Vegetation evolution and its response to climatic change during 3.15–0.67 Ma in deep-sea pollen record from northern South China Sea

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In order to study vegetation evolution and environmental change during 3.15–0.67 Ma, a total of 608 pollen samples with an average time resolution of 4 ka has been analyzed from ODP Site 1145 (water depth 3175 m), northern South China Sea. The deep-sea sediments (213.62–91.9 m) cover from 3.15 to 0.67 Ma based on micropaleontological stratigraphy. The characteristic features of the pollen diagram include that, pollen influx rises twice obviously around 2.58 Ma and during 2.0–1.8 Ma, in response to global climatic cooling and winter monsoon enhancement. Before 2.58 Ma, tropical and subtropical vegetation, mainly evergreen *Quercus* (E) and *Altingia*, predominated around northern SCS with much more tropical montane conifers and ferns relatively. From 2.58 Ma, temperate vegetation increased obviously, implying climatic cooling and winter monsoon enhancement. Spectral analysis shows that percentage variation in tropical and subtropical taxa has a strong 20 ka procession cycle probably due to the summer monsoon; while pollen influx has 100, 41 and 19 ka cycles, indicating the sea level and winter monsoon change response to the ice-sheet variations.

Site 1145, pollen, vegetation evolution, South China Sea, monsoon

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Comparison among paleoclimate records in between the Pliocene and Pleistocene of the East Asian monsoon, Indian monsoon and West African monsoon reveals that obvious climatic transformation happened during 2.8–2.5 Ma and during 1.8–1.6 Ma [1–4], mostly focusing on the formation of Northern Hemisphere Ice Sheet and its influence on global climate change [5–10]. Recent researches show that the tropical sea around the West Pacific Warm Pool plays a key effect on the global climate change [11,12]. The South China Sea attracts wide attention in paleomarine research [13–20]. The East Asian Monsoon is one of the chief components of the global climatic system. Its genesis is due to the different sea-land thermal effect between the Asian Continent and the West Pacific Warm Pool, behaving as the seasonal conversion of wind and precipitation. Deep sea

sediment pollen analysis proves that during the Last Glaciation the winter monsoon enhancement and the summer monsoon decreasing results in dry climate [21]. Up to now research on the long-term variation of the East Asian monsoon mainly focuses on loess research. Few records come from marine sediment. Sun et al. [22–24] have used the tree pollen influx as a winter monsoon proxy and the proportion of fern spores to total pollen sum as a summer monsoon proxy to reconstruct vegetation evolution and monsoon history during the past 1 Ma from the deep sea pollen in ODP Site 1144. Yuan et al. [25] reconstruct the history of vegetation evolution and climate change during 3.0–2.0 Ma based on the deep sea pollen record from ODP Site 1143 in the southern South China Sea. Boulay et al. [26] use clay mineral assemblages and isotopic data of sediment from ODP Site 1145 to trace the sources of sediment seeding the north part of the South China Sea and to investigate the evolution of

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East Asian Monsoon intensity over the last 450 ka. Wehausen et al. [27] use geochemical data and carbonate component variation to reconstruct the East Asian Monsoon variation during 3.2–2.5 Ma and its response to orbital force. In this paper, the high-resolution pollen record from deep sea sediments of ODP Site 1145 is used to reconstruct the vegetation evolution and the history of the East Asian Monsoon during 3.15–0.67 Ma.

1 Physical geography of the studied area

The SCS is a marginal sea in the western Pacific Ocean. The northern continental shelf of the SCS is ca. 165–278 km wide, ca. 100 km long and covers an area of ca. 400000 km². Water depth varies between 0 and 150 m [28,29]. Off the continental shelf with gentle slope (average 5°) is the comparatively steep continental slope with a water depth between 1500 and 3200 m. ODP Site 1145 (19°35.05'N, 117°37.86'E) is located on the northern continental slope of the South China Sea at a water depth of 3175 m. Bordered by China and Indochina in the north and west, and Indonesia and the Philippine Archipelago in the 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. With seasonal changes in wind, the East Asian monsoon plays a great role in the climate of the SCS and its ambient landmasses. The winter monsoon blows northeasterly from the Asian continent to the ocean and the summer monsoon blows southwesterly from the ocean to the Asian continent [30]. 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 stratigraphy of the hemipelagic sediments. As a semi-enclosed basin in connection with the open ocean, it is able to record both global (glacial/interglacial oscillations) and local (monsoon) climatic changes. High sediment inputs and good carbonate preservation provide reliable information about the paleoenvironmental variations affecting the Southeast Asian continent and allow reconstruction of the East-Asian monsoon history.

