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Short Paper

Palynological records of Holocene monsoon change from the Gulf of Tonkin (Beibuwan), northwestern South China Sea

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ABSTRACT

Palynological records in cores C4 and B106 from the Gulf of Tonkin reveal signals of paleo-monsoon and paleoenvironmental change during the late Pleistocene and Holocene. Before ~13.4 cal kyr BP, the Gulf of Tonkin was exposed to the atmosphere and covered by grassland. Starting at ~11.7 cal kyr BP, the Gulf of Tonkin was inundated by brackish water, indicated by the appearance of the brackish algae *Cleistosphaeridium*, *Sentusidinium* and *Spiniferites*, a decrease of herb content, and an increase of *Pinus*. After Hainan Island was completely separated from the Leizhou Peninsula by Qiongzhou Strait at ~8.5 cal kyr BP, a continuous marine sedimentary environment was found. The current patterns were similar to those of the present, with a general trend of current homogenization reflected by gradually decreasing quantities of *Quercus* pollen and a narrowing gap between the palynological concentrations of the southern and northern parts of the region. The data suggest that three short periods of strengthened winter monsoons and currents were centered at ~6.0 cal kyr BP, ~2.7 cal kyr BP and ~0.2 cal kyr BP and that two short periods of strengthened summer monsoons and currents were centered at ~7.5 cal kyr BP and ~3.4 cal kyr BP.

Introduction

The climate of the South China Sea (SCS) region is strongly influenced by the East Asian Monsoon System, which controls the atmospheric heat budget in the Northern Hemisphere and influences or is influenced by global climatic changes (Tchernia, 1980; An, 2000). To better understand monsoon fluctuations and their role in the global climate system, researchers have studied the paleo-Asian monsoon using sediment records in the SCS and terrestrial sediments surrounding the SCS region. Climate records from lake sediments, stalagmites in caves, loess, and coastal and marine sediments show a teleconnection with ice-rafting events in the Atlantic Ocean area and indicate a linkage to insolation (Wang, 1999; Wang et al., 1999, 2005; Yu et al., 2005; Yancheva et al., 2007). An intensified winter monsoon is linked primarily to dry and cold stages, whereas an intensified summer monsoon with high moisture content is associated with a warming climate and increased precipitation (Kudrass et al., 1991; Banerjee, 1995; Porter and An, 1995; Wang et al., 1999). Numerous investigations of pollen assemblages from the SCS and surrounding terrestrial regions have also been performed, providing ample information about monsoon-related climate change in the Holocene (Maxwell, 2001; Li et al., 2006a,b; Penny, 2006). Unfortunately, most climate studies have focused on the southern and eastern SCS; few studies have covered the northwestern region. This paper presents a record of monsoon and current variability resulting in environmental change over the past 13,000 yr based on a palynological analysis of two sediment cores from the Gulf of Tonkin.

Environment setting

The Gulf of Tonkin is a semi-closed gulf located northwest of the SCS and connected with the SCS through the southern end of the gulf and Qiongzhou Strait, which is located between Hainan Island and the Leizhou Peninsula. The depth of the water in the gulf ranges from 0 to 100 m. The Song Hong (Red River) provides the major riverine discharge into the gulf, along with some smaller coastal rivers. Discharge from the Pearl River, about 400 km to the northeast, may reach the gulf through Qiongzhou Strait (Tang et al., 2003).

Located in the northern tropics, the region experiences a monsoonal climate driven by the southwest monsoon in summer and the northeast monsoon in winter. The latter is a stronger and more constant dry wind and the former is rain bearing, deriving moisture from evaporation over the SCS. The annual mean temperature is 24.5 °C (First Institute of Oceanography, SOA, 2001). The seasonally reversing monsoon wind plays an important role in

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hydrological features and general circulation in the study region. In winter, the northeast monsoon creates an anticlockwise circulation pattern in the Gulf of Tonkin. The wind pushes cooler coastal waters down to circulate west- and southward along the coast of China and Vietnam (Morton and Blackmore, 2001). In summer, the southwest monsoon creates clockwise current circulation. The tide system is characterized by reversing currents and diurnal tides with mean and maximum tidal ranges of 2.53 m and 7.00 m, respectively.

