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TERTIARY BASIN EVOLUTION IN NORTHERN THAILAND: A PALYNOLOGICAL POINT OF VIEW

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ABSTRACT

Tertiary basins in northern Thailand developed in Oligocene to Middle Miocene time. At the beginning of development the region was in a warm temperate climate. The terrain was occupied by forest types comparable to the present mid-latitude forests of the northern hemisphere. These forests consisted of conifer communities composed of *Dacrydium, Podocarpus* (Podocarpaceae), *Picea, Pinus, Tsuga* (Pinaceae), *Sequoia* and *Taxodium* (Taxodiaceae). Broadleaf deciduous mesothermal taxa were also present, including *Acer* (Aceraceae), *Alnus, Betula, Carpinus, Corylus* (Betulaceae), *Carya, Juglans, Pterocarya* (Juglandaceae), *Fagus, Quercus* (Fagaceae), *Ilex* (Aquifoliaceae), *Liquidambar* (Hamamelidaceae), and *Ulmus* (Ulmaceae) with ferns common, especially Polypodiaceae and *Pteris* (Pteridaceae). In the Early Miocene the climate changed and became warmer until in the late Early Miocene it was completely tropical, persisting until the end of the Middle Miocene. At this time conifers and mesothermal taxa declined and were replaced by evergreen megathermal taxa. These included *Alangium* (Alangiaceae), *Ammannia, Lagerstroemia* (Lythraceae), *Anogeissus* (Combretaceae), *Bursera* (Burseraceae), *Caesalpinia* (Leguminosae-Caesalpinoideae), *Calophyllum* (Guttiferae), Combretaceae, Dipterocarpaceae, *Dipterocarpus, Hopea* (Dipterocarpaceae), *Homonoia* (Euphorbiaceae), *Ilex* (Aquifoliaceae), Leguminosae-Mimosoideae, Myrtaceae, *Oroxylum, Radermachera* (Bignoniaceae), *Pandanus* (Pandanaceae), Sonneratiaceae, and *Spondias* (Anacardiaceae) with abundant spores from *Lygodium* (Schiazaeaceae), Polypodiaceae, Cyatheaceae, and *Pteris* (Pteridaceae) in some horizons. These two palynological assemblages came from different stratigraphic positions strongly suggesting that there are two major stratigraphic zones on the basis of palynology and there was a major climatic change from a warm temperate to a tropical condition across the period of Oligocene to Middle Miocene. Generally, coals from Oligocene to early Early Miocene formations are sub-bituminous in rank while coals from late Early Miocene to Middle Miocene formations are lignites. Since the older, sub-bituminous coals all contain warm temperate palaeofloras and the younger, less deeply buried lignitic coals all contain tropical palaeofloras. Distribution pattern of the warm temperate and tropical formation exposures in this region caused by mountain building and cordilleran erosion is proposed.

INTRODUCTION

Northern Thailand ranges in latitude from about 16° to 20° north and in longitude from about 98° to 101° east and is predominantly in the tropical zone (Fig. 1). The region is

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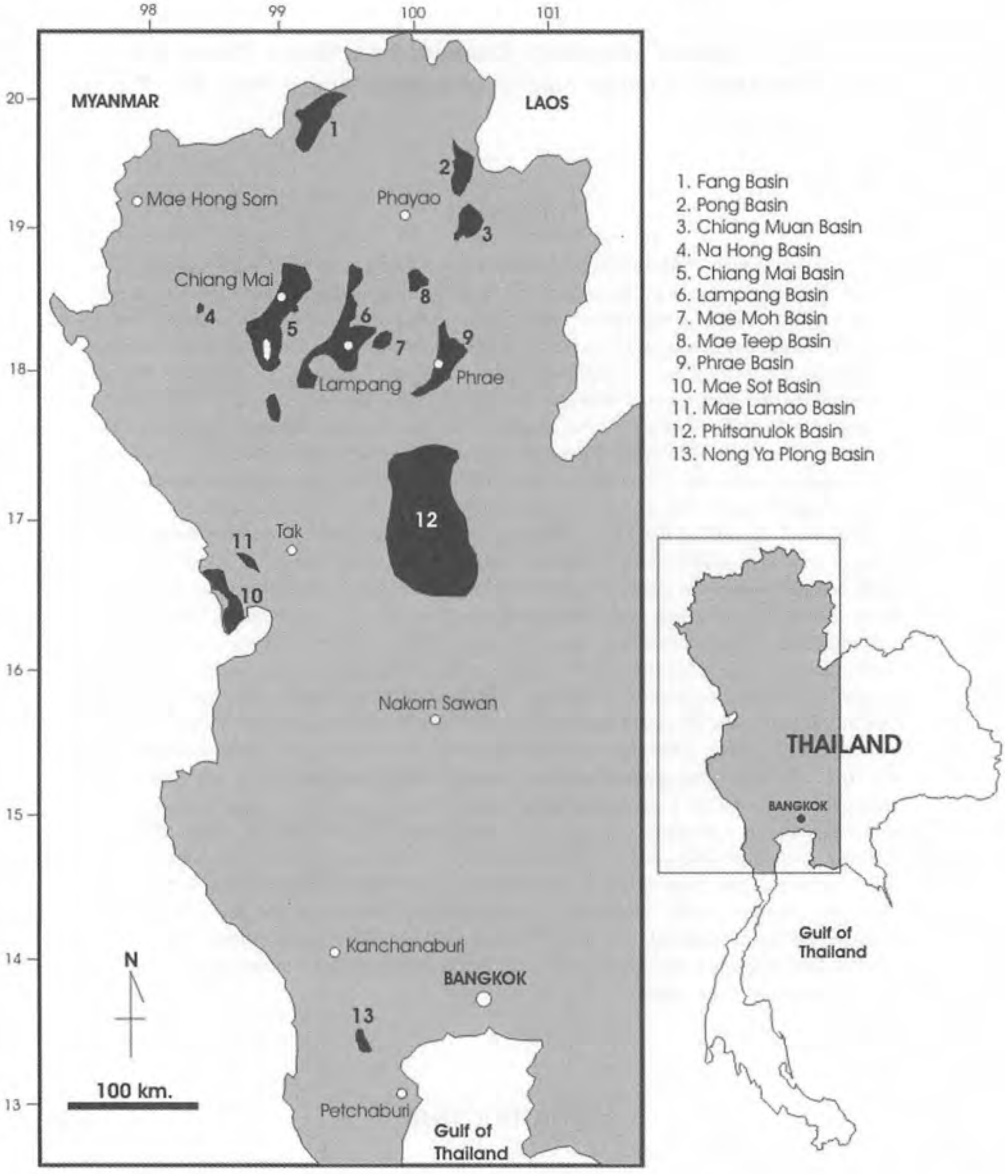

