The vegetation and climate at the last glaciation on the emerged continental shelf of the South China Sea

Xiangjun Sun a,b,*, Xu Li a, Yunli Luo a, Xudong Chen a

a Institute of Botany, Chinese Academy of Sciences, Xiangshan, Beijing 100093, People’s Republic of China
b Laboratory of Marine Geology, Tongji University, Shanghai 20092, People’s Republic of China

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Abstract

Studies on the dispersal mechanism and source areas of pollen from hemipelagic sediments recovered from the continental slopes of the South China Sea (SCS) reveal that vegetation existed on the exposed shelves at the Last Glacial Maximum (LGM) and the latter part of the Marine Isotope Stage 3. At the low sea level stand, Artemisia-dominated grassland covered the northern continental shelf and tropical lowland rainforest and mangroves grew on the southern shelf ‘Sunda Land’. Consequently, the climate in the northern SCS must have been much colder and drier during the last glacial period compared to the present. Sunda Land experienced only a marginally lower temperature but was not drier than today. The enhanced contrast between the northern and southern parts of the SCS in vegetation and climate during the LGM may be ascribed, at least partly, to the strengthening of Winter Monsoon during the last glacial period. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

At the Last Glacial Maximum (LGM), an enormous change in the geography of Asia was registered through the exposure of the continental shelf. At that time, the continents of North America and Europe were covered by great ice sheets, whereas the continental shelf of East Asia, exposed at the low sea-level stand, was the most extensive in the world. The total area of the continental shelves there, including the East China Sea, Yellow Sea, Sunda Shelf of the South China Sea (SCS), and Sahul of northeast Australia, was some 390 million km², equal to the whole area of the Indian Subcontinent (Wang et al., 1997). The northern and southern continental shelves of the South China Sea together occupied >200 million km². Such a great change of land and sea distribution must have affected the albedo, and the types of vegetation growing on the exposed shelves also strongly influenced albedo and the carbon cycle. Since sediment from the last glaciation is not often preserved on the continental shelf and deep-sea pollen records have not been available until recently, the nature of palaeovegetation on the emerged shelf has remained a matter of speculation. For example, in reconstructing conditions for the glacial Earth of 18 000 yr ago, the CLIMAP Project Members (1976) assigned both northern and southern continental shelves of the SCS to forested and thickly vegetated land. At the same time, they pointed out that supporting data for
this reconstruction were scarce compared with those from Europe. In mapping vegetation at the maximum cooling of the last glaciation, Frenzel et al. (1992) considered vegetation on the northern continental shelf and the southern coast of China to have been dense, hydrophytic, mixed coniferous and broad-leaved forest, and that on the Sunda Shelf of the southern SCS to tropical savanna. Working on a deep-sea core, Broecker et al. (1988) found an abrupt decrease in sedimentation rate from glacial (33 cm ka $^{-1}$) to Holocene (15 cm ka $^{-1}$) in the south part of the SCS (core V35-5, 7°11'N, 112°05'E, water depth 1953 m) and ascribed the pattern to higher glacial erosion rates during the glacial periods resulting from drier conditions which prevailed in the Southeast Asia region and hence reduced vegetation cover (savanna rather than rainforest). This disagreement in palaeovegetation interpretation together with the lack of persuasive evidence hinders any good palaeoclimate reconstruction and modelling.

This paper presents new evidence for the vegetation on the continental shelves of the SCS during the LGM and the latter part of Marine Isotope Stage 3 (MIS 3) based on palynological data gathered from hemipelagic sediments of the continental slopes and an understanding of the mechanism of dispersal routes and source areas of pollen grains. Furthermore, it aims to review the available data on palaeovegetation on three of the largest exposed shelves in the low-latitude Western Pacific region, namely the East China Sea Shelf, the Sunda Shelf and the Sahul Shelf, in an attempt to determine the nature of climate changes in the region and their possible relation to the monsoonal system.