High temperature and precipitation enable rich and diverse vegetation to grow on the surrounding land (Fig. 1). The most important vegetation includes tropical rain forest, tropical seasonal rainforest, tropical and subtropical grassland and cultivated land (Sun et al., 1999). Tropical rainforest grows in lower-altitude areas, such as the Song Hong delta, the valley of the Song Hong (<500 m), and the Hainan hills (Wu, 1980; Thin, 1998; Sun et al., 1999; Zhang et al., 2002; Li et al., 2006b). The vegetation is generally distributed in vertical zones: tropical seasonal rainforest occupies the valley, hills and terraces at altitudes lower than 1000 m; subtropical rain forest is found at altitudes of 1000–2200 m; and temperate broad-leaved forest is found above 2200 m (Guangdong Institute of Botany, 1976; Thin, 1998; Sun et al., 1999; Li et al., 2006b, 2008).

Materials and methods

Two cores obtained from the Gulf of Tonkin in the southwestern SCS were used for this palynological analysis of past climate change. Core C4 was collected from 18º22'36"N latitude, 108º03'46"E longitude at a water depth of 76 m. Core B106 was collected from 19º54'4"N latitude, 108º36'02"E longitude at a water depth of 50 m (Fig. 1). Cores C4 and B106 are 260 cm and 296 cm long, respectively. The sediments were characterized by grey silty clay and clayey silt; we found no obvious hiatus. We subsampled the cores at 10-cm intervals to process for palynological analysis. All samples were treated chemically according to the procedure outlined by Faegri and Iversen (1992). Before treatment, tablets containing exotic *Lycopodium* spores were added to aid in calculating palynological concentration and influx. Pollen, spore and algae types were counted under an optical microscope. Percentages of pollen groups, spores and algae were calculated based on the sum of the identified grains, whereas pollen components were calculated on the basis of the sum of pollen counts.

Palynological diversity serves as index for the degree to which pollen and spores from various terrestrial vegetation types are sorted by marine currents, with low diversity indicating a high degree of sorthing. Both palynological richness and evenness were estimated to reflect palynological diversity, as recommended by van der Knaap (2009). Rarefaction analysis was used to estimate palynological richness based on the formula $E(Tn) = \sum_{i=1}^{T} 1 - \left[\frac{(N-Ni)!(N-n)!}{(N-Ni-n)!N!}\right]$, where $E(Tn)$ is the expected palynological richness in a standardized pollen count Ni, T is the palynological richness in the original pollen count, N is the overall palynological grain sum, and n is the number of grains selected for standardization in the rarefied sample (Birks and Line, 1992; Peros and Gajewski, 2008). All types of pollen, spores and algae were included in the rarefaction calculations using the software PAST (Hammer et al., 2001).

We used Hurlbert's (1971) probability of interspecific encounter (PIE) to measure evenness according to the formula $\Delta_1 = 1 - \sum_{i=1}^{T} \left(\frac{ni}{N}\right)\left(\frac{ni-1}{N-1}\right)$, where $\Delta 1$ is the PIE, T is the richness of the sample, n_i is the abundance of the ith taxa, and N is the overall sum of palynological grains.

Eight accelerator mass spectrometry (AMS) radiocarbon dates (^{14}C yr BP) were measured and calibrated (cal yr BP) using the program Calib 5.0.1. The marine reservoir effect (ΔR) was corrected for according to the method of Southon et al. (2002) (Table 1). The age-depth model was based on linear interpolation between the mean calibrated ^{14}C ages. Sedimentation rates were calculated without taking into account sediment compaction effects or basin subsidence.

