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Research article

Middle Eocene East Asian monsoon prevalence over southern China: Evidence from palynological records

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ABSTRACT

The initiation of Asian monsoon systems is a complex and controversial issue, and the existence of monsoon systems in the Eocene has not yet been confirmed by commonly applicable proxy data. Eocene palynological records from three basins in southern China provide an ideal opportunity to investigate the early stage of the Asian monsoon due to their unique geographical location. The palynological assemblages suggest that the middle Eocene vegetation in southern China was composed of mixed evergreen and deciduous broad-leaved forests, accompanied by abundant subtropical to tropical evergreen taxa, thus bearing strong resemblance to the modern vegetation in southern China, and indicating a warm-humid subtropical climate. By analysing the palynological data using a coexistence approach (CA), we quantitatively reconstructed seven climatic parameters, which indicate a subtropical monsoon climate with a mean annual temperature (MAT) in the range 16.5 to 23.5 °C and a mean annual precipitation (MAP) in the range 1035 to 1724 mm, similar to those of the modern subtropical monsoon climate in southern China although the MAT was surprisingly lower than present. Significant seasonal variations in precipitation and temperature and as well as the spatial distribution of MAP during the middle Eocene were most similar to those of the modern East Asia Monsoon (EAM) climate of southern China, clearly indicating that the Eocene climate of southern China was mainly influenced by the EAM, rather than the Indian monsoon (IM) or Inter-tropical Convergence Zone (ITCZ) monsoons. By combining the above results with previously published geological evidence, we infer that the EAM developed in southern China as early as the middle Eocene, albeit with an intensity that may have been weaker than present. The establishment of the middle Eocene EAM in southern China was most likely driven by the northward drift of the Indian Subcontinent and its collision with the Eurasian continent, associated with the uplift of the Central-Southern Tibetan Plateau, which enlarged the land-sea thermal contrast and deepened the low pressure over continental Asia in summer, thus greatly intensifying the East Asian subtropical summer monsoon over southern China.

1. Introduction

Deep-sea $\delta^{18}O$ records and terrestrial records indicate that the Eocene epoch was an extremely warm interval in the Cenozoic (Miller et al., 1987; Zachos et al., 2001, 2008; Greenwood et al., 2010). The Eocene global mean annual surface temperature was markedly warmer than present (Greenwood and Wing, 1995; Zachos et al., 2001, 2008; West et al., 2015; Suan et al., 2017), and the early Eocene was the warmest interval of the past 65 Ma (Zachos et al., 2001, 2008; Keating-Bitonti et al., 2011; West et al., 2015), yet global climate subsequently transitioned from “greenhouse” to “icehouse” conditions, marked by global climatic cooling and the widespread Antarctic glaciation in the middle to late Eocene (Zachos et al., 2001, 2008; Tripati et al., 2005; Carter et al., 2017). Meanwhile, the Eocene was a highly active period in Asian tectonics, with events such as the India-Eurasian collision and associated uplift of the Tibetan Plateau (Tapponnier et al., 2001; Dupont-Nivet et al., 2008; Wang et al., 2008, 2014; Molnar et al., 2010), and the westward retreat of the Paratethys Sea from the Tarim Basin (Bosboom et al., 2011, 2014a, 2014b; Sun et al., 2016). These events would have increased the land-sea thermal contrast and could have initiated the Asian monsoon. Therefore, the Eocene may have been a critical interval for the onset of Asian monsoon systems, but it

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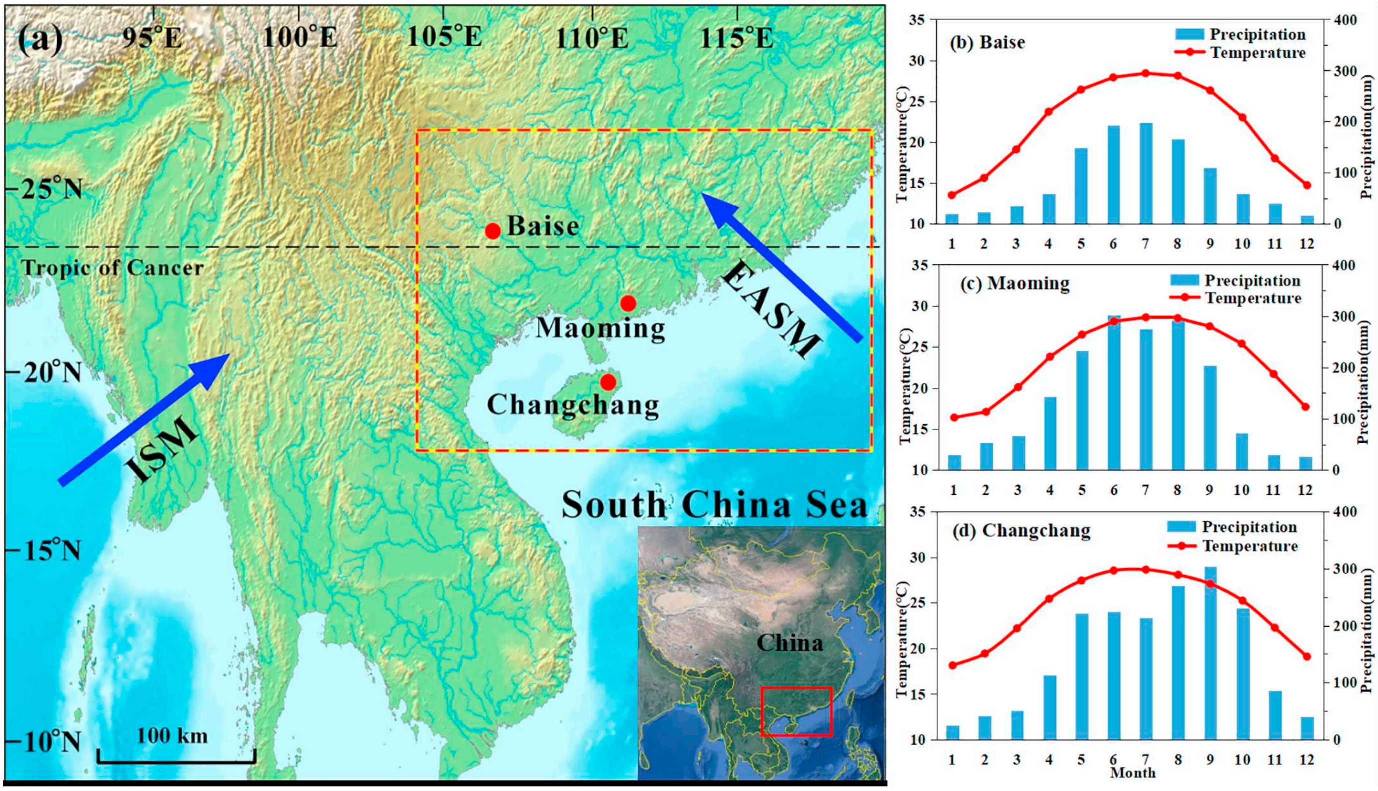

Fig. 1. Maps showing the geographic locations (a) and climatology (Monthly-mean precipitation and temperature) of Baise (b), Maoming (c) and Changchang Basins (d). ISM, Indian summer monsoon; EASM, East Asian summer monsoon.

was only recently that geological records and numerical simulations have suggested that the Asian monsoon might have existed during the Eocene (Quan et al., 2012, 2014; Huber and Goldner, 2012; Wang et al., 2013; Licht et al., 2014; Meng et al., 2018). Nevertheless, the cause and timing of the Asian monsoon development remain controversial and largely unknown.

Evidence from aeolian sediment, lithological and palaeobotanical records reveals that a climate transformation from a planetary wind dominant pattern to a monsoon dominated pattern occurred roughly in the late Oligocene to early Miocene (Liu et al., 1998; Guo et al., 2002, 2008; Sun and Wang, 2005); however, it is still unclear when and how the planetary climate system became disrupted or the monsoon system began developing, or whether the monsoon systems prevailed prior to this period. Indeed, in southern China, this transformation occurred much earlier. In the Paleogene period, the most striking environmental change was the northward migration of the humid zone during the Eocene (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008), but the potential forcing mechanisms remain ambiguous. One view is that increased humidification in southern China could imply the existence of a tropical monsoon primarily driven by seasonal migration of the ITCZ (Guo et al., 2008; Huber and Goldner, 2012; Sorrel et al., 2017). Owing to the complexity of Asian monsoon systems, the possible existence of monsoon systems in the Eocene has not yet been confirmed by commonly applicable proxy data. Lithological records have revealed a possibly humid monsoonal climate in southern China during the Eocene; however, these records have considerable uncertainties, and are largely based on roughly compiled records (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008).

Palynological analysis of fossil pollen preserved in the strata is a well-established method of reconstructing palaeoclimate and palaeovegetation. Palynological records may be able to detect more subtle climatic signals, and better capture more seasonality, than those based on lithological proxies. Therefore, it is essential to carry out palynological analysis in southern China. Fortunately, there are numerous Paleogene sedimentary basins in southern China that contain thick Eocene sedimentary successions which have documented the Eocene climate conditions (Gu and Renaut, 1994; Spicer et al., 2014; Aleksandrova et al., 2015). Southern China is particularly interesting, not only because it is situated in a transitional zone between the IM and EAM (Wang and Ho, 2002), but also because it is an area inevitably subjected to the effects of ITCZ seasonal migration, and recent simulations have suggested that ITCZ migration extended further northward under the Eocene greenhouse conditions (Huber and Goldner, 2012). Therefore, the individual monsoon systems are hard to distinguish from each other. A crucial question is whether the monsoon prevailing in southern China during the Eocene was merely a reflection of wider ITCZ migration or a monsoon modified by topography or land-sea distribution.