2. Environmental setting

The SCS, one of the largest marginal seas of Southeast Asia, is bordered by the Chinese mainland in the north, the Indochina Peninsula in the west, the Philippines in the east and Sumatra and Borneo in the south and southeast (Fig. 1). The climate of the SCS and adjacent landmasses is dominated by the East Asian Monsoon System. Seasonal reversal in wind direction plays an important role for climate and vegetation in the region. The southern part of the mainland China, south of the Tropic of Cancer is relatively flat with hills <150 m a.s.l., and some isolated mountains. The southwest summer monsoon from May to September transports abundant moist air masses and rainfall (ca. 80% of 1000–1800 mm total annual rainfall) and the reverse for the cold and dry northeast winter monsoon (EBPGC, 1979). Consequently, the region experiences highly uneven rainfall and the regional vegetation is tropical seasonal rainforest or tropical semi-evergreen rainforest dominated by species of families such as Moraceae, Meliaceae, Sapidaceae, Tiliaceae, Euphorbiaceae, Sapotaceae and Dipterocarpaceae. The average annual temperature ranges from 20–22 to 25–26°C. Tropical lowland rainforest with
very high floristic diversity is restricted to the extreme southern part of the mainland with average annual temperatures between 22 and 26 °C and annual precipitation >2000 mm evenly distributed through the year. North of the Tropic of Cancer, the region is occupied by the Nanling Mountains 300–1200 m high with the highest peak at 1902 m, and is mainly covered by evergreen broad-leaved forest (Fagaceae, Theaceae, Lauraceae etc.). Above 1200 m Podocarpus, Cyclobalanopsis, Betula and other taxa appear (GB, 1976; Wu, 1980; Sun and Li, 1999).

The Malay Peninsula, Sumatra, Java and Borneo border the southern continental shelf (Sunda Shelf). This region contains high mountains, particularly on Borneo (up to 4101 m), Java (up to 3676 m) and Sumatra (up to 4101 m) (Flenley, 1996). Short rivers flow rapidly from these mountains, some of them discharging onto the southern part of the Sunda shelf. The vegetation of this region changes with altitude. Up to 1000 m a.s.l. lowland rainforest occurs, dominated mainly by Dipterocarpaceae. Above this, up to 2500 m, is a low montane rainforest dominated by Fagaceae, Lauraceae and Hamamelidaceae. This gives way, at about 2000 m, to upper montane rainforest, principally of Podocarpus, Dacrycarpus, Dacrydium, Phyllocladus, Vaccinium, Rhododendron and Myrica, which continues to the timberline at ca. 3800 m. Above the forest limit lies tropical alpine grassland. Mangroves (Rhizophora, Sonneratia, Avicennia, Lumnitzera, Bruguiera etc.) are found along the coasts and river mouths of these islands. (Hill, 1979; Newsome, 1988; Flenley, 1996). Located near the Equator and close to the ‘West Pacific Warm Pool’ (WPWP), this region has a non-seasonal climate with high temperature (24–28 °C) and precipitation (above 2000 mm).

Water movement in the SCS is controlled by the East Asia monsoon system. In winter, the northeast winter monsoon drives surface water into the SCS through the Bashi Strait and out to the Indian Ocean across the Sunda Shelf. In summer, the reverse occurs (Wang et al., 1995).

3. Materials and methods

Two pollen profiles were constructed from cores taken from the SCS during the Sonne Cruise 95 in 1994. The first core 17940 (20°07′N, 117°23′E) is located on the northern continental slope, ca. 400 km southeast of Hong Kong, at a water depth of 1727 m. The 13.3 m long core is quite homogeneous, composed of olive-grey silty clay throughout, and the terrigenous component contains 25–30% silt in the Holocene component (0–660 cm) and 45–50% silt in the glacial component (L. Wang, 1999, personal communication). A total of 103 samples with ca. 10 cm sampling interval were counted for pollen. Chronology was provided by 39 AMS 14C dates and an interpolated 14C age for the bottom of the core is 37 ky BP (40 cal. ky BP) (Wang et al., 1999). Core 17964 (6°9.5′N, 112°12.8′E) is located on the southern continental slope, northwest of Borneo and is well within the west part of the WPWP at a water depth 1556 m. Sixty-two pollen samples were studied from the 13.03 m long profile, which is composed of homogenous dark-grey silty-clay. A timescale is provided by eight AMS 14C ages and the base is dated to 26 ky BP (30 cal. ky BP). Table 1 shows the main information about the studied cores.

All pollen samples were prepared for pollen analysis in the Laboratory of the Institute of Palynology and Quaternary Sciences at Göttingen University and followed techniques conventionally used there including the use of hydrochloric and hydrofluoric acids to remove carbonates and silicates. The material remaining after the cold hydrofluoric reaction was sieved through a 10 μm mesh in an ultrasonic basin bath. Percentages of pollen and spores were calculated based on the total pollen sum of terrestrial arboreal and herbaceous plants. Pollen influx was determined from addition of Lycopodium tablets technique and expressed as number of pollen grain per cm² per year.