Results and interpretations

Palynological components were similar between the two cores. Five major taxon groups (conifers, broad-leaved arboreal sclerophyll taxa, herbs, fungi and algae) were well-represented (Fig. 2). The major arboreal conifer type was *Pinus*, contributing ~20–85%, followed by *Dacrydium* at ~10% of the total pollen. Pollen of *Quercus*, the primary representative of broad-leaved mountainous rain forest taxa, has only low representation. Other taxa from that group were infrequently found. By contrast, lowland rainforest taxa (*Sapindus*, *Myrica*, Euphorbiaceae) were minor components, found only in trace amounts, even though the vegetation around the Gulf of Tonkin is characterized by rainforest. Monolete fern spores (the majority of pteridophytes) and trilete spores (such as *Pteris*, *Hicriopteris*, and *Dicranopteris*) occurred in similar frequencies. Herbs (dominated by

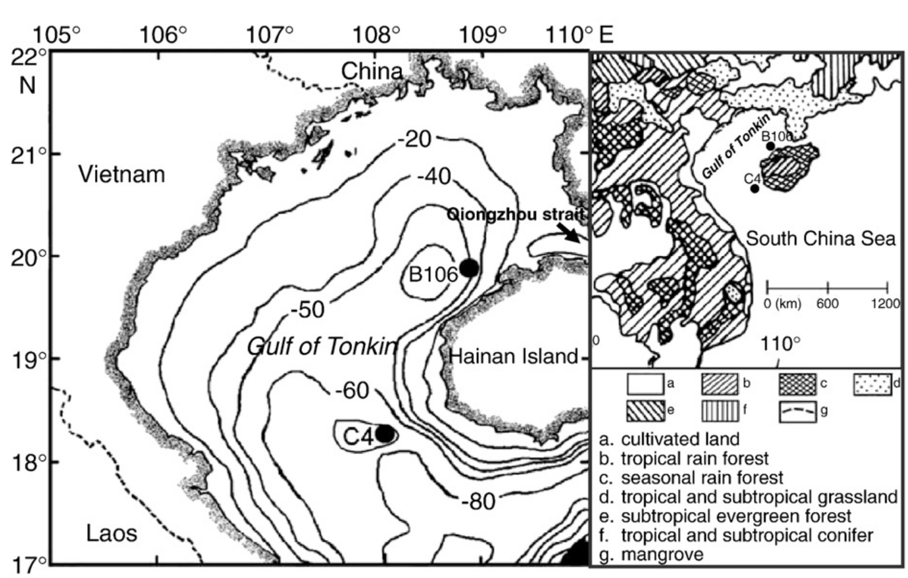

Figure 1. Map of the topography, surrounding vegetation distribution and the core sites.

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Table 1
List of ^{14}C ages used to establish the chronology of cores C4 and B106 in the Northwesten South China Sea.

Depth (cm)	Material	Conventional ^{14}C age (^{14}C yr BP)	Calibrated ^{14}C age[a]		
			Age ranges (cal yr BP)	Probability[b]	Mean (cal yr BP)[c]
C4					
50–52	Molluscan shell	2870 ± 30	2349–2703	1	2530
100–102	Molluscan shell	3510 ± 30	3134–3475	1	3310
150–152	Molluscan shell	3990 ± 35	3694–4093	1	3890
200–202	Molluscan shell	4910 ± 35	4911–5306	1	5110
258–260	Molluscan shell	9800 ± 40	10421–10821	0.9953	10620
			10857–10869	0.0047	10863
B106					
50–52	Molluscan shell	3370 ± 40	2941–3333	1	3140
100–102	Molluscan shell	5665 ± 35	5849–6179	1	6010
258–260	Bulk mud	11530 ± 45	13164–13464	1	13360

Note: Dates were measured by Accelerator Mass Spectrometry laboratory, Peking University, China.
[a] Relative area under the distribution curve.
[b] Precision is 2-sigma in the program Calib 5.0.1.
[c] The intermediate age with the maximum probability, rounded to the nearest multiple of 10 yr.

