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Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre[1,2], D. Jolly[2], S. Ducrocq[3], Y. Chaimanee[4], and J.-J. Jaeger[3]

[1]Laboratoire des Sciences du Climat et de l'Environnement/Institut Pierre Simon Laplace,
UMR CEA/CNRS/UVSQ, Orme des Merisiers, bât. 709, 91191 Gif-sur-Yvette cedex, France
[2]Laboratory of Palaeoenvironments, ISE-M, UMR 5554, Case 61, Université Montpellier II,
34095 Montpellier Cedex 05, France
[3]Institut International de Paléoprimatologie, Paléontologie Humaine: Evolution et
Paléoenvironnements, UMR 6046 CNRS, Université de Poitiers, 40 avenue du Recteur
Pineau, 86022 Poitiers, France
[4]Paleontology Division, Bureau of Paleontology and Museum, Department of Mineral
Resources, Rama VI Road, Bangkok 10400, Thailand

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

| |◄ | ►| |
| ◄ | ► |

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

Only few data from South-East Asia document paleoenvironments evolution during the Cenozoic. Here we analyse palynological records from four sites of Thailand. The unique site dated from the Oligocene shows a temperate signal, while younger Miocene
5 records show a tropical signal with variations in the hydrology of the deposition basin, as well as a temperate extra-local signal that could be related to a mid-altitude flora. The mid-Miocene Chiang Muan basin has delivered several occurrences of an opened biotope (*Poaceae*) alternatively replaced by what could be *Syzygium* gallery-forests. Khorat (−9 to −6.5 Ma) pollen records deliver similar results, but linked to a strong
10 local signal. Regional and local signals remain difficult to separate, notably because of badly known palynomorphs, but our high resolution record confirm oceanic data that suggest high variability in Miocene climate, as well as modelling studies inferring an early onset of the Asian monsoon.

1 Introduction

15 The recent fossil record from Southeast Asia has shown that this area was crucial to assess the evolution of hominoids, especially during the Miocene period. Among several important discoveries (Chaimanee et al., 2003, 2004), remains of a middle Miocene hominoid (*Khoratpithecus chiangmuanensis*), which might be an ancestor of the living orang-utans, have been described from Thailand. A preliminary palynological
20 study of the sediments in which the fossils were found revealed a mosaic of tropical freshwater swamps and a *Syzygium* dominated forest flora, reminiscent to the extant African habitat that characterizes the White Nile headwaters (Chaimanee et al., 2003). Moreover, the Miocene has been a key-period in terms of climates, since a "climatic optimum" has been described, followed by a sudden decrease in temperatures be-
25 tween approximately 16 and 9 Ma, and contemporaneous with the establishment of the East Antarctic Ice sheet (Zachos et al., 2001). Other palynological investigations in

the Siwaliks (Central Nepal) have shown evidence of such climatic shifts between the middle and late Miocene. The uplift of the Himalaya and its possible link with monsoon intensification may have played a role in the replacement of subtropical and temperate forests by grassland (Hoorn et al., 2000). Numerous palynological studies have been carried out by petroleum companies in this part of the world, but they were not published until Morley (2000) made some of them available. It is thus critical to reconstruct Southeast Asian palaeoenvironments in order (i) to document and understand more precisely the environments in which the hominoids evolved, and (ii) to collect more information on the evolution of climatic conditions.

Here we present the results of the analysis of several palynological samples from Thailand that have been processed at the Institut des Sciences de l'Evolution in Montpellier, France (ISEM), and ranging from the late Oligocene (25 Ma) to the late Miocene (9 to 6.5 Ma). We provide an attempt to reconstruct paleoenvironments of Tertiary basins of Thailand and we propose hypotheses about the climatic evolution in southeast Asia during the Tertiary.

2 Regional environmental setting

2.1 Physiographic areas and climate

The main part of Thailand extends approximately between 12° N and 20° N and 97° E and 105° E. The southernmost part of Thailand corresponds to the Malaysian peninsula that extends downward to 6° N. This particular setting led Ogawa et al. (1961) to divide Thailand into four physiographic areas:

The North Western Highlands (Fig. 1) are a mountainous region which corresponds to the southern extension of Myanmar (Burma) Shan highlands. Several parallel ridges extend southward and four important rivers run between the valleys, permitting the existence of narrow alluvial plains. As everywhere in Thailand, rainfall has a strong seasonal cycle over the North Western Highlands. Maximal precipitations occur be-

Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre et al.

tween May and September, during the monsoon season, with rates ranging from 4.5 to 7 mm/day.

The Khorat plateau ~~lies on the whole~~ north-east part of the country. Its northern and eastern sides drain ~~the rainfall waters down~~ to the Mae Kong River. The southern and western borders are marked ~~with~~ the presence of flat-topped peaks (up to 1600 m). ~~Rainfall~~ seasonal cycle is very similar to that from the North Western Highlands, with a higher peak in September (9 mm/day) and a totally dry season between November and February (Fig. 1).