The vegetation of Southeast China and Taiwan Island is the main pollen source of the northern SCS. The coastal area of South China is relatively flat, with hills less than 150 m a.s.l. and some isolated mountains, reaching 1870 m in Hainan and 3950 m in Taiwan [31]. Restricted to areas of Hainan and Taiwan islands, tropical rainforests are represented mainly by Dipterocarpaceae (*Dipterocarpus*, *Hopea*, *Vatica*, *Shorea*) and accompanied by *Pterospermum*, *Heritiera*, *Sterculia*, *Dysoxylum*, *Aglaia*, and some genera of Moraceae, Sapindaceae and Sapotaceae. In the lowlands (ca. 500 m a.s.l.) with a short dry season in late autumn and winter, semi-evergreen forests are found consisting mainly of taxa from Moraceae, Sapindaceae, Meliaceae, Tiliaceae,

Euphorbiaceae, Annonaceae, Sapotaceae, Bombacaceae and Dipterocarpaceae. In the low montane zone (ca. 600–1500 m a.s.l.) tropical montane rainforest and seasonal evergreen forest occur. The main taxa in these forests are from Lauraceae, Fagaceae, Magnoliaceae, including such genera as *Castanopsis*, *Lithocarpus*, *Quercus*, *Cyclobalanopsis*, *Machilus*, *Cinnamomum*, *Phoebe*, *Magnolia* and *Michelia*. On the mountains at middle elevation (above 1500 m a.s.l.), temperate broadleaved deciduous forests are found, which are dominated by *Carpinus*, *Betula*, *Alnus*, *Acer* and *Nyssa*. With increasing altitude, tropical montane conifers occur, including *Podocarpus*, *Dacrycarpus*, *Dacrydium*, *Pinus kwantungensis*, *Cephalotaxus*, *Tsuga*, *Keteleeria* and *Cadocedrus*. On the high mountains of Taiwan (3000 m a.s.l.), montane conifers such as *Abies* and *Picea* appear. Along the southern and southeastern coast of China are scattered mangroves, mainly Rhizophoraceae (*Rhizophora kandelia*, *Bruguiera*, *Ceriops*, etc.) [31,32]. North of the seasonal rainforest zone mentioned before, roughly between the Tropic of Cancer and 34°N, lies the subtropical evergreen broadleaved forest zone. The vegetation is chiefly composed of *Castanopsis*, *Quercus*, *Cinnamomum*, *Lindera*, *Liquidambar*, *Altingia*, *Theaceae*, and some taxa of Guttiferae, Annonaceae and Myrtaceae. North of the Tropic of Cancer, between 24° and 27°N, is the Nanling Mountains. The vegetation there consists mainly of evergreen broadleaved forest (e.g. *Castanopsis*, *Theaceae*, *Lauraceae*), while above 1200 m *Podocarpus*, *Cyclobalanopsis* and *Betula* appear.

2 Material, methods and chronostratigraphy

Pollen samples were taken from ODP Site 1145 (19°35.05'N, 117°37.86'E) on a sediment drift located in the northeastern SCS at water depth of 3175 m [33]. The sediment consists of deep sea sedimentary clay with 5%–50% carbonate [33].

In order to study vegetation evolution and environmental change during 3.15–0.67 Ma BP, a total of 608 pollen samples with an average time resolution of 4.0 ka were analyzed from 213.62–91.9 m of the core. As there is a lack of Isotope age control, the micropaleontological age data are used in this study to reconstruct chronostratigraphy (Table 1) [33]. Based on these age controls, the ages for every sample are obtained by Linear interpolation.