4. Pollen assemblages

This paper focuses on a reconstruction of the vegetation that grew on the continental shelf at the low sea level stand of the last glaciation, so pollen counts from other geological periods are not discussed at length here. All pollen diagrams have been simplified to show only the most important ecological groups and taxa only (Table 1).
Table 1
Location and sample information of study cores

<table>
<thead>
<tr>
<th>Core</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
<th>Core length (m)</th>
<th>Number of samples</th>
<th>Size of samples (ml)</th>
<th>Sampling interval (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17940</td>
<td>20° 07' N</td>
<td>117° 23' E</td>
<td>1727</td>
<td>13.30</td>
<td>103</td>
<td>10-20</td>
<td>Every 10</td>
</tr>
<tr>
<td>17964</td>
<td>6° 57' N</td>
<td>112° 12' E</td>
<td>1536</td>
<td>13.03</td>
<td>62</td>
<td>20</td>
<td>Every 20</td>
</tr>
</tbody>
</table>

4.1. Core 17940 (Table 2, Fig. 2a and b)

Pollen assemblages of the LGM (15 000–25 300 yr BP) and MIS 3 (25 300–37 000 yr BP) are quite similar and, in comparison with those of the Holocene, have much lower percentages and influx values of tree pollen and much more of herbaceous pollen. There are two major ecological assemblages: conifers, including pine and montane conifers (Pinus, Abies and Tsuga, amounting to 25% of the total pollen sum of land seed plants, the same below) and montane rainforest Gymnosperms (Podocarpus, Dacrycarpus, Dacrydium and Phyllocladus up to 24%) and herba-
ceous taxa dominated by Artemisia with high representation of Cyperaceae and Poaceae. The pollen spectra display a frequent alternation in dominance of the two above-mentioned pollen assemblages, implying rapid changes in vegetation and climate (Sun and Li, 1999).

Table 2
Stratigraphy, dating and main feature of pollen assemblages, Core 17940, The South China Sea

<table>
<thead>
<tr>
<th>Stage</th>
<th>AMS 14C age (y BP)</th>
<th>Calendar year (y BP)</th>
<th>Interval (cm)</th>
<th>Feature of pollen assemblages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>Present-10 000 700±65; 60</td>
<td>Present-11 600 0-660</td>
<td>0-660</td>
<td>Absolute dominance of Pinus pollen (&gt;90%), low proportion of herbs, montane conifers and tropical montane rainforest gymnosperms</td>
</tr>
<tr>
<td>Termination</td>
<td>Younger Dryas</td>
<td>10 000–11 300 11 280±110</td>
<td>11 600–13 300 660–725</td>
<td>Rise of montane conifers and tropical montane rainforest gymnosperms</td>
</tr>
<tr>
<td>Bolling-Allerød</td>
<td>11 300–15 000 13 090±140</td>
<td>13 300–18 250 723–870</td>
<td>13 090±140</td>
<td>High percentages of tropical evergreen taxa and montane conifers</td>
</tr>
<tr>
<td>Last glacial maximum (LGM)</td>
<td>15 000–25 300 16 490±220</td>
<td>18 250–28 800 870–1050</td>
<td>16 490±220</td>
<td>Alternations of two types of pollen assemblages, namely herb-dominated and montane conifer-marked. Details in text.</td>
</tr>
<tr>
<td>Marine Isotope Stage 3 (MIS)</td>
<td>25 300–37 000 35 500±2400</td>
<td>28 800–40 900 1050–1306</td>
<td>35 500±2400</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Simplified pollen diagrams of Core 17940 in the northern SCS. (a) Percentage diagram (based on total pollen sum of land seed plants). (b) Influx diagram (grains cm$^{-2}$ year$^{-1}$).
4.2. Core 17964 (Table 3, Fig. 3a and b)

Pollen spectra are characterized by alternating predominance of two ecological groups of pollen. The first group includes tropical montane rainforest gymnosperms (Podocarpus, Dacrycarpus, Dacrydium and Phyllocladus) reflecting a cool and humid climate. The second group is of tropical lowland rainforest taxa. One hundred and fourteen taxa were identified in this group and include Elaeocarpaceae, Euphorbiaceae, Actinidiaceae, Araliaceae, Sapotaceae Altingia, Alchornea, Mallotus. This group also contains the mangroves Rhizophora, Sonneratia and Lumnitzeria (shown separately in the pollen diagrams). This group indicates a hot and humid climate. Both pine pollen and fern spores (Cyathea, Gleichenia, Stenochlaena etc.) are recorded in high percentages and change simultaneously with the montane rainforest gymnosperms. In contrast to the pollen taxa cited above, herbaceous pollen representation is much lower in both percentage and influx, and remains very stable throughout the profile of the last glaciation.

