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# Palaeovegetation and palaeoclimate of tertiary sediments from Hongsa Coalfield, Xayabouly province, Lao PDR – Implication from palynofloras

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## Abstract

Palynological contents of organic-rich Tertiary sediments of the Hongsa coalfield, Xayabouly Province, north-western Lao PDR, were investigated. Palynomorphs that were used to reconstruct the palaeovegetation and palaeoclimate, were extracted from a sediment drill core from the central part of the Hongsa coal mine. Three pollen zones from bottom to top (Hongsa I zone, Hongsa II zone, and Hongsa III zone) were divided based on the quantitative change of the palynological assemblages. They indicate the change of climate from subtropical to temperate during the deposition of the Hongsa coal. The Hongsa vegetation composes of subtropical to warm temperate broad-leaved forests. *Quercus*, *Fagus*, castanoids, *Salix*, Fabaceae, and Myrtaceae were the dominant trees and shrubs, and ferns were commonly found on the forest floor. The palynological assemblages from the Hongsa Basin are different from the Oligocene and Miocene from northern Thailand; however, they are similar to the middle to late Miocene of southwest China.

**Keywords**: palynology, tertiary, Hongsa coal mine, palaeoclimate, palaeovegetation

## 1. Introduction

The coal mine in Hongsa, Xayabouly Province, in the northwestern part of Lao People's Democratic Republic (PDR) has been operated since 2015. The basin is located at 19° 39′ N to 19° 43′ N, and 101°14′ E to 101° 24′ E, and is situated between northern Thailand and southern China (Figure 1). The basin is roughly triangular and it is a sub-elongate shape. It is located in an ENE-WSW direction with a long axis about 12 km and an average short axis of about 5 km (Figure 2). This basin is an area influenced by the Cenozoic major tectonic event of Sundaland that caused by a collision between the Indian and Eurasian plates in the middle Eocene (~45 Ma) and complex fault systems can be recognized in the mine (Chaodumrong & Songtham, 2014; Friederich, Moore, & Flores, 2016; Hall & Morley, 2004; Jain, 2014; Lacassin *et*

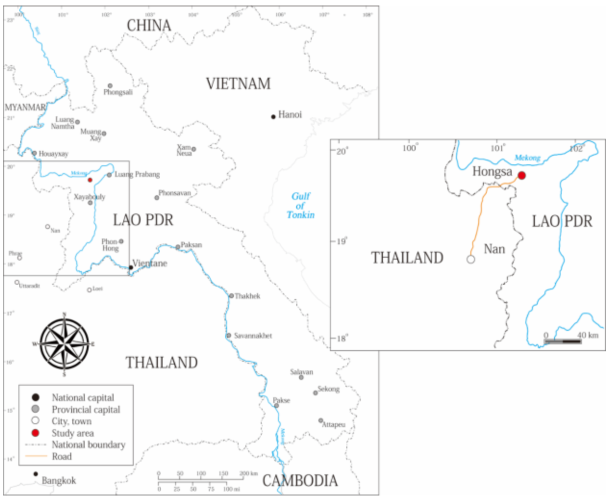


Figure 1. Location of the Hongsa coalfield shown as red circle. The road from Nan to Hongsa is shown as an orange line, which is the most convenient way to reach the Hongsa Basin.

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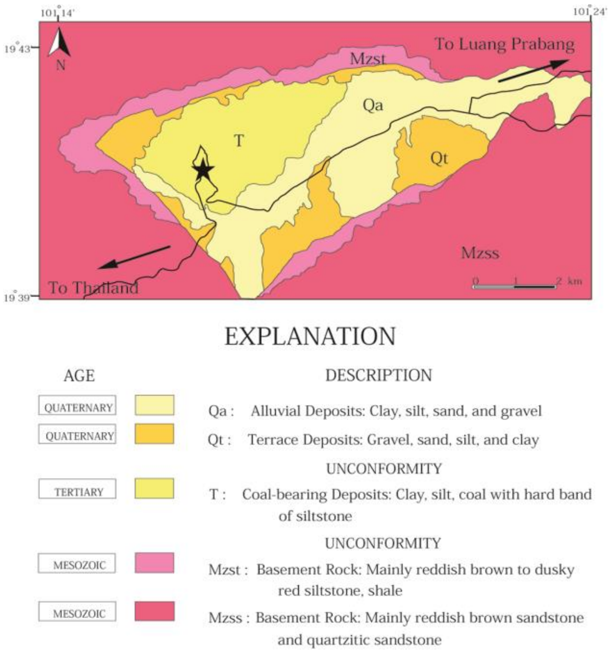


Figure 2. Geologic map of the Hongsa Basin (modified after General Department of Geology and Mines of Vietnam). Black star is the location of Hongsa mine-mouth power plants.

*al.*, 1997; Tapponier, Peltzer, & Armijo, 1986). The northern edge of the basin is bounded by a set of en-echelon faults trending ENE-WSW while the western edge of the basin is bounded by NW-SE trending normal fault (Hofmann *et al.*, 2008). The relatively long time of the deposition process in the Hongsa Basin took place between Oligocene and Pliocene, starting approximately 35 million years ago and ending around 2 million years ago (Morley & Racey, 2011). The uncertainty of this time frame is due to the lack of any detailed studies of this basin and the failure to find any mammalian fossils. There are floodplains, hills, and high mountains surrounding the Hongsa Basin. The mountainous area is mainly composed of Mesozoic red bedrock. This intermontane basin mainly comprises of light-grey silty clay, also includes clay with some siltstone hard bands and coal-bearing sequences which have a cumulative thickness of over 100 m (The General Department of Geology and Minerals of Vietnam, 1988; Vilaihongs & Areesiri, 1997). The coals are low-rank and are classified as lignite A and lignite B; they deposited with a high content of mineral matter in a forest swamp environment (Sattraburut, 2017; Sattraburut, Thasod, & Ratanasthien, 2017). The uppermost layer is Quaternary sediments that compose of alluvial clay, silt, sand, and gravel from the Mekong River and its tributaries (Figure 2). The Cenozoic succession of the Hongsa coal mine (Figure 3a) has been subdivided into eight rock units by Hofmann *et al.* (2008).