Poaceae) were found in very low quantities, except at the bottom of core B106. Fungi and algae also were also found in small quantities, including freshwater types (*Concentricystes* and *Zegnema*), brackish water types (*Cleistosphaeridium* and *Sentusidinium*), and a saline water type (*Spiniferites*) (Fig. 2).

Sedimentary environment

Before ~13.4 cal kyr BP, the period corresponding to zone I in Core B106, herb pollen reaches its highest content in the entire core, while arboreal pollen and fern spores correspondingly at their lowest content. *Pinus* exhibited its lowest abundance in this zone, whereas *Quercus* and Poaceae had their highest percentage values. *Dacrydium* pollen and tropical arboreal pollen occurred occasionally. The high abundance of herb pollen and absence of brackish algae indicate an extensive grassland environment. Angular pebbles in the sediments also indicate a terrestrial environment. At that time, the Gulf of Tonkin was exposed to the atmosphere (Li et al., 1990; Huang et al., 1995; Xia et al., 2008), and the shoreline migrated to near the present shelf slope, where various morphological units (such as paleo-channels, submarine deltas and submarine sand hills) were formed (Wu et al., 1993; Kou and Du, 1994; Lin, 1995; Fan et al., 1999; Xie et al., 2008).

During the period from 13.4 to 11.7 cal kyr BP (zone II in Core B106), *Pinus* increased rapidly, whereas *Quercus* decreased. *Dacrydium* also increased but continued to make up a small percentage of the total. Herb abundance decreased due to the reduced contribution of Poaceae pollen and wetland non-aboreal pollen (NAP). An environment influenced by brackish water is reflected by the appearance of the brackish algae *Cleistosphaeridium*, *Sentusidinium* and *Spiniferites*. However, the core site was not located far from terrestrial sources, as the percentage of fern spores did not rise substantially. This evidence is consistent with the sea level at ~11.6 cal kyr BP, which was about 52 m lower than at present, according to the sea level curve of the western margin of the SCS (Fig. 3) (Tanabe et al., 2003). With the rising sea level, the shoreline migrated landward and the Gulf of Tonkin originated as a narrow gulf after inundation by brackish water. However, Qiongzhou Strait had not yet opened to the SCS (Chen and Fan, 1988; Zhao et al., 2007; Yao et al., 2009).

After 11.7 cal kyr BP (zone III in core B106 and zones I, II, and III in core C4), fern spores increased rapidly in abundance and were more frequent than either AP (arboreal pollen) or NAP. Polypodiaceae and *Pteridium* contributed most of the fern spores. More fern taxa with trilete spores occurred. The abundances of both *Quercus* and Poaceae were lower than before. *Pinus* increased sharply and remained at a stable, high level, ranging from ~58% to ~91% of total pollen (Fig. 2). *Pinus* pollen and trilete spores can be enriched in marine environments far from their sources by flotation in water (Sun et al., 1999; Bush, 2000; Romagnoli et al., 2003; Patrick et al., 2005; Li et al., 2008). Brackish algae also reflect a marine sedimentary environment (Fig. 2). The Gulf of Tonkin was similar to its present configuration at about 10 cal kyr BP (Yao et al., 2009) but was not connected with the SCS by Qiongzhou Strait until 8.5 cal kyr BP, when Hainan Island was completely separated from the Leizhou Peninsula (Zhao et al., 2007; Yao et al., 2009).

Monsoon climate changes during the mid–late Holocene

After Qiongzhou Strait separated Hainan Island from the Leizhou Peninsula, the Gulf of Tonkin remained inundated. To interpret marine pollen data, it is crucial to understand the mechanisms of pollen dispersal from source areas, since all pollen and fern spores come from somewhere on land. In the Gulf of Tonkin, pollen concentrations vary substantially in different areas: about 5000 to 15,000 grains/g are found in sediments offshore from Guangxi (Wang et al., 1990; Zhang et al., 1999; Li et al., 2010); 10,000–25,000 grains/g are found in mangrove systems (Li et al., 2008); and high values from 20,000 to 50,000 grains/g (or even 100,000 grains/g) are found in the Song Hong delta, where pollen grains are primarily transported by regional river systems (Li et al., 2006a,b). The present study shows low values of 500–3,500 n/cm^3 (about several thousands grains/g) in the area west of Hainan Island and Qiongzhou Strait, where pollen taphonomy was influenced strongly by currents after being transported by wind or river from regional sources (Zhang and Long, 2008).