Southward is ~~a wide region (~~Central Plain~~)~~ which ~~gathers~~ vast deltas and alluvial plains formed by the rivers coming from north and south. This region is regularly flooded during the rainy season.

The peninsular region, which extends from the Gulf of Thailand as a long belt, is characterized by mountains stretching southward with an altitude up to 1800 m.

Rainfall distribution depends on topography that faces ~~to~~ dominant monsoon winds. Following the seasons, these winds are from ~~North-East~~ (dry monsoon) or ~~South-West~~ (wet monsoon). North-eastern winds bring less than 50 mm of rainfall ~~on~~ Thailand during January, while south-western winds bring up to 400 mm of rainfall during July, depending on the location. ~~Rainfall season~~ is longer here than in the northern parts of the country, and rainfall rates are higher ~~all year long~~.

2.2 Regional vegetation

The question ~~as to defining the types of vegetation~~ in Thailand has been subject to many debates between botanists and ecologists for at least 40 years. In 1957, the Royal Forest department of Thailand (Ogawa et al., 1961) recognized 6 main types of forest vegetation and only one type of grassland (savanna), whereas modern authors (Maxwell and Elliott, 2001) defined only three vegetation types, each of them subdivided in sub-types (Fig. 1). The North Western Highlands are covered essentially by what can be called the "Mixed Deciduous Forest", with Teak (*Tectona grandis*; very important for the local economy), as well as many other tropical deciduous trees such

as the genera *Xylia, Dalbergia, Acacia, Nauclea*. ~~On the contrary~~, the Khorat Plateau is dominated by deciduous dipterocarps forests, although they have been strongly reduced due to human activities, as shown by the cropland cover in Fig. 1. Among the natural indigenous taxa, species such as *Shorea obtusa, Dipterocarpus tuberculatus,* and *Dipterocarpus obtusifolius* tend to form pure (monospecific) stands. The Peninsular and the Central Plain regions are covered by ~~the~~ so-called "Tropical Evergreen Forest", including both needleaves and broadleaves.

2.3 Tertiary basins

The Tertiary fossiliferous localities of Thailand discussed here are situated in three main areas:

(1) The Nong Ya plong coal mine (13°9′ N, 99°40′ E) is located in the Phetchaburi Province, 100 km south-west of Bangkok at the northern end of the Peninsular Region. Fossil mammal have been discovered in a black claystone bed situated under a 30 m lignite bed and they suggest a late Oligocene age, between 26 and 24 Myr (Marivaux et al., 2004, 2006).

(2) Western deposits: The Mae Moh (18°19′ N, 99°41′ E) and Chiang Muan (18°56′ N, 100°14′ E). Basins are located in the northwestern part of the country, in a rift zone that crosses Myanmar and Laos and ends in the Gulf of Thailand (Malaysian and Indonesian Rifts). This NW-SE system lies over more than 2000 km and is delimited by two faults zones: the Sagaing Fault Zone to the west and the Red River Fault Zone to the east (Morley, 2001). These faults are believed to result from the India-Asia collision. During the early Miocene, this tectonic extrusion mechanism was responsible for the creation of the basins considered here.

The Mae Moh and Chuang Muan Basins have a similar three-step sedimentation scheme. When they began to fill, the subsidence of the basins was weak and fluvial and fluviolacustrine sediments were deposited. Then, the subsidence started to increase and lignite and claystone sediments, originating from swamps or little lakes progressively laid in the basins. Finally, the subsidence slowly decreased and the

Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

basins filled with fluvial sediments with a deltaic regime.

The Mae Moh Basin (Lampang province) ~~is~~ the largest coal deposit in Thailand (16.5 km long and 9 km wide). In 1985, the stratigraphy ~~has been~~ divided into three formations (Corsiri and Crouch, 1985; see also Morley, 2001): the Huai King Formation (fluvial and alluvial sandstones, up to 320 m thick), the Na Khaem Formation (lignite interbedded with lacustrine claystones and mudstones, ca. 420 m thick), and the Huai Luang Formation (red-brown and grey claystones and mudstones, up to 400 m thick). ~~Biostratigraphy~~ studies suggested that the Mae Moh sequence extends from the middle Miocene to the beginning of the late Miocene (Ginsburg, 1984, 1988; Tassy et al., 1992; Ducrocq et al., 1994; Peigné et al., 2006). A magnetostratigraphy study (Bennami et al., 2002) has provided more precise dating: they have correlated the Na Khaem sequence to the geomagnetic polarity time scale (GPTS), and they have shown that it is situated between the C5ABn and C5An chrons, between −13.5 and −12.2 Ma. The palynological samples of Mae Moh come from the Q and K lignite layers in which remains of a sivaladapid primate has been discovered. This layer is correlated with the chron C5Aar dated from −13.3 to −13.1 Ma.