Pollen samples were prepared in the Institute of Botany, Chinese Academy of Sciences, using hydrochloric and hydrofluoric acids to remove carbonates and silicates. To concentrate pollen and charcoal the remaining material after acid reactions was sieved through a 7 µm mesh in an ultrasonic bath. More than 200 pollen grains of land seed plants per sample were counted (i.e. excluding fern spores and pollen of aquatics). The pollen sum exceeds 100 pollen grains per sample; even when pine pollen and fern spores

Table 1 Micropaleontological chronostratigraphy of ODP Site 1145, SCS^{a)}

Code	Events	Depth (mbsf)	Depth (mcd)	Age (Ma)
CN	LO <i>P. lacunosa</i>	77.92	85.56	0.46
BF	LO <i>Stilostomella</i>	86.54	94.33	0.75
CN	LO <i>C. macintyreii</i>	139.90	152.77	1.67
PF	LO <i>G. fistulosus</i>	139.90	152.77	1.77
CN	LO <i>D. brouweri</i>	154.70	164.85	1.95
PF	FO <i>G. truncatulinoides</i>	161.41	171.58	2.0
PF	LO <i>G. multicamerata</i>	180.84	192.10	2.40
CN	LO <i>D. pentaradiatus</i>	180.84	192.10	2.45
CN	LO <i>D. tamalis</i>	190.39	201.97	2.83
PF	LO <i>S. seminulina</i>	199.87	212.54	3.12

a) CN, Calcareous nannofossil; PF, planktonic foraminifera; BF, benthic foraminifera, FO, first occurrence; LO, last occurrence.

were excluded. The percentages of groups and individual taxa were calculated on the pollen sum of all land seed plant pollen. The influx values were calculated by adding exotic pollen as a number of pollen grains accumulated on 1 cm² during a year (grains cm⁻² a⁻¹).

3 Results

A total of 120 pollen types have been identified. Except pine and some herbs, most pollen types occur only rarely, particularly some of the tropical and subtropical taxa. To make the pollen diagram easier to interpret, several groups of taxa are presented according to their plant ecology and modern distribution, namely as follows:

Temperate broadleaved taxa: *Betula*, *Alnus*, *Carpinus*, *Juglans*, *Ulmus*, *Fagus*;

Tropical and subtropical evergreen taxa: *Quercus*, *Altingia*, *Ilex*, *Castanopsis/Lithocarpus*, *Mallotus/Macaranga*, *Palmae*, *Melastomataceae*, *Meliaceae*, *Euphorbiaceae* and *Moraceae*;

Herbaceous group: *Artemisia*, *Poaceae* and *Cyperaceae* are the main components. *Compositae* and *Chenopodiaceae* occur only rarely;

Montane (boreal) conifers: *Picea* and *Abies*;

Tropical montane conifers: *Podocarpus*, *Dacrycarpus*, *Dacrydium*, *Tsuga*, *Phyllocladus*;

Aquatics: *Typha*, *Myriophyllum* and *Nymphaeoides*.

Mangroves: mainly *Rhizophora* and *Sonneratia*;

Besides pollen, there are sporadic *Anthoceros* and abundant fern spores including *Gleichenia*, *Davallia* and *Cyathea*.

Based on their pollen percentage and influx variations (Figures 1 and 2), three pollen zones are identified for ODP site 115 deep-sea sediments.

Pollen Zone I: 213.62–195.52 m, 3.15–2.58 Ma. Influx rates of pollen and spores are quite low. The total pollen influx is only 113 grains cm⁻² a⁻¹ by average (the same below).

Figure 1 Location of ODP Site 115 in the northern South China Sea.

This pollen zone is characterized by the high percentage of tropical-subtropical taxa (20% on average), mean pollen percentage of *Pinus* is 47.8%, of temperate broadleaved taxa is 12.5%, of tropical montane conifers 10%, percentages of other taxa are quite low. Mean percentage of fern spores is 75%.

Pollen Zone II: 195.52–171.5 m, 2.58–2.00 Ma. Compared with pollen zone I, pollen influx rises greatly up to 353.8 grains cm⁻² a⁻¹, about three times as high as that in Zone I.

This pollen zone is characterized by high mean percentages of temperate broadleaved taxa (up to 18.7%), and percentage of tropical montane conifers (13.7%) rises a little; while percentage of tropical-subtropical taxa (12.7%) drops obviously. Percentages of other taxa are quite low. Percentage of fern spores drop to 62.8%.

Pollen Zone III: 171.5–91.9 m, 2.00–0.67 Ma. Compared with pollen zone I and zone II, pollen influx rises continuously up to 685 grains cm⁻² a⁻¹, about six times as high as that in Zone I.

