. We constructed a stratigraphic subdivision and correlation according to the characteristics of diatom assemblages together with ^{14}C dating and carbonate analysis. We also discuss the sedimentary environment in the sea area since the last glacial times. The research shows that the diatom assemblages coincide with interglacial and glacial times, and changes in diatom abundance reflect the instability of the climate in the southern part of the SCS, such that short-term, temperature descending events correlate with the interglacial interval. The abundance of diatoms is relevant to interglacial and glacial times, since high abundance values were associated with an interglacial interval, and low abundance values with the last glacial maximum. We assume that strong upwelling developed in the interglacial interval, the development of which was influenced by variations of monsoons in the East Asian region.

Keywords: Diatoms; Last glacial times; Sedimentary environment; South China Sea

1. Introduction

The South China Sea (SCS) is one of the largest marginal seas of the western Pacific Ocean. This sea is sensitive to environmental change because of its unique geographic location and terrain conditions. The SCS is located in the East Asian monsoon zone and experiences the earliest onset of the Asian summer monsoon [1]. In recent years, with many cruises of the German research vessel Sonne to the SCS and the operation of ODP Leg 184, studies on the paleoenvironment of the SCS receive more and more attention. In the past, many scholars have conducted studies of paleobiota in this region, such as foraminifera [2,3], radiolarians [4,5], calcareous nannofossils [6], sporopollen [7,8] and diatoms [9,10], to investigate the development of paleo-oceanic environments in the SCS. However, among these studies of the sedimentary core and column samples, the ones aiming to make high-resolution surveys of diatom-bearing sediments were mainly carried out in the northern part of the SCS. Few studies of the sedimentary diatoms in core samples have been derived from the southern part of the region. Specifically, the only report on diatoms was made from core ODP 1143 [11]. Unfortunately, the sampling interval of this core was too long (low resolution) to identify paleoenvironmental changes in this area. Moreover, diatoms have siliceous skeletons and require different eco-environmental conditions to preserve them compared to calcareous microfossils. Thus, to completely identify the characteristics of the paleo-oceanic environment, we must describe the structure and composition of all types of organisms living in these settings.

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1002-0071/$ - see front matter © 2009 National Natural Science Foundation of China and Chinese Academy of Sciences. Published by Elsevier Limited and Science in China Press. All rights reserved.
doi:10.1016/j.pnsc.2009.03.007

Through high-resolution studies of core SA08-34 from the southwestern continental slope of the SCS, together with results of ^{14}C dating and carbonate analysis, this paper intends to explain the evolution of paleoenvironments in the SCS region since last glacial times.

2. Materials and methods

2.1. Materials

Core SA08-34 was sampled from the southwestern continental slope of the SCS (8°54.9660′N, 110°59.8620′E) (Fig. 1) at 1834 m water depth. The core is 778 cm long. The lithology of core samples is almost the same, mainly composed of caesious clay and silty clay. No turbidity current sediment was found. Diatom analyses of 106 samples were conducted within 8 cm intervals, with the exception of a few samples collected at 4 cm intervals.

The data on carbonate analysis and ^{14}C dating for this core sample were provided by the Guangzhou Marine Geological Survey. The results of ^{14}C dating (without age correction) were $10,890 \pm 350$ aBP in the interval of 162–165 cm, $21,080 \pm 1,000$ aBP in the interval of 460–463 cm, and >30,000 aBP in the interval of 765–768 cm.

2.2. Methods

Dry samples of 10 g were obtained by weighing with an electronic balance. The samples were then placed in a 10 ml small test tube with distilled water. All samples were scattered with an ultrasonic sonicator for 3 min and then filtered with a bolting cloth with 15 μm holes. The remaining solution was transferred into centrifugal tubes and fixed onto slides with Canadian balsam. All species were identified and counted through an optical biological microscope. More than 300 diatom valves were counted for each sample. Diatom species identifications were performed following Jin [12–14], Lan et al. [9] and Guo [15].

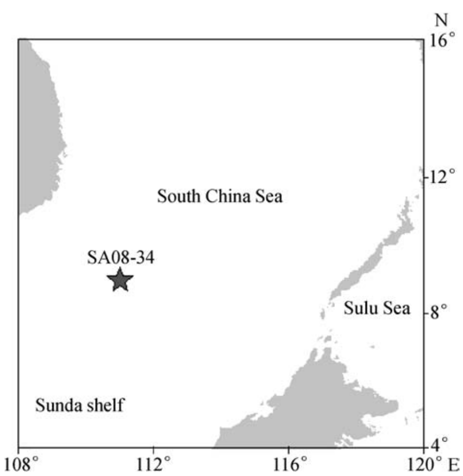

Fig. 1. Sampling station.