Palynology is a powerful tool for the reconstruction of palaeovegetation and palaeoclimates. A palynological approach is now widely used to answer ecological questions about palaeovegetation and environmental changes; however, no palynological data has ever been collected or studied from the Hongsa coalfield. Thus, this study uses palynology to compare palaeovegetation and palaeoclimates with nearby Tertiary basins.

## 2. Materials and Methods

Samples for palynological analysis were collected from Tertiary organic-rich fine-grained sediments that were obtained from the Hongsa coalfield. The examined material comprised of drill core samples from the central part of the Hongsa coal pit and it was provided by the Hongsa Power Company Limited. The material was 34 samples which were selected at varying intervals from a total core length of 331.40 m, starting from the Lower Lignite Zone formation and reaching up to Overburden (Figure 3b). They were evenly spaced approximately 10 m apart. Sample slices measuring 10 cm were cut longitudinally from the core.

Samples mainly consisted of carbonaceous clays with a minor amount of carbonaceous silty clays. The samples were treated following a standard palynological technique as described by Moore, Webb, & Collinson (1991). Firstly, 10 g from each sample was crushed and washed by distilled water. The washed sample was dissolved carbonate, basing the amount of hydrochloric acid (HCl 10%) used upon the reaction's intensity. The siliceous component was removed by adding hydrofluoric acid (HF 40%). Then, acetolysis treatment was applied to eliminate the cellular content, clean pollen surfaces, and dye the pollen grains brown in order to clarify the pollen surface's texture and other details. Dehydration was accomplished with an application of glacial acetic acid ($CH_3COOH$) before acetolysis treatment to avoid a highly exothermic reaction between the acetolysis mixture and water. Afterwards, 9:1 mixture of acetic anhydride [$CH_3(CO_2)O$] and concentrated sulphuric acid ($H_2SO_4$) was added into the samples and the suspension was placed in a boiling water bath for three minutes. Samples were then sieved to remove the larger organic matter, using a nylon filter with a mesh size of 150 µm. Finally, the palynomorphs were mounted in a colorless glycerin jelly and they were determined with a magnification of x400 under a light microscope. For generating pollen diagram (Figure 4), 400 sporomorphs were counted per each sample. In this diagram, the percentages of palynomorphs taxa in each sample were calculated based on the total amount of pollen grains and spores while non-pollen palynomorphs were omitted. The material was described in the Department of Geological Sciences, Faculty of Science, Chiang Mai University.

## 3. Results

### 3.1 Composition of the palynomorphs

In this study, all thirty-four samples were proved to be palynologically productive. The fossil palynomorphs have mainly been identified through their genus and family levels. Table 1 lists all taxa identified for, together with their life forms, occurrences, and semi-quantitative distribution of palynomorphs recovered in the study. The descriptions of major fossil pollen morphologies are given in App. I. Photographs of selected pollen grains and spores are shown in Figure 5. The entire diversity is discussed below.

The most diverse group of palynomorphs in the Hongsa coalfield belongs to angiosperms (48 taxa), with a total percentage of 59.82%. The extinct *Florschuetzia*, *F. trilobata* Germeraad *et al.* (Figure 5ae) and *F. semilobata* Germeraad *et al.* (Figure 5ef) which are considered to relate to