Studying sporopollen records in southern China is thus critical for understanding the Eocene climate of southern China and the initiation of the Asian monsoon. In this exploratory study we focused on the Eocene sporopollen fossils from three sedimentary basins, with the aim of reconstructing the palaeoclimate and paleovegetation of southern China during the Eocene, using coexistence approach (CA) (Mosbrugger and Utescher, 1997) to quantitatively reconstruct the seasonality of precipitation and temperature and illustrate the spatial distribution of precipitation, from which we infer the possible existence of an Eocene monsoon in southern China. We also attempt to clarify what kind of monsoon systems existed, and investigate the possible forcing mechanisms of the Eocene monsoon in southern China.

2. Geographic and geological settings

2.1. Geographic settings

The Baise, Maoming and Changchang Basins are located in Guangxi, Guangdong and Hainan provinces, respectively, in southern China (Fig. 1a). Although the paleolatitude of southern China in the Eocene has not been studied in detail at present, reconstructed global paleogeographic maps (Ziegler et al., 1983; Scotese, 2001) indicate that southern China has remained more or less in a fixed geographical position since the Eocene.

The modern climate in the Baise and Maoming Basins exhibits the features of the southern subtropical monsoon climate, while the Changchang Basin belongs to the tropical monsoon climate (Fig. 1b, c, d). The MAT ranges from 22.1 to 24.3 °C; the mean temperature of the coldest month (CMT) ranges from 13.5 to 18.1 °C and the mean temperature of the warmest month (WMT) ranges from 28.4 to 28.6 °C; the MAP ranges from 1066 to 1823 mm, and over 75% of the precipitation falls in May to September with a peak mean rainfall ranging from 198 to 304 mm (http://data.cma.cn/data/weatherBk.html). The spatial distribution of precipitation in southern China follows a southeast-northwest distribution due to its primary control by the EASM, but is also subject to the effects of the ISM to a lesser degree.

The modern natural vegetation in the Baise and Maoming Basins consists of south-subtropical evergreen broadleaved forest, while the Changchang Basin belongs to tropical monsoon forest (ECVC, 1980). However, the natural vegetation of the Baise Basin is a mixture of evergreen and deciduous broad-leaved forest, due to its location in a karst area where limestone is widely distributed, such that the species composition and physiognomy are different from the zonal vegetation evergreen broad-leaved forest (Su, 1998).

2.2. Geological settings

2.2.1. The Baise Basin

The Baise Basin (106°34′~107°2 l'E, 23°23′~23°47′N) is located in the western Guangxi Zhuang Autonomous Region, southern China (Fig. 1a). The basin extends in a northwesterly direction, approximately 109 km long and 2–14 km wide, with a total area of 830 km^2 (CGPGDQG, 1992; Du et al., 2001). It is a typical Tertiary intracontinental rifted basin filled with Paleogene and Neogene continental sediments, and is well-known as a coal-bearing basin. The Paleogene stratigraphy of the Baise Basin mainly consists of fluvial and lacustrine sediments. Previous studies have divided the Paleogene stratigraphy of the Baise Basin from bottom to top into four Formations (Fm) based on lithofacies, paleontological and palynological characteristics: the Liuniu (Fig. 2a), Dongjun, Nadu (Fig. 2b) and Baigang Fms (BGMRGP, 1985).

The Nadu Fm is the subject of this study. The Nadu Fm is mainly characterized by greyish-brown mudstones, calcareous mudstones and grey siltstones, interbedded with coals and petroliferous sandstone (Fig. 2b). Coal-bearing sequences in the lower part are characterized by shallow lacustrine and deltaic deposits, while the upper part predominantly comprises mudstones rich in organic matter that formed in a deep lacustrine environment (Gu and Renaut, 1994). This Fm has yielded abundant pollen (Wang, 1993; Liu and Yang, 1999; Tong et al., 2001), leaf (Guo, 1979, 1990), and mammal fossils (Tang et al., 1974; Tang, 1978; Qiu, 1977, 1978; Li and Chen, 2001; Liu, 2001; Zhai et al., 2003).

The precise age remains ambiguous due to a lack of volcanic rocks in the Nadu Fm. Fortunately, many mammal fossils have been discovered in the Nadu Fm (Qiu, 1977, 1978; Li and Chen, 2001). Previous studies based on lithofacies, mammal fossils (Tang et al., 1974; Tang, 1978; Qiu, 1977, 1978; Tong, 1989) and palynology (Wang, 1993; Liu and Yang, 1999) support the Nadu Fm as belonging to the late Eocene in age, but Tong et al. (1995), Ma (2005) and Yuan et al. (2007) assigned the age of Nadu Fm to the middle-late Eocene on the basis of mammal and ESR dating (47.7–35.5 Ma), respectively, not merely the Late Eocene. Further age constraint comes from fauna comparison: the Nadu fauna correspond well with those in the Pondaung fauna of Myanmar, including *Indomeryx*, *Anthracothema* and *Anthracokeryx* (Qiu, 1977; Li, 1984; Tong, 1989). Therefore, the ages of the Nadu fauna are comparable to those of the Pondaung fauna (40.1–38.6 Ma), which were based on magnetostratigraphic dating (Benammi et al., 2002), U/Pb and fission-track ages of detrital zircons (Tsubamoto et al., 2002, 2011; Zaw et al., 2014). These analyses indicate that the Nadu Fm mainly belongs to the middle Eocene in age, and only partially to the late Eocene (Fig. 3).

2.2.2. The Maoming Basin

The Maoming Basin (21°42′N, 110°53′E) is an intramontane basin located in southwestern Guangdong Province, southern China (Fig. 1a), which is one of the most famous oil shale producing areas in China (Aleksandrova et al., 2015). Maoming Basin is a NW-extending graben-like structure filled with Paleogene sediments (Nan and Zhou, 1996; Ye et al., 1996). From bottom to top, the Paleogene fluvial and lacustrine sedimentary succession of the basin can be divided into the Tongguling Fm, Shangdong Fm, Youganwo Fm, Huangniuling Fm, Shangcun Fm, Laohuling Fm, and Gaopengling Fm (BGMRGP, 1988, 1996;

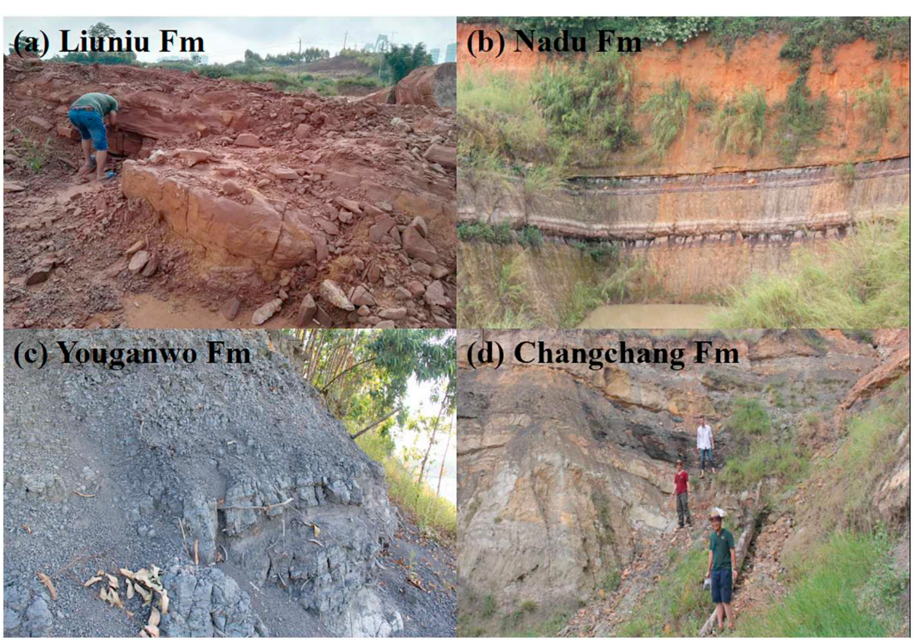

Fig. 2. Lithology of the Liuniu Fm (purplish red mudstones and siltstone) (a) and Nadu Fm (b) of the Baise Basin, Youganwo Fm (c) of the Maoming Basin and the Changchang Fm (d) of the Changchang Basin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