3. Results and discussion

3.1. Major diatom species

A total of 165 diatom species belonging to 45 genera were identified from core SA08-34. Of these, nine dominant species were *Bacteriastrum hyalinum* Lauder, *Coscinodiscus nodulifer* Schmidt, *Coscinodiscus radiatus* Ehrenberg, *Cyclotella stylorum* Brightwell, *Melosira sulcata* (Ehr.) Kützin, *Roperia tesselata* (Rop.) Grunow, *Thalassiosira excentrica* (Ehr.) Cleve, *Thalassiosira simonsenii* Hasle and Fryxell, and *Thalassionema nitzschioides* Grunow. Seventeen species with high frequency were *Actinocyclus ehrenbergii* Ralfs, *Actinocyclus ehrenbergii* var. *tenella* (Bréb.) Hustedt, *Actinoptychus undulates* (Bail.) Ralfs, *Asterolampra marylandica* Ehrenberg, *Asteromphalus flabellatus* (Breb.) Greville, *Campylodiscus brightwellii* Grunow, *Coscinodiscus africanus* Janisch, *Coscinodiscus decrescens* Grunow, *Cyclotella striata* (Kütz.) Grunow, *Hemidiscus cuneiformis* Wallich, *Nitzschia marina* Grunow, *Rhizosolenia bergonii* Peragallo, *Rhizosolenia styliformis* Brightwell, *Thalassiosira leptopus* (Grun.) Hasle, *Thalassiosira symmectica* Fryxell and Hasle, *Thalassiothrix longissoma* Cleve et Grunow, and *Trachyneis antillarum* Cleve.

3.2. Ecological characteristics of diatoms

In order to better classify diatom assemblages in Late Pleistocene sediments of the SCS and to interpret the environmental changes in the core, 18 types of eco-environments were identified for diatoms in the SCS (Table 1). This list is based on research findings by Chinese scholars, Jin Dexiang and Wang Kaifa, regarding the distribution of diatoms in surface sediments in areas of the China Sea and Pacific Ocean.

3.3. Characteristics of diatom assemblages in core SA08-34

According to the abundance and distribution of major diatom species and the main thermophilic, warm-water and coastal diatom species, the core sample can be divided from bottom to top into three diatom zones (Figs. 2 and 3).

Zone I is located in the range from 515 to 778 cm and contains assemblages of *C. nodulifer*, *C. stylorum* and *B. hyalinum*. The remarkable characteristic of this zone is the major diatom species that vary widely in abundance. The peak abundance (168,000 diatoms/g dry sample, similarly hereinafter) occurs in the interval from 621 to 629 cm. This zone also can be further divided into three sub-zones.

The first sub-zone is located in the range from 739 to 778 cm and contains assemblages of *C. nodulifer*, *C. stylorum* and *C. radiatus*. The average percentages of main thermophilic, warm-water and coastal diatom species in this sub-zone were 46.3, 6, and 19.9%, respectively.

The second sub-zone is located in the range from 699 to 739 cm. Diatoms are sparse in this sub-zone, and include *C. nodulifer* and *C. stylorum*. The peak abundance was only

Table 1
Ecological environments of diatom species commonly found in the SCS.

Species	Ecological environment		
	From Jin Dexiang	From Wang Kaifa	This text
Bacteriastrum hyalinum	Widespread species		Eurythermal species
Asterolampra marylandica	Warm-water species		Warm-water species
Coscinodiscus africanus	Warm-water species	Hot-water species	Thermophilic species
Coscinodiscus decrescens	Warm-water species		Warm-water species
Coscinodiscus nodulifer	Warm-water species	Thermophilic species	Thermophilic species
Coscinodiscus radiatus	Widespread species		Eurythermal species
Cyclotella stylorum	Widespread species		Coastal species
Cyclotella striata	Widespread species		Coastal species
Melosira sulcata	Widespread species		Coastal species
Hemidiscus cuneiformis	Warm-water species	Thermophilic species	Thermophilic species
Nitzschia marina	Warm-water species	Thermophilic species	Thermophilic species
Rhizosolenia bergonii	Warm-water species	Thermophilic species	Thermophilic species
Rhizosolenia styliformis	Widespread species		Eurythermal species
Roperia tesselata	Warm-water species		Thermophilic species
Thalassiosira excentrica	Widespread species		Eurythermal species
Thalassiosira simonsenii			Eurythermal species
Thalassiothrix longissoma	Widespread species		Eurythermal species
Thalassionema nitzschioides	Widespread species	Warm-water species	Eurythermal species