The Chiang Muan Basin (Ban Sa locality) is located northeast of the Mae Moh basin and is much smaller (1 km long and 300 m wide) ~~than it~~. The Miocene sediments roughly consist of sandstones, mudstones and thin lignite beds (Benammi et al., 2004). The lower and upper lignite seams of the Chiang Muan Basin yielded remains of the hominid *Khoratpithecus chiangmuanensis* (Chaimanee et al., 2003). Associated large fossil mammals in the Ban Sa locality led to ~~suggest~~ an age ~~comprised~~ between 10.8 and 14 Ma. Furthermore, paleomagnetic data of the Chiang Muan section revealed a reversed polarity zone between two normal events, which indicated four possible estimated ages between 13.5 and 10 Ma (Benammi et al., 2004).

(3) Northeastern deposits: Khorat (15°01′ N, 102°16′ E). Samples ~~have been~~ collected in a palaeo-river pass which was exploited as a sand quarry. The stratigraphy of the sand pit is difficult to constrain, especially because of numerous cross-overs between sediment layers. Chaimanee et al. (2006) have described two sand units

Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre et al.

for the Somsak sandpit (Fig. 3): the upper sand unit consists of "yellowish sand, silt and gravel with cross-bedding structures" that indicate fluviatile deposit. The lower sand unit "consists of grey organic-rich sand and gravel, with some clay lenses intercalated. Intense cross-bedding indicates fluviatile regime with intermittent swamp deposits". The five pollen samples analysed here come from the lower sand unit: three of them were colledted from a sandy clay layer that yielded fossil mammal remains and two samples were obtained from the overlying dark organic clays. The large mammal fauna of Somsak sand pit (*Alicornops complanatum, Brachypotherium perimense, Deinotherium indicum*) reminds those from the Dhok Pathan Formation in the Siwaliks (Pakistan, ca. 8 Ma) and from the Shansi Red Claystones (China, ca. 7 Ma), and suggests a late Miocene age (Turolian: 9–6.5 Ma) for the sequence (Chaimanee et al., 2006).

3 Methods

3.1 Field and laboratory

The samples were collected by the ISE-M palaeoenvironment team in the four sites following the same technique, i.e. carefully scraping the beds in order to prevent present-day pollen contamination and immediately isolating the samples in sterile plastic bags. Our study includes 25 samples (Table 2). Mae Moh and Chiang Muan samples come from lignite deposits, whereas Nong Ya Plong and Khorat samples come from claystones. The Chiang Muan site includes 4 samples already published in a previous paper (Chaimanee et al., 2003) and 2 unpublished samples.

The samples have been submitted to a four-step chemical treatment. First, potash (KOH 10%) has been used to destroy humic acids and vegetal particules. In a second time, the samples were filtered with 180 μm grid cell and centrifuged several times (Faegri and Iversen, 1989). Then, the plugs have been treated with Fluorhydric Acid (FH) in order to destroy mineral elements. Finally, an acetolyse was performed in

order to get rid of possible remaining ~~vegetal particules~~ and a final centrifugation with glycerine water was carried out before mounting samples ~~between lams.~~

3.2 Pollen identification and counting~~s~~

Pollen grains ~~have been~~ observed ~~with~~ a light microscope at ~~a~~ ×600 magnification.
5   We counted one ~~lam~~ per sample. The minimum ~~spectrum~~ was 37 (Mae Moh) and the maximum was 1195 (Chiang Muan), the average being ca. 416. Since our aim was to describe the Miocene Thailand vegetation, we used modern ~~familial,~~ ~~generic~~ and species names for the identified taxa (Germeraad et al., 1968). The fossil palynomorphs were directly compared to palynological references which were essentially
10 the "Angiosperm Pollen Flora of Tropic and Subtropic China" (South China Institute of Botany, 1982), the "Pollen Flora of Taiwan" (Huang, 1972) and the "Pollens des savanes d'Afrique orientale" (Bonnefille and Riollet, 1980). Moreover, we made our determinations more accurate by using a Southeast Asia Flora (Jensen, 2001) and we compared our samples with the ISE-M palynological reference collection (48 000 ~~lams~~
15 of Angiosperms, 2400 ~~G~~ymnosperms, 2000 ~~P~~teridophytes).
     The state of preservation of the palynomorphs was very poor; out of the total ~~pollen~~ ~~sum (~~10 413 palynomorphs counted~~)~~, 14.9% were so strongly corroded that it was impossible to describe them. The bad state of preservation of the pollen grains might be explained by their oxydation during ~~their~~ fossilization (Hoorn et al., 2000). ~~Therefore,~~
20 ~~we will~~ distinguish indeterminable grains (corroded, indescribable grains) from unidentified grains, which have been described but not referred to any taxon.

3.3 ~~Pollen diagrams construction~~

Palynological data are ~~listed in~~ diagrams that exclude corroded pollen grains from the sum. The taxa have been grouped according to their ecological affinities (Table 2) in
25 order to analyze the regional climatic trends of the samples. The groups were chosen using online databases (Watson and Dallwitz, 2000) and specialized literature on India

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

(Blasco, 1971), East-Asia (Hooker, 1875), and Thailand (Ogawa et al., 1961; Kuchler and Sawyer, 1967; Maxwell and Elliott, 2001). A diagram including Pteridophytes (monolete and trilete spores) and aquatic taxa was first constructed. We then considered that both these groups represented a local vegetation, corresponding to the ferns and the aquatic plants living in the vicinity of the deposit location. Thus, we constructed a diagram excluding this signal in order to evaluate the extra-local variations.

