Deep-sea pollen from the South China Sea: Pleistocene indicators of East Asian monsoon

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Abstract

A high-resolution pollen record (sampling interval averages 820 years) has been obtained from ODP Site 1144 (water depth 2037 m), northern South China Sea. The 504-m sequence (in composition length) covers the last 1.03 million years according to micropaleontological and isotopic stratigraphy. The pollen assemblages are characterized by high proportions of \textit{Pinus} and herb pollen, and by their frequent alternations. Based on these alternations, 29 pollen zones have been recognized that are closely correlated to the Marine Oxygen Isotope Stages (MIS) 1–29. \textit{Pinus}-dominant pollen zones correspond to interglacial periods with lighter $\delta^{18}O$ values, while herb-marked ones relate to the heavier $\delta^{18}O$ stages assigned to glacials. Judging from the pollen data, the exposed northern continental shelf of the South China Sea during the glacials was covered by grassland, and the extensive northern shelf has formed only since MIS 6 (ca. 150 ka), probably as a result of tectonic subsidence. Tree pollen influx values are indicative of winter monsoon which began to intensify 600 ka ago. The summer monsoon variations can be approximated by the fern percentage within the total pollen and spore abundance, and the result shows high values in general occurring at interglacials, with the maxima at MIS 15, 5e and 1. The relatively high fern percentage with smaller amplitude in variations before 600 ka might suggest more stable humid conditions before the intensification of winter monsoon.

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Keywords: South China Sea; glacial cycles; pollen and spores; vegetation; East Asian monsoon

1. Introduction

Marine sediments often provide long continuous and undisturbed pollen sequences (Dupon, 1992) and, in many cases, a unique opportunity to develop a high-resolution terrestrial paleoenvironmental record (Heusser, 1992). Taking advantage of high time resolution and global correlation of isotope stratigraphy, deep-sea pollen sequences have yielded vegetation history of the land and bridged paleo-environmental studies between land and sea. With the development of deep-sea drillings, marine palynology has made notable progress and a great number of papers covering the main oceanic and sea areas of the world have been published during the last
three decades. However, high-resolution palynological studies are mostly restricted to the late Quaternary, whereas long pollen sequences from the deep-sea cores are of relatively low resolution.

Thus, a series of pollen profiles covering the last 24 ka with very high time resolution of ca. 200 years in the Late Glacial Maximum (LGM; Heusser and Sirocko, 1997) and MIS 5 (Heusser, 2000) was reported from the Santa Barbara Basin, Eastern Pacific. Remarkably intensive palynological research has been carried out in the Atlantic Ocean off northwest Africa (e.g. Hooghiemstra et al., 1992; Jahns et al., 1998; Dupon et al., 1998, 2000; Shi et al., 1998). During the last decade interesting pollen studies have been going on in the SE Asian maritime continent, but all of the pollen sequences are no longer than 300 ka (Van der Kaars, 1991; Barmawidjaja et al., 1993; Van der Kaars et al., 2000). In general, long pollen sequences with high time resolution are rare. For example, long pollen records over the last million years have been reported from the Mediterranean (Nebout et al., 1999) and off Hokkaido (Igarashi, 1994), but the time resolution is lower than 10,000 years. Heusser has studied a number of pollen sequences off Japan covering the last 2.5 Ma and more, such as from ODP Site 798 (Heusser, 1992), but the resolution was as low as ca. 40 ka.

Located between the largest ocean and continent, the marginal seas of the Western Pacific offer ideal opportunities for high-resolution paleo-environmental studies. The sedimentation rate of hemipelagic deposits there is frequently one order of magnitude higher than that in the open ocean (P. Wang, 1999), and the deep-sea pollen sequence there provides simultaneous records of terrestrial and marine information. The South China Sea (SCS), with its sensitivity to monsoon variations and its carbonate preservation in deep-water sediments, has become one of the global foci in paleoclimate studies (Sarnthein et al., 1994; P. Wang et al., 2001). This paper presents the first high-resolution long pollen sequence in the Western Pacific, based on ODP holes drilled in the northern SCS.

2. Environmental setting

The SCS is a marginal sea in the western Pacific Ocean bordered by the East Asian continent and Indochina Peninsulas in its north and west, and by Indonesia and the Philippine Archipelago in its south and east. The semi-closed basin is connected with the Pacific Ocean through the Bashi Strait in the northeast and with the Indian Ocean through the Sunda Shelf in the south. Thanks to the great sill depth (2600 m) at the Bashi Strait and hence ventilation of the deep water in the SCS basin, carbonate is well preserved above the lysocline at about 3000 m permitting high-quality isotope stratigraphy of the hemipelagic sediments (P. Wang et al., 1995).

The climate of the SCS and its ambient landmasses is mainly under the control of the East
Asian monsoon system with seasonal changes in wind. During the winter season dry and cold wind blows to the southwest from the Asian continent and during the summer season the warm and humid wind comes from the ocean. Driven mostly by the seasonal alternation of the prevailing wind, the SCS displays a transition pattern of surface currents with opposite direction in summer and winter. In summer, surface water of tropical Indian Ocean origin flows northward into the SCS and then into the Pacific mostly through the Bashi Strait. In winter, the northeast wind drives the tropical and subtropical Pacific water together with colder water from longshore currents to the SCS through the Bashi and Taiwan Straits and then across the Sunda Shelf into the Indian Ocean (Fig. 1) (P. Wang, 1998; L. Wang et al., 1999a).