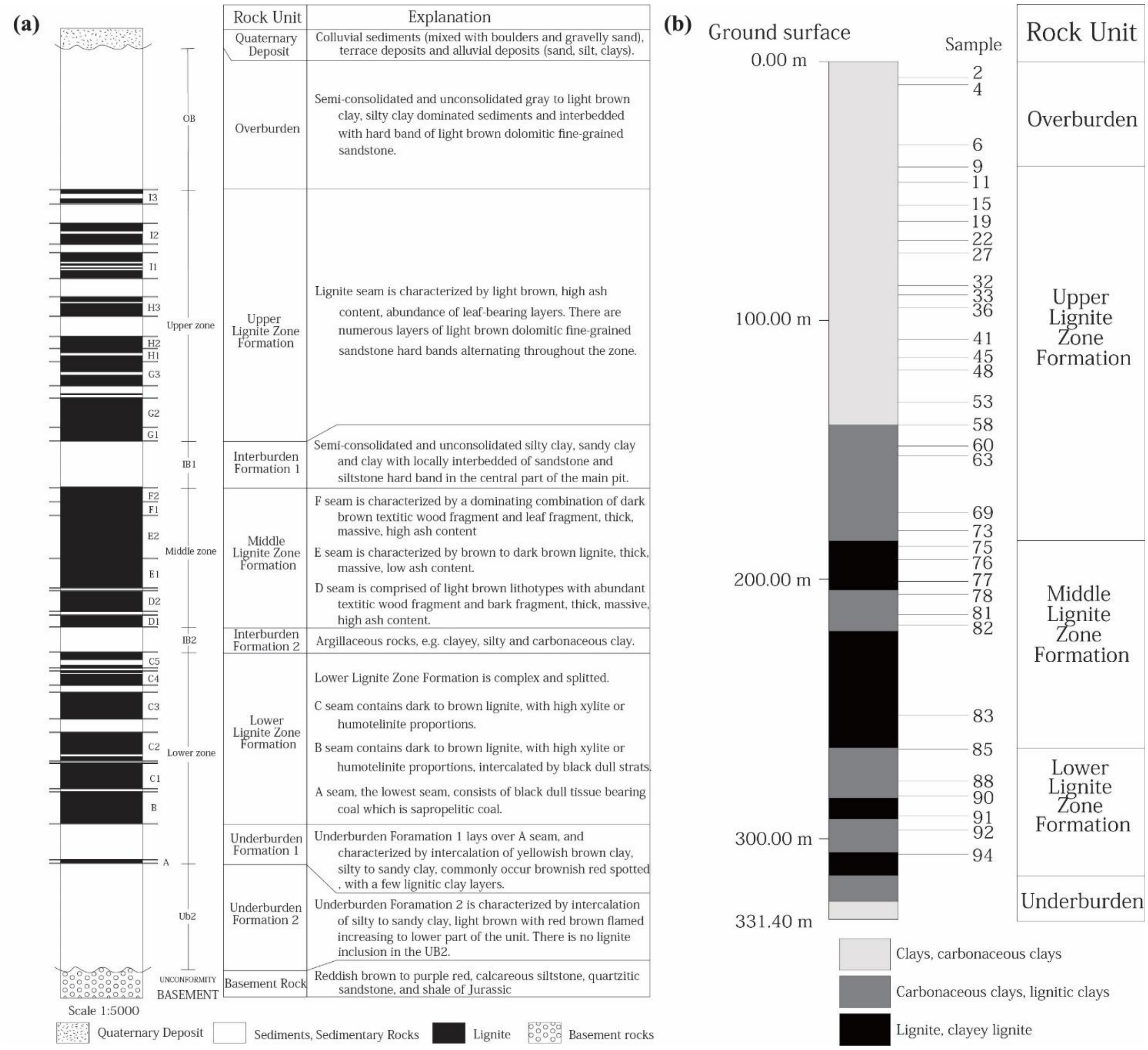


Figure 3. (a) Schematic stratigraphy of the Hongsa coalfield (modified after Hofmann *et al.*, 2008). (b) A partial schematic stratigraphic succession of the Hongsa coalfield showing the stratigraphic levels of the sample collecting.

Lythraceae as a possible ancestor of Sonneratia, belongs to this group (Graham, 2013). Six gymnosperms taxa and 4 sporomorphs types account for 3.19% and 28.67%, respectively. Only one taxon of algae (*Ovoidites*) is presented and the percentage received is negligible. Fourteen palynomorphs of unknown affinity (Figure 6) make up a total percentage of 8.32%.

*Quercus* is the most abundant element of the angiosperm component, followed by Fabaceae, Poaceae, *Salix*, *Acer*, *Fagus*, Myrtaceae, and castanoids. Gymnosperms present in relatively small numbers of taxa and also in percentage terms. Cupressaceae is the most common taxon for this group. At nearly 30 % of the assemblages, ferns and fern allies spores are the least diverse among the all main palynomorph groups, excluding algae. Although this group is the least diverse, Polypodiaceae is the most abundant taxon with 26.31% of total assemblages.

## 3.2 Palynological assemblage zones and age

Based on the composition of the palynomorphs, palynological assemblages can be divided into three pollen zones based on quantitative changes in certain palynomorphs from bottom to top (Figure 4).

Hongsa I zone: This is the lowest zone of the succession (seam C1 to D1). It has the least amount of pollen and spores, with only seven samples taken from this zone. The dominant broad-leaved tree is *Quercus* (11.21–29.63%, mean 20.69%). When compared to the other two zones, there are fewer warm temperate trees, including *Salix* (3.00–11.66%, mean 5.92%), *Fagus* (1.50–8.89%, mean 3.08%), *Acer* (0.50–13.68%, mean 2.57%), and castanoids (0.25–4.00%, mean 1.66%). Only a few Cupressaceae, *Sciadopitys*, and *Pinus* of conifers are found. Prominent herbs include Apiaceae, Poaceae, and Cyperaceae. Polypodiaceae is the only recognized fern in this zone.

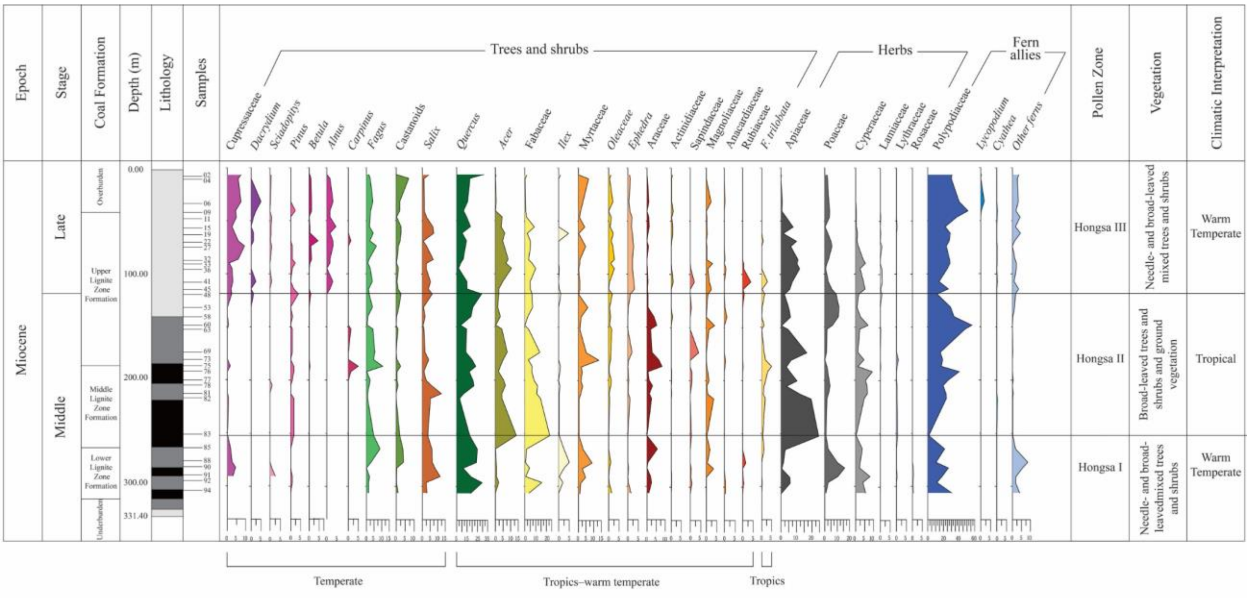


Figure 4. The percentage diagram of major palynomorphs from the Hongsa coalfield

Table 1. Semi-quantitative distribution of palynomorphs recovered in this study (+ = 0.1–2%, ++ = 2.01–10%, +++ = more than 10% of the entire diversity)