Figure 1. Map of northern and central Thailand showing provinces and Tertiary basin localities mentioned in this paper.

dominated by mountainous areas with some lowlands along four main tributaries of the Chao Phraya River, namely the Ping, Wang, Yom, and Nan rivers. The mountain ranges generally trend north-south, controlled by the main geological structures. The highest peak is Doi Intanon at 2,565 m above mean sea level. There are many lower peaks of approximately similar heights such as Doi Pha Hom Pok, Doi Chiang Dao, Doi Phu Soi Dao, and Doi Lang Kha. The lowland areas are generally 300 to 500 m above mean sea level and contain the main rivers and some tributaries.

The climate of northern Thailand is strongly seasonal and as is characteristic of a monsoonal climate consists of alternate wet and dry seasons each year. The warm, wet season is between May and October with an annual rainfall varying from 1,100 to 1,500 mm. The dry season consists of a cool dry and a hot dry period of time. The cool dry season, winter, is between November and February. December, January, and February are virtually without rain. The hot dry season, summer, is from March to May.

Vegetation in the region is a tropical forest naturally varied by two main factors, moisture and altitude. Altitude differences result in two major forest types namely tropical lowland forests and tropical montane forests. Tropical lowland forests are at elevation below 1,000 m above mean sea level and are regarded as typical tropical plant communities. On the other hand, the tropical montane between 1,000 and 2,565 m above mean sea level are mainly occupied by typical warm temperate plant communities.

Mountainous landforms with scattered isolated intermontane basins are the most obvious topographic features of northern Thailand. The basins are bound by pre-Tertiary rocks with ages from Precambrian, Paleozoic, to Mesozoic. Precambrian rocks are exposed and distributed over the western strip of the region extending north to south from Mae Hong Son, Chiang Mai, to Tak provinces. Precambrian rock types are metamorphic, including gneiss, schist, amphibolite-schist, quartzite, calc-silicate, marble, and biotite marble. The central strip of the region is dominated by younger marine Paleozoic rocks, including shale, sandstone, phyllite, quartzitic phyllite, limestone, metalimestone, and chert. Mesozoic rocks cover the eastern part of the region and are dominated by non-metamorphic clastic rocks. Marine Triassic rocks of the Lampang Group are confined to the central and eastern boundary. Terrestrial red-bed clastic Jurassic rocks occur along the easternmost strip with some scattered marine Jurassic deposits in the southwest of the region. Jurassic red-bed formations in the areas of Chiang Muan District of Phayao Province have yielded dinosaur bones which are now being studied by the Department of Mineral Resources.

Cenozoic deposits, including Tertiary and Quaternary sediments, occur in isolated fault-bound graben and half graben intermontane basins. The Tertiary deposits vary from unconsolidated to consolidated sediments, namely sand, clay, conglomerate, sandstone, claystone, mudstone, oil shale, diatomite, and coal with crude oil sources in Fang and Phitsanulok basins. The stratigraphic succession within each basin is different making the stratigraphy difficult to correlate in view of the differing depositional environments, the isolation of the basins and their differences in age and rock types (GIBLING & RATANASTHIEN, 1980). Palaeontologically, various macrofossil taxa have been reported from Mae Moh, Li, Mae Teep, Lampang, Chiang Mai, Chiang Muan, Mae Sot, and Pong basins. The fossils include related forms of elephant, rhinoceros, pig, rodents, bird, deer, barking deer, otter, and primates, with common crocodile, turtle, fish, and molluscs. The oldest known mammal fossils in northern Thailand are *Stegolophodon* remains from Na Sai coal field in the Li basin suggesting Lower Miocene or MN3 (TASSY *ET AL.*, 1992).

Normal and reverse magnetic polarity patterns from the Chiang Muan and Mae Moh basins indicate a late Middle Miocene age (BENAMMI *ET AL.*, 2002; CHAIMANEE *ET AL.*, 2003).

Some basins, such as Na Hong, Mae Tun, Mae Lamao, Nong Ya Plong, and Ban Pu and Ban Pa Kha coalfields in the Li basins, yielded no indicative macrofossils to enable establishment of both a meaningful stratigraphy and the paleoenvironmental and climatic conditions during deposition. This paper reports on the results of palynological research in both macrofossil-bearing and macrofossil-barren formations undertaken to check if they contain different palynological assemblages. This study also provides some ideas explaining basin evolution in northern Thailand in palynological terms.

MATERIALS AND METHODS

Tertiary sedimentary samples were collected from intermontane Cenozoic basins and processed for fossil sporomorphs. Each sample was initially cleaned to get an inner uncontaminated portion and was broken up into smaller pieces and put into a 250-ml polypropylene beaker. Diluted hydrochloric acid (10% HCl) was applied and left until air bubbles disappeared at which time all carbonates were removed. Subsequently, hydrofluoric acid (48% HF) was added for a week under room temperature to remove silicates and followed up with 10% HCl to prevent formation of calcium fluoride. The residues were then oxidised by concentrated nitric acid (HNO_3) for 3 to 5 minutes and washed with diluted potassium hydroxide (5% KOH). The residues were washed with distilled water and then centrifuged, up to three times, every time the chemicals were changed. Finally, the residues were sieved by nylon net to obtain the 11 to 133 micron fractions which were kept in a small vial with dilute polyvinyl alcohol solution (PVA). The vial was labelled with the sample number and date of preparation.

A few drops of the polyvinyl alcohol solution containing suspended sporomorphs were smeared onto a cover slip that was placed on a heated hotplate. This mixture would dispersed evenly over the cover slip surface and adhere as a film to the cover slip after it dried. The cover slip would then be sealed to a slide glass by one or two drops of Eukitt mounting medium solution and allowed to dry at room temperature overnight. Each slide was labelled with the sample number and some important identification information. This slide was examined under a light microscope.