The vegetation of southeast China and Taiwan Island, the two main pollen sources for the northern SCS, is briefly introduced as follows (Fig. 2). Tropical rainforest is restricted to a few places on Hainan and Taiwan Islands and is represented mainly by Dipterocarpaceae (Dipterocarpus, Hopea, Vatia, Shorea, etc.) and accompanied by Pterospermum, Heritiera, Sterculia, Dysoxylum, Aglaia, plus some genera from Moraceae, Sapindaceae, Sapotaceae, etc. The southern part of the continent, including Hainan and southern Taiwan, is assigned to the tropical rainforest and seasonal rainforest vegetation zone the northern boundary of which varies between 21 and 24°N – roughly south of the Tropic of Cancer. Topography there is relatively flat (<150 m) with some isolated montane peaks, reaching 1870 m in Hainan and 3950 m in Taiwan. Situated in the tropical belt and under the control of the Eastern Asian monsoon system, these areas are marked by high temperature (annual average temperature 20–22 to 25–26°C) and high, but seasonally distributed, precipitation. The average annual precipitation is above 1500 mm with a relatively dry season during late autumn and winter. In the lowland (ca. <500 m) with a short dry season in late autumn and winter the natural vegetation contains semi-evergreen forests comprised mainly of taxa from Moraceae, Sapindaceae, Meliaceae, Tiliaceae, Euphorbiaceae, Annonaceae, Sapotaceae, Bombacaceae and Dipterocarpaceae, such as Radermachera, Terminalia, Anesiodendra, Hainania, Vitia, Parashorea, and so on. In the low montane region (ca. 600–1500 m), which lacks a dry season, tropical montane rainforest and seasonal evergreen forest occur. These are dominated by taxa from Lauraceae, Fagaceae and Magnoliaceae, e.g. Castanopsis, Lithocarpus, Quercus, Cyclobalanopsis, Machilus, Cinnamonum, Phoebe, Magnolia, Michelia, etc. On the mountains of middle altitude (above 1500 m) temperate broad-leaved deciduous forests are to be found, represented by Carpinus, Betula, Alnus, Acer, Nyssa, etc. With the rising of altitude in succession warm-temperate, temperate and cold-temperate conifers appear, e.g. Podocarpus, Dacrydium, Pinus kwantungensis, Cephalotaxus, Tsuga, Keteleeria. On the high mountains of Taiwan (>3000 m) cold-temperate conifers occur, such as Abies and Picea. On lowland and low mountains large areas of tropical pine forest stretch, represented by Pinus khasya and P. khasya. Along the southern and southeastern coast of China scattered mangroves are to be found, composed of 15 genera and 24 species. Rhizophoraceae (Rhi-
zophora, Kandelia, Bruguiera, Ceriops, etc.) is the main component, and *Kandelia candel* is the most cold-tolerant species, with its natural northern boundary reaching 27°25'N.

To the north of the seasonal rainforest zone mentioned above, roughly between the Tropic of Cancer and 34°N, lies the zone of subtropical evergreen broadleaved forest (which is internally divided into southern and middle zones). Climate there is subtropical and monsoonal in nature with clear dry and wet seasons. During summer it is hot, humid and rainy under the influence of the Southeast Asian Monsoon circulation. By contrast, the areas experience a dry and cool period during winter, influenced by boreal cold air masses. The vegetation is represented chiefly by Fagaceae (*Castanopsis* and *Quercus*), Lauraceae (*Cinnamomum*, *Lindera*), Hamamelidaceae (*Liquidambar*, *Altingia*), and Theaceae accompanied by some taxa from Guttiferae, Annonaceae, Myrtaceae (Guandong Institute of Botany, 1976; Wu, 1980).

Southeast China at present is very densely populated, therefore, the native forests have been subjected to a great deal of disturbances and destruction for a long time. Tropical grasslands with scattered trees and shrubs are widely distributed on the lowland and the hill slopes. Most grassland is considered to be secondary, resulting from human activities, such as burning, cutting and hunting (Guandong Institute of Botany, 1976; Wu, 1980; Sun and Luo, 1999).

3. Pollen dispersal and source areas

All of the pollen grains and fern spores in the marine sediments come from somewhere on the land. Therefore, understanding of the mechanism of pollen dispersal, its routes and source areas is crucial for the interpretation of marine pollen data in terms of paleovegetation and paleoclimate.

Our study on the pollen distribution patterns in the surface sediments of the SCS has found that the northern SCS is marked by very high percentages (<90% of the total pollen sum) and concentrations of tree pollen, in which *Pinus* is absolutely dominant (Sun et al., 1999). The maximal values of concentration of tree pollen occur in the northwest adjacent to the convergence of the Bashi and Taiwan Straits, rather than near estuaries of big rivers, and stretches as a saddle from NE to SW, being consistent with the direction of the NE winter monsoon and surface current (Fig. 3a).

Such a distribution pattern implies that tree pollen, especially pine, adapted to wind transport and water flotiation, are mainly brought by the NE winter monsoon and wind-driven currents.

Fig. 3. Maps of pollen concentration isopolls (grains/ml) showing mechanism of pollen dispersal and routes (Sun et al., 1999). (a) Tree pollen distribution pattern. (b) Herb pollen distribution pattern.
from large source areas, probably including south 
and southeast China. Lithogenous particle in£ux 
by sediment traps in the north-central SCS 
(18°28′N, 116°01′E, water depth 3750 m; Jenner-
jahn et al., 1992; Su and Wang, 1994) shows that 
the maximum sediment in£ux values occur during 
winter (November^January), when the runo¡ 
from adjacent rivers such as the Pearl River is 
at a minimum (Editoral Board of Physical Geog-
raphy of China, 1979). Therefore, a proportion of 
the terrestrial particles such as tree pollen may 
also be brought by the strong winter monsoon 
winds and marine currents. In the pollen assem-
blages from surface sediments of the northern 
SCS very few herbaceous pollen grains were 
found and their concentration values decrease 
from the coast to the sea indicating a mainly £u-
vial and o¡shore current transport (Fig. 3b) (Sun 
and Luo, 2001).

4. Materials and methods 

Pollen samples were taken from ODP Site 1144 
on a sedimentation draft located in northeastern 
SCS (20°03.18′N, 117°25.14′E) at water depth 
2037 m (Fig. 1). The composite core length is 
520 m1, but the homogenous mud sequence is 
interrupted by some depositional hiata with the 
most signi£cant one at 504 m, corresponding to 
1.03 Ma, according to oxygen isotope stratigra-
phy (Bühring et al., in press). The present paper 
is based on results of 1250 studied pollen samples 
from the upper 504 m, with different sampling 
intervals from 154 to 1160 years. The average 
time resolution between pollen samples is about 
820 years (Table 1).

This site was chosen for pollen analysis to take 
advantage of the extremely high sedimentation 
rates. A nearby piston core SO 17940 (20°07′N, 
117°23′E, water depth 1727 m) recovered 13.3 m 
deposits representing a 37-ka sequence, with a 
sedimentation rate of 36 cm/ka, which has yielded 
a valuable high-resolution paleo-environmental 
record for the region (Sun and Li, 1999; L. 
Wang et al., 1999a). ODP site 1144 provides 
even higher sedimentation rates averaging 49 
cm/ka (0–504 m). The sediments are composed 
of homogeneous hemipelagic mud with quartz 
silt and nannofossils. Variations in the lithology 
reflect the abundance of iron sul£des in the upper 
280 m, and pyrite in the lowermost part with a 
remarkably high magnetic susceptibility (below 
420 m) (P. Wang et al., 2000; Sun and An, 2001).