| Palynotaxon/highest botanical determination | Life form | Climate | Ecology (habitat) | Frequency |
|---|---|---|---|---|
| Algae | | | | |
| Zygnemataceae | Plankton | Temperate, subtropical | Shallow, stagnant, oxygen-rich waters, lake margins (Worobiec, 2014) | + |
| *Ovoidites* sp. | | | | |
| Fern and fern allies | | | | |
| Cyatheaceae | Fern | Tropical | Wet forest | + |
| *Cyathea* sp. | | | | |
| Davalliaceae | Fern | Tropical, subtropical | High humidity, shady place | + |
| *Davallia* sp. | | | | |
| Lycopodiaceae | Fern | Indifferent | Moist, shady place, rich in humus and organic matters | + |
| *Lycopodium* spp. | | | | |
| Polypodiaceae | Fern | Indifferent | Moist, high humidity, shady or semi-shady place | +++ |
| Polypodiaceae gen. indet. | | | | |
| Gymnosperms | | | | |
| Cupressaceae | | | | |
| Cupressaceae gen. indet. papillate | Tree | Temperate | Wetlands to dry soils, sea level to high elevations in mountainous regions | ++ |
| Ephedraceae | | | | |
| *Ephedra* sp. | Shrub | Tropical | Open, light forest | + |
| Ginkgoaceae | | | | |
| *Ginkgo* sp. | Tree | Temperate | Moist soils, sunlit place | + |
| Pinaceae | | | | |
| *Pinus* sp. | Tree | Subtropic, temperate | Mountainous regions, favorable soils, some water | + |
| Podocarpaceae | | | | |
| *Dacrydium* | Tree | Subtropic | Lowland and montane forest, canopy tree | + |
| Sciadopityaceae | | | | |
| *Sciadopitys* sp. | Tree | Temperate | Mild damp regions with warm humid summer, good loamy soils, tolerating a wet place | + |
| Angiosperms | | | | |
| Monocotyledons | | | | |
| Araceae | | | | |
| Araceae gen. indet. | Herb | Tropical, subtropical | Forest floor, humid regions | + |
| Cyperaceae | | | | |
| Cyperaceae gen. indet. | Herb | Indifferent | Sunny, moist to wet regions | ++ |

Table 1. Continued.

| Palynotaxon/highest botanical determination | Life form | Climate | Ecology (habitat) | Frequency |
|---|---|---|---|---|
| Poaceae | | | | |
| Poaceae gen. indet. | Herb | Indifferent | Indifferent | ++ |
| Potamogetonaceae | | | | |
| *Potamogeton* sp. | Herb | Indifferent | Aquatic, freshwater, strongly influenced by water depth | + |
| Dicotyledons | | | | |
| Actinidiaceae | | | | |
| Actinidiaceae gen. indet. | Shrub | Temperate, subtropical | Moist montane forest | + |
| Anacardiaceae | | | | |
| Anacardiaceae gen. indet. | Tree | Warm temperate, tropical | Rainforest, some tolerate or prefer a seasonal climate | + |
| Apiaceae | | | | |
| Apiaceae gen. indet. | Herb | Indifferent | Indifferent | ++ |
| Aquifoliaceae | | | | |
| *Ilex* sp. | Tree | Indifferent | Mixed deciduous or humid evergreen forest | + |
| Asteraceae | | | | |
| *Artemisia* sp. | Herb | Temperate | Dry or semiarid | + |
| Betulaceae | | | | |
| *Alnus* sp. | Tree | Temperate | Near streams, rivers, and wetlands | + |
| *Betula* sp. | Tree | Temperate | Sunlight, well-drained, particularly acidic soils | + |
| *Carpinus* sp. | Tree | Temperate | Mixed deciduous or humid evergreen forest | + |
| Cornaceae | | | | |
| *Cornus* sp. | Tree | Temperate | Moist but well-drained soils, slightly acidic | + |
| Dipterocarpaceae | | | | |
| Dipterocarpaceae gen. indet. | Tree | Tropical | Lowland rain forest, evergreen or deciduous | + |
| Ericaceae | | | | |
| *Erica* sp. | Shrub | Indifferent | Evergreen, limited to acidic or very acidic soils | + |
| Eucommiaceae | | | | |
| Eucommiaceae gen. indet. | Tree | Temperate | Forest areas | + |
| Euphorbiaceae | | | | |
| Euphorbiaceae gen. indet. | Shrub, tree | Indifferent | Indifferent | + |
| Fabaceae | | | | |
| Fabaceae gen. indet. | Tree | Indifferent | Indifferent | +++ |
| *Mimosoideae* sp. | Tree | Tropical, subtropical | Lowland rainforest | + |
| Fagaceae | | | | |
| Castanoids | Tree | Temperate | Well-drained lowland and upland forest | ++ |
| *Fagus* sp. | Tree | Temperate | Well-drained lowland and upland forest | ++ |
| *Quercus* spp. | Tree | Tropical, cool temperate | Well-drained lowland and upland forest | +++ |
| Hamamelidaceae | | | | |
| Hamamelidaceae gen. indet. | Shrub | Temperate, tropical | Scrubland, open placed or woodland (temperate), rainforest (tropical) | + |
| Juglandaceae | | | | |
| *Carya* sp. | Tree | Temperate, subtropical | Well-drained lowland and upland forest | + |
| *Juglans* sp. | Tree | Temperate, subtropical | Wet, well-drained lowland | + |
| Lamiaceae | | | | |
| Lamiaceae gen. indet. | Herb | Indifferent | Indifferent | + |
| Loranthaceae | | | | |
| Loranthaceae gen. indet. | Shrub | Tropical, temperate | Wooded places, almost invariably growing on dicotyledonous angiosperms | + |
| Lythraceae | | | | |
| Lythraceae gen. indet. | Herb, shrub | Tropical, temperate | Aquatic, semi-aquatic, lake margin | + |
| *Florschuetzia* spp. | Uncertain | Tropical | Lacustrine fresh-water swamp (Morley, 2000) | + |
| Magnoliaceae | | | | |
| *Magnolia* sp. | Tree | Temperate, tropical | Well-drained lowland and upland forest | + |
| Meliaceae | | | | |
| Meliaceae gen. indet. | Tree | Tropical | Woodland or wood grassland | + |
| Myricaceae | | | | |
| *Myrica* sp. | Tree, shrub | Indifferent | Well-drained lowland in full sun to part shade | + |
| Myrtaceae | | | | |
| Myrtaceae gen. indet. | Tree | Tropical, warm temperate | Indifferent | ++ |
| Oleaceae | | | | |
| *Fraxinus* sp. | Tree, shrub | Temperate, tropical | Indifferent | + |