4 Palynological results

Here we consider the palynological diagram including the Pteridophytes and aquatic taxa (Fig. 2).

4.1 Nong Ya Plong (1 sample)

A total of 313 pollen grains have been counted, but 31% were indeterminable. Among the 216 other grains, 20% remained unidentified. 13 taxa are constant in the samples: *Pteridophytes* (Monolete spores, 41%) and *Alnus* (21%) are the most representative, followed by *Pinus* (7.5%), *Poaceae* (2.8%), *Castanea* (1.8%) and *Loranthaceae* (1%). Other taxa (*Celtis, Eleagnaceae, Nyssa, Platycarya*, cf. *Quercus, Taxodiaceae*) represent less than 1% of the total number of taxa.

4.2 Chiang Muan (6 samples)

A total of 4877 (360 grains in the smallest sample and 1195 in the largest one) pollen grains have been counted. The pollen spectra are characterized by a high taxonomic diversity (between 12 and 24 taxa) suggesting a better pollen preservation which is confirmed by the low percentage of indeterminable pollen grains (<6%). Moreover, the low percentage of unidentified pollen (7%) leads us to consider that these spectra are a significant representation of the vegetation of the Ban Sa Basin (see further

for local/regional distinction). The level that has yielded hominoids is dominated by *Syzygium* (56%), ~~*Rubiaceae*~~ (27%) and ~~*Pteridophytes*~~ (9.5%). Tropical forest taxa (*Alchornea, ~~Celastraceae, Combretaceae~~*) and grassland ~~taxa (*Poaceae*)~~ represent less than 5% of the sum. Level CM1 is very ~~specific~~ because it contains a high percentage of *Ilex*, along with *Syzygium*, *Nauclea* and ~~*Rubiaceae*~~. *Ilex* is present today in the lower montane forests of northwestern Thailand (Kanzaki et al., 2004).

4.3 Mae Moh (13 samples)

A total of 3342 grains ~~have been~~ counted, but the state of preservation was very ~~bad~~ since 31.5% are undeterminable. The percentage of unknown pollen grains is also high, ranging from 8.7% (MM7) to 46% (MM8). ~~*Pteridophytes*~~ are omnipresent with a percentage between ca. 20% and 80%. ~~The *Rubiaceae* spectrum~~ is significant (up to 30%), although this group is not represented in all levels. Tropical Forest taxa are rare (<5%) or absent. *Syzygium* is absent except in one level that yielded 8 grains (1.4%). Other taxa ~~represent~~ less than 15% except for one level (19.4%) which is essentially composed of monocotyledons. Temperate Forest taxa are present in 11 out of the 13 levels analysed, although their percentage is rather low, except for one particular level (MM3) where *Castanopsis*, *Betula, Pinus* and ~~*Tiliaceae*~~ are the only pollen grains observed (~~*Pteridophytes*~~ excluded). No ~~*Cyperaceae*~~ pollen grain ~~has been~~ observed.

4.4 Khorat (5 samples)

A total of 1881 pollen grains ~~have been~~ counted, among which 11% were indeterminable. Four levels contain well-preserved material (93.2%) but the level K1 has 33% of corroded pollen grains. The herbaceous signal (hereafter NAP for Non Arboreal Plants) signal is consistent (between 20 and 47%), especially for ~~the *Poaceae* taxa~~. The ~~*Pteridophytes*~~ signal is more variable (between 4 and 43%). Tropical Forest taxa

718

are also present with a great variability (between 3 and 28%). These observations allow to distinguish two groups that correspond to two kinds of clay: KA and KB samples are very similar in their composition, with a high amount of spore (>40%) and herbaceous taxa (40%), a very weak signal corresponding to temperate trees, and 10% of pollen grains referred to tropical trees. These levels are also characterized by the presence of aquatic taxa, especially Cyperaceae. Levels K1, K2, and K3 contain very few spores but high percentages of tropical trees (*Syzygium*) and *Rubiaceae*.

Former studies (Watanasak, 1989) have described the setting of *Dipterocarpaceae* family over Thailand since the early Miocene. No *palynomorphs* corresponding to this family has been found in our samples, but this may be linked to the poor preservation of this kind of pollen grains, since other studies have reported Miocene dipterocarps in Thailand (Songtham et al., 2004).

5 Discussion

5.1 Local and regional vegetation: the hydrological signal

The common abundance of *Pteridophytes* in all studied sites likely corresponds to a local signal extending from several m to a few hundreds of m around the deposit sites. This hypothesis is supported by the low situation of the gametophytes on most of the fern species we know, which prevents the spores to be transported by the wind on long distances. The percentage variations might be interpreted as variations of the hydrology in the deposit zones, with more ferns during wet periods and more trees when the basin is well drained. Maley and Brenac (1998) have hypothesized that spores might be transported on longer distances by water flooding. However, a high percentage of spores might correspond to a high volume of water invading the basin, whereas a lower volume of water would correspond to a weaker hydrological dynamism. This pattern is very well documented in the Mae Moh section.