Pollen samples were prepared in Tongji Univer-
sity using hydrochloric and hydro£uoric acids to 
remove carbonates and silicates. To get more 
concentrated pollen and charcoal the remaining ma-
terial after acid reactions was sieved through a 
7-£m mesh in an ultrasonic bath. More than 200 
pollen grains of land seed plants per sample were 
counted (excluding fern spores and pollen of 
aquatics). Besides pine pollen no less than 100 
pollen grains were calculated when pine pollen 
exceeded 100 grains. The percentages of each 
group and of individual taxa were calculated on 
the pollen sum of land seed plants. The in£ux 
values were calculated by the exotic pollen meth-
od as the number of pollen grains accumulated on 
1 cm2 during a year.

1 Depth ‘m’ in this paper denotes mcd – meter of compo-
sition depth (mcd).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Ages (ka)</th>
<th>Number of samples</th>
<th>Sampling interval (cm)</th>
<th>Time resolution (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–28</td>
<td>0–30</td>
<td>165</td>
<td>17</td>
<td>154</td>
</tr>
<tr>
<td>28–72</td>
<td>30–79</td>
<td>31</td>
<td>142</td>
<td>1250</td>
</tr>
<tr>
<td>72–228</td>
<td>79–360</td>
<td>478</td>
<td>32</td>
<td>600</td>
</tr>
<tr>
<td>228–503</td>
<td>360–1020</td>
<td>583</td>
<td>48</td>
<td>1160</td>
</tr>
<tr>
<td>0–520</td>
<td>0–1028</td>
<td>1250 (total)</td>
<td>41 (average)</td>
<td>820 (average)</td>
</tr>
</tbody>
</table>

Table 1 
Table showing numbers of counted pollen samples, sampling intervals and time resolutions between sample
5. Chronological framework

In result of on-board study a low-resolution chronological framework of ODP 1144 was derived from calcareous nannofossils and planktonic foraminiferal zones and events (P. Wang et al., 2000) which were refined and revised later (e.g. Zhou, 2001). Although the magnetopolarity stratigraphy was limited because of high sedimentation rates and magnetic overprint, the Brunhes/Matuyama (B/M) boundary was recognized by the occurrence of microtektites at 386.4 m. The Australasian microtektites are widely distributed in the region very close to the B/M boundary assigned to 780 ka in age (Zhao et al., 1999; J. Wang et al., 2000). A refined and more detailed age model is produced based on δ¹⁸O of Globigerinoides ruber (Fig. 4; Bühring et al., in press). The δ¹⁸O-based age model was adopted except for individual misleading points (such as 230.24 mcd as 360.17 ka) which leads to misunderstanding high sedimentation rate for late MIS 10. Sediments of the profile over the studied section of 504 m are almost continuing except for a remarkable deposition hiatus at 196.64 m where MIS 8 is almost missing, and two short-term ones within MIS 5.5 and MIS 11.31.

Of particular interest is the striking resemblance between δ¹⁸O and pollen curves, especially in the upper part (above 350 m, MIS 16). As shown in Fig. 4, lighter δ¹⁸O stages are correlated to pine-predominant pollen zones assigned to interglacials, and heavier δ¹⁸O stages correspond to herb-predominant pollen zones belonging to glacials. On this basis a total of 29 pollen zones have been recognized which almost completely coincide with isotopic stages MIS 1–29 (Fig. 4). Only 10 of the 29 zonal boundaries have some minor difference in depth as given in Table 2. Because of the close similarity between pollen zones and isotope stages, MIS will be used instead of pollen zone for further discussions on pollen assemblages to ease

<table>
<thead>
<tr>
<th>Pollen zone</th>
<th>Interval (m)</th>
<th>Age (Ka)</th>
<th>MIS</th>
<th>Interval (m)</th>
<th>Age (Ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0–8.9</td>
<td>0–13.2</td>
<td>1</td>
<td>0–8.9</td>
<td>0–11.5</td>
</tr>
<tr>
<td>2</td>
<td>8.9–22</td>
<td>13.2–21</td>
<td>2</td>
<td>6–33</td>
<td>11.5–21</td>
</tr>
<tr>
<td>4</td>
<td>65–72</td>
<td>21–63.3</td>
<td>4</td>
<td>65–85.3</td>
<td>21–78.9</td>
</tr>
<tr>
<td>5</td>
<td>72–115.3</td>
<td>63.3–131.5</td>
<td>5</td>
<td>85.3–113</td>
<td>78.9–129.4</td>
</tr>
<tr>
<td>11</td>
<td>227–252</td>
<td>355.7–432.3</td>
<td>11</td>
<td>227–249</td>
<td>355.7–416.5</td>
</tr>
<tr>
<td>12</td>
<td>252–284</td>
<td>432.3–471</td>
<td>12</td>
<td>249–281</td>
<td>416.5–467.5</td>
</tr>
<tr>
<td>13</td>
<td>284–293</td>
<td>471–482.4</td>
<td>13</td>
<td>281–303</td>
<td>467.5–501.7</td>
</tr>
<tr>
<td>14</td>
<td>293–308</td>
<td>482.4–527</td>
<td>14</td>
<td>303–313</td>
<td>501.7–551</td>
</tr>
<tr>
<td>15</td>
<td>308–330</td>
<td>527–634.2</td>
<td>15</td>
<td>313–323</td>
<td>551–611.7</td>
</tr>
<tr>
<td>16</td>
<td>330–350</td>
<td>634.2–669</td>
<td>16</td>
<td>323–350</td>
<td>611.7–669</td>
</tr>
</tbody>
</table>
interpretation and comparison of pollen data with other records.

6. Results

A total of 174 pollen types have been identified (see Appendix). Except pine and some herbs, most of the pollen types contain very few grains, some tropical and subtropical taxa in particular. To make the pollen diagram more readable, several groups of taxa are distinguished according to plant ecology, namely: (1) Herbs (Artemisia, Poaceae and Cyperaceae as the main components, with sparse Asteraceae, Chenopodiaceae etc.); (2) Boreal conifers (Picea, Abies, and Tsuga); (3) Tropical upper mountain group (Podocarpus, Dacrycarpus, Dacrydium and Phyllocladus); (4) Temperate deciduous group (Betula, Alnus, Carpinus, Juglans, Ulmus, etc.); (5) Tropical and subtropical evergreen group (Quercus, Altingia, Ilex, Castanopsis/Lithocarpus, Mallotus/Macaranga, Euphorbiaceae, Palmae, Melastomataceae, Meliaceae, Euphorbiaceae, Moraceae); (6) Mangroves (mainly Rhizophora and Sonneratia), and (7) Aquatics (Typha, Myriophyllum, Nymphoides). To demonstrate the results of the analyses, we start with percentages of pine, herbs, and the above groups in succession (Fig. 5), followed by pollen influx.