5. Vegetation on emerged continental shelf, SCS

What kind of vegetation, if any, colonized the new land of the exposed continental shelf of the SCS? Because there are normally no fine-grained sediments preserved on continental shelves, pollen from sediment of the nearby deep sea provides the only guide to answer this question. Since pollen transport and deposition processes in the deep sea is complicated, dependable reconstruction of vegetation based on marine pollen data demands consideration of these mechanisms and of pollen source areas. Generally, there are two transport media to marine sediments: wind and water. A study of the modern distribution pattern of pollen in the surface sediments from 46 cores of the SCS (Sun et al., 1999) suggests two principal pollen transport components in the northern SCS. Pollen grains of large size, inclined to dispersal by wind and flotation on water, such as pine pollen and fern spores, are transported chiefly by sea currents driven by the winter monsoon and enter the SCS through the Bashi Strait. These pollen and spores are counted in great numbers and have large source areas, probably including the southeast part of China. On the other hand, small and dense pollen grains, such as those of most herbs and tropical and subtropical plants, are transported mainly by rivers from the south coast areas of China and are found commonly in very low concentrations (Sun et al., 1999). Pollen grains recovered from the southern SCS cores usually occur in very low numbers (ca. one-tenth of those of the northern part) and reached there mainly by river transport from Borneo (Sun et al., 1999). During the last glaciation, lowering of the sea level closed the passageway between the Indian Ocean and the SCS, and the latter became somewhat, a more or less closed basin, thus changing the source area and route and mechanisms of transport of pollen (Wang and Wang, 1990).

5.1. The Northern Continental Shelf

The pollen spectra from Core 17940 show that the climate was in general much colder and drier at the last glaciation, but the alternating pollen assemblages of the two ecological types mentioned above should be related to two different vegetation patterns. The recurrent assemblage characterized by montane conifers indicates periodic expansion of the cold tolerant montane conifer forest from the north and northwest to the southeast of the China mainland, whereas the herb-dominant assemblages represent the development of dry grassland. Their quasi-cyclic occurrence implies a frequent alternation of comparatively cold and humid phases, with more temperate and drier phases, both superimposed upon the generally cold dry climate characteristic of the last glaciation. Nevertheless, one question remains unknown: where was the grassland? Extremely high percentages and influxes of herbaceous pollen from the glacial samples reveal that Artemisia-dominant grassland, with Poaceae (Gramineae) and Cyperaceae occupying wet places or swamps, occurred somewhere near the study site. Two possible regions support such grassland, the southern coastal areas of the China continent or the emerged northern continental shelf of the SCS. The percentage isopoll map (lines joining points
Table 3
Stratigraphy, dating and main feature of pollen assemblages, Core 17964, the South China Sea

<table>
<thead>
<tr>
<th>Stage</th>
<th>AMS 14C age (y BP)</th>
<th>Calendar year (y BP)</th>
<th>Depth (cm)</th>
<th>Main feature of pollen assemblages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>Present–9692</td>
<td>Present–10 400</td>
<td>0–288</td>
<td>Low pollen influx. Upper part (2.3–0.5 ka). Dominated by Pinus pollen and fern spores.</td>
</tr>
<tr>
<td></td>
<td>950 ± 35 – 35</td>
<td></td>
<td></td>
<td>Middle part (5.2–2.3 ka). Dominance of lowland rainforest and mangroves. Lower part (9.7–5.2 ka). Slight increase of lowland rainforest pollen and decrease of montane rainforest gymnosperms.</td>
</tr>
<tr>
<td></td>
<td>4280 ± 60 – 59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6120 ± 66 – 65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7305 ± 74 – 73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9690 ± 93 – 92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Termination</td>
<td>9692–16 000</td>
<td>10 400–19 700</td>
<td>288–600</td>
<td>The highest pollen influx of the profile. Frequent alternation of dominance of montane rainforest gymnosperms and lowland rainforest taxa. Very similar to LGM and MIS 3, but more frequent alternations.</td>
</tr>
<tr>
<td></td>
<td>11 110 ± 120 – 120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Last Glacial Maximum</td>
<td>16 000–22 000</td>
<td>19 700–25 400</td>
<td>600–918</td>
<td>High pollen influx. Frequent alternation of the two types of assemblages mentioned above. Detail in text</td>
</tr>
<tr>
<td>Marine Isotope Stage 3 (MIS3)</td>
<td>22 000–26 000</td>
<td>25 400–30 035</td>
<td>918–1178</td>
<td></td>
</tr>
</tbody>
</table>