In contrast to dilution effects due to high sedimentation rates when pollen dispersal depends primarily on wind (Xu et al., 2005; Beaudouin et al., 2007), palynological flux here is positively correlated with sedimentation rates. High palynological flux values correspond closely to high sedimentation rates (Fig. 3). The consistency of palynological flux and sedimentation rates indicates that water prevails over wind in palynological distribution. The high and stable evenness values with general low richness indicate well-sorted palynological records. Moss et al. (2005) have suggested that rivers contribute a major proportion of pollen to offshore sediments, but these pollen grains are size-sorted by marine action. Abundant *Pinus* pollen and fern spores, which are adapted to flotation and are easily dispersed by water (Florin, 1963; Heusser, 1988; Sun et al., 1999; Duplessy et al., 2001; Li et al., 2008), are also associated with current-dominated transport in marine environments.

Controlled by the seasonally reversing monsoon wind, currents play an important role in the palynological records studied here. In

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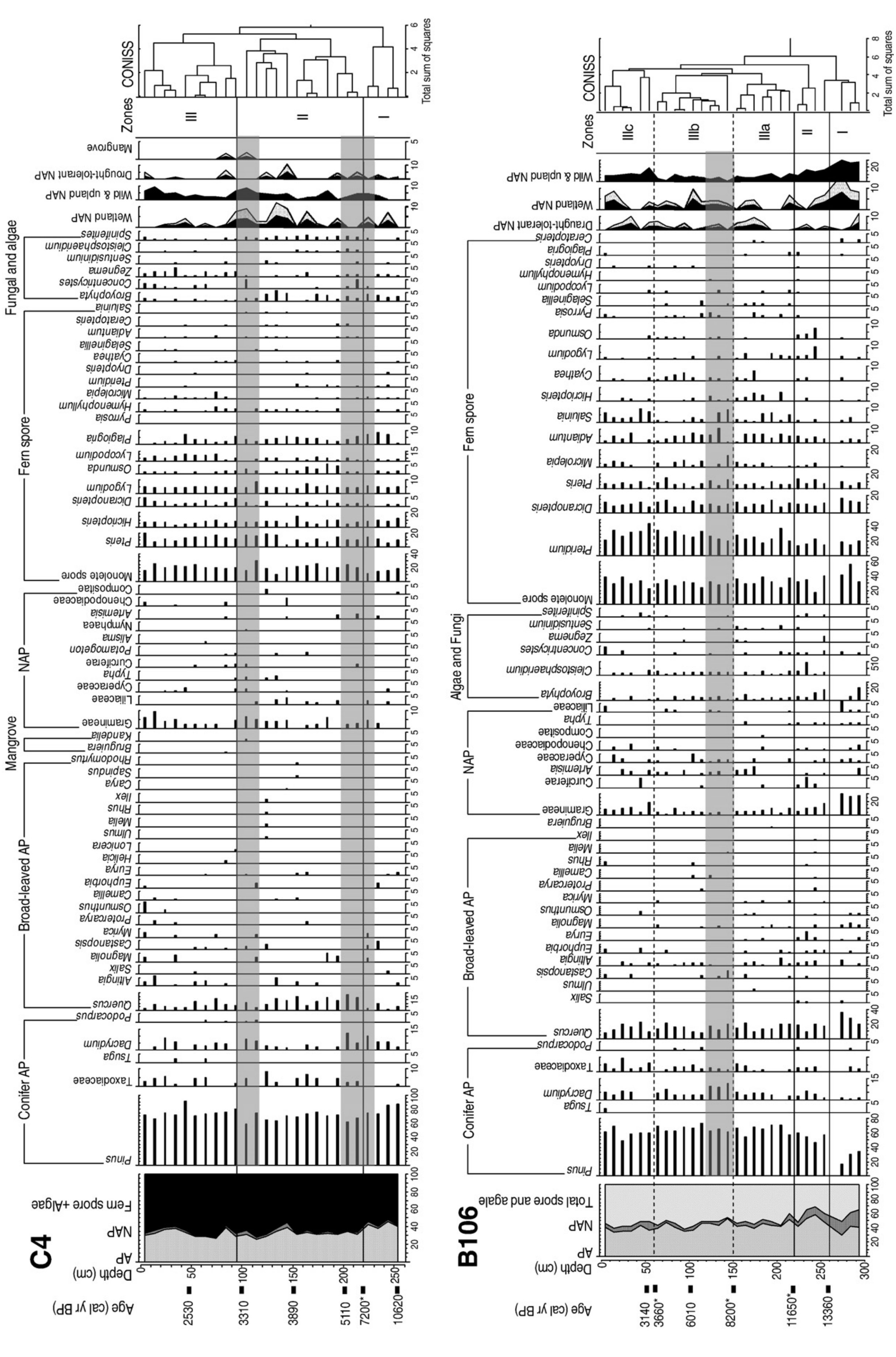