Pinus predominates the pollen assemblages throughout the profile, followed by herbs in percentages. The two types together can reach up to 80% of total pollen sum of land seed plants, although the downcore variations are very significant. The highest percentage of Pinus occurs in MIS 1 or the Holocene (81% in average for the zone, the same in the following text) and the lowest in MIS 2 or LGM (30%). Pinus almost always shows higher percentages in the interglacial (the values vary between 39% and 81%) than in the corresponding glacial stage (30–54%), what is most prominent in glacial cycles of MIS 1/2, 11/12, etc., but exceptions are observed at the MIS 9/10 and MIS 25/26 cycles where the Pinus percentage shows very little changes (49.4%/51.1% and 39.2%/39.1%, respectively).

Herbs include 29 pollen taxa (see Appendix), with the most important components from Artemisia, Poaceae and Cyperaceae. pollen from Chenopodiaceae and other Asteraceae are moderate and all other taxa are very low in percentages. In contrast with Pinus, the percentages of herbs and their main taxa are low in interglacial periods (4.9–25.5%), but considerably higher during glacials (12.8–32.7%). The extremely high values at MIS 12, MIS 6 and MIS 2 correspond to the last three major Alpine glaciations – Mindel, Riss, and Würm (Raymo, 1997). MIS 3, as an interstadial in the Last Glaciation, also bears a large amount of herb pollen similar to that found in the other great glaciations. From various groups of herbs, Artemisia, Poaceae and Cyperaceae deserve special attention.

The pollen percentage of Artemisia varies significantly in the sequence. It begins with very low values at the bottom of the profile (+1%), but suddenly reaches the maximum in MIS 28 (22%), then continually decreases upwards. Its content is negligible in the interval between MIS 19 and MIS 13 (<1%) and then rises again from MIS 12 onwards, with higher percentages mainly occurring in glacial periods, particularly in MIS 6 (8.6%) and MIS 2 (16.6%). As compared with Artemisia, the pollen percentage of Poaceae remains more or less stable in its amplitude of variations throughout the profile, being clearly higher in glacial periods, especially at MIS 12 (13.1%), MIS 6 (10.3%), MIS 2 (7.4%) and much lower in interglacials in the upper part (MIS 1–17) of the sequence. The glacial/interglacial difference, however, becomes much less clear in its lower part (below MIS 17). The percentage of Cyperaceae pollen ranges from 1.2% (MIS 1) to 11.7% (MIS 4), being significantly inferior to the two above-mentioned herb pollen types. There is no systematic difference observed in the Cyperaceae pollen proportions between the glacial and interglacial periods, as is found in Artemisia and Poaceae, and in some cases its percentage is even higher in the interglacial than in the glacial periods, such as MIS 7, MIS 13, and MIS 19 (Fig. 5).

The tropical and subtropical group includes a large number of taxa (see Appendix), but only a few grains of each taxa can be encountered per sample, except Quercus (evergreen type). This
Fig. 5. Pollen percentage diagram of ecological groups and selected taxa from ODP Site 1144 (percentages are calculated on the total pollen sum of land seed plants).
group ranks third, inferior to Pinus and herbs in pollen percentages, and ranges from 6.3% to 20%. No distinct glacial/interglacial variations in its percentage can be found, although the middle part of the profile (from MIS 19 to MIS 12) bears higher percentages than the upper and lower parts. The downcore variations of its taxa in percentage become much more remarkable if the proportion of each taxon to a total sum of tropical and subtropical group is calculated. Thus, the diagram (Fig. 6) shows more or less clear differences among the lower, middle and upper parts of the profile. The short lower section (from bottom to MIS 25) is marked by higher percentages of Altingia, whereas pollen from Celastraceae, Cycas, Eugenia, Mallotus/Macaranga, Dipterocarpaceae, and Trema characterize the middle part (from MIS 26 to MIS 11), and in the upper part evergreen Quercus reaches its maximum, together with higher values of Carya, Olacaceae, Sapindaceae and Symplocos.

Pollen types of some broadleaved deciduous trees are assigned to the temperate broadleaved group, with deciduous Quercus and Ulmus being the major components. Pollen percentages of this group range from 4.8% (MIS 1) to 22.4% (MIS 11). The low values (less than 10%) occur in the lower part (below MIS 20), becoming higher (9.3–13.4%) in the middle part (MIS 20 to MIS 13) and the highest (9.1–22.4%) in the upper part, with the maximum values recorded in MIS 2 and MIS 11. The lower part is marked by higher percentages of Ulmus and Pterocarya; the middle one by Alnus and Tilia and the upper one is dominated by deciduous Quercus.

The tropical montane group is mainly represented by Podocarpus, Dacrycarpus, Dacrydium, and Phyllocladus, with Rhododendron, Myrica, Myrsine, and Dodonaea found in low proportions. Pollen percentages of this group are higher and include several spikes from single samples in the lower part (MIS 29 to MIS 23) of the profile ranging from 8.5% to 13.6%. From MIS 24 upwards, the average percentage of the tropical montane group declines below 5%, the only exception being a peak up to 30% in MIS 15. No clear difference between glacial and interglacial periods can be found.
The Boreal conifer group includes three taxa, namely, *Tsuga*, *Picea* and *Abies*. In contrast to the tropical montane group, its pollen percentage is somewhat lower (less than 5%) in the lower part of the sequence (below MIS 11) with some peaks from single samples, and becomes a little higher in the upper part (from MIS 11 to the top, 3–7.2%). Again, no clear difference is observed between glacial and interglacial periods, except for the low pollen proportion in the Holocene compared with relatively high values in the LGM (Fig. 5).

Mangroves are represented by five pollen types, of which *Rhizophora* is the most important one. Pollen percentages are very low, ranging from 0 to 0.3%. There is almost no mangrove pollen found before MIS 12, while they occur only in trace numbers since MIS 12. The maximum values are found during the LGM and the Holocene (MIS 2 and MIS 1).

*Anthoceros* is a dwarf liverwort genus from which spores of three species (*A. levis*, *A. dichotomus* and *A. sp.*) are recorded. The spores occur in insignificant percentage values before MIS 16 and drop to zero in the middle part of the profile (MIS 17–12). The spores reappear again from MIS 11 and mainly occur in the glacial periods, especially in MIS 10 (1.2%), MIS 6 (1.0%), and MIS 2 (1.4%), with single samples reaching 16% (in MIS 2) of the total pollen sum of land seed plants. Only insignificant numbers of *Anthoceros* spores are found in interglacial periods.

Aquatic plants are represented by *Typha*, *Alisma*, *Nymphoides*, and *Utricularia*, and occur in low proportions (less than 2%) throughout the profile.

Fern spores are found in large numbers ranging from 11.7% to 58.2% (average % of pollen zone) of total land seed plants and represent a variety of types of which spores of *Cyathea* and *Gleichenia* are the most important types. In general, fern spores are more frequent in interglacials, with the highest percentages occurring in MIS 1, MIS 5e and MIS 15.