Table 1. Continued.

| Palynotaxon/highest botanical determination | Life form | Climate | Ecology (habitat) | Frequency |
|---|---|---|---|---|
| Plantaginaceae | | | | |
| Plantaginaceae gen. indet. | Herb | Temperate | Open and disturbed areas | + |
| Polygalaceae | | | | |
| Polygalaceae gen. indet. | Herb, shrub | Indifferent | Indifferent | + |
| Polygonaceae | Herb | Temperate | Indifferent | + |
| Polygonaceae | | | | |
| Rosaceae | | | | |
| Rosaceae gen. indet. | Herb | Temperate | Indifferent | + |
| Rubiaceae | | | | |
| Rubiaceae gen. indet. | Tree | Subtropical | Indifferent | + |
| Rutaceae | | | | |
| Rutaceae gen. indet. | Uncertain | Tropical, subtropical | Indifferent | ++ |
| Salicaceae | | | | |
| *Flacourtia* sp. | Shrub | Tropical, subtropical | Indifferent | + |
| *Salix* sp. | Tree | Temperate | Moist soils, cold regions | ++ |
| Sapindaceae | | | | |
| Hippocastanoideae gen. indet. | Tree | Temperate | Indifferent | + |
| *Acer* sp. | Tree | Temperate | Indifferent | ++ |
| Sapotaceae | | | | |
| Sapotaceae gen. indet. | Tree | Tropical | Lowland moist forest | + |
| Saxifragaceae | | | | |
| *Saxifraga* sp. | Herb | Temperate | Indifferent | + |
| Ulmaceae | | | | |
| *Ulmus* sp. | Tree | Temperate, tropical | Well-drained lowland and upland forest | + |
| Vitaceae | | | | |
| Vitaceae gen. indet. | Shrub | Tropical, temperate | Indifferent | + |

Hongsa II zone: Thirteen samples between seam E1 and H3 were determined in this zone. When compared to the Hongsa I zone, this zone has fewer *Quercus* (7.75–29.06%, mean 17.55%), *Acer* (0.25–7.71%, mean 3.83%), *Fagus* (0.25–10.70%, mean 2.93%) and castanoids (0.46–2.71%, mean 0.80%). The percentages of tropical to subtropical pollen related to Araceae, Myrtaceae, and *F. trilobata* are high in this zone. Conifers are rarely present. Ferns and grasses (Poaceae) are less dominant than in other zones.

Hongsa III zone: Fourteen samples between seam I1 and I3 were determined in this uppermost zone. The pollen was from hardwood trees, mainly Fagaceae, *Quercus* (6.86–31.12%, mean 14.60%), *Acer* (0.26–10.54, mean 4.16%), *Fagus* (0.98–6.53%, mean 2.79%), and castanoids (0.25–6.93%, mean 1.69%). There has been an expansion in the number of conifers (Cupressaceae, *Dacrydium*, *Sciadopitys*, and *Pinus*) in this zone. *Ephedra* is mostly found together with *Fraxinus* (Oleaceae). Ferns have been found and among them most frequently Polypodiaceae.

Trees of *Quercus*, *Fagus*, castanoids, *Acer*, *Salix*, Fabaceae, and Myrtaceae present in all zones and they are found throughout the time interval. These plants are widespread in warm-temperate to temperate zones in the northern hemisphere. The tropical to subtropical elements of Araceae, *F. trilobata*, Magnoliaceae, and Sapindaceae mostly occur in the Hongsa II zone. Conifers, which are notably dominant in a cool climate in mountainous areas, are mostly found in Hongsa I and Hongsa III zones, while *Pinus* exists in all zones. The palynological assemblages of the Hongsa coalfield suggest that a forest composed mainly of subtropical to warm-temperate broad-leaved elements. The results suggest that the climate in the Hongsa Basin has changed from time to time.

## 4. Discussions

### 4.1 Palaeovegetation and palaeoclimate

It is clear that the vegetation during the period of deposition of the Hongsa coal was rich and diverse. A flourishing of Fagaceae with some conifer trees indicates that the vegetative constituents composed of subtropical to warm temperate broad-leaved forest. As there was a high proportion of *Quercus*, *Fagus*, castanoids, *Salix*, Fabaceae, and Myrtaceae, the vegetation of Hongsa was dominated by mixed deciduous and evergreen trees. The herb floor was dominated by ferns (mainly Polypodiaceae), Apiaceae, Poaceae, and Cyperaceae. The high proportions of ferns and Cyperaceae suggest that the shady undergrowth had high humidity (Zhang, Ferguson, Mosbrugger, Wang, & Li, 2012).

Based on the palynological assemblages, the small number of conifers in Hongsa I zone, the absence of conifers but a high proportion of tropic plants in Hongsa II zone, and then an increasing of conifers in Hongsa III zone, indicate that Hongsa I and II zones had warmer climates than Hongsa III zone. It also suggests that the climate had changed from a warmer subtropical to a cooler temperate condition over time. Changes in pollen assemblages may be related to variations in climate, topography, altitude, and tectonic evolution (Morley, 1978, 1991; Yao *et al.*, 2017).

Yao, Bruch, Mosbrugger & Li (2011) discussed that most regions of southern China and Europe were both warm and humid during the Miocene. The climate had changed because uplifts of the Himalayas and Tibetan Plateau, causing Asian monsoons, heavy rainfall, and resulting in an evolution to a warm temperate climate in these areas. This is probably why the Hongsa coalfield climate also changed.