5.2 Nong Ya Plong: an Oligocene temperate signal

Paleoenvironments in this site can be interpreted as "temperate" since pollen grains of *Alnus* and *Pinus* are the most common taxa. The paleogeography history of south-east Asia cannot explain this difference with younger Tertiary paleoenvironments as Briais et al. (1993) suggested that the Oligocene paleolatitude and paleoaltitude of the peninsula ~~was~~ not significantly different from its present situation. The lack of further information on Oligocene paleoenvironments cannot lead to any conclusion concerning the background climatic mechanism of this temperate signal.

5.3 Middle Miocene records: Mae Moh and Chiang Muan

It is difficult to compare the dynamics of vegetation between Mae Moh and Chiang Muan because of their different age. Indeed, if magnetostratigraphy provides a precise date for Mae Moh deposits (the samples of Mae Moh document a 200 000 years time span, between 13.3 and 13.1 Ma), it is not the case for Chuang Muan, for which the ~~datation~~ varies between 13.5 and 10 Ma.

In terms of spore presence, Chiang Muan section is similar to Mae Moh where spores are correlated with herbaceous taxa and not trees. ~~This implies that the environment was first characterized mostly by trees; the latters were then replaced by herbaceaous taxa (mainly *Poaceae*).~~ *Poaceae* and *Cyperaceae* co-occur in 4 levels at Chiang Muan, which means that this signal for an open vegetation might not be linked to a water stress, at least at the local scale. Indeed, the water pond where the pollen grains have been deposited may have been colonized several times by *Syzygium*, and the main current species of this genus in Africa are known to colonize borders of rivers in quasi-monospecific populations (Letouzey, 1968). However, *Syzygium*, with eighty-four known species, is today the most diversified genus of *Myrtaceae* in Thailand (Parnell et al., 2003), and it occurs there in a wide range of types of vegetation, from dry evergreen to deciduous Dipterocarps forests (Sookchaloem, 2004). Chaimanee et al. (2003) have suggested that the presence of *Syzygium* during the Miocene might indicate a connec-

tion with floras from eastern Africa. (Songtham et al., 2004) challenged this hypothesis, arguing that *Syzygium* originated from Southeast Asia or Oceania. ~~Several authors .~~ (Sytsma et al., 2004; Wilson et al., 2005) also suggested that *Syzygium* belongs to a clade clearly separated from other Myrtaceae, but the question of the timing of African colonization and possible Miocene connections with Asia remains unresolved. However, *Syzygium*-like pollen grains have been found recently in the Turkana basin (Kenya, eastern Africa) and dated from about 25 Ma (Vincens et al., 2006), suggesting that this genus was present earlier in East Africa, giving more credit to the hypothesis proposed by Chaimanee et al. (2003). Further studies on the Miocene of central Asia and the Paleogene of Africa are needed in order to solve the debate. ~~On~~ a climatic point of view, environmental connections between Southeast Asia and eastern Africa are supported by the study of Sepulchre et al. (Sepulchre et al., 2006) who suggested that the uplift of eastern African topography might have triggered a strong aridification by 8 Ma and that southern Asia and eastern Africa might have been subjected to seasonal rainfalls. Miocene data from the Indian Subcontinent are necessary to validate this hypothesis.

Syzygium and ~~*Cyperacea*~~ are absent from the Mae Moh samples (except one level that displays only *Syzygium*). The absence of *Cyperaceae* (and the very weak percentage of other aquatic taxa) suggests less humid conditions for Mae Moh than for Chiang Muan, which can be related to the different sizes of both basins. Mae Moh samples are also characterized by the constant presence of taxa that are frequently interpreted as "temperate" (*Myrica*, *Castanopsis*, *Alnus*, *Betula*) (Songtham et al., 2003). They might represent (i) a mid-altitude forest including tropical taxa, or (ii) higher altitude forests dominated by temperate taxa. Although Rubiaceae are today distributed over several bioclimatic conditions, they are mainly found in the lower montane forests of northwestern Thailand (*Psychotria, Lasianthus, Nauclea, Mycetia, Tarenna*), associated with temperate taxa like *Castanopsis* and *Cryptocarya* (Kanzaki et al., 2004). If we consider *Rubiaceae* as tropical trees, it implies a much higher percentage of that kind of vegetation in the pollen spectrum and it allows ~~assuming~~ that the middle

Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre et al.

Miocene sediments were deposited in ponds surrounded by a low to mid-altitude tropical forest. However, *Myrica, Alnus* and *Betula* are unknown in tropical stands, and their occurrence suggest a larger scale signal from surrounding mountains.