Figure 2. Palynological diagrams of sediment core C4 and B106 from the Gulf of Tonkin in the northwestern South China Sea. Shading indicates depths with elevated abundance of *Dacrydium* pollen. Ages marked with an asterisk were estimated based on the age-depth model.

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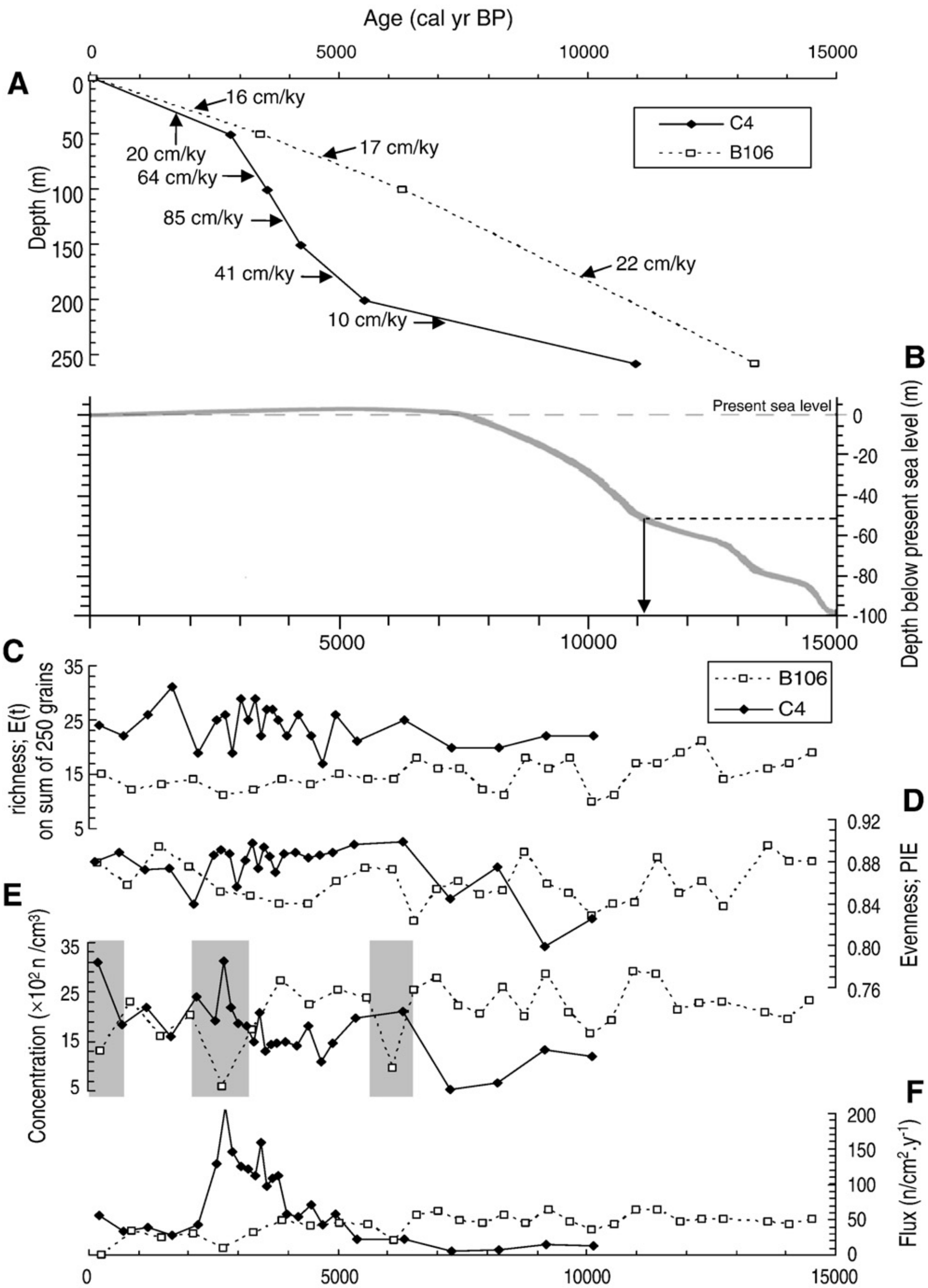