A small drop of polyvinyl alcohol solution with suspended sporomorphs was also applied to a warm 1-cm diameter rounded cover slip, which was equal in size to the scanning electron microscope (SEM) stub being used. This mixture dispersed evenly over the cover slip surface and adhered as a film to the cover slip when it dried. The cover slip was then placed on the SEM stub with a small piece of carbon sticky tape. Then the sporomorphs were coated with gold under a vacuum. This coating needed to be as thin as possible and yet effective for SEM. A 15 to 30-nanometre coating satisfied this need. The stub was stored in a desiccator to keep the specimens dry at all times prior to use in SEM work.

Microscopic work was done with both a light microscope and a SEM. The light microscope was used for sporomorph observation and statistical counting. The SEM was used for detail study of features observed under the light microscope. Sporomorphs were described and photographed with both light and SEM.

The sporomorphs were studied using a Zeiss light microscope, Axiolab, which was usually connected to digital equipment and a computer. The analogue image from the microscope was transferred to digital form by special computer hardware and then displayed on a computer monitor by specific KS-200 software, version 2.00. This operation made statistical counting easier. This work was done at the Department of Mineral Resources in Bangkok.

A Jeol JSM 5410 model was used as the scanning electron microscope system. This equipment is at the National Science and Technology Development Agency (NSTDA) in Pathumthani.

PALYNOLOGY

Fossil sporomorphs identified here are generally named using form generic nomenclature. Some features of fossil sporomorphs are well comparable to those of recent forms, particularly at the generic and family levels. Therefore, some fossil sporomorphs were named using Linnaean nomenclature where they were deemed identical to the recent forms, especially with respect to tropical pollen. Linnaean names are used (Table 1) as their botanical affinities where the palaeophytogeographic setting is described.

Fossil sporomorphs from this study are classified into two main groups. One group contains pollen with morphologies close to recent warm temperate pollen, and the other group is tropical. Warm temperate and tropical pollen are clearly distinguishable by differences in their general morphology. Pollen classification using the Linnean system is the best way to group pollen assemblages when reconstructing palaeophytogeographic settings at the time of sedimentation and to compare fossil with modern vegetation. Thus fossil pollen can be used as indicative of a similar ecological tolerance to its modern form when its morphology is comparable to that form. However, many fossil sporomorphs, including some pollen, spores, and microscopic algae, cannot be placed into the warm temperate or tropical group. Some of these are used as supplementary evidence in the elucidation of depositional environments. Some pollen and spores like *Cyperaceaepollis neogenicus, Sporotrapoidites medius* and *Striatriletes susannae*, as well as the algae *Actinastrum, Botryococcus, Closterium,* and *Pediastrum*, are freshwater elements suggesting sedimentation in a lacustrine environment.

Some elements of the warm temperate and tropical fossil pollen assemblages are illustrated on Plates I, II, and III.

Warm Temperate Pollen Assemblages

These assemblages were derived from five sedimentary formations namely Na Hong, Mae Tun, and Mae Lamao basins and Ban Pu and Ban Pa Kha coalfields in the Li basin. These formations yielded exclusively warm temperate pollen without the presence of any distinctive tropical pollen. Pollen compositions of the five formations are somewhat similar. They comprise conifer pollen *Dacrydiumites florinii, Podocarpidites ellipticus, Tsugaepollenites igniculus, Inaperturopollenites dubius, Pinuspollenites,* and *Piceaepollenites.* Angiosperm pollen consists of *Aceripollis, Alnipollenites verus, Caryapollenites simplex, Faguspollenites, Ilexpollenites iliacus, Juglanspollenites verus,*

Table 1. Lists of fossil sporomorphs recovered from the Tertiary sediments of northern Thailand with their botanical affinities.

Sporomorph/Basin	Na Hong	Ban Pu	Ban Pa Kha	Mae Lamao	Mae Tun	Nong Ya Plong	Mae Moh	Na Sai	Mae Long	Mae Sot (IMS-1)	Fang (IF-2)	Botanical affinity
Gymnosperms												
Araucariacites australis		x	x									*Araucaria* (Araucariaceae)
Dacrydiumites florinii									x		x	*Dacrydium* (Podocarpaceae)
Inaperturopollenites dubius	x	x	x	x	x	x	x					*Taxodium, Sequoia*
Piceaepollenites	x	x	x	x		x	x			x		*Picea* (Pinaceae)
Pinuspollenites	x	x	x	x		x	x	x		x	x	*Pinus* (Pinaceae)
Podocarpidites ellipticus	x	x	x	x		x	x			x	x	*Podocarpus* (Podocarpaceae)
Tsugaepollenites igniculus	x	x	x	x	x	x	x					*Tsuga* (Pinaceae)
Angiosperms												
Aceripollis		x					x			x	x	*Acer* (Aceraceae)
Alnipollenites verus	x	x	x	x	x	x	x			x	x	*Alnus* (Betulaceae)
Caryapollenites simplex	x	x	x	x		x	x			x	x	*Carya* (Juglandaceae)
Faguspollenites	x	x	x	x		x				x	x	*Fagus* (Fagaceae)
Ilexpollenites iliacus	x	x	x	x			x	x		x	x	*Ilex* (Aquifoliaceae)
Juglanspollenites verus	x		x	x			x					*Juglans* (Juglandaceae)
Liquidambarpollenites stigmosus	x	x	x	x		x	x					*Liquidambar*
Momipites coryloides	x	x	x	x		x	x				x	*Corylus* (Betulaceae)
Polyporopollenites carpinoides		x										*Carpinus* (Betulaceae)
Pterocaryapollenites stellatus	x	x	x							x		*Pterocarya* (Juglandaceae)
Quercoidites		x	x	x		x	x			x	x	*Quercus* (Fagaceae)
Retitrescolpites	x		x									Oleaceae
Salixpollenites discoloripites		x					x				x	Salicaceae
Trivestibulopollenites betuloides	x		x			x	x			x		*Betula* (Betulaceae)
Ulmipollenites		x										*Ulmus* (Ulmaceae))
Ammania							x			x		*Ammania* (Lythraceae)
Bombacacidites							x					Bombacaceae
Bursera							x			x		*Bursera* (Burseraceae)
Calophyllum												*Calophyllum* (Guttiferae)
Cardamine							x					*Cardamine* (Cruciferae)
Cephalomappa												*Cephalomappa* (Euphorbiaceae)
Combretaceae												Combretaceae
Dipterocarpaceae							x	x				Dipterocarpaceae
Dipterocarpus							x			x	x	*Dipterocarpus* (Dipterocarpaceae)
Florschuetzia											x	Sonneratiaceae
Homonoia							x	x	x			*Homonoia* (Euphorbiaceae)
Hopea							x			x		*Hopea* (Dipterocarpaceae)
Lagerstroemia			x				x	x		x		*Lagerstroemia* (Lythraceae)
Margocolporites vanwijhei							x			x	x	*Caesalpinia* (Leguminosae-Caesalpinoideae)
Myrtaceidites mesonesus							x				x	Myrtaceae
Oroxylum							x					*Oroxylum* (Bignoniaceae)
Pandaniidites texus							x					*Pandanus* (Pandanaceae)
Perfotricolpites digitatus				x								*Merremia* (Convolvulaceae)