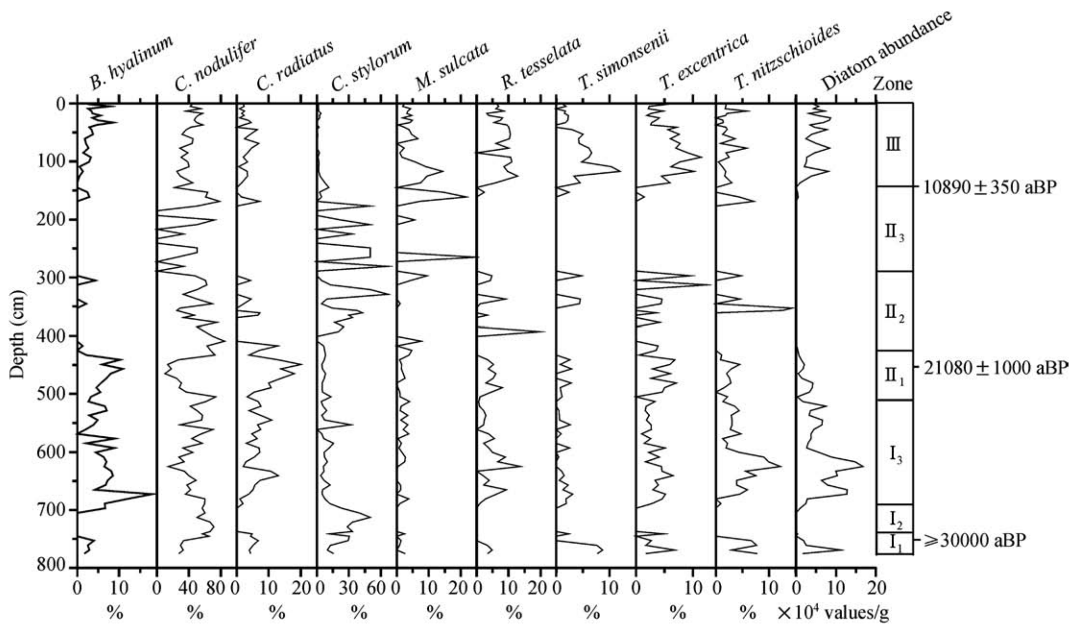

Fig. 2. Diatom assemblages and dominant species in core SA08-34.

93 diatoms/g, which might be the reflection of one cooling event.

The third sub-zone is located in the range from 515 to 699 cm and contains assemblages of *C. nodulifer*, *C. stylorum*, *B. hyalinum* and *C. radiatus*. The average percentages of these four diatoms were 44.7, 9.1, 6.5, and 5.7%, respectively. The average percentages of main thermophilic, warm-water and coastal diatom species were 50.8, 2.1, and 2.6%, respectively.

As far as the three smaller zones are concerned, the first and third sub-zones reflect warm climatic characteristics, but the second one reflects cold climatic characteristics.

Zone II is located in the range from 162 to 515 cm, and is a diatom poor zone. According to the abundance and distribution of diatoms, this zone also can be divided from bottom to top into three sub-zones.

The first sub-zone is located in the range from 415 to 515 cm and contains assemblages of *C. nodulifer*, *C. radiatus* and *C. stylorum*. The average percentages of these three diatoms were 40.5, 10.7, and 6.6%, respectively. In addition, there also were significant numbers of *B. hyalinum* and *T. excentrica*. In this sub-zone, the average percentage of main thermophilic, warm-water and coastal diatom species were 45.9, 5.1, and 11.9%, respectively.