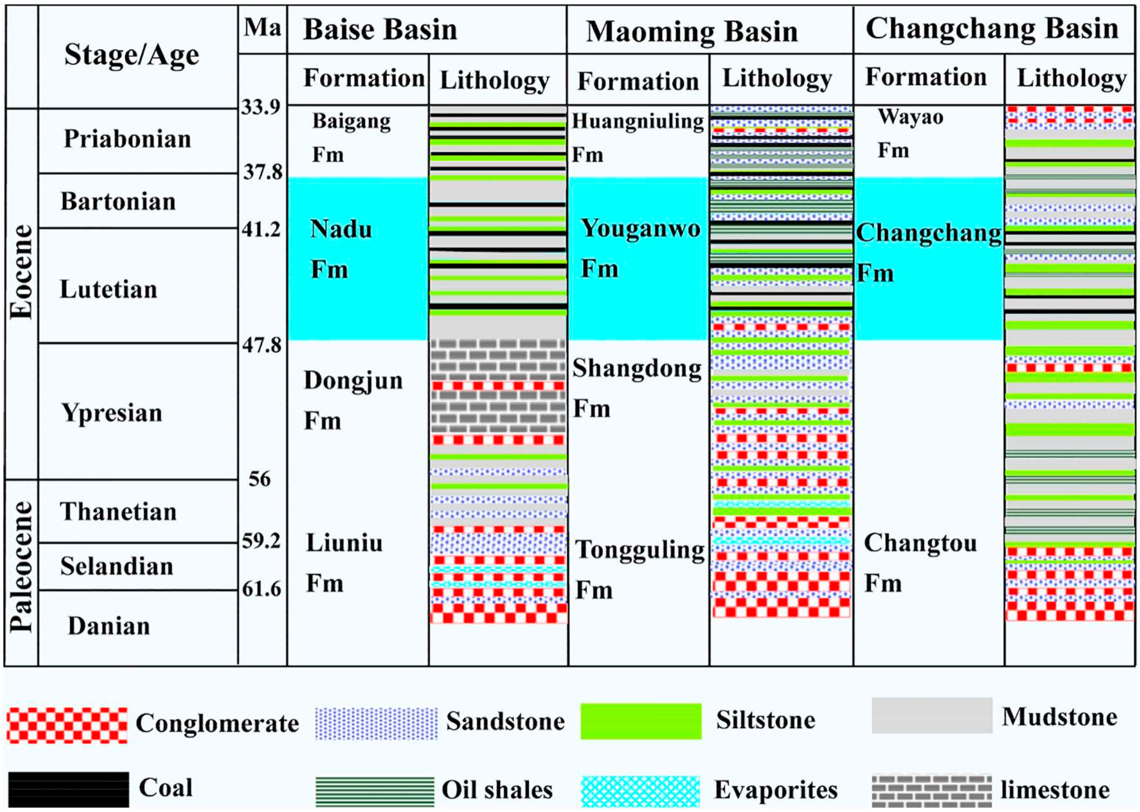

Fig. 3. Lithological and stratigraphic correlation of the Paleocene and Eocene between the Baise, Maoming and Changchang Basins.

Aleksandrova et al., 2015). The Youganwo Fm is the subject of this study (Fig. 2c). The Youganwo Fm is characterized by sandy conglomerates, sandstones, grey-green to purple-red clayey shale, and coal seams in the lower part, while the upper part is dominated by dark-grey to dark-brown oil shale with subordinate yellowish-brown mudstones alternating with coals (BGMRGP, 1996; Aleksandrova et al., 2015). The oil shale of the Youganwo Fm has yielded abundant mammal (Wang et al., 2007), fish (Liu, 1957), turtle (Chow and Liu, 1955; Chow and Yeh, 1962) and crocodile fossils (Yeh, 1958; Li, 1975; Skutschas et al., 2014). The Youganwo Fm has been dated by preliminary magnetostratigraphic data (Wang et al., 1994) and palynological analysis (Aleksandrova et al., 2015), suggesting that the Youganwo Fm is most likely middle Eocene in age (Fig. 3).

2.2.3. *The Changchang Basin*

The Changchang Basin (19°38′N, 110°27′E) is located in the northern part of Hainan Island (Fig. 1a). The Paleogene sediments of the Changchang Basin are divided into the Paleocene Changtou Fm, Eocene Changchang Fm and Wayao Fm (Zhou and Chen, 1988; Lei et al., 1992). The Changchang Fm is the subject of our study (Fig. 2d). The lower part of the Changchang Fm consists of varicolored (grey green, purple red, brownish red, brownish yellow) lacustrine mudstone, siltstone and sandstone. This is overlain by a coal-bearing series with a dark-colored lake-swamp coal-bearing structure, dominated by dark grey mudstone, grey black carbon-containing shale, brownish grey oil-bearing shale, yellowish brown, grey yellow, grey white muddy siltstone and sandstone, and coal (BGMRGP, 1988; Jin et al., 2002, Jin, 2009). The coal-bearing series contains abundant pollen and plant fossils (Jin et al., 2002; Jin, 2009; Li et al., 2009; Yao et al., 2009). A comprehensive review of the fossils suggests that the Changchang Fm was most probably deposited in the middle Eocene (Spicer et al., 2014), approximately contemporaneous with the Youganwo Fm of the Maoming Basin (Fig. 3).

3. Materials and methods

3.1. *Palynological analysis*

A total of 48 samples were obtained from outcrops exposed at the Baise, Maoming and Changchang Basins for palynological analysis. Sporopollen extraction was performed using standardized techniques. To avoid contamination of the samples, the outer layers of samples exposed to the air were removed. Samples of approximately 50 to 100 g sediment were washed and crushed, and then successively treated with 10% HCl and 39% HF to remove carbonates and silicates, respectively. For the coal samples, approximately 10 g of coal were first oxidized in 30% HNO_3 to remove the organic material. After neutralization, the organic matter was further treated with 10% aqueous NaOH solution to dissolve the organic matter and then washed to neutralization in distilled water. After chemical treatment, the remains were sieved using a 10-μm-mesh nylon sieve to separate the palynomorphs from the residue. Finally, the palynomorphs were mounted in glycerin jelly.

All samples were identified under a light microscope at 400× magnification at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Pollen identification was performed referring to Song et al. (1999) and Zhang (2009). More than 300 pollen grains per sample were identified in order to obtain the detailed palynomorph content of each sample. Some selected pollen and spores recovered from the three basins are shown in Plate 1 and Plate2.

3.2. *Coexistence approach*

To quantitatively reconstruct the middle Eocene climate in southern China, the nearest living relative (NLR) analysis (Detailed in Appendix 1) and coexistence approach (CA) (Mosbrugger and Utescher, 1997) were performed. Seven paleoclimatic parameters were reconstructed: MAT, CMT, WMT, MAP, mean precipitation of the driest month (lowest monthly precipitation: LMP), mean precipitation of the warmest month

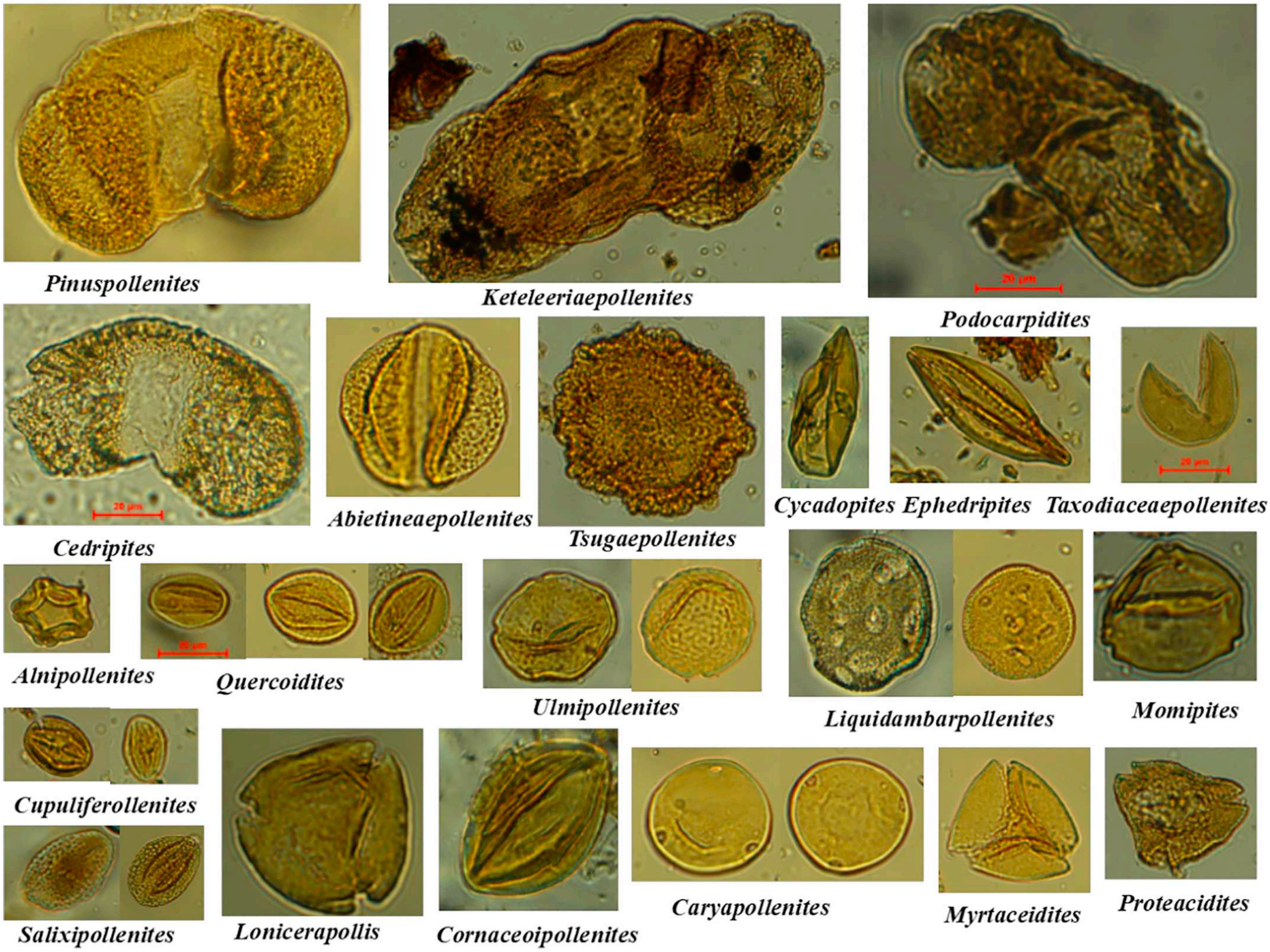

Plate 1. Representative photographs of spores and pollen from the Baise, Maoming and Changchang Basins.