This pollen zone is characterized by high mean percentage of *Pinus* (56%), while the mean percentage of temperate broadleaved taxa drop to 13.5% and percentage of tropical montane conifers drops to 8.8%; percentage of tropical-subtropical taxa is 13.3%. Percentages of other taxa are quite low. Percentage of fern spores drop to 60.8%.

The variation of pollen assemblage percentage is characterized by the alternation of *Pinus*, temperate taxa and tropical-subtropical taxa in ODP Site 1145.

Pinus (40%–80%) dominates the pollen assemblages throughout the profile (Figure 3). The maximum value (reaching up to 80%) occurs in pollen Zone 3 (2.0–0.8 Ma). In the lower part of Pollen zone I (3–2.7 Ma), pollen percentage of *Pinus* (60%) is a slightly higher, while it varies around 50% most of the time.

Temperate broadleaved taxa. Pollen types of some

Figure 2 Pollen influx diagram from ODP Site 1145, northern South China Sea (grains $\text{cm}^{-2} \text{a}^{-1}$).

Figure 3 Pollen percentage diagram from ODP Site 1145, northern South China ($\%$).

broadleaved deciduous trees are assigned to the temperate broadleaved group, with deciduous *Quercus*, *Alnus* and *Ulmus* being the major components. Pollen percentages of temperate taxa are lower than 20% (14.5% on average) of the total core. But in the lower part of Pollen Zone II (2.58–2.20 Ma), percentage of temperate taxa rises clearly, mainly above 20% (24.7% on average). As shown in Figure 4, before 2.5 Ma, *Alnus* pollen occurs sporadically; from 2.5 Ma, percentage of *Alnus* pollen rises obviously, usually varying around 5%, especially from 1.4 to 0.8 Ma up to 10%. Percentage of *Ulmus* pollen is quite low throughout the total core, but in the Pollen Zone II (2.58–2.20 Ma),

Figure 4 Pollen percentage diagram of main temperate taxa from ODP Site 1145, northern South China Sea.

percentage of *Ulmus* pollen rises up to 10%. Before 2.0 Ma BP, percentage of deciduous *Quercus* pollen is lower than 5%, while after that, it varies around 5%.

Tropical and subtropical taxa. As shown in Figure 5, pollen percentages of tropical and subtropical taxa are 14.7% on average of the total core, with higher values (20% on average) in Pollen Zone I and dropping to 13% in Pollen Zone II and III. The tropical and subtropical group includes a large number of taxa, but only a few grains of each taxa can be encountered per sample. Evergreen *Quercus*, *Altingia* with higher percentage are the main components in Zone I. In Zone II (2.58–2.0 Ma), the percentage of Evergreen *Quercus* drops to the minimum value throughout the core. From 2.58 Ma, the content of *Altingia* pollen drops clearly. *Trema*, *Araceae*, *Engelhardtia* *Combretaceae*, etc. occur mainly before 2.0 Ma, while *Carya*, *Castanopsis*, occur mainly after 2.0 Ma with higher quantity relatively.

Montane conifers: mainly *Abies* and *Picea*, percentage of Montane conifer pollen is quite low throughout the total core, only 3.7% on average.

Tropical montane conifers: Percentage of the tropical montane group is 10% on average, mainly represented by *Podocarpus* (3%), *Dacrydium* (2.4%), *Dacrycarpus* (4.1%). The pollen percentage of this group is higher before 2.0 Ma, varying above 10% with cyclic oscillation; from 2.0 Ma, the content of this group drops to 8.5% on average, varying stably.

Herbs: Herbaceous taxa consist of *Chenopodiaceae*, *Artemisia*, *Gramineae*. The percentage of herbaceous pollen is quite low throughout the total core, only 5% on average. In very few samples its maximum value is no more than 20%. Due to the lower content, there is no obvious varying feature in herbs throughout the total core.

Aquatic and Mangroves occur in low proportions (less than 2%) throughout the total core.

Figure 5 Pollen percentage diagram of main tropical-subtropical taxa from ODP Site 1145, northern South China.

Fern spores are found in large numbers, varying above 50%, with an average proportion about 64% in the total core. In pollen zone I, the fern spores shows a higher proportion about 75%, while its proportion drops to 62% and 60% respectively in Zone II and III. From 2.0 Ma, it varies with a regular cyclic oscillation in relatively larger amplitude.