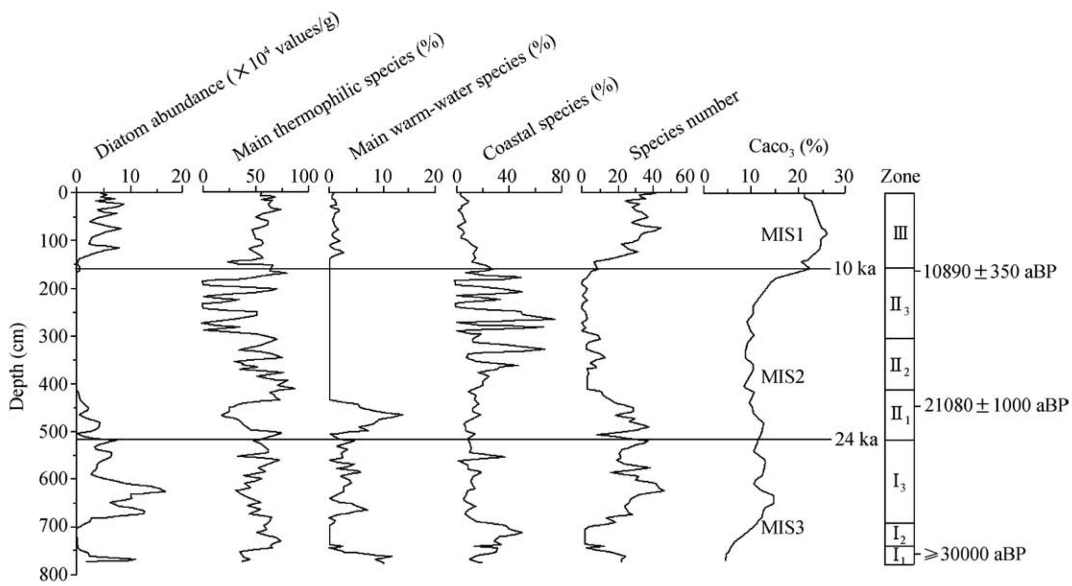

Fig. 3. Diatom abundance, and distribution of main thermophilic, warm-water and coastal diatom species, and $CaCO_3$ from core SA08-34.

The second sub-zone is located in the range from 293 to 415 cm and contains assemblages of *C. nodulifer*, *C. stylorum*, *R. tesselata* and *T. excentrica*. The abundance and species composition of diatoms in this sub-zone were low. The mean abundance was 223 diatoms/g. The mean percentages of the four diatoms in this sub-zone were 51.9, 21.6, 2.5 and 2.3%, respectively.

The third sub-zone is located in the range from 162 to 293 cm. Diatoms are sparse in this sub-zone and include *C. stylorum*, *C. nodulifer* and *M. sulcata*.

In general, the mean abundance of diatoms in Zone II was very low, which indicates clear sedimentary changes in the environment. Compared with Zone I, the first sub-zone of Zone II had low numbers of main thermophilic and warm-water diatom species. The climate during accumulation of sediment in this zone must have been colder than that of Zone I.

Zone III is located in the range from 0 to 162 cm and contains assemblages of *C. nodulifer*, *R. tesselata* and *M. sulcata*. This zone has a high diversity of diatom species. The peak abundance was 87,000 diatoms/g, and the lowest abundance was 134 diatoms/g. The mean abundance was 44,000 diatoms/g. The mean percentages of the three dominant diatoms in this zone were 42.7, 7.1, and 5.2%, respectively. The mean percentage of main thermophilic, warm-water and coastal diatom species were 55.9, 0.8, and 8.4%, respectively. This assemblage zone demonstrates typical features of tropical pelagic flora, similar to modern sedimentary environments.

3.4. Chronological framework

Many results of the carbonate contents in core samples from the SCS show that carbonate cycles above the thermocline (below 3000 cm) belong to the Atlantic type. The curve of percent calcium carbonate is parallel to that of benthic foraminifer oxygen isotopes, low during glacial times and high during interglacial times. It also corresponds well with the two curves of core MD05-2897, close to core SA08-34 [16]. Therefore, the plot of percent $CaCO_3$ in core SA08-34 can serve as a proxy for correlated strata of the oxygen isotope curve. According to ^{14}C dating and a comprehensive analysis of the features of the percent $CaCO_3$ plot for core SA08-34, we can determine that core SA08-34 encompasses the oxygen isotope stage MIS3 (⩾30 kyr), since the last glacial times, and the positions at 162 and 515 cm correspond to the respective lower boundaries of MIS1 and MIS2, respectively. Their ages are, respectively, 10 and 24 kyr BP; and positions below 515 cm correspond to the upper parts of MIS3.

3.5. The sedimentary environment of the southwestern continental slope of the SCS since the last glacial period

The diatom zones divided according to their abundance and the variation of their percentages correspond to different oxygen isotope stages (Fig. 3). The statistical results of diatom identification show that the individual abundance of diatoms in the strata varied during different periods. Generally, the abundance was low during the last glacial maximum and high during the interglacial interval.

(1) The last interstadial (515–778 cm) corresponds to upper parts of the MIS3 stage. This interval contains caesious calcareous biogenic clays, and the interlayer contains caesious siliceous calcareous silty clays. The mean diatom abundance was high, which reflects high biological productivity in this depositional interval. Moreover, the variation of diatom abundances is large, which indicates climatic instability. A low abundance of diatoms occurs in the interval from 699 to 739 cm, which might be the reflection of one cooling event. While researching on planktonic foraminifera, Wu Lushan also noticed this phenomenon [17].