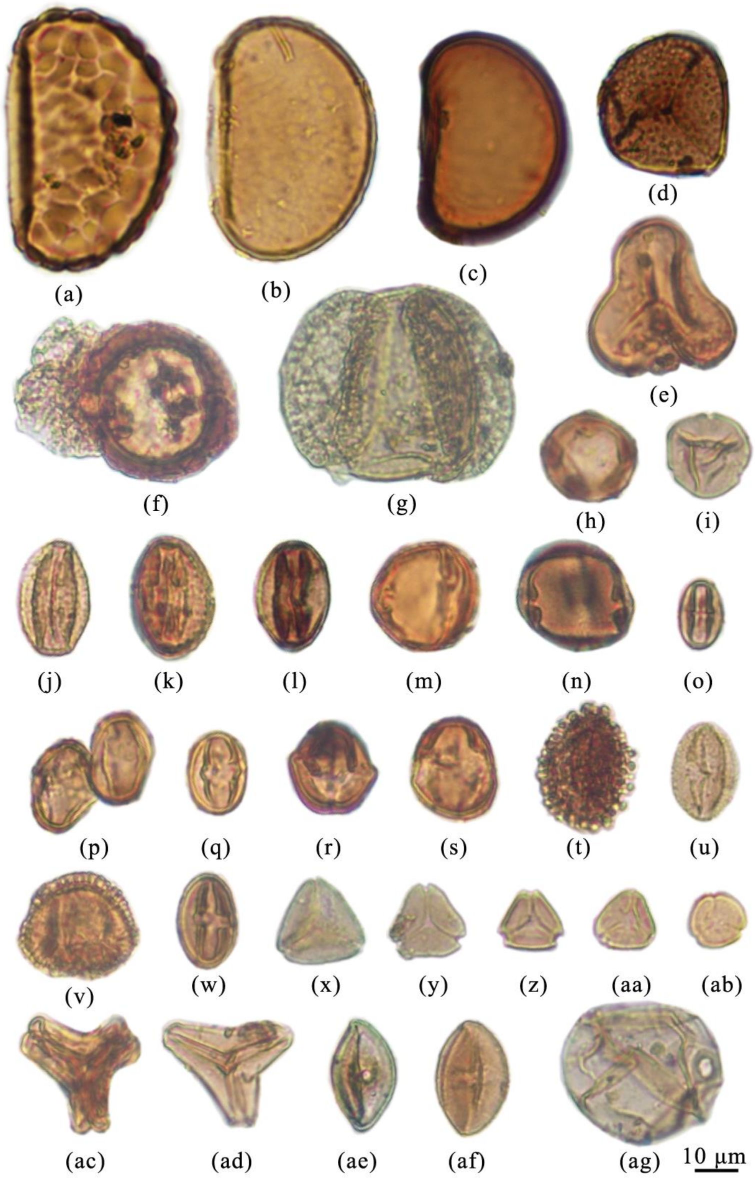


Figure 5. Representative palynomorphs from the Hongsa coalfield. Coal seams, sample numbers, and depths (m) are provided (these details are separated by '/'). (a) Polypodiaceae, I3/09/40.60; (b) Polypodiaceae, OB/04/10.25; (c) Polypodiaceae, OB/06/32.00; (d) *Lycopodium*, OB/06/32.00; (e) *Cyathea*, I3/09/40.60; (f) *Dacrydium*, OB/06/32.00; (g) *Pinus*, I1/33/89.90; (h) *Alnus*, I2/27/73.75; (i) *Carpinus*, G3/75/187.00; (j) *Quercus*, OB/02/6.55; (k–l) *Quercus*, I3/15/55.60; (m–n) *Fagus*, G3/75/187.00; (o) Castanoids, OB/04/10.25; (p) *Acer*, I1/36/94.80; (q) Hippocastanoideae, HI/48/118.90; (r) Fabaceae, I1/36/94.80; (s) Fabaceae, D2/83/252.20; (t) *Ilex*, I2/19/61.65; (u) *Salix*, G1/81/212.75; (v) *Fraxinus*, I1/36/94.80; (w) Rutaceae, C3/90/282.70; (x) Myrtaceae, I2/22/68.95; (y–z) Myrtaceae, 53/HI/131.25; (aa) Myrtaceae, H1/73/180.75; (ab) Myrtaceae, C3/91/290.85; (ac) Loranthaceae, I3/15/55.60; (ad) Loranthaceae, HI/53/131.25; (ae) *Florschuetzia semilobata*, HI/45/114.15; (af) *Florschuetzia trilobata*, G3/75/187.00; (ag) Poaceae, C4/88/277.40. OB = Overburden, HI = soil parting between seams H and I.

## 4.2 Comparison with adjacent areas

As previously discussed, there have not been any intensive palynological investigations conducted in Lao PDR. Thus, our results are compared with other palynological investigations and palaeofloras from the Oligocene to Miocene data of northern Thailand and Miocene data of southwest China. Moreover, the table comparing the Hongsa Basin palynomorphs to similar palynomorphs of published late Oligocene to late Miocene plant assemblages of northern Thailand and southwest China was compiled in Table 2.

The late Oligocene to early Miocene localities in northern Thailand includes the Na Hong Basin and Ban Pa Kha coalfield that situated southwest of Hongsa coalfield (Figure 7). Based on the types of vegetation, the period of deposition in the Hongsa Basin was warmer than those Thai basins. The dominant elements that have been reported in the late Oligocene to early Miocene Thai basins, such as *Pinus*,