4 Discussion

All of the recovered pollen and fern spores of terrestrial plants must have been dispersed from land. Pollen and spores deposited in deep-sea sediments are mainly transported by wind and water. Understanding the relationship between modern pollen distribution in surface sediments and the distribution of source vegetation is essential for the interpretation of fossil pollen assemblages in terms of paleoclimate and paleovegetation. Research on the tectonics of the South China Sea by Yao reveals that, the seafloor spreading NW-SE happened in Eocene-early Oligocene, producing the northwest and southwest basins. Another seafloor spreading occurred in the late Oligocene-early Miocene, and caused the Central Basin [34]. The sediment records on the evolution of the South China Sea from ODP Leg 184 indicate that the sedimental environment difference between the northern and the southern South China Sea developed before 3 Ma BP, which is similar to the modern pattern [35].

Research on pollen distribution patterns in the surface sediments of the SCS shows that the northern SCS is marked by very high percentages (up to 90% of total pollen sum) and concentrations of tree pollen, in which *Pinus* (80%) is dominant. Pine is an evergreen conifer distributed widely in temperate and subtropical areas of the Northern Hemisphere. It is a prolific pollen producer and its pollen is easily dispersed. The *Pinus* pollen distribution pattern in surface sediments of the SCS implies that pine pollen, adapted to wind and water transport, is mainly transported by the NE winter monsoon and wind-driven currents from large source areas (probably including South and Southeast China) through Bashi Strait and then spreading southwestward. Although tropical and subtropical plants are common on the mainland of South China and the Islands, their pollen concentrations in surface sediments in the northern SCS are quite low. However, the fact that their concentrations are somewhat higher along the coast implies that fluvial and offshore current transport is mainly responsible for their distribution [34,35].

4.1 Vegetation evolution during 3.15–0.67 Ma on the ambient land around northern South China Sea

Based on the variation of pollen percentage and pollen influx, there are two significant changes in vegetation composition around 2.58 Ma and around 2.0 Ma. Vegetation evolution

during 3.15–0.67 Ma can be divided into three phases as follows.

Pollen Zone I, 3.15–2.58 Ma. In this period, low pollen influx rate is the most obvious feature. In the pollen assemblage, percentages of tropical-subtropical taxa (20% by average) and fern spores are the maximum, while percentages of *Pinus* and temperate taxa are the minimum value throughout the total core. It is considered that, the source of pollen and spores is mainly from the South China continent, vegetated with tropical evergreen forest. There are abundant plant taxa, including evergreen *Quercus*, *Altingia*, *Trema*, Araceae, Combretaceae. A large number of tropical taxa and fern plants indicate hot and humid environment.

As mentioned above, pollen in deep sea sediments in northern South China Sea are mainly transported by the NE winter monsoon and wind-driven currents from large source areas. The lower pollen influx and lower percentage of *Pinus* pollen indicate the weakest winter monsoon during this period.

Pollen Zone II, 2.58–2.0 Ma. During this period, pollen influx rises greatly. Variation of the pollen assemblages show that percentage of tropical-subtropical taxa (12.7%) drops obviously, especially the *Altingia* pollen component, while the pollen percentage of temperate broad-leaved taxa rises obviously and the percentage of tropical montane conifers (13.7%) rises a little. All those variations indicate that the climate cooled from 2.58 Ma BP, resulting in temperate plants moving southward and tropical-sub-tropical plants decreasing. The rising of total pollen influx, especially *Pinus* pollen influx, indicate that the winter monsoon enlarge during this period, which allowed much more *Pinus* pollen to be transported to the sediment site by enlarging winter monsoon.

Based on the variations of the pollen assemblages, this zone can be divided into two sub zones, in the the lower part (2.58–2.2 Ma), the main feature of pollen variation is the obvious increasing of *Ulmus* pollen. Besides, *Alnus* pollen begins to occur during this period. In the upper part (2.2–2.0 Ma), *Pinus* pollen percentage rises to 56% (on average), while the percentage of the temperate taxa drops, mainly consisting of deciduous *Quercus*. *Alnus* pollen begins rising with *Ulmus* pollen percentage dropping. In the tropical plants, there are much more evergreen *Quercus* pollen and scarcely *Trema*, Araceae, or Combretaceae, while *Altingia* pollen begins dropping during this period.