According to the absolute age determination data, the paleo-oceanic event recorded by the diatom flora might be the Heinrich cooling event during the late Pleistocene. This interval is usually considered to fall within the warm interstadial, but considering the characteristics of diatom assemblages, the main thermophilic diatom species-content is lower than that during post-glacial times. Therefore, we can conclude that the paleo-climate in this interval was colder than that during the post-glacial period.

(2) The last glacial maximum (162–515 cm) corresponds to stage MIS2. Below 450 cm, this interval contains caesious calcareous biogenic clays, and above 450 cm caesious calcareous biogenic silty clays. The diatom abundance here is low and decreasing. Radiolarians become fewer, even devoid in some intervals. However, the abundance of planktonic foraminifera is relatively stable [17]. Apparently, the record of diatom changes shows that the paleoecological setting in this interval was not conducive to the growth and preservation of siliceous planktonic microorganisms, but did not have an obvious effect on calcareous planktonic microorganisms. From Fig. 3, it is evident that at the early stage of MIS2, the quantity of diatoms decreases sharply, as do the percentages of the main thermophilic diatom species. These sudden changes demonstrate abrupt events occurring in the paleoenvironment. During the middle and late MIS2 stage (162–415 cm), diatoms become extremely rare, which results in content deviations of special species. Therefore, based on data for diatom percentages in the study interval, it is difficult to determine the detailed characteristics of climate changes.

(3) The post-glacial period (0–162 cm) corresponds to the MIS1 stage. This interval contains caesious calcareous biogenic silty clays, and the interlayer contains brown grey calcareous biogenic clays. Diatoms are abundant in the interval, which indicates that the paleoenvironment was conducive to the growth and preservation of siliceous planktonic microorganisms. The boundary of the Holocene is clearly reflected by the abundance of diatoms.

Because the research area is far from a continental margin, the upper water is in poor nutritional condition, which deters the growth of diatoms and other phytoplankton species. Thus, the quantity of sedimentary diatoms is small. On the other hand, the SCS is influenced by monsoons all year round, so upwelling moves frequently through local sea areas. The abundance of diatoms is high within areas of upwelling, but low in other sea areas [18]. The changes in diatom abundances during glacial and interglacial intervals might indicate the development of upwelling. We can presume that the upwelling was strong in the area during the interglacial interval. However, the growth of upwelling is also under the influence of monsoons, and in the southern part of the SCS the upwelling is mainly driven by summer monsoons. Therefore, we can evaluate the evolution of the East Asian monsoon in this region since the last glacial times. During the interglacial interval, winter monsoons are weak, but summer monsoons are strong. Powerful summer monsoons help upwelling develop and provide plenty of nutritious material for diatoms in the upper water column. In this case, diatoms bloom, and are well preserved in sediments. However, during the glacial interval, the inverse occurs. Winter monsoons hardly trigger the upwelling, so the upper water column always lacks nutritious material, and hence does not support the multiplication and preservation of siliceous microorganisms.

4. Conclusion

(1) A total of 165 diatom species belonging to 45 genera were identified from cores SA08-34. Of these, nine dominant species were *B. hyalinum*, *C. nodulifer*, *C. radiatus*, *C. stylorum*, *M. sulcata*, *R. tesselata*, *T. excentrica*, *T. simonsenii*, and *T. nitzschioides*. According to the abundances and percentage of major diatom species, the core samples can be divided from bottom to top into three diatom zones.

(2) According to ^{14}C dating and the comprehensive analysis of the features of the curve of percent $CaCO_3$ of core SA08-34, we can determine that core SA08-34 corresponds to the oxygen isotope stage MIS3 ($\geqslant$30 kyr), since the last glacial times. Diatom assemblages coincide with interglacial and glacial intervals, and changes in diatom abundance reflect the instability of the climate in the south of the SCS, such that short-term temperature descending events have occurred during the interglacial interval.

(3) The abundance of diatoms is relevant to the interglacial and glacial interval. We suspect that strong upwelling developed in the interglacial interval. The development of the upwelling was influenced by variations of monsoon periods, which furthermore revealed the evolution of the East Asian monsoon in this region, since the last glacial times. During the interglacial interval, winter monsoons are weak but summer monsoons are strong, whereas the glacial maximum reflects the inverse conditions.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No.40676026).

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