with similar pollen percentages) of Artemisia in China at 18,000 yr BP (Fig. 4) shows that the highest percentages of Artemisia pollen occurred in northern China, declining gradually to the south. In terrestrial pollen records from southern China and Taiwan, Artemisia pollen is found usually with values of ca. 10% or less, which, in most cases, are dominated by Poaceae during the LGM. For example, pollen assemblages of peat dated to 17,830 ± 890 yr BP from Fujian [Fig. 6(Site 5)] are dominated by Poaceae (19.5–36.3%). At that site, Artemisia ranges from 3.7 to 8.5%. The pollen spectra indicate a grassland or woodland (Zheng and Gao, 1986). Pollen recovered from clay sediments from Chao-Shan Plain [Fig. 6(Site 6)] indicate a mixed broad-leaved evergreen and deciduous forest with considerable temperate taxa, for example, Carpinus, Alnus, Fagus, Quercus during the period 28,000 to 23,000 yr BP (Zheng, 1991). Grassland or savanna vegetation on Leizhou Peninsula [Fig. 6(Site 9)] is suggested from pollen spectra dominated by Poaceae (28–55%) with Artemisia 7–10% between 29,000 and 15,000 yr BP (Zheng and Lei, 1999). Pollen assemblages from Toushe peat bog [Fig. 6(Site 8)] in central Taiwan are dominated by herbs (Poaceae up to 50%, Artemisia 12%) suggesting an open vegetation and dry climate during the LGM. In the Taiyeh Basin of northern Taiwan [Fig. 6(Site 7)] a semi-open to open vegetation is indicated by a pollen record dominated by herbs (up to 65%). Poaceae pollen is the chief element of that site (Liew et al., 1998). Consequently, as Core 17940 is situated further south than continental southern China, not much Artemisia pollen could have derived from that source. The alternative explanation is that the Artemisia grassland occupied the exposed northern continental shelf from where it supplied pollen during the last glaciation. Today Artemisia, as herb or small shrub, is widely distributed in temperate grassland in the Northern Hemisphere. High percentages of its pollen occur in modern surface sediment samples from Northwestern China. A pollen-climate response surface for northern China shows that 30–50% of Artemisia pollen is indicative of an annual precipitation range of 300–500 mm, with an average July temperature range of 15–24°C. This implies a climate much colder and drier than that of the studied area at present (Sun et al. 1996). This also suggests that the northern SCS during the last glacial time was much colder and
Fig. 3. Simplified pollen diagrams of Core 17964 in the southern SCS. (a) Percentage diagram (based on total pollen sum of land seed plants). (b) Influx diagram (grains cm$^{-2}$ year$^{-1}$).
drier than today. Pollen data for the last glacialation from southern China and Taiwan discussed above also point a much cooler and drier climate, probably ca. 4–6°C lower than today (Zheng and Gao, 1986; Zheng and Lei, 1999).

The northern continental shelf is composed mainly of sandy soil, a favourite habitat for Artemisia (Sun et al., 1994). This might be another factor, probably no less important than climate, which controlled the grassland growing on the exposed shelf during low sea level stands. The pollen assemblages marked by montane conifers and montane rainforest gymnosperms probably imply that their forests grew on the mountains of the Chinese mainland, expanding during periods of colder and more humid climates than those of the grassland phases. Their pollen was blown to sea by enhanced northeast winter monsoons. A portion of the pollen of montane rainforest gymnosperms was brought from lower latitudes, for example, Borneo and Sumatra, especially Phyllocladus that does not grow in the areas around the northern SCS. These relative short-term oscillations may be due to climatic fluctuations but the influence of otherwise unrecorded and minor changes in water circulation cannot be ruled out.

5.2. The Southern continental shelf — the 'Sunda Shelf'

The pollen spectra of Core 17964 indicate that, during the last glacialation, the lowland was covered by tropical lowland rainforest, and mangroves grew along the river mouths and along the coast. Mountains were covered by montane rainforest gymnosperms, and these periodically were migrated down-slope. The climate was periodically cooler than that of present day, but no dry conditions were observed (Li and Sun, 1999).