Figure 3. Summary diagram for palynological data from cores C4 and B106 from the Gulf of Tonkin in the northwestern South China Sea. (A) Age-depth models indicating sediment accumulation rates; (B) Sea level curve (Tanabe et al., 2003); (C) Palynological diversity (i.e., richness, calculated for a constant sum of 250 grains); (D) Palynological evenness (i.e., probability of interspecific encounter; PIE); (E) Palynological concentration; shading indicates ages when concentrations increase for C4 and decrease for B106; (F). Palynological flux (grains/cm^2/yr); not that high flux values correspond closely with high sedimentation rates.

winter, the wind pushes cooler, coastal waters through Qiongzhou strait and downward to circulate west- and southward along the coast of China and Vietnam and then southeastward to the SCS. In summer, the warm southwest wind enters the Gulf of Tonkin and creates a small current circulation through Qiongzhou Strait to the SCS (Zhao et al., 1999; Morton and Blackmore, 2001). Since 5.2 cal kyr BP, sea levels have remained relatively stable. Located near the center of the summer currents and in relatively stable depositional conditions, core C4 exhibits higher palynological concentrations and sedimentation rates than core B106, which is located in a more turbulent environment adjacent to Qiongzhou Strait. The high sedimentation rates during the period from about 5.5 to 3.0 cal kyr BP in core C4 may reflect high terrestrial input, corresponding to an increase in eolian or fluvial terrestrial inputs to the northern SCS (Lin et al., 2006). Currents carry more pollen to deposit at the site of core C4 than at the site of core B106. Differences in palynological concentrations in the two cores tend to decrease from a large gap in the early Holocene until reaching similar levels at the present time, except for three fluctuations after about 8.0 cal kyr BP, during which concentrations increase in core C4 while decreasing in core B106. These three periods are centered at ~6.0 cal kyr BP, ~2.7 cal kyr BP and ~0.2 cal kyr BP (Fig. 3). The three fluctuations are probably associated with enhanced monsoons and summer-winter currents, perhaps similar to the events that occurred at ~5.4 ka BP as indicated by coral $\delta^{18}O$ values in eastern Hainan Island (Su et al., 2010). These three periods may have been induced by strengthened winter monsoons, corresponding to the two cooling

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climate events that occurred from 6.5 to 5.5 cal kyr BP and from 0.6 to 0.1 cal kyr BP and the drying period that occurred from 3.3 to 2.1 cal kyr BP in the Song Hong (Red River) delta area (Li et al., 2006a,b).