Pollen influx (Fig. 7) is expressed as the numbers of pollen grains accumulated on one cm²
during one year. There are two distinct characters of pollen influx patterns through the profile.

1. Total pollen and pollen of each ecological group or taxon occur in very low influx values (4 grains/cm²/yr) in the lower part of the profile (from the bottom of the profile to MIS 17), then begin to rise upwards and reach the maximum (864 grains/cm²/yr) in MIS 2 (LGM). The range of pollen influx variations can exceed two orders of magnitude (Fig. 7).

2. The influx values of total pollen and pollen of each ecological group or taxon are clearly greater in glacial than those at the corresponding interglacials. The differences are especially great at glacial cycles MIS 16/15, MIS 12/11, MIS 10/9, and MIS 2/1.

7. Discussion

All pollen and spores of terrestrial plants in marine sediments are dispersed from the land. In a geological context, the composition of a pollen assemblage in deep-sea sediments is determined by a complex of factors including vegetation of the source area, the route and mechanism of pollen transport to the sea, and the hydrodynamic conditions within the marine basin such as surface currents and downslope transport from the shelf during sea-level changes. The current knowledge of the pollen transport to the SCS is quite limited, and the reader is referred to our studies on pollen distribution in its surface sediments (Sun et al., 1999). To facilitate interpretation of the above described pollen results, ecology and pollen dispersal dynamics of selected pollen types are briefly reviewed as follows.

7.1. Ecology and dispersal dynamics

7.1.1. Pinus

This evergreen conifer is widely distributed in temperate areas of the Northern Hemisphere, two of its species, P. kesiya and P. merkusi, are tropical forms spreading southwards down to 20°S (Kowal, 1966; Cooling, 1968). Pine is a high pollen producer and its pollen is easily dispersed. Usually huge amounts of its pollen are found in Quaternary marine sediments, and in modern surface sediments of the northern SCS pine can exceed 80% of the total pollen sum of land seed plants. According to its distribution pattern, pine pollen is transported mainly by northeast winter monsoon from the mainland of China through Bashi Strait and then spreading southward driven by sea currents (Sun et al., 1999).

7.1.2. Herbs

As discussed already, Artemisia, Poaceae and Cyperaceae are the main components of herbs. Artemisia is a herb or shrub widely distributed in temperate grassland today. Results of pollen–climate response surface of northern China (Sun et al., 1996) show that Artemisia prefers a cooler and more semiarid environment. Both the families Poaceae and Cyperaceae encompass a large number of genera with different ecology. A high percentage of Poaceae in a pollen assemblage usually indicates grassland vegetation. Pollen grains of plants from Cyperaceae growing in or near wet places are easily preserved in sediments, so that a large amount of Cyperaceae pollen in assemblages infers a swampy or wet environment.

7.1.3. Anthoceros

Anthoceros is distributed mainly in temperate areas. This small liverwort (ca. 10 cm) is recorded in Northeast China (Heilongjiang and Liaoning provinces) growing on the edge of forest or on moist soil (Gao and Zhang, 1981). There are no references of the genus recorded from the southern coastal areas of China.

Due to the page limitation, we will not continue to review the ecology of the long list of pollen types, but proceed directly to paleovegetation reconstruction.

7.2. Paleovegetation

Since ODP Site 1144 is situated ca. 200 km away from the continental coastline, today the studied site receives low amounts of pollen, particularly from tropical/subtropical plants and herbs. As a result, modern vegetation is not easily reconstructed solely based on pollen from the surface sediments. The situation has been almost the
same for other interglacial periods, i.e. only limited information about the terrestrial vegetation can be provided by marine pollen records from locations far from the land. In contrast, absolute pollen quantities from glacial sediments are much more than those from the interglacials. The large amount of pollen from glacial sediments at the site might be brought by a strengthened northeast winter monsoon from the Asian mainland and from Taiwan Island. In addition, pollen grains could also have been transported from the exposed continental shelf by water flow and wind at the glacial low sea-level stand. Our discussion on paleovegetation, consequently, will mostly be restricted to that of glacial periods.

7.2.1. Continent

In general, evergreen broadleaved forests, probably more open than today, still survived in the southern coastal areas of China in glacial times including the LGM. A pollen-based biome reconstruction for 18 ka BP (±2 ka) also shows that the subtropical evergreen forest was greatly shrunk in its distribution as compared with that of today, but still present at the extremely southern end of the China mainland (MCQPDB, 2000). Meanwhile, the pollen sequence has revealed the changes in evergreen forest composition through the last million years (see Fig. 6).

Three periods can be distinguished in the vegetation history there: the early period before 908 ka (from the bottom to MIS 24), the middle period from 908 to 355 ka (MIS 23 to MIS 11), and the late one from 355 ka to the present (MIS 10 to MIS 1). The early stage is marked by relatively high percentages of tropical montane pollen (Fig. 5) and Altingia within the tropical and subtropical pollen (Fig. 6). Then the occurrence of Dipterocarpaceae, Celastraceae, Cycas, Eugenia, Mallo-tus/Macaranga, and Trema from MIS 23 to MIS 11 (ca. 908–355 ka) indicates that the climate at that time was more suitable for growth of forests with tropical nature than in the earlier and latter periods. About 355 ka BP (MIS 10) trees from Fagaceae (mainly Quercus and Castanopsis) began to expand and have become absolutely dominant in the forest since then. At the present day the evergreen species of Quercus is the main element in the subtropical evergreen forest zone and is widely distributed in southern China where the climate is marked by distinct seasonality. The sudden expansion of Fagaceae in the pollen assemblage about 355 ka, by both its evergreen and deciduous forms, might imply strengthened seasonality and a cooler climate than previously. The relative climatic cooling during this late period was also confirmed by the rising of pollen percentages of the boreal conifers and probably also by the presence of the dwarf liverwort (An-thoceros). In sum, the pollen record suggests cooler early and later periods and a warmer middle one, which is supported by the higher sea surface temperatures (SST) inferred during MIS 23 to MIS 11 in the southern SCS on the basis of the paleoecological transfer function of planktonic foraminifera (Jian et al., 2000).