(WMP), and mean precipitation of the wettest month (highest monthly precipitation: HMP). The CA is based on the assumption that the climate tolerance of a fossil plant is similar to that of its NLR when its modern affinity is determinable, the climatic tolerances ranges of each parameter of all the NLRs are overlapping and the coexistence interval of all NLR is obtained (Mosbrugger and Utescher, 1997). The climatic tolerances of each NRL genus were taken from the Palaeoflora database (Utescher and Mosbrugger, 1997–2012) and complemented with data from Yao et al. (2009) and Fang et al. (2009). It should be noted that the pollen assemblages may contain a certain proportion of pollen derived from plants growing at relatively high elevations nearby, which would underestimate the temperature. To address these limitations, pollen types from mountainous areas, such as *Cedripites* and *Laricoidites*, were ignored. Although some limitations of the CA were highlighted by Grimm and Denk (2012), the CA is still considered to be one of the most reliable methods of paleoclimate reconstruction.

In this study, the main aim is to investigate the possibility of a monsoonal climate in southern China during the Eocene. In general, 'monsoon' refers to the seasonal cycle of alternating wind direction and precipitation during a year (Zhang and Wang, 2008). Paleo-wind direction is difficult to recover or interpret in geological records; therefore, seasonal variations in precipitation have been regarded as an important indicator of monsoon climate in previous studies (Quan et al., 2011; Xing et al., 2012; Shukla et al., 2014; Spicer et al., 2017; Herman et al., 2017). Such seasonality can be also driven by migration of the ITCZ in low latitudes, and thus should be used with caution in southern China. By comparing the middle Eocene vegetation and climate with those of the modern East Asia Monsoon area, it is possible to determine if the Eocene monsoon in southern China was the EAM or ITCZ monsoons.

4. Results

4.1. Palynological records

4.1.1. Baise Basin palynological records

The palynoflora from Baise Basin is diverse and abundant, including 90 palynomorph taxa and some types with unknown affinities. Most are angiosperms pollen (53.63%~88.72%, av. 76.68%), followed by gymnosperms pollen (7.28%~33.73%, av. 18.3%), and relatively infrequent fern spores (0.6%~15.03%, av. 4.8%). The percentages of principal taxa of the Nadu Fm are presented in Fig. 4.

The angiosperms include 60 palynomorph taxa. The dominant taxa are *Ulmipollenites* (av. 20.53%), *Alnipollenites* (av. 15.75%), *Quercoidites* (av. 9.14%); pollen of *Juglanspollenites*, *Liquidambarpollenites*, *Caryapollenites*, *Salixipollenites* occur frequently; and there are minor amounts of *Betulaepollenites*, *Rutaceoipollenites*, *Cornaceoipollenites*, *Pterocaryapollenites*, *Platycaryapollenites*, *Magnolipollis*, *Palmaepollenites*, *Carpinipites*, *Zelkovaepollenites*, *Cupuliferollenites*, *Faguspollenites*, *Rhoipites*, *Fraxinoipollenties*, *Celtispollenites*, *Euphorbiacites*, *Lonicerapollis*, *Gothanipollis*, *Liliacidites*. The gymnosperms consist of 12 palynomorph taxa, with dominant taxa *Taxodiaceaepollenites*, *Pinuspollenites*,

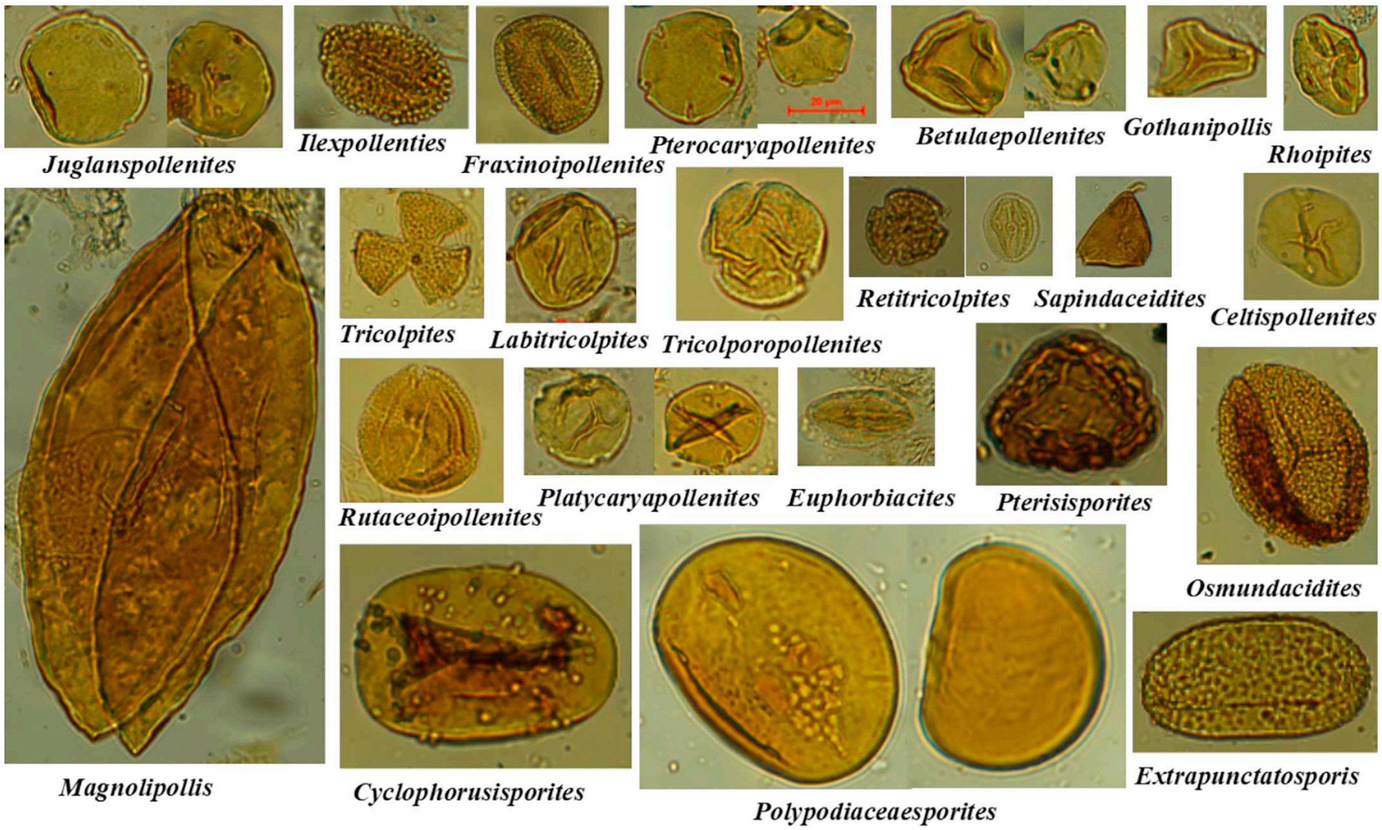

Plate 2. Representative photographs of spores and pollen from the Baise, Maoming and Changchang Basins.

Abietineaepollenites occurring frequently and throughout the sequence; pollen of *Cedripites*, *Ginkgopites*, *Cycadopites* are common, while *Tsugaepollenites*, *Keteleeriaepollenites*, *Podocarpidites* are rare. Ferns include 18 sporomorphs, the dominant taxa are *Polypodiaceaesporites*, *Polypodiisporites*; there are only a few occurrences of *Osmundacidites*, *Extrapunctatosporis*, *Deltodospora*, *Pterisisporites*, *Lycopodiumsporits*, *Crassoretitriletes*.

Some important taxa such as *Ulmipollenites*, *Alnipollenites* show consistent records in the sporopollen diagram (Fig. 4), but their percentages noticeably change from the lower part to the upper part, whereas percentages of other taxa such as *Quercoidites*, *Juglanspollenites* are stable. Other taxa, such as *Liquidambarpollenites*, occur irregularly with occasional peaks. Above all, the most conspicuous characteristic of this palynological assemblage is the increase of the *Alnipollenites* and the decrease of *Ulmipollenites*.

4.1.2. Maoming Basin palynological records

The palynoflora from Maoming Basin is diverse and abundant, including 52 palynomorph taxa and some types with unknown affinities. Most are angiosperms pollen (69. 73%), followed by gymnosperms pollen (13.06%), and relatively infrequent fern spores (16.62%). The percentages of the principal taxa of the Youganwo Fm are presented in Fig. 5.