Table 1. (continued)

Sporomorph/Basin	Na Hong	Ban Pu	Ban Pa Kha	Mae Lamao	Mae Tun	Nong Ya Plong	Mae Moh	Na Sai	Mae Long	Mae Sot (IMS-1)	Fang (IF-2)	Botanical affinity
Radermachera								x				*Radermachera* (Bignoniaceae)
Spondias							x					*Spondias* (Anacardiaceae)
Striatricolpites catatumbus												*Crudia* (Leguminosae-Caesalpinoideae)
Monoporopollenites gramineoides		x				x	x	x		x		Gramineae
Cyperaceaepollis neogenicus							x			x		Cyperaceae
Sporotrapoidites medius	x		x	x								*Trapa* (Trapaceae)
Ferns												
Baculatisporites primarius		x				x						Hymenophyllaceae
Crassoretitriletes vanraadshoovenii							x					*Lygodium* (Schizaeaceae)
Cyathidites minor		x					x					Cyatheaceae
Foveotriletes margaritae	x	x										Lycopodiaceae
Laevigatosporites haardtii	x	x	x	x		x	x	x		x	x	Polypodiaceae
Polypodiaceoisporites retirugatus	x		x	x		x					x	*Pteris* (Pteridaceae)
Polypodiisporites alienus		x				x				x	x	Polypodiaceae
Polypodiisporites inangahuensis	x		x									Polypodiaceae
Polypodiisporites minimus	x		x					x				*Nephrolepis* (Davalliaceae)
Polypodiisporites pohangensis		x								x	x	Polypodiaceae
Polypodiisporites radiatus	x		x	x				x				Polypodiaceae
Polypodiisporites usmensis												Polypodiaceae
Rugulatisporites quintus		x										Polypodiaceae
Striatriletes susannae			x				x	x		x	x	*Ceratopteris thalictoides* (Pteridaceae)
Undulatisporites unduliradius		x										Fern
Algae												
Actinastrum			x	x								*Actinastrum*
Botryococcus cf. *B. braunii*	x		x					x				*Botryococcus* cf. *B. braunii*
Closterium				x			x					*Closterium*
Pediastrum boryanum	x		x			x	x	x		x	x	*Pediastrum boryanum*
Pediastrum duplex			x									*Pediastrum duplex*
Pediastrum simplex	x		x			x	x	x		x	x	*Pediastrum simplex*