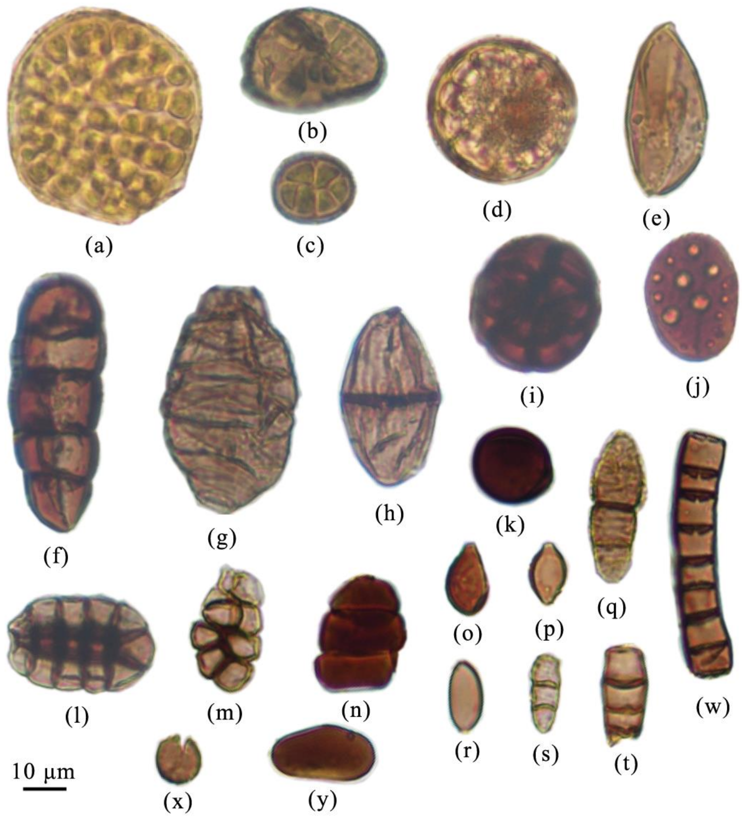


Figure 6. Representative indeterminate (a–e) and fungal remains (f–y). Coal seams, sample numbers, and depths (m) are provided (these details are separated by '/'). (a) H3/60/148.30; (b) H2/63/151.90; (c) I1/32/86.35; (d–e) C1/94/306.15; (f–g) HI/53/131.25; (h) C2/92/296.35; (i–j) H3/60/148.30; (k) OB/04/10.25; (l) HI/53/131.25; (m–w) OB/04/10.25; (x–y) OB/02/6.55. OB = Overburden, HI = soil parting between seams H and I.

*Tsuga*, *Alnus*, *Quercus*, *Fagus*, *Juglans*, *Pterocarya*, *Carya*, etc. (Grote, 2015; Songtham, 2000; Songtham *et al.*, 2005; Songtham, Ratanasthien, Midenhall, Singharajwarapan & Kandharosa, 2003; Watanasak, 1989, 1990), suggested a warm temperate to temperate climate at that time. By contrast, it differs from the climate during the middle Miocene and late Miocene deposits in northern Thailand such as the Mae Moh Basin (13.3–13.1 Ma) and the Chiang Muan Basin (13.5–10 Ma) that are mainly composed of tropical forest taxa, including Rubiaceae, *Syzygium*, and Pteridophytes with a low percentage of temperate forest elements. These basins were mainly characterized by trees and then replaced by herbaceous taxa (Sepulchre, Jolly, Ducrocq, Chaimanee & Jaeger, 2009). This suggests that the palaeoclimates of the Mae Moh and Chiang Muan Basins were the same as the present-day and warmer than the Hongsa Basin.

Comparing to the southwest China, the pollen evidence and plant fossils from the middle Miocene localities such as the Hexi and Dajie coal mines (Figure 7), were investigated (Zhang, Ferguson, Mosbrugger, Wang & Li, 2012). The fossils were formed from mixed evergreen and deciduous broad-leaved forests, mainly *Alnus*, *Castanopsis*, *Betula*, *Corylus*, *Ulmus*, *Juglans*, castanoids, *Carya*, *Quercus*, and *Ilex*, with some conifers (*Pinus*, *Dacrydium*, Cupressaceae), that grew under subtropical conditions. A large amount of Polypodiaceae indicates that there was high humidity in the forests. This fossil assemblage is considered to be comparable to the Hongsa I zone.

The middle to late Miocene Xiaolongtan Basin was predominantly characterized by the appearance of angiosperm elements, showing the parental plants of a broad-leaved evergreen forest accompanied by a few deciduous elements. The dominant woody elements are *Quercoidites*, *Cupuliferoipollenites*, *Caryapollenites*, *Salixipollenites*, *Ilexpollenites*, and *Juglanspollenites*. Pteridophyte spores were represented by a large number of *Polypodiaceasporites* (Wang, 1996). These fossil assemblages are similar to the Hongsa I and II zones.

During the late Miocene, the forest was covered with a sequence of broad-leaved evergreen trees with a large number of evergreen oaks (*Quercus*) and *Salix.* These were accompanied by a few deciduous elements such as *Rhus*, *Juglans*, *Betula*, *Celtis*, *Magnolia*, *Acer*, and *Corylus*, which were found in the Xiaolongtan Basin, Lühe Region, and in the Hengduan Mountains (Wang, 2006; Xu, Ferguson, Li & Wang, 2008). These indicate that the climates ranged from tropical or subtropical with mild winters to a more temperate climate with a cold season. This period is comparable to the Hongsa III zone.

The palynological assemblages identified that the palaeoclimate of the Hongsa coalfield is similar to the middle and late Miocene of southwest China than the Oligocene and Miocene of northern Thailand.

Table 2. Comparison between the Oligocene to Miocene palynotaxon in different adjacent regions of the Hongsa Basin

| | | Lao PDR | Northern Thailand | | | | Southwest China | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Palynotaxon | Hongsa Basin | Ban Pa Kha coalfield | Nahong Basin | Chiang Muan Basin | Mae Moh Basin | Xiaolongtan Basin | Dajie coal mine | Hexi coal mine | Hengduan Mts. | Lühe Region |
| | | | (Oligocene–Early Miocene) | (Late Oligocene–Early Miocene) | (Middle Miocene) | (Middle Miocene) | (Middle Miocene–Early Pliocene) | (Middle Miocene) | (Middle Miocene) | (Middle–Pliocene) | (Late Miocene) |
| Temperate taxa | *Picea* | | √ | √ | | | | √ | | √ | √ |
| | *Pinus* | √ | √ | √ | | √ | | √ | √ | √ | √ |
| | *Abies* | | | | | | √ | √ | √ | √ | √ |
| | *Tsuga* | | √ | √ | | | | √ | √ | √ | √ |
| | Cupressaceae | √ | √ | | | | | √ | | | |
| | *Juglans* | √ | √ | √ | | | √ | √ | | √ | |
| | *Carya* | √ | √ | √ | | | √ | √ | | | √ |
| | *Alnus* | √ | | | | √ | | √ | √ | | √ |
| | *Betula* | √ | | | | √ | | √ | √ | | √ |
| | *Myrica* | √ | | | | √ | | | | | |
| | *Fagus* | √ | √ | | | | | | | | |
| | *Castanea* | √ | | | | | | | √ | √ | √ |
| | *Quercus* | √ | √ | | | √ | √ | | √ | √ | √ |
| | *Ilex* | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| | *Salix* | √ | | | | | √ | | | √ | |
| | *Acer* | √ | | | | | | | | √ | |
| Tropic taxa | Myrtaceae | √ | | | √ | | | √ | | | |
| | Sapindaceae | √ | | | | | | √ | | | √ |
| | Fabaceae | √ | | | | | | | | | |
| | *Syzygium* | | | | √ | | | | | | |
| | *Ephedra* | √ | | | | | | | | | |