The angiosperms include 34 palynomorph taxa; the dominant taxa are *Quercoidites* (21.39%~32.85%), *Ulmipollenites* (10.95%~12.72%), *Liquidambarpollenites* (4%~6.36%); pollen of *Cupuliferollenites*, *Juglanspollenites*, *Rutaceoipollenites*, *Momipites*, *Platycaryapollenites*, *Palmaepollenites*, *Carpinipites*, *Rhoipites*, *Fraxinoipollenties*, *Euphorbiacites* occurs frequently. The gymnosperms consist of 8 palynomorph taxa, the dominant taxa are *Pinuspollenites*, *Abietineaepollenites*; other taxa like *Taxodiaceaepollenites*, *Cycadopites*, *Podocarpidites*, *Keteleeriaepollenites*,

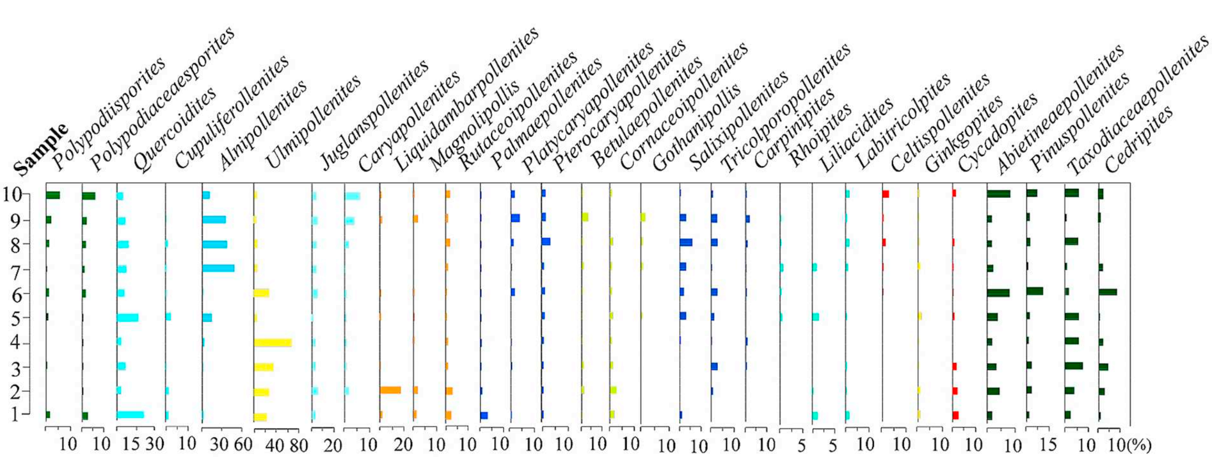

Fig. 4. Sporopollen diagram showing the percentages of the principal taxa of the Nadu Fm, Baise Basin.

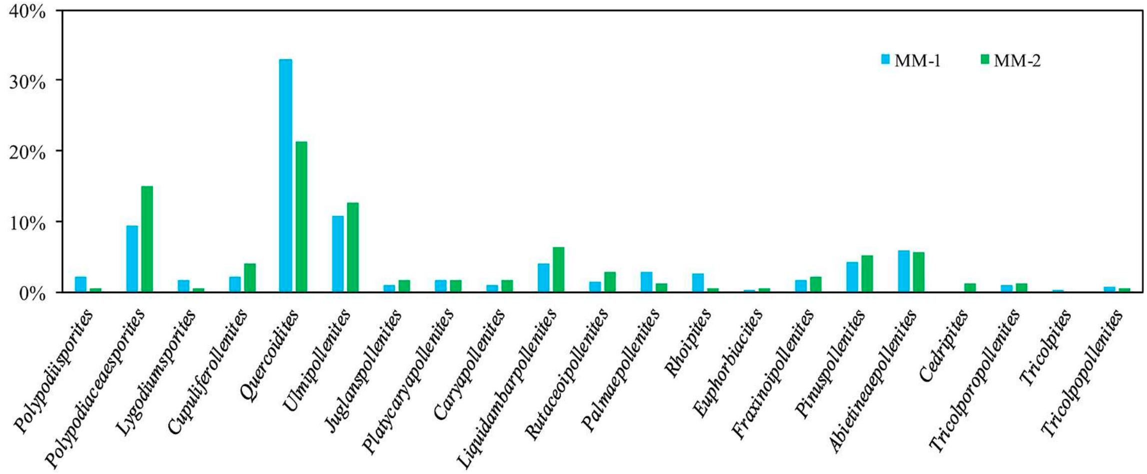

Fig. 5. Sporopollen diagram showing the percentages of the principal taxa of the Youganwo Fm, Maoming Basin.

Cedripites are also present. Ferns include 10 sporomorphs, dominated by *Polypodiaceaesporites*, with only a few occurrences of *Polypodiisporites*, *Lygodiumsporites*, *Osmundacidites*, *Deltodospora*, *Crassoretitriletes*.

4.1.3. Changchang Basin palynological records

The palynoflora from the Changchang Basin is diverse and abundant, including 47 palynomorph taxa and some types with unknown affinities. Most are angiosperms pollen (61.2%), followed by fern spores (31.65%), and relatively infrequent gymnosperms pollen (7.15%). The percentages of the principal taxa of the Changchang Fm are presented in Fig. 6.

The angiosperms include 34 palynomorph taxa. *Quercoidites* (22.88%) is the most common taxa, but *Liquidambarpollenites* (6.38%), *Ulmipollenites* (3.74%), *Juglanspollenites*, *Rutaceoipollenites* also occur frequently; other pollen taxa such as *Cupuliferollenites*, *Platycaryapollenites*, *Salixipollenites*, *Betulaepollenites*, *Pterocaryapollenites*, *Momipites*, *Palmaepollenites*, *Faguspollenites*, *Rhoipites*, *Fraxinoipollenties*, *Celtispollenites*, *Euphorbiacites*, *Gothanipollis* are also present. The gymnosperms consist of 7 palynomorph taxa, represented by *Taxodiaceaepollenites*, *Pinuspollenites*, *Abietineaepollenites*, *Cycadopites*. Ferns include 6 sporomorphs; the dominant taxa are *Polypodiaceaesporites* (24.33%), while *Polypodiisporites*, *Cyclophorusisporites* appear sporadically.

4.2. CA results

Middle Eocene sporopollen fossils from the three basins were analyzed using CA to reconstruct seven climatic parameters. The estimated climatic parameters are illustrated in Fig. 7 and given in Table 1.

5. Discussion

5.1. Paleovegetation

Our sporopollen results described above provide records of vegetation and climatic conditions of the middle Eocene in southern China. The features of the palynological compositions in the three basins are almost the same: the angiosperms were dominant in the three basins, while the percentages of angiosperms, gymnosperms and ferns taxa in each basin show some differences from each other (Fig. 8). The decrease in angiosperm and gymnosperm pollen, and the increase in fern spores, from northwest to southeast may imply that the Maoming and Changchang Basins were wetter than the Baise Basin. The high similarity in taxonomic composition suggests that the three palynological assemblages may be close in age, as they exhibit similar vegetation types under similar climatic conditions.

Based on the pollen percentages above, one striking feature is that the deciduous broad-leaved taxa *Ulmus*, *Alnus* and *Liquidambar* and

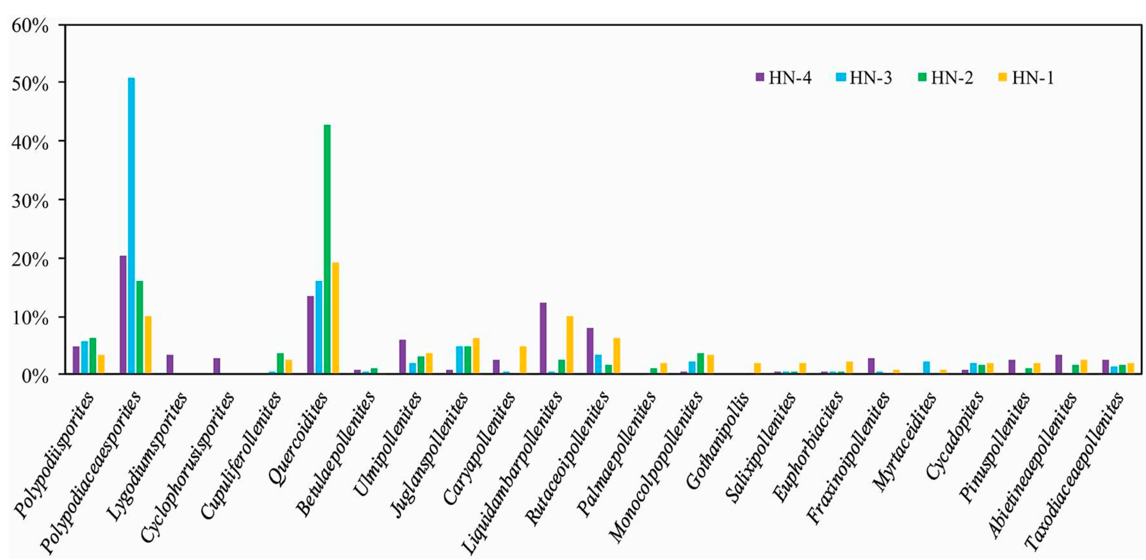

Fig. 6. Sporopollen diagram showing the percentages of the principal taxa of the Changchang Fm, Changchang Basin.