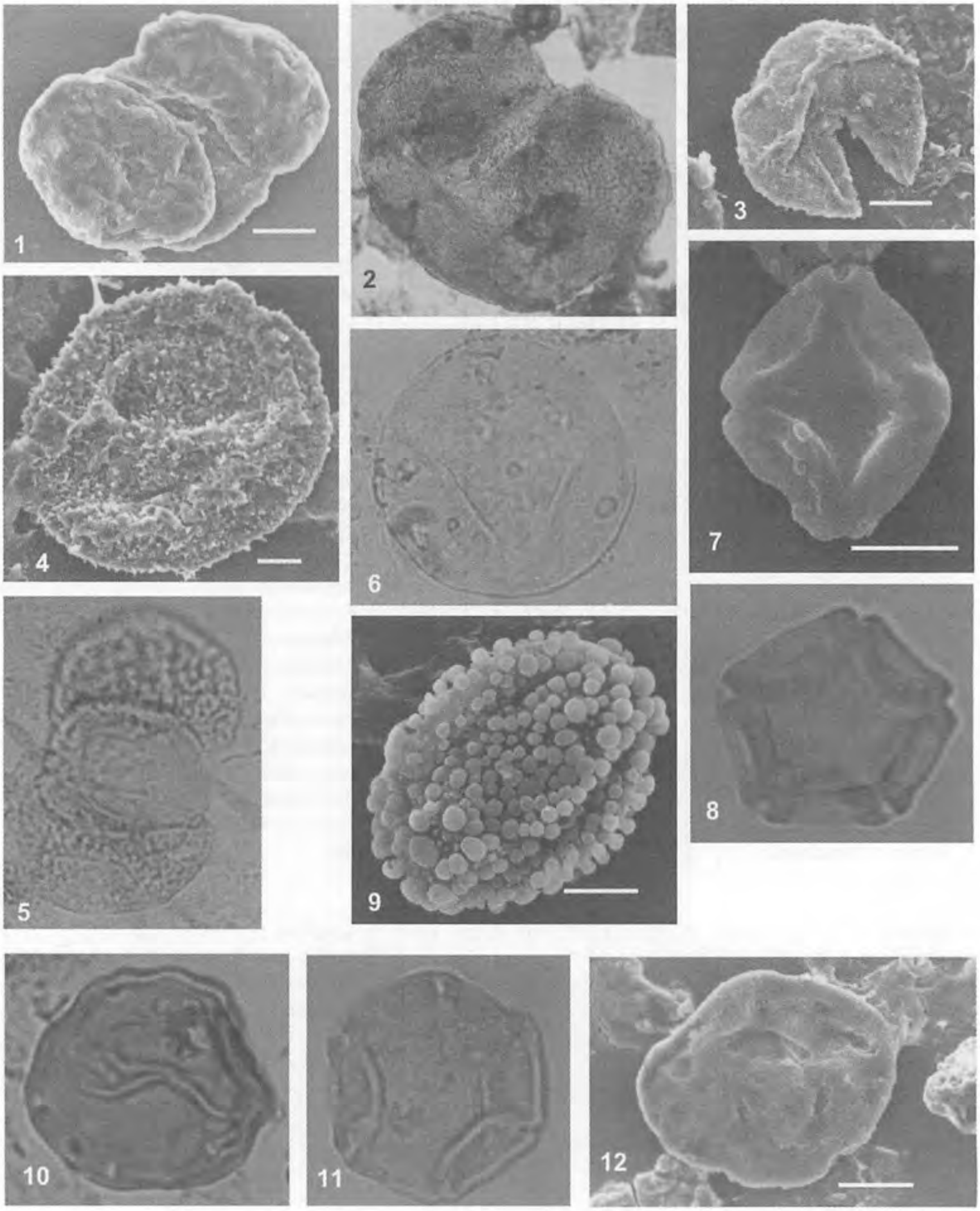

Plate I 1: *Pinuspollenites* — Ban Pa Kha; 2: *Piceaepollenites* — Ban Pa Kha; 3: *Inaperturopollenites dubias* — Ban Pa Kha; 4: *Tsugaepollenites igniculus* — Ban Pa Kha; 5: *Podocarpidites* — Ban Pa Kha; 6: *Caryapollenites simplex* — Na Hong; 7–8: *Alnipollenites verus* — Ban Pa Kha; 9: *Ilexpollenites iliacus* — Ban Pa Kha; 10: *Juglanspollenites verus* — Ban Pa Kha; 11: *Pterocaryapollenites stellatus* — Ban Pa Kha; 12: *Liquidambarpollenites stigmosus* — Ban Pa Kha. All scale bars are 10 microns.

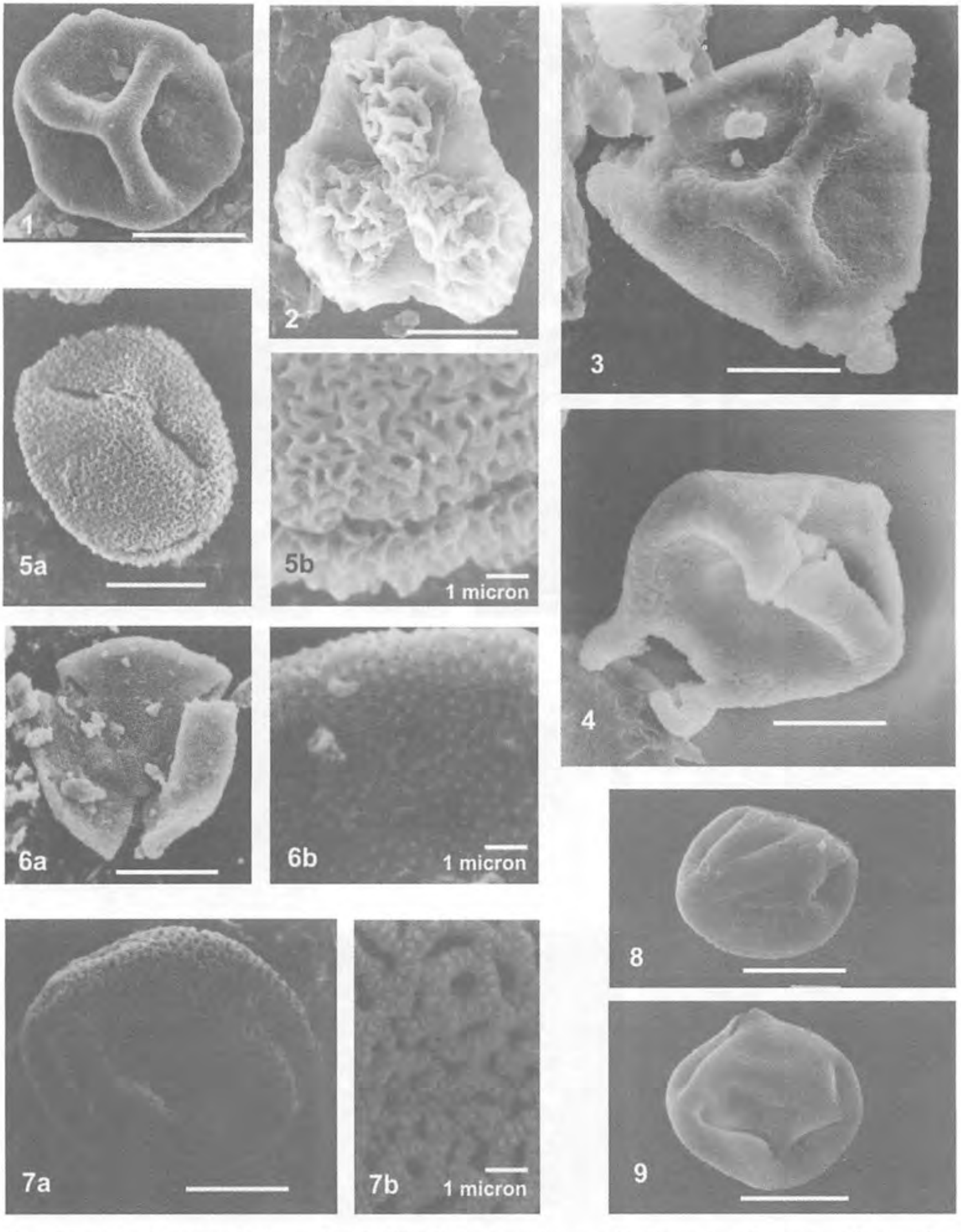

Plate II. 1: *Momipites coryloides* — Ban Pa Kha; 2: *Retitrescolpites* — Na Hong; 3–4: *Sporotrapoidites medius* — Na Hong; 5: *Calophyllum* — Na Sai; 6: *Homonoia* — Mae Long; 7: *Hopea* — Chiang Muan; 8–9: *Lagerstroemia* — Chiang Muan. All scale bars are 10 microns except where otherwise stated.