The subaerially exposed Sunda Shelf was connected with Sumatra, Java and Borneo to form a single large landmass — 'Sunda Land' — during the last glacial low sea level stand. On it existed a large river system called Sunda River or Molengraaff River, as established by numerous depth soundings (Tjia, 1980). One part of the old river system, on the middle of the Sunda Land, flowed from what is now the eastern shore of Sumatra and the west coast of Borneo across a thousand kilometres of Sunda Land to eventually discharge into the southern continental slope of the SCS, very close to the study core. By contrast, during the high sea level stand of the Holocene and today, all the local rivers are small, discharging
from the individual islands directly into the southern part of the Sunda Shelf that is submerged by the sea. Therefore, during the last glacial period the distance between the studied core and the river mouths was shorter and the river catchment much larger than today; much more sediment and pollen could therefore have reached the core during the last glaciation. This explains why the pollen fluxes of the last glacial time were dramatically larger by comparison with those of the Holocene. This situation does not only apply to this core, but more clearly to a nearby core 17962 (Fig. 5). The pollen grains and spores from the latter study core originated chiefly from the vegetation covering Sunda Land and were carried by the Sunda River during the last glaciation.

Palynological studies at montane sites in West Java (Stuijt et al., 1988; Heaney, 1991; Van der Kaars and Dam, 1995), Central Sumatra (Stuijts, 1984; Newsome and Flennley, 1988) and New Guinea (Walker and Flennley, 1979) showed that the montane vegetation zones reached lower altitudes at the last glaciation than today. Large amounts of montane rainforest gymnosperm pollen found at lower montane sites before 10 000 yr BP indicate a depression of some 200-1700 m in montane vegetation zones and postulated temperatures would have been ca. 2-7 °C lower than today. This vegetation is probably the source of montane rainforest gymnosperm pollen represented in the study sites during the glacial period. We suggest that, at that time, most of lowland rainforest and mangrove pollen came to the study site from the exposed parts of Sunda Land, whereas the montane rainforest gymnosperm pollen came from the mountains of Sumatra and Borneo. Although the present lowlands of these islands may have provided a small proportion of the lowland rainforest pollen at last glaciation, most of it was drawn from the forest on the then exposed Sunda Shelf. The montane rainforest, represented by the gymnosperm taxa such as Podocarpus, Dacrycarpus, Dacrydium and Phyllocladus, most probably grew on mountains of surrounding islands and migrated up and down slope as a result of temperature changes.

6. Vegetation on other exposed continental shelves at low-latitude in the Western Pacific

As mentioned above, there are two other large shelves exposed during the last glaciation in the low-latitude West Pacific region aside from the SCS shelves: the East China Sea and the Sahul Shelf. We attempt here to review the available pollen spectra so as to examine palaeovegetation on all large exposed shelves within this region.

6.1. East China Sea

Apart from the Okinawa Though, the entire area of the East China Sea was exposed at the last
glacial low sea-level stand, including the Yellow Sea and Bohai Gulf. There are a number of cores with pollen spectra and $^{14}$C ages in the northern (the Yellow Sea) and middle parts of the East China Sea revealing vegetation and environment on the continental shelf during the last glaciation, although the time resolution of some pollen records is rather low (Liu et al., 1987; Qin et al., 1987; Zheng, 1989). Available pollen data [Fig. 6(Sites 1–4)] for the ca. 11 000–20 000 yr BP period show a predominance of herbs (ca. 60–70%), with Artemisia and Chenopodiaceae as the main components and Poaceae in high numbers. Ephedra, a drought-tolerant shrub, is found occasionally in considerable pollen frequencies (e.g. up to 29% in site 1); Typha (a shallow water herb) and Cyperaceae (swampy herb) also have high values and tend to increase from north to south. Tree pollen is present in low percentages and composed chiefly of pine, temperate broad-leaved deciduous taxa (Quercus, Betula etc.) and montane conifers (Abies and Picea, up to 4–5%). Fern spores usually occur in relatively low frequencies (ca. 1%).

In contrast to the pollen assemblage of the glacial time, the Holocene is characterized by higher frequency of tree pollen taxa, absence of montane conifers, higher percentage of fern spores and a small proportion of herb pollen. This implies that grassland consisting mainly of Artemisia and Poaceae, and salt-water marsh with Chenopodiaceae were widely distributed on the continental shelf of the north and middle East China Sea which was exposed at the low sea-level stand during the last glacial period. Freshwater habitats and swamps with Typha and Cyperaceae probably were also scattered on the exposed shelf. The composition of tree pollen perhaps indicates that mixed temperate woodland or forests were distributed on the adjacent land and the montane conifers, such as Abies and Picea, occurred on nearby mountains during the last glaciation. This is in contrast with the warm temperate mixed pine and oak forests in the north and subtropical evergreen broad-leaved forest in the middle parts of the adjacent land at present. In comparison with the Holocene, the climate during the last glaciation was much colder and drier and the level of dryness probably increased northward.