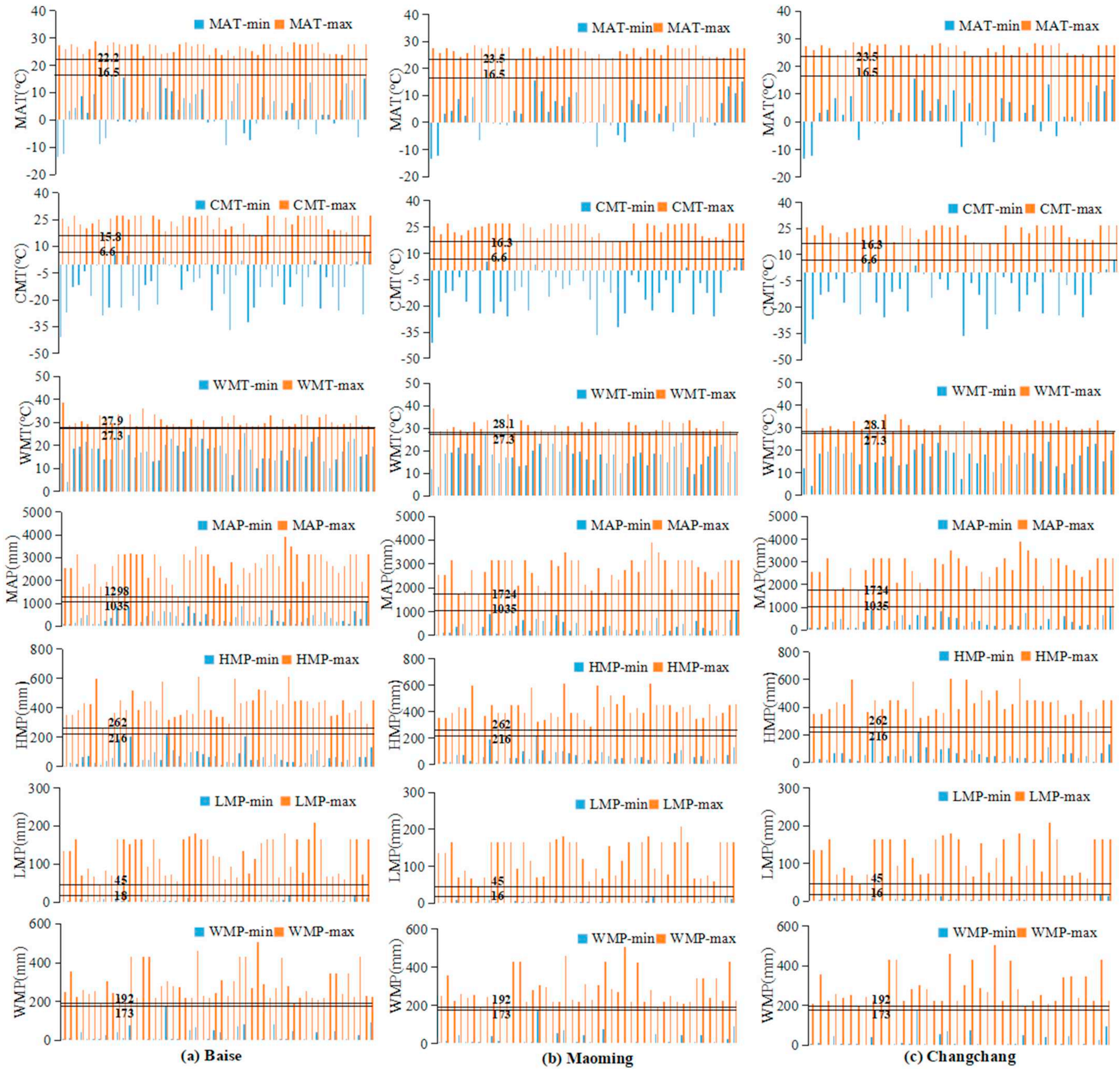

Fig. 7. The climatic tolerances of NLR of the fossil taxa in Baise (a), Maoming (b) and Changchang (c) Basins palynoflora and the intervals of their climatic parameters calculated using CA.

evergreen *Quercus* dominated the angiosperms, while the seasonal variation of deciduous broad-leaved trees reflects the seasonality of temperature and precipitation that collectively indicate a seasonal climate. The moisture-loving trees such as *Alnus*, *Salix*, *Fraxinus*, *Pterocarya* and *Taxodiaceae* are mainly distributed in moist regions (riparian, lake, valleys). The stable proportions of the riparian plants reflect the stable local aquatic environment. Moreover, conifers such as *Abies*, *Tsuga*, *Picea* and deciduous broad-leaved tree Betulaceae probably flourished on the mountains close to the basin. *Quercus*, *Juglans*, *Liquidambar*, *Ulmus*, Myrtaceae, Rutaceae, Palmae and Ilex were dispersed over the plains, slopes or hills, while moisture-loving ferns grew in the shady areas of woodlands.

The palynological assemblages suggest that the middle Eocene vegetation of the three basins was composed of a mixture of evergreen and deciduous broad-leaved forests, accompanied by subtropical and tropical taxa such as *Liquidambar*, *Carya*, Ilex and Palmae, Myrtaceae, Rutaceae, Anacardiaceae, Magnolia, Loranthaceae, Cycadaceae, Euphorbiaceae, Sapindaceae; there were also coniferous forests growing under subtropical conditions. This paleovegetation type is similar to that of the modern mixed evergreen and deciduous broad-leaved forests in southern China, indicating a warm, humid subtropical climate; it is also compatible with the depositional environment and consistent with previous knowledge of a broad humid zone across southern China in the Eocene (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008). These results further suggest that the modernization of the flora in southern China had occurred at least by the middle Eocene. Thus, the middle Eocene represents a crucial period in the development of the flora of southern China.

Comparison of our palynological results with previous palynological studies at the same sites, those palynofloras highlights notable

Table 1
Comparison between climatic parameters in the middle Eocene and modern day (pink color) in Baise, Maoming and Changchang Basins. Climatic parameters were obtained by CA (yellow, with mean values in brackets) and Climate Leaf Analysis Multivariate Program (CLAMP) (blue) ([b]Spicer et al., 2016, [c]Herman et al., 2017, [d]Spicer et al., 2014). [a]The modern climatic data come from the China Meteorological Data Service Center, with data from 1981 to 2010 (http://data.cma. cn/data/weatherBk.html).

Climatic parameters	Baise		Maoming		Changchang	
	Middle Eocene	Modern [a]	Middle Eocene	Modern [a]	Middle Eocene	Modern [a]
MAT(°C)	16.5-22.2(19.35)	22.1	16.5-23.5(20)	23.5	16.5-23.5(20)	24.3
			20.2[b]&20.65[c]		21.3[bd]&21.6[d]	
CMT(°C)	6.6-15.8(11.2)	13.5	6.6-16.3(11.45)	16.4	6.6-16.3(11.45)	18.1
			7.9[b]&8.52[c]		10.8[bd]&11.2[d]	
WMT(°C)	27.3-27.9(27.6)	28.4	27.3-28.1(27.7)	28.6	27.3-28.1(27.7)	28.6
			28.4[bc]		28.4[bd]	
MAP(mm)	1035-1298(1166.5)	1066	1035-1724(1379.5)	1731	1035-1724(1379.5)	1823
HMP(mm)	216-262(239)	198	216-262(239)	302	216-262(239)	304
LMP(mm)	18-45(31.5)	16	16-45(30.5)	26.5	16-45(30.5)	25
WMP(mm)	173-192(182.5)	198	173-192(182.5)	275	173-192(182.5)	214

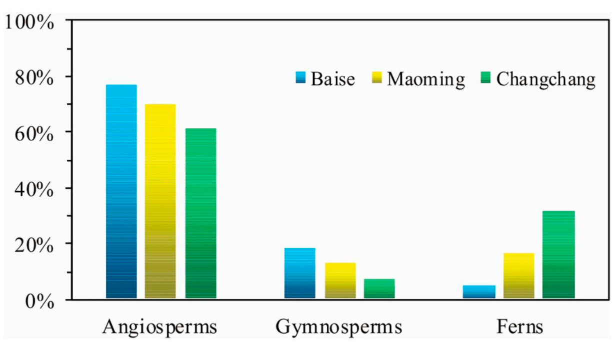

Fig. 8. The percentages of angiosperms, gymnosperms and ferns from the Baise, Maoming and Changchang Basins.

similarity in the taxonomic composition while some differences in the abundance of taxa (Wang, 1993; Liu and Yang, 1999; Tong et al., 2001; Yao et al., 2009; Aleksandrova et al., 2015). As a whole, the palynological assemblages are comparable with the *Quercoidites-Ulmipollenites-Alnipollenites* assemblages from previous palynological results, both palynological assemblages are dominated by mixed of evergreen and deciduous pollen, mainly including *Quercoidites*, *Ulmipollenites*, *Alnipollenites*, *Liquidambarpollenites*. There are also some gymnosperms pollen represented by *Pinuspollenites*, *Abietineaepollenites*, *Taxodiaceaepollenites*, and ferns spores are dominated by *Polypodiaceaesporites*, *Polypodiisporites*.

5.2. Middle Eocene climate in southern China

In order to constrain the prevalence of the middle Eocene monsoon over southern China, we compared the climatic parameters between the middle Eocene and modern day at the three sites (Table 1; Fig. 9). Our quantitative estimates of climatic parameters indicates a subtropical monsoon climate with a MAT ranging from 16.5 to 23.5 °C and a MAP ranging from 1035 to 1724 mm (Table 1). These values are similar to those of the modern subtropical monsoon climate in southern China and suggest that the middle Eocene climate of southern China was warm and humid; in addition, the amount of precipitation is consistent with sedimentary environment from southern China during the middle Eocene, such as the coal and oil shale (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008). Significant variations of precipitation and temperature between the wettest (warmest) and the driest (coldest) months are indicative of seasonality, though seasonal variations of precipitation are not as strong as the present day. High precipitation during the warmest month (WMP, 173–192 mm) also supports the monsoonal character of the precipitation. These results further demonstrate that a monsoonal precipitation pattern similar to that of the present day may already have existed in the middle Eocene in southern China (Fig. 9); however, our results show that the WMP during the middle Eocene was lower while the LMP was higher than those of the modern climate in southern China, which is currently under the strong influence of the EAM, implying that the monsoon intensity in southern China may have been weaker than present during the middle Eocene.