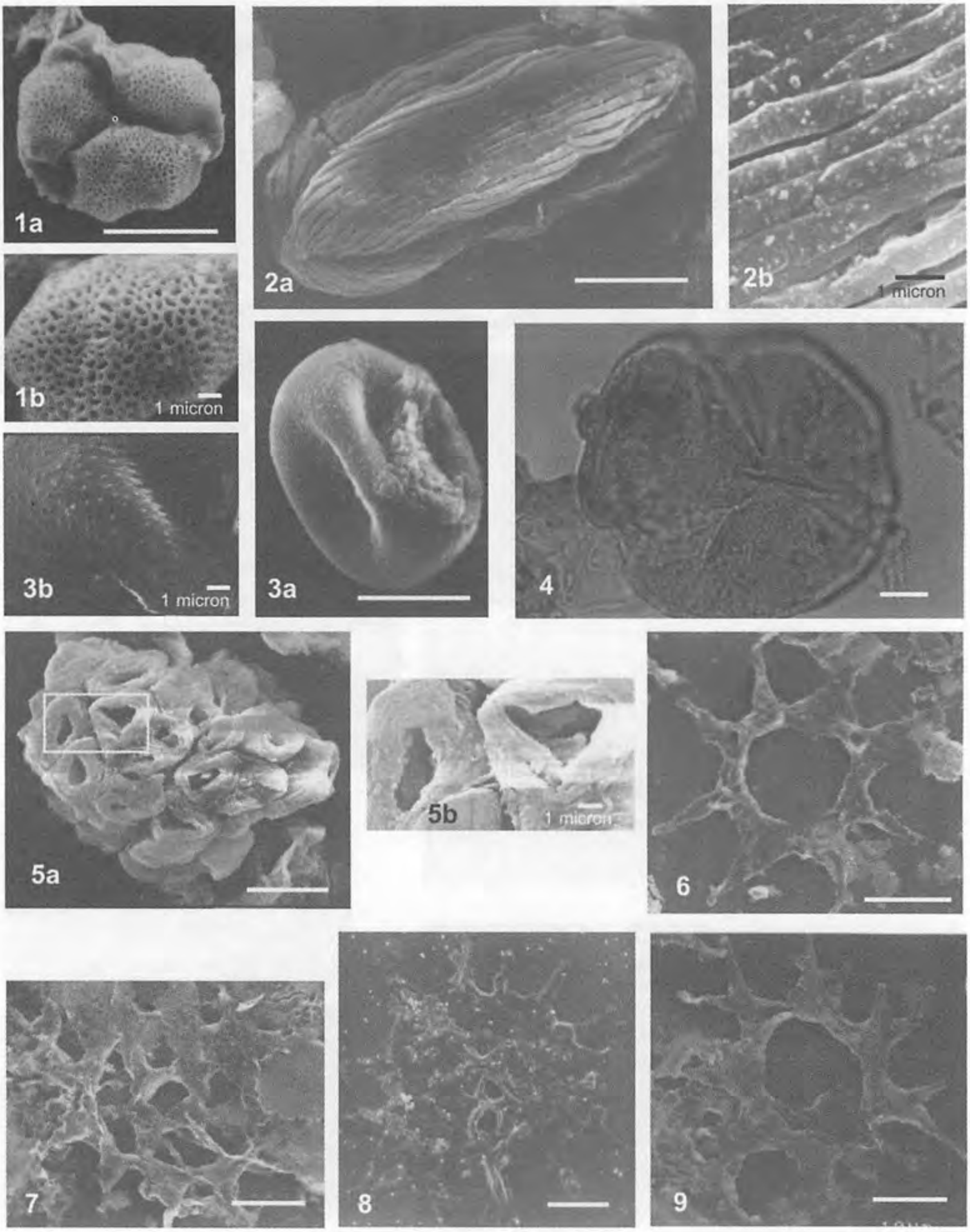

Plate III. 1: cf. *Oroxylum* — Mae Moh; 2: *Striatricolpites catatumbus* — Na Sai; 3: *Anogeissus* — Chiang Muan; 4: *Alangiopollis* — Ban Pa Kha; 5: *Botryococcus* — Na Sai; 6: *Pediastrum simplex* — Ban Pa Kha; 7: *Pediastrum simplex* — Ban Pa Kha; 8: *Pediastrum boryanum* — Ban Pa Kha; 9: *Pediastrum duplex* — Ban Pa Kha. All scale bars are 10 microns except where otherwise stated.

Liquidambarpollenites stigmosus, Momipites coryloides, Polyporopollenites carpinoides, Pterocaryapollenites stellatus, Quercoidites, Trivestibulopollenites betuloides, Ulmipollenites, and abundant *Retitrescolpites.* This pollen assemblage has also been reported from Nong Ya Plong basin in Petchaburi Province (WATANASAK, 1988), which is considered to be the southernmost basin containing warm temperate palynofloras in Thailand.

Tropical Pollen Assemblages

Tropical pollen assemblages were obtained from Mae Moh, Chiang Muan, and Fang basins, Na Sai coalfield and Mae Long locality in the Li basin. About 30% of the sporomorphs from these formations were identified; the rest are as yet unidentified. Recognition of the pollen assemblage as tropical is, however, certain since there are only negligible amounts of some warm temperate pollen types from taxa like *Pinuspollenites. Pinuspollenites* can also be considered as a tropical element that came from tropical highland sources. Wind dispersal would have brought *Pinuspollenites* pollen from the montane forests into the basins. Inclusion of *Pinuspollenites* was common and is comparable to situations in present tropical areas like Thailand, Sumatra, and Philippines where *Pinus* still grows (SANTISUK, 1997).

Some samples from Mae Teep basin yielded sparse pollen and spore assemblages which included *Crassoretitriletes vanraadshoovenii*, Osmundaceae, Polypodiaceae, Fagaceae, Rubiaceae, and Simaroubaceae which were previously described as representing a temperate moist forest with high humidity, perhaps surrounded by drier land (MEESUK, 1986). However, this palynological assemblage is too poor to describe palaeophytogeographically but the presence of the ancestral elephant *Stegolophodon* vertebrate remains had been reported (BUFFETAUT *ET AL.*, 1988), and so it is tentatively suggested that Mae Teep is a tropical basin.