Pollen data over the last 37 ka from the nearby core SO 17940 reveal a considerable increase of pollen percentages of the cold-tolerant boreal conifers (Picea, Abies and Tsuga) during the LGM in comparison with those in the Holocene, implying an expansion of its distribution areas on the mainland of China as a response to the glacial climatic cooling. Although the Holocene and LGM difference in pollen percentages of boreal conifers at ODP Site 1144 is not as drastic as in core 17940, still pollen from boreal conifers is almost twice as frequent in the LGM than in the Holocene, which is also indicative of glacial expansion of boreal conifers. This kind of glacial/interglacial contrast in the percentages of boreal conifers, however, does not apply to other earlier glacial cycles. No systematic differences between glacial and interglacial stages were found in temperate and tropical/subtropical groups. In some cases the tropical/subtropical group was even represented by higher percentages in the glacial rather than in the corresponding interglacial periods, such as MIS 11 and MIS 12 (Fig. 5). At the moment, no paleoclimatic interpretation of these groups can be provided.

7.2.2. Emerged shelf

A question of broad interest is the nature of vegetation covering the exposed continental shelves at the low sea-level stand during the gla-
ciation. Our pollen data show that during glacial times the emerged part of the continental shelf was mainly covered by grassland, and this is inferred from the high percentages of herb pollen and the presence of *Anthoceros* spores.

In pollen assemblages from modern surface sediments of the SCS, only a few pollen grains of herbs occur in rare samples adjacent to the northern continent, and no spores of *Anthoceros* are found (Sun et al., 1999). A similar situation is found in pollen records of interglacial periods from the studied profile. By contrast, pollen percentages of herbs are very high in glacial sediments, increasing upwards in the sequence and reaching a maximum in MIS 2 (LGM). Spores of *Anthoceros* are more or less confined to glacial sediments and almost disappear during interglacials.

During the LGM, high percentages of *Artemisia* pollen occur in the northern part of China, e.g. the steppes of Inner Mongolia and northern slopes of Qinling Mountains, and its percentage decreases southwards to less than 10% in the southern coastal areas (Sun et al., 1996, 2000). As compared with *Artemisia*, more pollen grains of Poaceae are found in the LGM, reaching 28–55% during 29–15 ka in Leizhou Peninsula (Zheng and Lei, 1999). Nevertheless, forest vegetation still survived in many places during the LGM. An example is the terrestrial sediments of the Huangmao Sea, located southwest of the Peal River mouth, where pollen assemblages indicate mixed conifer and broadleaved forests growing during the LGM and only 4.4–11.2% of herb pollen is found. The place was flooded by sea transgression and turned into a bay since the Holocene (Lei and Zheng, 1990). Pollen records from Chaoshan Plain, southern coast of China, indicate a mixed evergreen and deciduous forest growing during 28–23 ka (Zheng, 1990).

However, the glacial pollen assemblage at ODP Site 1144 is different, and the high proportion of herbaceous pollen is significant given its long distance (ca. 200 km) from the modern coast. Since most of herbaceous plants (e.g. Cyperaceae and Poaceae) are small in size, their pollen grains are unable to disperse far away. Though *Artemisia* is a high pollen producer and its pollen is easily transported, no sources from the nearby land could deliver so much pollen (up to 40%) to the studied site. *Anthoceros*, a dwarf plant of no more than 10 cm in height, produces a very limited number of spores with thick walls, which are not prone to long-distance dispersal. During glacial periods the northern continental shelf of the SCS was exposed in varying extent due to the lowering of sea level, for example by 120–150 m during the LGM (P. Wang et al., 1995). On the continental shelf off the Peal River mouth the Last Glacial paleo-coastline was found 130 m below the present sea level, including terraces, channel, sand dune and marshes (Chen et al., 1990). A reasonable explanation is that during the glacial periods the herbaceous pollen and *Anthoceros* spores were transported by wind or water to the studied core from the exposed continental shelf of the SCS, which was covered by grassland and liverwort under a relatively dry and temperate climate. Site 1144 could receive great amounts of pollen and spores from the emerged shelf during the glacial. The migration of coastline within the glacial cycles changes the availability of herb pollen to the studied site, hence the variations in the pollen diagram.

In addition, the long-term trends in the pollen record also bear information about evolution of the shelf and its vegetation during the glacial emergence. In glacial stages of the early period (before MIS 22 or 897 ka), the narrowly emerged shelf was probably covered by grassland – *Artemisia* steppe, which was replaced by Poaceae and Cyperaceae during the glacial stages between MIS 22 and the middle part of MIS 6 (about 897 to 160 ka BP). *Artemisia* increased again and occupied most of the extensive emerged continental shelf during the Last Glacial stage. As seen from Fig. 5, there are three major herb pollen peaks found at MIS 12, MIS 6 and MIS 2, which happen to correlate with three great ice ages in the Alps – Mindel, Riss and Würm (Raymo, 1997), when expansion of the ice sheets caused remarkable regressions and significant exposure of the continental shelf and, consequently, expansion of grassland cover.

Of course, there were also sedge swamps and wetlands on the continental shelf during glacia-
tions, inferred by the pollen of Cyperaceae, water plants like Typha and Myriophyllum, and small liverwort (Anthoceros). Climate at the glacial periods might be cooler and drier than that at the present day, but the finding of mangrove pollen since MIS 10 (Fig. 5), even in very low percentages, indicates that mangrove survived along the northern coast of the SCS during some glacial periods within the last 355 ka. Mangrove is an ecologically specific group thriving in brackish-water environments along tropical coasts under strict climatic conditions. In modern China, small patches of mangrove occur along the southern coast with its northern limit in the south of the Fujing Province (Lin and Fu, 2000).

7.3. Sea-level changes

The most outstanding feature of the pollen sequence at Site 1144, as mentioned already, is the frequent alternation of pine and herbaceous pollen, correlating with isotopically identified glacial cycles. It is also inferred from the above discussion that herbaceous pollen mainly came from the exposed continental shelf and the pine pollen from the mainland of China. As found from the studies on pollen dispersal dynamics, the pollen ratio between shore plants and upland ones may indicate the relative distance of the studied site to the coast (Traverse, 1988). The high ratio implies a shorter distance to the coast, while the low ratio means the reverse. In our profile herbaceous pollen is taken as shore type (H), and pine pollen as upland type (P). Their ratios (H/P) are used to indicate the relative distance between the studied Site 1144 and the coastline. Since there is no tectonically induced horizontal shift in the SCS during the middle and late Pleistocene, the palynologically inferred changes in the distance from the coast can only be ascribed to eustatic sea-level changes of the glacial cycles. A rise of H/P value should indicates regression, exposure of the continental shelf and proximity of the coastline, and a decline in H/P value means transgression, shelf submergence and increasing distance to the coastline.