6. Sahul Shelf

The Sahul Shelf or the great Australian Bank, includes the Timor Sea Shelf, the Arafura Shelf and the Gulf of Carpentaria. Pollen spectra are provided by Van der Kaars (1991), who presented a number of pollen diagrams of marine piston-cores from eastern Indonesia with some sites from the seas northwest of Australia [Fig 6(Sites 17–19)]. The pollen diagrams are remarkably similar to each other, showing very high percentages of Poaceae, low proportions of fern spores and reduced amounts of montane forest and tropical lowland taxa at around 18 000 yr BP. It is assumed that the large part of pollen was derived from northern Australia and the exposed part of Sahul Shelf during this period of low sea-level stands. The high frequency of grass pollen reflects an expansion of grassland vegetation in northern Australia, advancing over the emerged parts of the Sahul Shelf. This implies a very dry climate with annual rainfall of 100–500 mm (Van der Kaars, 1991). Pollen records from a piston-core situated in the deep part of Ceram Trench [Fig. 6(Site 16)] indicate expansion of grassland and woodland, a shrinkage of the fern cover and a reduction of the middle-upper-montane forest taxa, again suggesting drier and cooler conditions between 9500 and 14 000 yr BP. The pollen grains at those sites are thought to have come from New Guinea (Van der Kaars, 1991).
Fig. 6. Sketch vegetation reconstruction for the exposed shelves of low-latitude West Pacific during the LGM [for Sahul Shelf cited from Van der Kaars (1991)].

1. Core H80-17, Yellow Sea (northern East China Sea) (Liu et al., 1987).
2. Core QC 2, Yellow Sea (Zheng, 1989).
3. Core H80-14, Yellow Sea (Liu et al., 1987).
4. Core Ch 1, East China Sea (Qin et al., 1987; Meng et al., 1989).
7. Taipri Basin, Taiwan (Liew et al., 1998).
8. Toudhe peat bog, Taiwan (Liew et al., 1998).
11. Danau di Atas, Sumatra (Stuijt et al., 1988).
15. Core K12, Halmahera, north Malucca Sea (Bemawidjaja et al., 1989).
17. Core G4-121P, the Molucca Sea (Van der Kaars, 1991).
18. Core G5-2-140P2, the Flores Trench (Van der Kaars, 1991).
19. Core G6-4, the Lombok Rige (Van der Kaars, 1991).

Filled circles show the studied core sites. Sites marked by triangles indicate pollen-based climate without aridity during the last glaciation. Cores 17964 and 17962 marked by black circles are also included. Sites marked by circles indicate arid climate during the last glaciation.
Sea and Poaceae for the Sahul region. Moreover, all the shelves experienced a colder and drier climate during the last glacial time than today, apart from Sunda Land.

Sunda Land was covered by lowland rainforest and mangroves, which seem not much different from the vegetation growing on the lowlands of today’s surrounding islands. The periodic expansion of montane gymnosperms implies falling temperature, at least on the mountains of surrounding islands, but no desiccation was found during the glacial period.

To better understand and interpret the characteristics of the Sunda Land at low sea level, a brief summary of the palaeovegetation and palaeoclimate deduced from pollen data of related areas in the Southeast Asia is necessary. In the north, the offshore pollen records from the East China Sea [Fig. 6(Sites 1–4)], as well as terrestrial data from Taiwan [Fig. 6(Sites 7 and 8)] and from the southern coast of the Chinese mainland [Fig. 6(Sites 5, 6 and 9)] indicate grassland to open-forest vegetation and a cooler and drier climate during the last glaciation. In the south, almost all marine cores from eastern Indonesia [Fig. 6(Sites 15–19)] show open vegetation and a drop of temperature and humidity for the northern Australia and southeast New Guinea during the glacial period. However, the situation was more complicated in the terrestrial records. For instance, in Sumatran and west Javan Highlands [Fig. 6(Sites 11 and 14)] the lowering of forest altitudinal zones and increased abundance of gymnosperms at moderate elevation (1300–1500 m a.s.l.) imply a considerable fall of annual temperature down to 7°C lower than at present, but no dryness was observed during last glacial period (Stuji et al., 1988). Moreover, abundant pollen of Nothofagus and gymnosperms from the last glacial time in north lowland Irian Jaya [Fig. 6(Site 20)] shows a downward shift of the higher-altitude forest, and cool, but moist and probably misty conditions prevailed there (Hope and Tulip, 1994). By contrast, a clear indication for cooler and drier climates in the lowland of Java [Fig. 6(Site 13)] is provided by lowering the montane forest vegetation boundaries by 1200 m, associated with changes from closed freshwater-swamp forest to open herbaceous-swamp dominated by Poaceae and Cyperaceae (Van der Kaars, 1998). Similarly, a pollen diagram from southeast Borneo [Fig. 6(Site 10)] shows an increase of savanna at ca. 20,000 yr BP, this might serve as an indicator of a drier climate than at present (Flenley, 1998). However, Flenley pointed out that dating for this diagram was poor. A very dry climate with Eucalyptus woodland or savanna occurred between 26,000 and 8000 yr BP at Lynch’s Crater [Fig. 6(Site 20)] in the humid tropics, north-east Australia (Kershaw, 1976, 1994).