It is interesting to note that the temperatures in the three basins were surprisingly low for such a low latitude in a greenhouse world: they are lower than the present temperatures in the three basins, and the relatively low Eocene temperatures derived from CLAMP analysis for Maoming, Changchang (Spicer et al., 2014, 2016; Herman et al., 2017) and northwestern India (Shukla et al., 2014) also show similar climatic characteristics. In summary, our climatic parameters based on CA for the three basins are compatible with previous results derived from CLAMP analysis (Table 1). Previous studies based on both the Eocene flora from low latitude Asia (Shukla et al., 2014; Spicer et al., 2014, 2016; Herman et al., 2017), and the sea-surface temperature estimated by Keating-Bitonti et al. (2011) and Clementz and Sewall (2011), indicate that the Eocene temperatures in low latitudes might not have been as high as previously thought. The long-term Cenozoic climatic cooling may have occurred mainly in the middle and high latitudes, and had little effect on low latitudes (Zachos et al., 2008). Southern China is located at a relatively low latitude; therefore, the slight difference between the middle Eocene and the modern climates is reasonable.

The spatial variations of annual temperature and precipitation in the middle Eocene are illustrated in Fig. 10. Compared to Baise, the MAT of Maoming and Changchang are slightly higher, most likely due to the lower latitudes of Changchang and Maoming. Meanwhile, the spatial distribution of MAP followed a southeast-northwest distribution, decreasing from southeast (Changchang, Maoming) to northwest (Baise) (Fig. 10). This result is similar to the modern monsoon-type precipitation regime in southern China, suggesting not only that a pronounced monsoon had developed, but also that a spatial

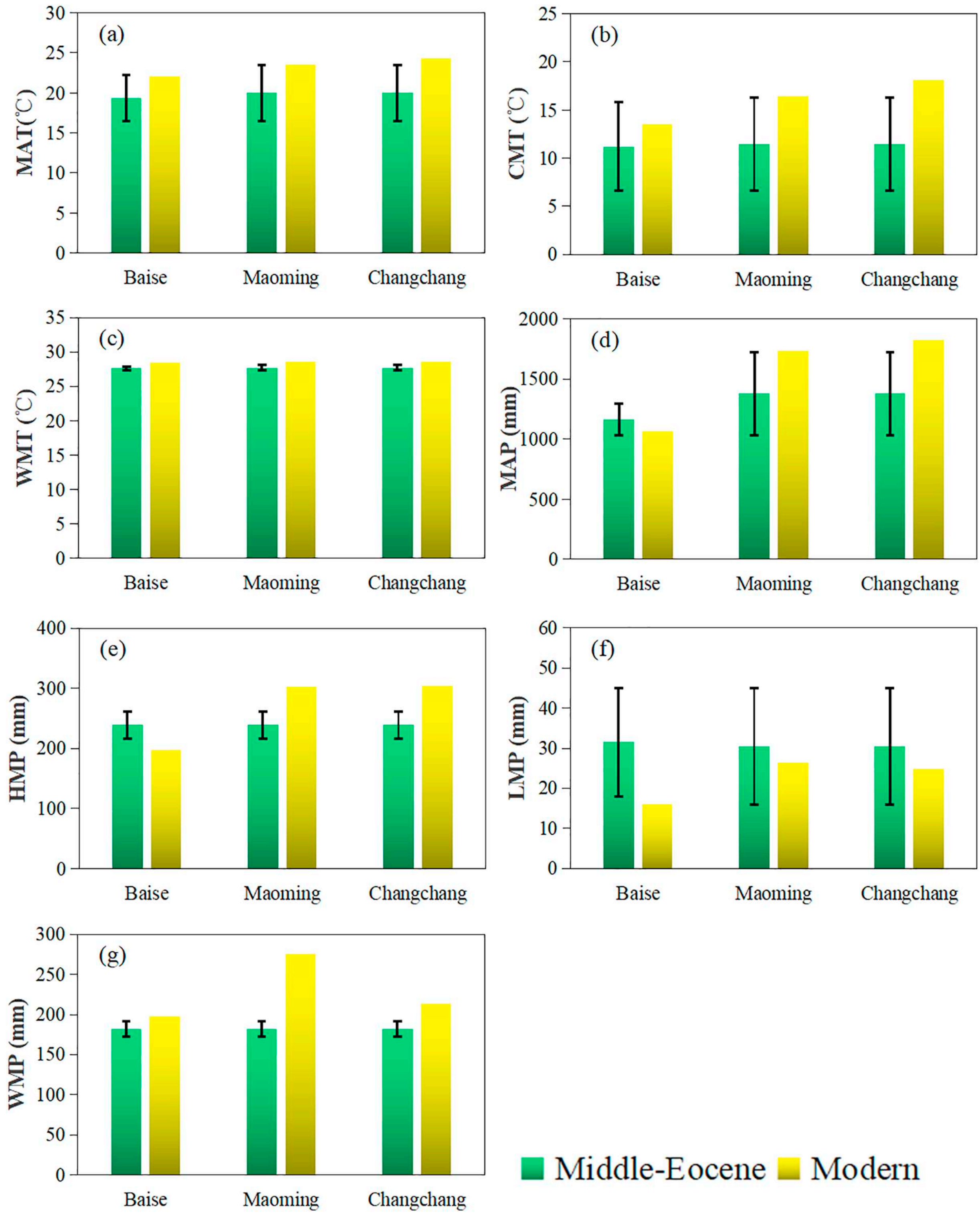

Fig. 9. Comparisons of seven climatic parameters between the middle Eocene and the modern day in the Baise, Maoming and Changchang Basins.

precipitation gradient existed in the middle Eocene.

5.3. Middle Eocene monsoon climate in southern China indicated by other evidence

An abundance of environmental indicators has been preserved in the Paleogene sedimentary basins in southern China, such as coal, oil shale, evaporites (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008). In the Paleocene and early Eocene, a broad arid and semi-arid belt stretched across southern China from east to west, represented by the widely distributed red beds or evaporites, which resulted from the influence of the planetary wind system (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008). The wide occurrences of xerophilous pollen taxa such as *Ephedripites*, *Pentapollenites*, *Nanlingpollis*, *Ulmipollenites* and drought-resistant *Palibinia* leaves in southern China also indicates an arid-semiarid environment (Guo, 1979; Wu and Yu, 1981; Li, 1989; Yang, 1993; Yang, 1996). Consistent with the geological evidence, numerical simulations also found that southern China remained

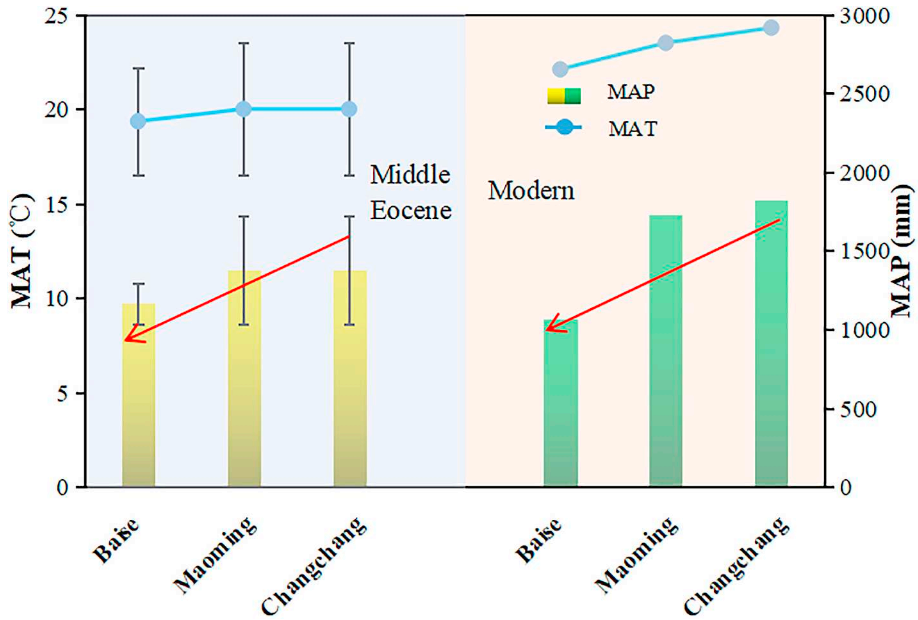

Fig. 10. Spatial comparison of MAT and MAP between the middle Eocene and the modern day in southern China.

dominated by arid-semiarid climates, with limited monsoons, even in the early Eocene (Zhang et al., 2012).

In southern China, evidence for the middle Eocene monsoon has been widely reported. The deposits, pollen, plant fossils and mammalian distributions indicate a northward migration of the humid zone after the middle Eocene. Lithological, coal-bearing deposits and oil shale were widely distributed across southern China (Gu and Renaut, 1994), while the red beds or evaporites were absent. The middle Eocene flora of the Maoming Basin was represented by wet subtropical forests with evergreen Fagaceae, Lauraceae and Palmae (Aleksandrova et al., 2015). The architectures of fossil leaves from Changchang and Maoming Basins exhibited monsoon-adapted morphologies (Spicer et al., 2016; Herman et al., 2017). An abundance of mammal fossils preferring moist and forested, swamp habitats has been discovered in southern China (Qiu and Li, 2005), including *Indomeryx, Notomeryx* (Qiu, 1978) and *Anthracothema* and *Anthracokeryx* (Tang et al., 1974; Qiu, 1977; Li and Chen, 2001). More robust evidence has come from the Nadu Fm, Baise Basin, where the δ^{18}O of mollusk shells showed a strong seasonal cycle, strongly suggesting the presence of a monsoonal climate (White and Dettman, 2007).

5.4. Possible driving mechanisms of the middle Eocene monsoon in southern China

If a monsoon climate prevailed over southern China in the middle Eocene, we now ask what was the water vapor source for the precipitation, and consider what type of monsoon was occurring. At present, the formation of the humid belt, the prevalence of the monsoon system over southern China in the middle Eocene, and the underlying driving mechanisms remain unknown.