Fig. 4 shows the H/P variations over the years. Remarkable is the general upward trend of increasing glacial H/P values along the profile reaching a maximum in the LGM. Several peaks of high H/P value occur in the late period of the sequence, e.g. MIS 12, MIS 6 and MIS 2, again corresponding to the three major glacials in the Alps, when significant expansion of the boreal ice sheet caused large-scale regression and emergence of extensive shelves, including those in the SCS. The minimum average H/P value (0.01) of the Holocene just accords with the record of maximum transgressions in coastal areas of Guangdong Province (P. Wang et al., 1981), and the maximal H/P (5.5) of the LGM corresponds well to the regression recorded at the shelf break off the Pearl River mouth (Chen et al., 1990). The large amplitude variations of H/P values in MIS 3 may suggest significant sea-level changes in the area, as recorded in the coastal zone of China (P. Wang et al., 1981).

However, the H/P value depends not only on the distance from the coast and hence sea-level fluctuations, but is controlled also by the width of the continental shelf and the nature of the vegetation cover which is not necessarily composed of herbs only. Given other conditions unchanged, a broader emerged shelf should result in a higher H/P ratio than a narrow one. Therefore, the increase of the glacial H/P ratio from MIS 12 through MIS 6 to MIS 2 cannot be explained only by increased amplitude of regressions. The δ18O data of planktonic foraminifera from Site 1144 (Bühring et al., in press) or of benthic foraminifera from Site 1143 in the southern SCS (P. Wang et al., 2001) do not show such an increase in amplitude of regressions; moreover, there is no evidence from the global isotopic records to support increasingly lower sea level from MIS 12 to MIS 2 as inferred by the H/P ratios. Rather, changes in size or width of the exposed continental shelf in the northern SCS is probably another factor exerting its influence on the H/P variations.

It was a couple of decades ago when Chinese geologists noticed the absence of early and middle Pleistocene transgressions in the coastal deposits of East China (P. Wang et al., 1981), and a similar finding was reported from the inner shelves (P. Wang et al., 1985). The lack of transgression records before MIS 6 suggests that the altitude of
these areas was insufficiently low at the time to be accessible to the eustatic sea-level changes (Min et al., 1992). In addition, the small amplitudes in variations and low values of H/P before MIS 6 suggest a narrow and steep continental shelf, with only a limited area exposed at the lower sea-level stand. The extensive northern continental shelf of the SCS as seen today probably had not formed yet. The distance of coastline migration was rather short in glacial/interglacial cycles during glacial times before MIS 6 and the exposed shelf area was very limited. This resulted in only minor grassland cover of the exposed shelf so that the glacial/interglacial contrast in H/P values was quite small.

The broadening of the continental shelf around MIS 6 can be explained by neotectonics of the China continent. Geomorphologists in China believe that the recent uplift of the Qing-Zang (Tibet) Plateau around 150 ka was accompanied by subsidence of the coastal areas of East China and resulted in cutting through of the Longyang Gorge, which eventually brought about the entire Yellow River flowing eastward into the Yellow Sea (Li, 1991; Li and Fang, 1996). The uplift in the west and subsidence in the east around 150 ka (MIS 6) obviously changed not only the hydrological network in China, but also its sensitivity to the eustatic changes in the east. The large-scale migration of the coastline and the rapid progradation of the large river deltas have led to the formation of extensive and flat continental shelves in the northern SCS and the East China Sea. Therefore, extensive grassland-covered shelves can have appeared only after this subsidence around MIS 6 but not earlier. By contrast, the coastline shift before MIS 6 could have taken place only near the present outer shelf break due to a higher stand of the China continent above global sea level. Only the most significant sea-level fluctuations may lead to noticeable coastline migration around the shelf break and leave the sediment record at Site 1144. This can be demonstrated with the moderately high H/P ratio at MIS 12 as an example. All of the oxygen isotope records from the world (e.g. Berger et al., 1993; Farrell et al., 1995) indicate that MIS 12 witnessed the greatest regression over the last several million years, and the regression/transgression cycle of MIS 12/11 might be recorded in drill holes on the outer shelf off the Pearl River mouth (Min et al., 1992). The two types of continental shelves before and after MIS 6 are schematically represented in Fig. 8.

8. Paleomonsoons

In the last few years, the hemipelagic deposits in the SCS have been extensively studied for the paleomonsoon records, though up to now only the late Quaternary monsoon history has been published (e.g. L. Wang et al., 1999a,b,c; Sun and Li, 1999; Sun and Luo, 2001; Jian and Huang, 2001). The high-resolution pollen record from Site 1144 enables us for the first time to investigate the East Asian monsoon history over the million years directly calibrated to the deep-sea isotopic time scale. Unlike its South Asian counterpart, the East Asian monsoon system has a much stronger winter component (Chen, 1992), hence our discussion begins with the winter monsoon.

8.1. Winter monsoon

As seen from the modern pollen distribution pattern in the northern SCS, the tree pollen concentration is highest in the lower part of the northeastern continental slope, near the Bashi and Taiwan Straits (Fig. 3a). It means that tree pollen is transported mainly by the northeastern winter monsoon wind and monsoon-forced surface currents (Sun et al., 1999). Therefore, the
The similarity in variations between global ice volume and monsoon proxy again implies their causal relationship. Accordingly, it appears that the intensification of the winter monsoon may be more gradual in the pollen record as compared with its abrupt warming.

A general trend superimposed on glacial cycles is the enhancement of the winter monsoon since MIS 16. Over 1 Ma the tree pollen influx value was very low in the early stages before MIS 17 and they noticeably increased since MIS 16, indicating that the Asian winter monsoon began to intensify since ca. 670 ka ago when the European Alps experienced the first major glacial, the Günz glaciation. Grain size analysis of a number of loess sequences from the Loess Plateau in central China also shows the intensification of the winter monsoon since the last ca. 0.6-0.45 Ma. The significant advance of Mu Us desert (north of the Loess Plateau) and better development of paleosols than those formed before, imply enhancement of both winter and summer monsoons during the last 0.6 Ma (Ding et al., 1999). Increased dust influx in Lingtai and Xifen loess profiles is regarded as an increase of aridity and, hence, of winter monsoon intensity during the last ca. 0.6 Ma (Hovan et al., 1989; Sun and An, 2001). Extension of eolian dust accumulation to the middle-lower reaches of the Yangtze River and Lake Biwa region in the central part of Honshu Island, Japan, from 0.55 to 0.45 Ma also indicates intensification of the winter monsoon since that time (Xiao and An, 1999).

The tree pollen influx proxy of the winter monsoon is well supported by other pollen records such as herbs. The high values of tree pollen influx at MIS 2, MIS 5 and MIS 12 are accompanied by similar peaks of Artemisia and herbs in general (Fig. 5), all displaying a sawtooth-like curve. This is understandable since the winter monsoon from the continental interior brings a dry climate. An early zone of high percentages of Artemisia (Fig. 5) has no comparable peak in the tree pollen influx curve, but this may correspond to the dry stage recorded in the Loess Plateau as L9 (Ding et al., 1999).