Tropical pollen is generally characterised by tricolpate and tricolporate forms. Recognition of these tropical pollen types needs detailed investigation of the surface sculpturing. Application of the light and scanning electron microscopy is needed together with comparison of the fossil forms with the recent species based on a huge pollen data bank that is yet to be developed.

There are many forms of fossil sporomorph with morphologies close to those of modern tropical taxa namely *Alangium* (Alangiaceae), *Ammannia, Lagerstroemia* (Lythraceae), *Anogeissus* (Combretaceae), *Bombacacidites, Bursera* (Burseraceae), *Calophyllum* (Guttiferae), *Cardamine* (Cruciferae), *Cephalomappa, Homonoia* (Euphorbiaceae), Combretaceae, *Dipterocarpus, Hopea* (Dipterocarpaceae), *Ilexpollenites, Margocolporites vanwijhei, Myrtaceidites mesonesus, Pandaniidites texus, Acaciapollenites myriosporites, Striatricolpites catatumbus, Florschuetzia, Perfotricolpites digitatus, Pinuspollenites, Radermachera* (Bignoniaceae), and *Spondias* (Anacardiaceae). Those taxa with modern names do not have a form generic equivalent.

BASIN EVOLUTION

Even though there is no evidence to assign an Oligocene age to the warm temperate pollen-bearing formations, there are, however, warm temperate pollen-bearing formations

Figure 2. Age ranges of Tertiary formations in northern Thailand against the geological time scale with a proposed mid-Early Miocene marker of climatic change from a warm temperate to a tropical condition.

stratigraphically underlying tropical pollen-bearing formations. This was proved by information obtained from drilling of the Li basin (SNANSIENG & MANEEKUT, 1985; SONGTHAM *ET AL.*, 2003a). Normal and reverse magnetic polarity patterns from the Chiang Muan and Mae Moh basins indicate a late Middle Miocene age where the samples were all from tropical pollen-bearing sequences (BENAMMI *ET AL.*, 2002; CHAIMANEE *ET AL.*, 2003; WATANASAK, 1988; SONGTHAM *ET AL.*, 2003b). The vertebrate remains-bearing formations are now regarded as tropical on the basis of palynology with late Early Miocene as the oldest age assigned by a mammalian assemblage (TASSY *ET AL.*, 1992). Therefore, the warm temperate pollen-bearing formations must be older than late Early Miocene. When these warm temperate pollen assemblages are compared to the assemblages from Borneo (GERMERAAD *ET AL.*, 1968), Oligocene to Early Miocene is a possible age for the warm temperate pollen assemblages in northern Thailand. This age determination provides justification for rearranging the history of basin formation in northern Thailand during the Oligocene to Middle Miocene (Fig. 2).

Oligocene – Early Early Miocene

The exact commencement of basin development in northern Thailand is so far unknown but is regarded as being not younger than early Early Miocene and probably also Oligocene. At this time the region had a warm temperate climate during which the overall vegetation was completely different from that of the present day. The forests consisted of conifers including *Pinus, Picea, Tsuga* (Pinaceae), *Taxodium, Sequoia* (Taxodiaceae), *Araucaria* (Araucariaceae), *Podocarpus*, and *Dacrydium* (Podocarpaceae) with broad-leaf deciduous mesothermal taxa namely *Acer* (Aceraceae), *Alnus, Betula, Carpinus, Corylus* (Betulaceae), *Fagus, Quercus* (Fagaceae), *Ilex* (Aquifoliaceae), *Carya, Pterocarya, Juglans* (Juglandaceae), *Liquidambar* (Hamamelidaceae), *Salix* (Salicaceae), and *Ulmus* (Ulmaceae). These forest types suggest that the climate was strongly seasonal with four seasons as found in the mid-latitudinal belt today in the northern hemisphere, extending from South Europe to South China.

The fault-bounded basins were formed as a result of the Himalayan orogeny and subsequent extrusion tectonics of the Southeast Asian landmass (SONGTHAM *ET AL.*, 2003a). Sediments accumulated in the basins in fluvial-lacustrine depositional environments. Freshwater lakes and swamps were the main features with some associated fluvial systems. Common to abundant freshwater palynofloras were obtained from the sediments and included pollen of *Trapa* (Trapaceae) and *Cyperus* (Cyperaceae), spores from an aquatic fern *Ceratopteris thalictoides* (Pteridaceae), and a number of microscopic freshwater algae, namely *Actinastrum, Botryococcus* cf. *B. braunii, Closterium*, and various forms of *Pediastrum* spp.

Coal deposits in this period are of relatively good quality and in general of sub-bituminous rank. Coal from the Na Hong basin and some parts of the Ban Pu and Ban Pa Kha coalfields in the Li basin are tree-trunk deposits and probably come from *Taxodium* swamps. Many parts of these coal seams show cross-sections of tree trunks and twigs in which annual rings were clearly observable. Many coal mine companies use the high quality coal from these formations to mix with the low rank, poor quality coal from other basins to fully utilize the commercial opportunities all these deposits provide.

Late Early Miocene to Middle Miocene

In the late Early Miocene in northern Thailand, the warm temperate climate completely changed to a tropical climate with tropical rain forests as found in the Na Sai coalfield and Mae Long locality of the Li basin. The sediments have yielded tropical pollen types including Dipterocarpaceae, *Radermachera* (Bignoniaceae), *Crudia* (Leguminoceae-Caesalpiniaceae), *Homonoia* (Euphorbiaceae), *Lagerstroemia* (Lythraceae), and *Calophyllum* (Guttiferae). The common occurrence of the alga *Botryococcus* cf. *B. braunii* in the Na Sai coalfield suggests a freshwater lake, confirmed by the additional evidence of fish (Cypinidae), crocodiles, turtles, and molluscs. Mammals including mastodon, pig, deer, rhinoceros, and rodents have also been recovered from the Na Sai and Mae Long localities. Tropical climatic conditions persisted until the end of the Middle Miocene. Late Middle Miocene sediments from the Mae Moh and Chiang Muan basins yield tropical palynofloras containing pollen of *Alangium* (Alangiaceae), *Ammannia, Lagerstroemia* (Lythraceae), *Anogeissus* cf. *A. acuminate* (Combretaceae), *Bursera* (Burseraceae), *Caesalpinia* (Leguminosae-Caesalpinoideae), *Calophyllum* cf. *C. inophyllum* (Guttiferae), Combretaceae, Dipterocarpaceae, *Dipterocarpus, Hopea, Shorea* (Dipterocarpaceae), *Homonoia* (Euphorbiaceae), *Ilex* (Aquifoliaceae), Leguminosae-Mimosoideae, Myrtaceae, *Oroxylum* (Bignoniaceae), *Pandanus* (Pandanaceae), Sonneratiaceae, and *Spondias* (Anacardiaceae), and abundant spores from *Lygodium* (Schizaeaceae), *Pteris* (Pteridaceae), and Polypodiaceae.