5.4 Khorat

The samples collected in Khorat show the most spectacular variations of local vegetation. The composition of the two groups of clays collected from the Khorat is the result of a differential sedimentation. This can be explained by the oscillation of the river bed upon the sedimentation zone (Fig. 3); when the river runs over this zone, sandy clays are deposited, and when the zone is isolated, the sedimentation is slower, and organic matter ~~is accumulated and~~ produce black clays. This shift in the nature of the deposits and the transition from tropical trees to *Pteridophytes* and *Poaceae* describe a well known vegetation dynamic scheme. Sandy clays are deposited by the river whereas black clays are deposited in standing ponds. It is very likely that during a drier period, the current is less strong and the main river bed changes its course. Then, several ponds settle and their surroundings are colonized by heliophilous and aquatic plants such as *Pteridophytes, Poaceae* and *Cyperaceae*. The high percentage of *Syzygium* may be related to the existence of a gallery forest dominated by this genus and including other tropical taxa such as *Alchornea, Nauclea*, and the *Caesalpiniaceae, Combretaceae* and *Malpighiaceae* families. This particular type of forest, always located in the surroundings of a river has been well described in Africa, especially in Cameroon (Letouzey, 1968). This variability in the samples from Khorat can be due to a background shift in rainfall, and it suggests ~~a~~ climatic variability during the Miocene.

5.5 Significance of the palynological record: Palaeoclimatic interpretations

We saw that the local taxa (*Pteridophytes*) underline variations of the basins hydrology. The hydrological changes can be explained in two ways at different timescales: (i) microclimatic changes implying variations in soil hydrology (the local ~~nape~~) can be

due to a marked seasonality cycle. This assumption is reinforced by the presence of deciduous taxa (temperate taxa: *Betula, Alnus*; tropical taxa: *Celtis, Combretaceae*); (ii) the second explanation is extralocal and implies regional changes in rainfall. In this case, the high percentage of *Poaceae* can be interpreted as an opening of the ecosys-
5 tems due to dry climatic phases. This is consistent with former studies on Miocene pollen grains (Muller, 1970) that suggest several dry phases during the Mio-Pliocene. Our chronosequence very likely reflects the two kinds of climatic signals, i.e. local and regional. Climate simulations (Ramstein et al., 1997; Fluteau et al., 1999) have suggested that the monsoon onset occurred during the Oligocene (30 Ma), involving a
10 background seasonal climate in Thailand during the Miocene. The paleoenvironments we described with shifts in the hydrology of different basins is consistent with the existence of the monsoon and the variability of rainfall linked to this phenomenon.

6   Conclusions

Our results bring new evidence on the Neogene flora of southeast Asia. Despite dif-
15 ficulties that arose in the interpretation of our data due to an incomplete database for Tertiary pollen grains from southeast Asia, and to a long timespan of the fossil record, our analysis allows giving a detailed description of fossil flora from the late Oligocene to the late Miocene of Thailand. The studied samples show that the composition of this flora was not homogeneous both in time (intra-site variability) and in space (inter-sites
20 differences). Some fossil assemblages are similar with those of extant lower montane forest from northern Thailand, which suggests that a strong seasonal cycle in rainfall was already settled in this area during the Miocene. This is consistent with simulations that indicate an Oligocene onset of the Asian monsoon system (Ramstein et al., 1997). We also described strong variations in the hydrology of the deposition sites. Although
25 the timing of this variability needs further data to be discussed, our samples suggest that the climate was far from being stable during the middle to late Miocene in Thailand. Oceanic records (Westerhold et al., 2005) suggested that this warmer period

Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre et al.

was marked by several glaciation periods, ultimately driven by insolation variations. This variability has to be considered in the tropical records, and further studies using numerical modeling might be crucial to unravel the different background mechanisms (Hay et al., 2002; Liu and Yin, 2002) (insolation, uplifts) that have driven climate and
5 environments changes in southeast Asia during the Miocene.

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Table 1. Summary of the characteristics from the four studied sites.

	Nong Ya Plong	Chiang Muan	Mae Moh	Khorat
Age	26–24 Ma	13.5–10 Ma	13.3–13.1 Ma	9–6 Ma
Sediment type	Claystone/lignite	Lignite	Lignite	Clay lenses in sand Deciduous dipterocarps
Present-day vegetation	Tropical evergreen forest	Mixed deciduous forest + Seasonal dry evergreen		Forest/cropland
Present-day climate	Dry during boreal winter, wet during boreal summer (monsoonal). Max rainfall ranges from 7 to 9 mm/day.			

Table 2. Pollen counts for the 4 sites.