Quercus and *Pinus* both occur in tropical montane rainforests (above 1000 m) and subtropical-temperate forests. Thus, an intensified monsoon climate would positively affect the distribution of *Quercus* and *Pinus* pollen in marine sediments from regional sources. Many previously published studies have shown that rivers transport conifer pollen (e.g., *Pinus*) less often than *Quercus* pollen (e.g., Zheng and Li, 2000; Sun et al., 1999; Li et al., 2006b). Li et al. (2006a) have found that the Song Hong carried *Quercus* pollen from upstream montane vegetation sources to the submarine delta area. Strong offshore currents could carry the pollen further into the marine environment. Moreover, in contrast to records from the Song Hong delta area (Li et al., 2006a), *Pinus* and *Quercus* abundances do not show obvious shifts in this study, but remain stable in core B106 near Qiongzhou Strait. However, in core C4, which is located far from terrestrial sources, *Pinus* abundance is the lowest whereas *Quercus* abundance is the highest and gradually decreases. This pattern reflects the general weakened currents control the distribution of *Quercus* in core C4 during a stable relative sea level period after ~7.0 cal kyr BP (Zong, 2004). Two short periods with relatively higher *Dacrydium* abundances (from 8 to 6 cal kyr BP and from 3.5 to 3.3 cal kyr BP) are probably associated with strong summer monsoons (Fig. 2), because *Dacrydium* trees are ubiquitous in the tropical areas, extending northward as far as Hainan Island (Florin, 1963). The southwest wind and currents would facilitate *Dacrydium* pollen dispersal from southern tropical areas (Sun et al., 1999). The former period corresponds to a stronger summer monsoon recorded in the Leizhou Peninsula at ~6.8 kyr BP (Yu et al., 2005). Periods of weakened summer monsoons from 5.1 to 3.5 cal kyr BP, reflected by low abundances of *Dacrydium* pollen, may correspond roughly to the amplification of the Asian Monsoon that occurred at ~4.4 cal kyr BP, resulting in higher summer rainfall and cooler winters in response to greater Northern Hemisphere insolation seasonality during the mid Holocene (Sun et al., 2005). This phenomenon has been reported in various localities in China (Wang et al., 2005).

Conclusions

Before ~13.4 cal kyr BP, the Gulf of Tonkin was exposed to the atmosphere and covered by grassland, as reflected by the high concentration of herb pollen (dominated by Poaceae), the low concentration of fern spores, and the absence of brackish algae. From 13.4 cal kyr BP to 11.7 cal kyr BP, the Gulf of Tonkin was inundated by brackish water, as indicated by the appearance of the brackish algae *Cleistosphaeridium, Sentusidinium* and *Spiniferites,* a decrease in herb pollen and an increase in *Pinus* pollen. After Hainan Island was completely separated from Leizhou Peninsula by Qiongzhou Strait at ~8.5 cal kyr BP, a continuous marine sedimentary environment was found, and the current patterns were similar to those found at the present time. Very low palynological concentrations suggest that currents strongly affect pollen dispersal after transportation from regional sources. The consistency of palynological flux and sedimentation rates indicates that water prevails over wind in palynological distribution. The decreasing gap in palynological concentrations between the southern (C4) and northern areas (B106) indicates a general trend of current homogenization. Three opposite concentration fluctuations centered at ~6.0 cal kyr BP, ~2.7 cal kyr BP and ~0.2 cal kyr BP are associated with brief periods of strengthened winter monsoons and currents. Another period of weakened Asian monsoons from 5.1 to 3.5 cal kyr BP is suggested by relatively lower *Dacrydium* abundances. Higher *Dacrydium* abundances during two short periods centered at ~7.5 cal kyr BP and ~3.5 cal kyr BP indicate strengthened summer monsoons and currents.

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