Pollen Zone III (2.0–0.67 Ma). Around 2.0 Ma, pollen influx rises dramatically once more, to about six times as much as that in Zone I. This pollen zone is characterized by the high percentage of *Pinus* (up to 80%). In the middle and lower part of zone III, content of fern spores reach its minimum value throughout the total core, and rises a little from 10 Ma. Although with no obvious variation in percentage of tropical-subtropical taxa, there is an obvious change in its composition. From 2.0 Ma, pollen of *Trema*, Araceae, Combretaceae disappears. These occurred mainly in pollen

Zone I and Zone II before 2.0 Ma; *Altingia* pollen percentage decreases obviously. At the same time, some new tropical/subtropical taxa appear, such as *Carya*, *Engelhardtia*, *Castanopsis* and *Mallotus*. Evergreen *Quercus* also increases clearly. The pollen data shows that, from 2.0 Ma tropical and subtropical plants predominate in the South China, mainly consisting of evergreen *Quercus*, *Carya*, *Engelhardtia*, *Castanopsis*, *Mallotus*, *Altingia* and *Pailame*. Compared with that before 2.0 Ma, the tropical component of the vegetation composition weakens sharply. All those taxa mentioned above distribute to the subtropical zone, for example, *Castanopsis* can grow in Japan and Korea. High pollen influx and *Pinus* pollen indicate climate cooling and winter monsoon enhancement from 2.0 Ma.

4.2 Paleomonsoons

Based on pollen distribution patterns in the surface sediments of the SCS, great efforts have been made to study the mechanisms of pollen transportation, the routes of pollen dispersal, and pollen source areas in relation to distribution in surface sediments there [36,37]. As seen from the modern pollen distribution pattern in the northern SCS, the tree pollen concentration (especially *Pinus*) is highest in the lower part of the northeastern continental slope, near the Bashi and Taiwan Strait. It means that tree pollen (especially *Pinus* pollen) is transported mainly by the northeastern winter monsoon and monsoon-driven surface currents from large source areas (probably including South and Southeast China) through Bashi Strait and then spreading southwestward.

Pine is widely distributed in temperate areas of the Northern Hemisphere. Pine is a high pollen producer and its pollen is easily dispersed. Usually huge amounts of *Pinus* pollen are found in Quaternary marine sediments, and in modern surface sediments of the northern SCS *Pinus* pollen can exceed 80% of the total pollen sum of land seed plants. According to its modern distribution pattern, pine pollen is transported mainly by the northeast winter monsoon from the mainland of China through Bashi Strait and then spreads southwestwards driven by sea currents. The research on sediment influx by catcher shows that, the sediment influx maximum appears in the winter from November to January, suggesting that the terrigenous clastic material is mainly transported by the winter monsoon. This research result supports our understanding on the pollen transportation mechanism in SCS.

Due to the sea level change, the coast line variation may change the distance from the pollen source to the depositional site, which affects the pollen influx variation to a certain extent. Research on pollen influx variations in deep sea sediment from ODP Site 1144 shows that, the component of herbaceous pollen is quite high in MIS 2, MIS 4 and MIS 6, while its value in the glacial period before 150 ka BP is not so high as that in MIS2 [22]. According to the ratio of Herbaceous pollen and *Pinus* pollen (H/P), Sun et al. [22] con-

sider that, the wide continent shelf in the northern South China Sea came into being from 150 ka BP, corresponding to the obvious transgression record along the coast in east and southeast China from MIS 5. It is considered that there is a narrow continent shelf before MIS 6 in northern South China Sea. Consistent with the lower parts before 150 ka BP at ODP Site 1144, the herbaceous pollen component is quite low throughout the total core in ODP Site 1145, usually lower than 10%, probably due to the narrow continental shelf during 3.15–0.67 Ma.

Sun et al. [22–24] have used the tree pollen influx (the absolute pollen number deposited on 1 cm² during a year) as a winter monsoon proxy and the proportion of fern spores to total pollen sum as a summer monsoon proxy to reconstruct vegetation evolution and monsoon history during the past 1 Ma the deep sea pollen in ODP Site 1144. Considering that the total tree pollen includes a considerable amount of pollen transported by fluvial and offshore current from short distance, such as tropical subtropical taxa, while *Pinus* pollen is mainly transported by the winter monsoon and sea currents driven by the winter monsoon, in this study, Pine pollen influx is used as the winter monsoon proxy. Higher influx of Pine pollen indicates a stronger winter monsoon.