Early to Middle Miocene sediments from the Mae Moh basin, however, also yield some warm temperate pollen types, such as *Dacrydium* (Podocarpaceae), *Pinus, Tsuga* (Pinaceae), *Taxodium, Sequoia* (Taxodiaceae), *Acer* (Aceraceae), *Carya, Juglans* (Juglandaceae), *Fagus* and *Quercus* (Fagaceae). This is because the Mae Moh Group is an unusually thick Tertiary sequence for northern Thailand, nearly 1,000 m thick, containing warm temperate elements in the lower portion, gradually changing to more common tropical elements in the upper portion. This sequence appears to demonstrate that the change from warm temperate to tropical conditions was not rapid, but a slow transition over a long period of time of as yet unknown length.

During this period the basins were still dominated by freshwater environments supported by fossil palynofloras which included pollen from *Cyperus* (Cyperaceae), spores from *Ceratopteris thalictoides* (Pteridaceae), and the algae *Actinastrum, Botryococcus, Closterium,* and *Pediastrum* (WATANASAK, 1988; SONGTHAM *ET AL.*, 2003a, 2003b).

Coal deposits in these formations are generally lignitic in rank and some have a high sulfur content, which may indicate the presence of plant materials in the original depositional environments, probably the remains of herbs and algae.

Warm temperate palynoflora-bearing sediments are mainly exposed in the western strip of the region along the mountain ranges bordering around the Na Hong basin in the north, extending southwards to Mae Lamao, Mae Tun, and then to Nong Ya Plong basin in the far south. However, some sediment from the Mae Sot basin, close to the Mae Lamao basin, also yields tropical pollen (WATANASAK, 1988). In the central strip of the region, the underlying formations of the Li and Mae Moh Groups, in the Ban Pa Kha and Huai King Formations, respectively, yield warm temperate pollen with tropical palynofloras in the overlying portions (WATANASAK, 1988; SONGTHAM *ET AL.*, 2003a). On the other hand, there is no report of warm temperate elements from basins in the eastern strip of the region, and only tropical sporomorphs have been found in the Chiang Muan (SONGTHAM *ET AL.*, 2003b) and Phrae basins (WATON, 1996). This distribution pattern of sediments type is explained on the basis of tectonics and cordilleran erosion. Mountain building along the western margin of Thailand is said to be an interaction between the Indian-Australian plate and Southeast Asian terrane, and probably occurred from Middle Miocene onward, producing a Southeast Asian region-wide Middle Miocene Unconformity marker (MMU). This Southeast Asian regional-scale unconformity indicates a regressive period in the Southeast Asian region that coincided with a period of tectonic activity (BEDDOES, 1980; PRADIDTAN *ET AL.*, 1990). Therefore, some tropical pollen-bearing sediments in the western mountain ranges were continuously eroded by the uplifting of the mountain ranges and the underlying warm temperate pollen-bearing formations are now mainly exposed. This is also why some basins, including the Mae Moh and Li basins, have both warm temperate and tropical pollen-bearing formations. It is possible that the basins in the eastern part of the region contain both warm temperate and tropical formations, but the underlying warm temperate formations are not exposed and are yet to be discovered.

CONCLUSIONS AND RECOMMENDATIONS

1. Palynological assemblages from Tertiary sediments of northern Thailand are classified into two types of palynoflora, namely warm temperate and tropical palynofloras.

These types are in different stratigraphic positions comprising Oligocene to early Early Miocene for the warm temperate assemblages and late Early Miocene to Middle Miocene for tropical pollen assemblages. The vertebrate-bearing formations are tropical while the vertebrate-barren formations are warm-temperate in palynological terms.

2. The Na Hong, Mae Tun, Mae Lamao, and Nong Ya Plong basins, and Ban Pu and Ban Pa Kha coalfields in the Li basin, were developed during Oligocene to early Early Miocene time. These basins developed in fault-bound intermontane basins containing fluvial-lacustrine environments deposited under warm temperate climatic conditions. Vegetation at this time included conifers and broad-leaf deciduous mesothermal taxa comparable to modern forest types in warm temperate regions of the northern hemisphere.

3. The stratigraphic sequence in the Fang and Na Sai coalfields, the Mae Long locality in the Li basin, and the upper part of Na Khaem Formation in the Mae Moh basin, were developed during late Early Miocene to Middle Miocene. These basins developed in the fault-bound intermontane basins with fluvial-lacustrine environments deposited under a tropical monsoonal climate. Vegetation at this time was a tropical rainforest closely comparable to the modern forest types in northern Thailand.

4. The climate changed from a warm temperate to a tropical situation during Oligocene to Middle Miocene time. This change was possibly caused by movement of the Southeast Asian landmass in a southeast direction as a result of extrusion tectonics.

5. Oligocene to early Early Miocene coal formations are sub-bituminous in rank while late Early Miocene to Middle Miocene coal formations are lignitic with high sulfur content. These different coal ranks result from a difference in the depth of burial, the ages of coalification of the coal formations and, less likely, possibly also from a difference in the original plant materials. The sequences containing warm-temperate palynofloras have been buried to a far greater depth than the overlying sequences containing tropical palynofloras, and the rank can be used to determine how deep these two assemblages have been buried and therefore the degree of tectonic uplift and subsidence can also be determined.

6. This study has obtained palynological data only from some parts of the whole sedimentary section within each basin and cannot be used to absolutely represent the full stratigraphic succession. Palynological investigations of the full sequence of each basin are strongly recommended to confirm this proposed stratigraphic model. Further studies could also confirm whether higher ranked and higher quality coals exist in some basins, and might determine if exploration drilling should be carried out.

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