The only features difficult to explain are the high tree pollen influx values at MIS 5b and
two spikes within MIS 3 (Fig. 9), which might indicate that the winter monsoon at MIS 5b was as intensive as in glacials, and MIS 3 was very much variable in terms of monsoon climate. The transfer function paleotemperature estimations at the same site also suggest that SST was high only at MIS 5e, whereas the SST of the remaining parts of MIS 5 was low and close to those of glacial stages such as MIS 4 and MIS 12 (Zhou, 2001). The unstable climate of MIS 3 is also evidenced by the high H/P ratio and high percentage of Anthoceros.

8.2. Summer monsoon

Because of the long distance of the studied site to islands in the southern SCS, we cannot expect to find pollen grains brought by southern winds in a statistically significant amount. Instead, there are humidity-indicative palynomorphs closely related to the summer monsoon intensity. Ferns usually grow under humid conditions, so that higher fern percentages suggest wetter climate (Van der Kaars, 1991; Van der Kaars et al., 2000). In addition, fern spores are produced in enormous numbers and hence suitable to quantitative analyses. We use, therefore, the fern spore proportions to the total pollen sum of land seed plants as the summer monsoon proxy in the present study.

As shown by the fern spore curve in Fig. 9, its percentage is as a rule higher in the interglacial stages and lower in glacials, suggesting enhancement of the summer monsoon in interglacials. The particularly high spikes at late MIS 1, MIS 5e and MIS 15 are most probably the result of the strengthened summer monsoon. Of interest is the nearly parallel trend between the fern curve and...
and the average annual sea surface temperature curve based on planktonic foraminifera over the last 500 ka (Zhou, 2001). Since the summer monsoon brings warmth and moisture, the similarity in records can be regarded as a common feature of monsoon variations of the area.

Another noteworthy feature is the relatively high and stable values of fern spore percentage before MIS 16. This may reflect a relatively strong and stable summer monsoon or a weaker winter monsoon. With only limited data available now, we are not able to distinguish the two possible factors.

8.2.1. Orbital forcing

In search for a causal relationship between the changes in pollen assemblages and those of ice-sheet variations, spectrum analysis and cross-spectrum analysis were applied to the herb and pine pollen percentage records at Site 1144. Univariate spectrum analyses of the SPECTRUM program of Michael Schulz (Schulz and Stattegger, 1997) were used to perform spectrum analysis of herbs and pine percentages for the last 1.05 Ma and the results display a set of Milankovich cyclicities: strong eccentricity-dominated (~100 ka), weakened obliquity-related (~41 ka) and precessional signal (~23 ka). An outstanding result is the existence of clear semi-precessional cycles (~11 ka, 10 ka, 9 ka), an important feature for tropical regions (Berger and Loutre, 1997) (Fig. 10). Therefore, the vegetation changes in the northern SCS during the last million years are primarily under control of the orbital forcing.

Blackman–Tukey cross-spectral analysis was performed on herb and pine pollen percentage values against global ice volume maxima (in the δ18O record) for the last 400 ka. The results show very high non-zero coherences (>90%) between the two parameters at eccentricity (100 ka) and precessional (23 ka) bands (Fig. 11). Phase wheels, completed from cross-spectrum data, show that the vegetation changes are nearly in phase with or slightly lag the global ice volume maxima at the 100-ka and 23-ka bands, respectively (Fig. 12).

All of this shows a correspondence between...
pollen record and orbital parameters at 100-ka and 23-ka periodicities and a close tie between the vegetation changes and those in ice-sheet volume, sea level and monsoons.

9. Conclusions

From the above a series of conclusions can be drawn.

(1) The one-million-year pollen data of ODP Site 1144 from the northern SCS are very well correlated with the oxygen isotopic records from the same site. The correspondence of alternating predominance of two major pollen groups, *Pinus* and herbs, to the fluctuations of oxygen isotopic values has enabled us to use the MIS sequence for division of the pollen zones.

(2) The pollen evidence shows that during the glacial periods tropical and subtropical evergreen forest (though it might be open) and mangroves still survived along the coast areas of the northern SCS, and the exposed northern continental shelf was covered by grassland mainly of *Artemisia*, Poaceae and Cyperaceae responding to the cooler and drier glacial climate.

(3) Superimposed on the glacial cycles is a general decrease in abundance of the tropical and subtropical group and a significant rise of both evergreen and deciduous *Quercus* during the last ca. 360 ka, suggesting generally lowering temperatures and developing seasonality.

(4) The pollen percentage ratio of herbs vs. pine (H/P) is used as an indicator of the relative distance of the study site from the coastline or, in other words, the extent of glacial exposure of the shelf. The results show a very limited extent of exposed continental shelf before MIS 6, which increased afterwards, reaching its maximum at the LGM. This change can be attributed to the neotectonics in eastern China and the uplift of the Qing-Zang (Tibetan) Plateau and subsidence of the eastern coast areas, giving rise to formation of the extensive and flat northern continental shelf. Consequently, large-scale coastline migration over SE China and its shelves took place only since then.

(5) The tree pollen influx and fern spore proportions are used as proxies of the winter and summer monsoons, respectively. The winter monsoon was strengthened during the glacial, with a general enhancement since MIS 16. The summer monsoon was intensified during interglacials, particularly MIS 15, MIS 5 and late MIS 1.

(6) The spectrum analyses of pollen percentages of pine and herbs have revealed presence of 100-ka, 41-ka and 21-ka Milankovich cyclicities and the tropical-specific 10-ka semi-precession cycles, showing the role of astronomical factors.

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Appendix

**Boreal conifer group**: *Abies*, *Picea*, *Tsuga*

**Tropical montane group**: *Cedrus*, *Keteleeria*, *Podocarpus*, *Dacrycarpus*, *Dacrydium*, *Phyllocladus*, *Rhododendron*, *Myrsine*, *Dodonaea*, *Myrica*


MARGO 3370 9-9-03
Mangroves: Rhizophora, Sonneratia, Avicennia, Barringtonia, Luminittera


Aquatics: Alisma, Nymphoides, Typha, Utricularia, Potamogetonaceae, Sparangiaceae, Nymphaea, Myriophyllum, Sagittaria

Ferns: Angiopteris, Ceaotopteris, Cibotium, Cyatheae, Drynaria, Dryopteris, Gleichenia, Hymenophyllaceae, Lepisorus, Lygodium, Microlepia, Microsorus, Ophioglossaceae, Osmunda, Parkeriaceae, Polypodium, Pteris, Pyrrosia, Selaginella, Sinopteris, Vittariaceae, Monoletea, Triteles

Anthoceros, A. levis, A. dichotomas, A. sp.

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