As seen in Figure 6, the pollen influx (including total pollen, *Pinus* pollen, temperate taxa and tropical subtropical taxa) rise dramatically twice, first around 2.6 Ma and second during 2.0–1.8 Ma. Research on loess-red clay reveals that the winter monsoon was enhanced around 2.60 Ma [1]. Marine planktonic foraminiferal Oxygen isotope record from deep sediments in northern South China Sea also reveal that the global ice volume reached up to now

Figure 6 Downcore variations of pollen influx (grains cm⁻² a⁻¹) as winter monsoon proxy, and of fern spores percentages (calculations based on total pollen sum of land seed plants) as summer monsoon proxy at ODP Site 1145, SCS.

around 2.7 Ma. The pollen influx rising dramatically in ODP Site 1145 around 2.6 Ma may be due to the global ice volume increasing and winter monsoon enhancement during this period [8–10].

A number of researches from land and sea reveal that the sea current, monsoon system, paleo productivity, and the ice sheet in the Northern Hemisphere change significantly around 2.0 Ma. The deep sea water turns shallow gradually around 2.0 Ma [38], which may be due to the uplift of Panama Isthmus. The final closing of the Indonesia seaway resulted in sea surface water cooling of the Namibiya coast around 2.1–1.9 Ma, which accounts for the appearance of the South Africa human beings and the appearance of mammals adapted to arid environment [39]. Around 1.8 Ma, the increase of sea surface water paleoproductivity in Indian Ocean may due to the enhancement of the South Asian monsoon [40]. During 2.0–1.8 Ma, the pollen influx from ODP Site 1145 rise dramatically once again indicates the winter monsoon further enhancement, probably due to the global ice volume variation? To prove this will need much more research.

4.3 Analysis of climatic cyclicity

Earlier researches reveal different climatic responses to the orbital force in different latitudes [41]. The climatic response in low latitudes is mainly influenced by the Precession cyclic with a 20 ka period, while that in the high latitude is mainly influenced by the 40 ka period, which correspond to the “monsoon response” and “ice sheet response” respectively. As the climatic response to the Precession cycle is controlled by the Earth Orbital Eccentricity, the period of 20 ka, 0.1 Ma and 0.4 Ma are all low latitude characters [41,42]. Research on the clay minerals from deep sea sediments during the past 450 ka in ODP Site 1145 by Boulay et al. [26] shows that there is a 23 ka period corresponding to precession cycle. The chemical analysis during 3.2–2.5 Ma

BP from ODP Site 1145 reveals that, the K/Si ratio variation corresponds to the Precession and Eccentricity periodicity. The K/Si ratio reflects the river output proportion in the deep sea sediment, and can indicate the variation of the summer monsoon. Meanwhile, the carbonate and the colour reflectance has 41 and 100 ka periods.

In search for a causal relationship between the changes in pollen assemblages and those of monsoon variation and ice sheet variations, spectral analysis has been applied to the pollen influx and pollen percentage of tropical and subtropical taxa. As shown in Figure 7, there are 100, 30, 19.6 ka cycles in the pollen percentages of the tropical/subtropical taxa, indicating that the variation of pollen percentage of tropical subtropical taxa is mainly reflecting the influence of low latitude, probably reflecting the summer monsoon variation. Meanwhile, there are 100, 41 and 19 ka cycles in the pollen influx variation, indicating that besides the low latitude factors, the pollen influx variation is also influenced by the high latitude factor, probably reflecting the winter monsoon variation due to the sea level change resulting from the ice sheet response in high latitude.

5 Conclusions

(1) Before 2.58 Ma, tropical and subtropical vegetation, mainly evergreen *Quercus* (E) and *Altingia*, predominated around northern SCS with much more tropical montane conifers and ferns relatively; from 2.58 Ma, temperate vegetation increased obviously, implying climatic cooling and winter monsoon enhancement.

(2) Pollen influx rises twice obviously around 2.58 Ma and during 2.0–1.8 Ma, in response to global climatic cooling and winter monsoon enhancement, probably due to the North Hemisphere ice sheet variation.

(3) Spectral analysis shows that percentage variation in tropical and subtropical taxa has a strong 20 ka precession

Figure 7 Spectral analysis on pollen influx variation and pollen percentage variation of tropical subtropical taxa.

cycle probably due to the summer monsoon; while pollen influx has 100, 41 and 19 ka cycles, indicating the sea level and the winter monsoon change response to the ice-sheet variations

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