The modern climate of southern China, including Hainan, Guangxi and Guangdong provinces, is influenced by complex monsoon climate systems (Wang and Ho, 2002), in which individual monsoon systems are difficult to distinguish from each other. Leaf architectural signatures revealed that the Asian Eocene monsoon in southern China is primarily driven by the wider seasonal migrations of the ITCZ (Spicer et al., 2016; Spicer et al., 2017; Spicer, 2017; Herman et al., 2017). If this is simply a reflection of wider ITCZ zonal migrations under a shallower equator-to-pole thermal gradient in the Eocene greenhouse conditions (Greenwood and Wing, 1995; Huber and Goldner, 2012), then southern China should have been subject to the effects of ITCZ seasonal migration prior to the middle Eocene, such as the extremely warm interval of the early Eocene. Consistent with geological evidence, numerical simulations also found that monsoon climates were restricted to the southern-most Hainan Island during the Paleocene to early Eocene, and that these tropical monsoons mainly resulted from the seasonal migrations of the ITCZ (Guo et al., 2008; Liu et al., 2015). The existence of ITCZ monsoons across southern Asia (south of 20°N) can be traced back to very early geological history (Guo et al., 2008; Liu et al., 2015), but the monsoons becoming established in subtropical China (20°∼25°N) during the middle Eocene are conceptually different from the tropical monsoons in low latitudes, and would have been controlled by other factors.

Present-day precipitation over southern China is derived from multiple sources, mainly the western North Pacific, the South China Sea or even the Indian Ocean. Southern China is mainly influenced by EASM, but also by the ISM to a lesser degree (Wang and Ho, 2002). The quantitative estimates of climatic parameters indicate that a wetter climate developed in the Maoming and Changchang Basins rather than Baise Basin, suggesting that the water vapor was more likely to have come from the western Pacific or South China Sea. The spatial distribution of MAP in the middle Eocene is clearly similar to the modern monsoon-type precipitation regime in southern China (Fig. 10), and that the seasonal variations of precipitation and temperature of the middle Eocene were most similar to that of the modern East Asia Monsoon climate of southern China, while distinct from those of the IM or ITCZ monsoons, from which we infer that the middle Eocene climate of southern China was mainly influenced by the EAM, rather than the IM or ITCZ monsoons. The above analysis implies that the EAM has influenced southern China since at least the middle Eocene. However, we did not rule out the possibility of southern China is to also be influenced by the IM or ITCZ monsoons to some degree.

The driving mechanisms of the EAM in southern China are complex, and it is difficult to distinguish the relative contributions of individual factors. To further understand the possible processes driving the establishment of the Asian monsoon in southern China, changes in the land-sea distribution and the uplift of Tibetan Plateau are considered. How, and to what extent, the two factors influenced the Eocene monsoon in southern China is now worthy of further discussion.

Numerical modeling results demonstrate that, when tropical lands are connected to a subtropical continent, the cross-equatorial flow (southeast trade winds, SETW) from the Southern Hemisphere are

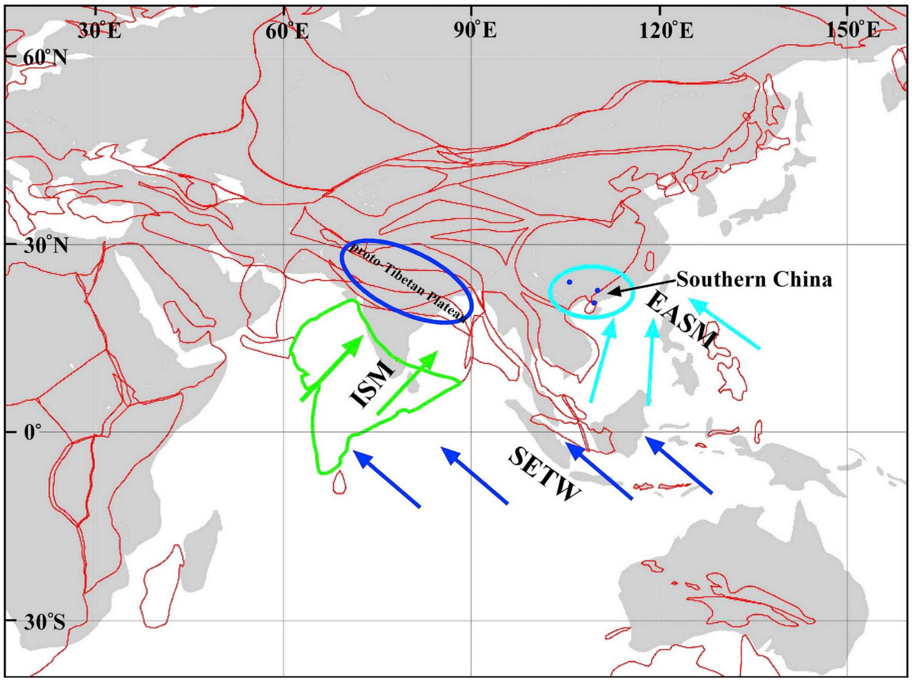

Fig. 11. Palaeogeographic map (http://www.odsn.de; Scotese, 2001) showing the location of southern China and the Indian Subcontinent during the middle Eocene (modified from Spicer et al. (2014)) and the contemporary monsoon circulation in Asia.

intensified (Fig. 11); abundant water vapor generated from the tropical ocean is transported to the subtropical continent by the enhanced northward flow, pushing the rain belt farther northward; and a prototype EAM is thus established (Liang et al., 2005, 2006; Wu et al., 2012). In this manner, when the Indian Subcontinent moved into the Northern Hemisphere and collided with the Eurasian continent in the middle Eocene (Molnar and Stock, 2009), the land-sea thermal contrast was enhanced and the summer low pressure over continental Asia was deepened, thereby greatly intensifying the East Asian subtropical summer monsoon over southern China.

Geological evidence and numerical simulations indicate that the uplift of the Tibetan Plateau had a profound impact on the onset and evolution of the East Asian monsoon (An et al., 2001; Guo et al., 2002; Liu and Yin, 2002; Molnar et al., 2010; Tang et al., 2013; Liu et al., 2017). Abundant geologic evidence indicates that a proto-Tibetan Plateau (Fig. 11) had achieved an elevation close to that of the present day Central-Southern Tibetan Plateau by the Eocene (Tapponnier et al., 2001; Rowley and Currie, 2006; Wang et al., 2008; Song et al., 2010; Ding et al., 2014). The existence of the proto-Tibetan Plateau amplified the land-sea contrast and strengthened the EAM circulation, pushing development of the EAM further northwards.

In conclusion, it seems that the land-sea distribution and the uplift of the Central-Southern Tibetan Plateau played a fundamental role in the establishment of the prototype EAM over southern China. Specifically, the establishment of the EAM in southern China during the middle Eocene was most likely driven by the northward drift of the Indian Subcontinent and its collision with the Eurasia continent, with the associated uplift of Central-Southern Tibetan Plateau. The tropical Indian landmass and the proto-Tibetan Plateau strengthened the land-sea thermal contrast and deepened the low pressure over continental Asia in summer, which induced the East Asian subtropical summer monsoon over southern China.

Although a large volume of geological evidence points to a humid belt stretching across southern China from east to west during the Eocene, it should be noted that the East Asian monsoon was restricted to southern China, and a broad arid belt remained across central China during the Eocene, insufficient to cause the major climatic shift in China until the late Oligocene to early Miocene (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008). The early EAM would have been fundamentally different from the modern EAM: the winter Siberian High was much weaker than present and the water vapor carried by the summer monsoon was limited to southern China. The formation and evolution of the monsoon in northern China was more dependent on the uplift of the central and northern part of the Tibetan Plateau (Tang et al., 2013; Liu et al., 2017), which occurred much later.

6. Conclusions

This paper reports our reconstruction of the middle Eocene vegetation types and monsoonal climate based on palynological records from three basins in southern China. The preliminary conclusions are listed as follows:

1) The palynological assemblages suggest that the middle Eocene vegetation of southern China was composed of mixed evergreen and deciduous broad-leaved forests, accompanied by abundant subtropical to tropical evergreen taxa. This paleovegetation type is similar to the modern vegetation in southern China, indicating a warm, humid subtropical climate.
2) Using the CA based on the palynological data from the three basins in southern China, we quantitatively reconstructed seven climatic parameters. These indicate a subtropical monsoon climate with a MAT ranging from 16.5 to 23.5 °C and a MAP ranging from 1035 to 1724 mm, which are similar to the modern subtropical monsoon climate in southern China, although the MAT is surprisingly lower than the present value. Significant seasonal variations of precipitation and temperature and that the spatial distribution of MAP during the middle Eocene were most similar to those of the modern East Asia monsoon climate of southern China, clearly showing that the Eocene climate of southern China was mainly influenced by the EAM, rather than the IM or ITCZ monsoons. By combining the above results and previously published geological evidence, we infer that the EAM has existed in southern China since at least in middle Eocene, though the monsoon intensity may not have been as strong

as that of the present day.

3) The establishment of the EAM in southern China during the middle Eocene was most likely driven by the northward drift of the Indian Subcontinent and its collision with the Eurasian continent, and associated uplift of the Central-Southern Tibetan Plateau, which enhanced the land-sea thermal contrast and deepened the summer low pressure over continental Asia in summer, thus greatly intensifying the East Asian subtropical summer monsoon over southern China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2019.01.019.

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