So all the relevant data agree that temperatures were lower during the last glacial but the indications of humidity differ between sites.

The Asian monsoon system may offer an approach to this problem (Wang, 1999), and glacial intensification of the winter monsoon may explain the difference in humidity at various sites. In the East Asian continent, moisture is mainly supplied by the summer monsoon, which was weakened during the glacial period. A combination of the glacial reduction in sea area and lowering of SST in the West Pacific marginal seas (Wang, 1999) resulted in a decrease in the evaporation rate from the sea, while the weakened summer monsoon would have brought less precipitation to the East Asian land intensifying aridity during the LGM (Wang et al., 1997). On the other hand, the amplified northeast winter monsoon would also give rise to a cold and dry climate, not only in the high and middle latitudes, but also in the low latitudes of the continent, including the northern SCS. These factors can explain the intense aridity and temperature cooling on the north shelf of the SCS.

In contrast, precipitation in the islands between Australia and Asian continent is derived chiefly from the northern (or boreal winter) monsoon, which becomes the summer monsoon when crossing the Equator. The modern boreal winter monsoon transfers vapour and cold air from the marginal seas to the southern islands, and the monsoon fluctuations are responsible for the variations in precipitation over the islands (Lim and Tuen, 1991). During the last glaciation, the strengthened northern monsoon absorbed moisture when crossing the sea and should have provided more precipitation to the islands south of the southern SCS including Sumatra, Java, Borneo, Malaysia. Therefore, the pollen sites with-
out relief obstruction would have received rainfall from the moisture-laden airmass from north. The sites from the southern SCS and Sunda Shelf [Danau di Atas (Fig. 6, Site 11)] from Sumatra (1535 m a.s.l.), Bayongbong [Fig. 6(Site 14)] from west Java (1300 m a.s.l.); Siruniki, Papua New Guinea [Fig. 6(Site 12)] and Hordorli [Fig. 6, Site 20] from Irian Jaya must belong to this group of sites, where no desiccation was registered by the vegetation reconstructed in the glacial period. All other sites, located in the rain-shadow areas behind mountains such as those of New Guinea could not receive much moisture from the monsoon. As a result of this phenomenon, these locations experienced arid climates during glaciation. This explains the discrepancy between sites showing arid versus humid climates during glaciation. The only exception is the Halmahera site [Fig. 6(Site 15)]. Halmahera should be assigned to the first group of sites without desiccation, but the pollen spectra reveal replacement of a tropical rainforest by a low montane oak forest which was ascribed to aridity of the climate (Barmawidjaja et al., 1989, 1993). In fact, the assignment of a low-montane oak to a dry climate requires further justification. As pointed out by Barmawidjaja et al. (1989) themselves, most of oak taxa (Castanopsis and Lithocarpus) require a humid climate. Without identification at species level, the question remains unanswered.

It is worth noting that the former climate being without desiccation as interpreted from the vegetation in the southern SCS and some places of Southeast Asia does not exclude the possibility of a decline in precipitation. Since the present climate is extremely humid, “there could be a decrease in the total precipitation which the area receives, without there necessarily being any recognizable effect on vegetation” (Newsome and Flenley, 1988). The scenario that differences in climate (precipitation in particular) were enhanced during the glaciation, between the northern and southern SCS regions, is supported.

8. Conclusion

1. Last-glacial pollen assemblages from the northern and southern slopes of the SCS reveal a significantly enhanced climate contrast between the two sides of the sea. The northern continental shelf of the SCS was covered by grassland indicative of a drier climate than today, and the southern shelf was occupied by tropical lowland rainforest characteristic of present day humid conditions.

2. During the last glaciation, three large continental shelves emerged from the lower latitude marginal seas of the western Pacific: the exposed East China Sea Shelf and the Sahul Shelf experienced a dry climate, whereas the Sunda Shelf enjoyed a humid climate.

3. The enhanced boreal Winter Monsoon is believed to be responsible for the discrepancy in climate between the various shelves. Thus, the strengthened northern monsoon wind gave rise to aridity in the northern shelf of the SCS, but brought moisture to its southern shelf.

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