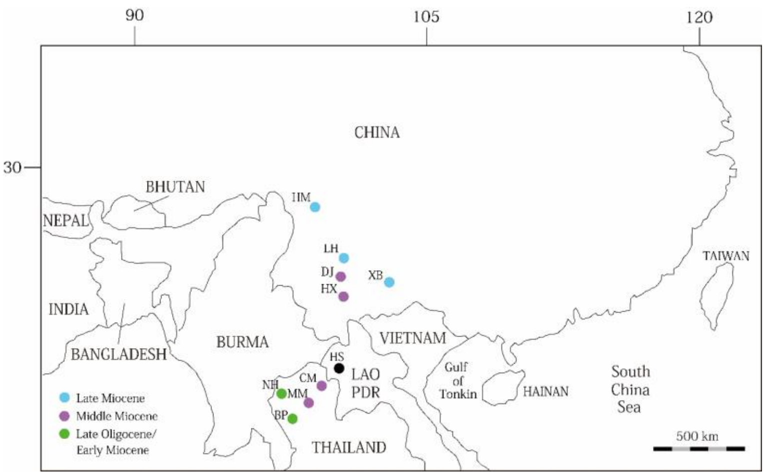


Figure 7. Regional map showing the location of the Hongsa coal mine (HS) and adjacent areas in Southwest China and Northern Thailand (HM; Hengduan Mountains; LH: Lühe Region; XB: Xiaolongtan Basin; DJ: Dajie coal mine; HX: Hexi coal mine; CM: Chiang Muan Basin; MM: Mae Moh Basin; NH: Na Hong Basin; BP: Ban Pa Kha coalfield) (modified after Wang, 1996; Songtham, 2000; Songtham *et al.*, 2003, 2005; Wang, 2006; Xu *et al.*, 2008; Sepulchre *et al.*, 2009; Yao *et al.*, 2011; Grote, 2015).

In summary, regional comparisons show that the vegetative successions and climatic patterns of the Hongsa coalfield and adjacent areas are certainly comparable, but some sites have unique characteristics depending upon their topography, altitude, microclimate, and tectonic evolution. Figure 8 shows the approximate time of deposition together with the climatic condition in basins from south to north across northern Thailand to southwest China based on a compilation of palynological data (Table 2). In northern Thailand, the climate changed from temperate to tropical during Oligocene to Miocene. Contrary to southwest China, the climate is considered to be warm temperate during Miocene. In this study, the Hongsa coalfield is comparable to the middle and late Miocene localities of southwest China based on palynological assemblages and coalification. *Florschuetzia trilobata*, because a species became extinct around the middle Miocene (Mao & Foong, 2013; Morley, 1978; Muller, 1984), was found in the Hongsa II zone and the

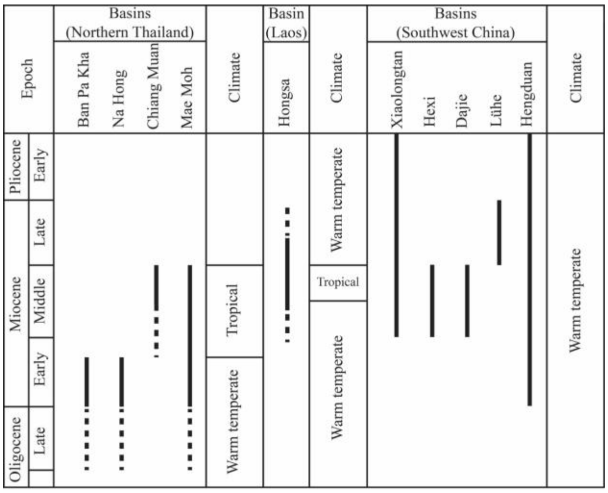


Figure 8. Schematic approximate timing of deposition together with the climatic interpretation in basins from south to north across northern Thailand to southwest China, based largely on palynological data from Wang, 1996; Songtham, 2000; Songtham *et al.*, 2003, 2005; Wang, 2006; Xu *et al.*, 2008; Sepulchre *et al.*, 2009; Yao *et al.*, 2011; Grote, 2015.

lower part of Hongsa III zone. This is supporting evidence for the depositional age of the Hongsa basin. The higher levels of tropic vegetation in the Hongsa II zone than in the Hongsa III zone may have resulted from higher global temperatures or the Miocene Climatic Optimum (Meng *et al.*, 2017).

The subtropical to warm temperate taxa in the study area suggest a mid-altitude tropical forest and a higher altitude warm temperate forest. This reinforces the assumption that the vegetation and climate during the time of deposition were quite similar to current conditions in the study area.

## 5. Conclusions

Tertiary organic-rich sediment drill core from the Hongsa coalfield, north-western Lao PDR were analyzed for a palynological study. Since there have been no detailed studies of the Hongsa Basin, this study reconstructed the palaeovegetation and palaeoclimate of the basin by using a palynoflora investigation. The palynofloras of the Hongsa coalfield indicate that there was a climatic change from a warmer subtropical to a cooler warm temperate condition during the deposition. The warmer subtropical elements were remarkably dominated by Araceae, *F. trilobata*, Magnoliaceae, and Sapindaceae, while *Quercus*, *Fagus*, castanoids, *Salix*, *Acer*, and some conifers were dominant in the cooler warm temperate elements.

The forest vegetative constituents were broad-leaved trees, dominated by *Quercus*, *Fagus*, castanoids, *Salix*, Fabaceae, and Myrtaceae trees and shrubs. A high number of ferns presented on the forest floor, indicating the high humidity of a shady undergrowth. According to the comparison between palynological data from the Hongsa coalfield and the adjacent basins, it is considered likely that the Hongsa Basin represents the deposition between the middle to late Miocene. Changes in pollen assemblages may have been related to variations in climate, topography, altitude, and tectonic evolution.

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