	NYP	Mae Moh													Chiang Muan						Khorat				
	NYP	MM1	MM2	MM3	MM4	MM5	MM6	MM7	MM8	MM9	MM10	MM11	MM12	MM13	CM1	CM2	CM3	CM4	CM5	CM6	K1	K2	K3	KA	KB
Temperate AP																									
Alnus	46	0	1	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Betula	0	1	0	1	0	0	1	0	0	0	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Myrica	0	0	0	0	0	0	0	0	2	1	1	0	1	2	0	0	0	0	0	0	0	0	0	0	0
Carya	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Castanea	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Castanopsis	0	2	0	1	7	0	0	0	0	0	0	2	0	4	0	0	0	0	0	0	0	0	0	0	0
Ilex	0	0	0	0	0	0	0	0	0	0	0	0	0	0	222	0	0	0	0	0	0	0	0	1	0
Podocarpus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Platanus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0
Platycaria	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	1
Elaeagnaceae	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pterocarya	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	52	3	2	2	7	0	1	0	2	1	5	3	2	6	224	2	0	0	0	0	0	1	1	4	1
Tropical AP																									
Aglae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Alchornea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	1	1	1	0	0	2	2	11	3
Caesalpiniaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	5	0	3
Bauhinia-Isoberlinia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Malpighiaceae	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Nauclea	0	0	0	0	0	0	0	0	0	1	0	0	0	0	64	0	0	0	0	0	0	0	0	11	3
Anacardiaceae	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	4	1	0	0
Meliaceae	0	0	4	0	1	0	0	0	4	2	0	0	0	1	1	0	0	2	2	0	0	0	1	0	0
Combretaceae	0	1	2	0	0	0	0	0	0	0	0	3	0	3	2	1	1	0	0	0	2	16	8	0	0
Antidesma	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Holoptelae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Phyllantus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
Phyllantus annamensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
Pilostigma	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Celastraceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Myrtaceae	0	0	0	1	1	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	1	0	1	0	0
Burseraceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Ficus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	0	0
Rubiaceae	0	1	22	0	15	3	2	0	112	58	30	74	0	23	73	5	197	0	0	2	31	27	27	0	0
Total AP tropicaux	0	2	30	0	17	4	2	0	118	61	30	79	0	27	143	12	201	4	3	2	34	56	54	31	10
Non attributed																									
Acrychnomene	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Ombelliferes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Renonculaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Taxodiaceae	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tiliaceae	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sambucus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Salix	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Rosaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Nyctaginaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Indigofera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Convolvulaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
cf. *Alcornea*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cf. *Anacardiaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
cf. *Artemisia*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
cf. *Bombacaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
cf. *Caesalpiniaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cf. *Castanopsis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	5	0	0
cf. *Commelinaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
cf. *Cyperaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
cf. *Eleagnaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
cf. *Euphorbiaceae*	0	0	0	0	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	0	3	0	0	0	0
cf. *Fabaceae*	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cf. *Flacourtiaceae*	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
cf. *Fraxinus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
cf. *Mallotus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
cf. *Moraceae*	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Mid-Tertiary palaeoenvironments in Thailand: pollen evidences

P. Sepulchre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 2. Continued.

|	NYP	MM1	MM2	MM3	MM4	MM5	MM6	MM7	MM8	MM9	MM10	MM11	MM12	MM13	CM1	CM2	CM3	CM4	CM5	CM6	K1	K2	K3	KA	KB
								Mae Moh									Chiang Muan						Khorat		
cf. *Moringaceae*	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cf. *Myrica*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
cf. *Potamogeton*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
cf. *Qercus*	1	0	0	0	9	0	0	0	0	0	3	0	0	0	5	6	0	0	0	0	0	2	1	3	1
cf. *Randia*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
cf. *Rhamnaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
cf. *Ricinus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
cf. *Rubiaceae*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
cf. *Rutaceae*	0	0	2	0	0	0	0	0	4	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
cf. *Urticaceae*	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Euphorbiaceae	0	0	2	0	0	0	0	0	0	0	1	1	0	0	0	0	0	4	5	1	0	0	3	0	0
Euphorbiaceae																									
type *Euphorbia*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alcalypha	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Capparidaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Lasianthus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Loranthaceae	4	0	4	0	0	0	0	0	0	1	1	0	0	1	7	0	0	6	6	0	0	0	0	0	0
Pometia (sapindaceae)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Sapindaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Moraceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	1	1	0	0	0	1	0	0
Mimosaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fabaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	4	14	99	0	5	0	0	0
Sapotaceae	0	0	8	0	0	0	0	0	2	1	0	0	0	7	4	1	0	0	0	0	0	0	0	0	0
Syzygium	0	0	8	0	0	0	0	0	0	0	0	0	0	0	382	0	409	3	0	0	2	95	25	0	0
Celtis	1	0	0	0	0	0	0	0	0	0	0	0	0	0	7	36	0	0	1	0	0	6	6	5	3
Cyperaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	43	191	0	8	6	11	10
Monocotyledons	0	0	0	0	0	0	0	19	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Pinus	16	0	0	1	0	1	2	0	0	0	0	1	0	0	0	0	0	0	0		0	0	0	0	0
Cephalanthus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	11	1	0	0	0	0	0
Basella	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0
Trema	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
Merremia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	6	0	0	0	0	0
Urticaceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Aquatic NAP																									
Typha	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nyssa	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Potamogeton	0	0	5	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lemna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
Polygonum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3	0	0	0	0	0
Monolet spores	88	8	400	18	34	63	58	68	53	195	37	127	31	68	75	82	66	475	782	36	15	21	23	172	113
Trilet spores	2	0	45	0	2	2	5	6	23	1	0	2	0	20	53	50	4	0	1	3	7	0	6	0	0
Undentified	44	12	55	2	26	8	32	9	154	31	41	27	18	47	215	45	25	53	21	18	107	39	50	24	20

Figure 1
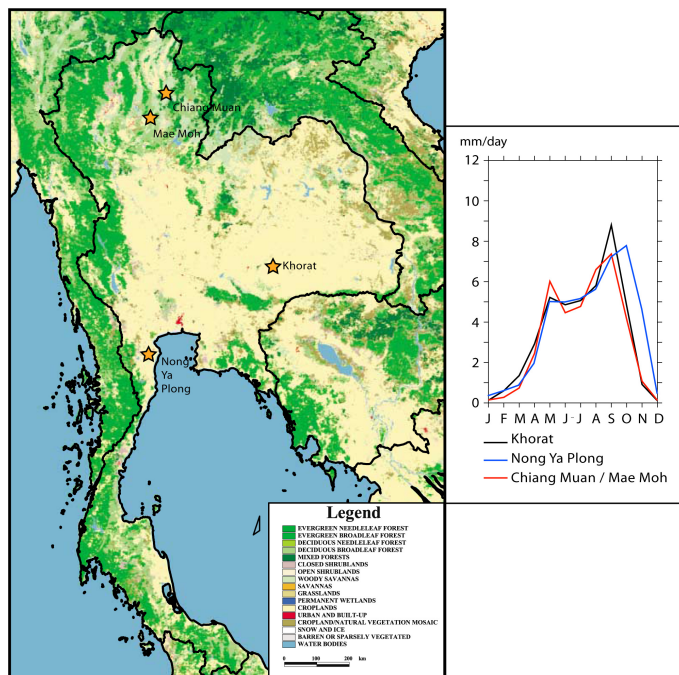
Fig. 1. Map of Thailand indicating the present-day land cover and vegetation types. Modified after Parnell et al. (2003). Plots indicate rainfall seasonal cycle for the three areas of interest, from the Climate Research Unit, averaged between 1961 and 1990 (New et al., 2002). Units are mm/day.
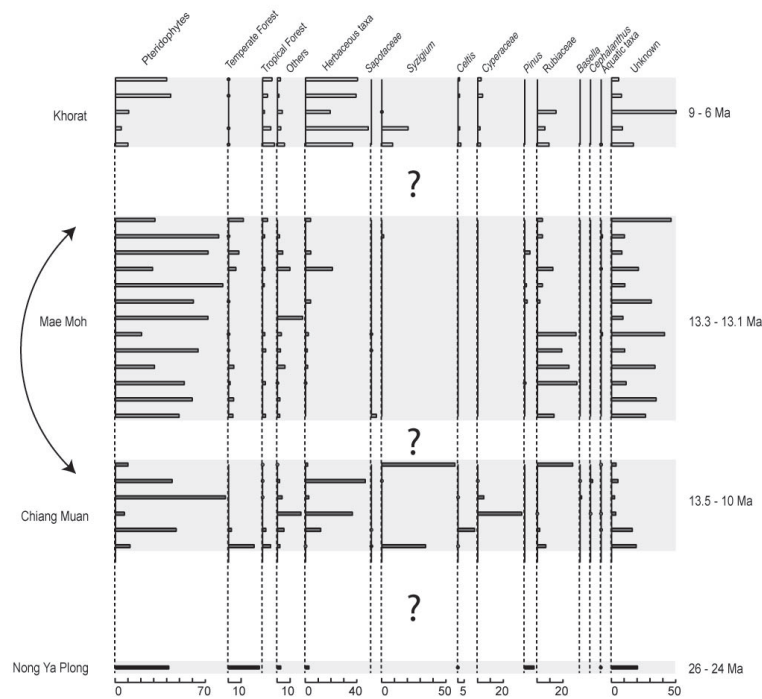
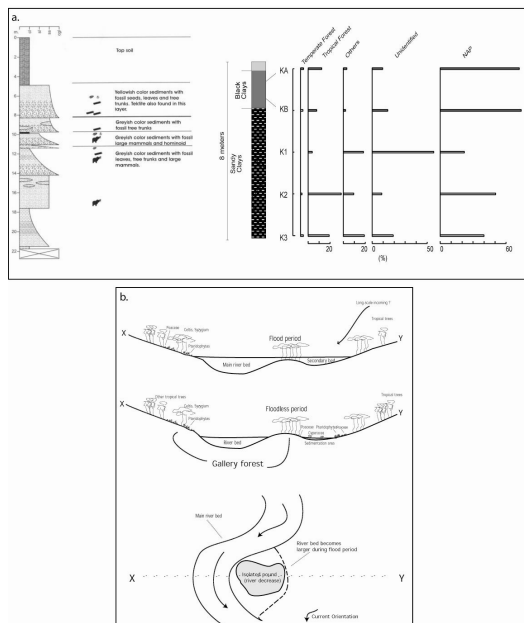**Fig. 2.** Synthesis of the pollen record for the 4 areas discussed in the text. Taxa have been assigned to separate categories (see text).

Fig. 3. Simplified sketch of Miocene sedimentation process in the Khorat. Stratigraphy from Chaimanee et al. (2006).