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***Xenoxylon*, a boreal fossil wood in the Mesozoic redbeds of southeast Asia:
potential for the stratigraphy of the Khorat Group and the palinspatic
reconstruction of southeast Asia.**

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Abstract: The fossil wood genus *Xenoxylon* is reported in-situ for the first time in the Indosinian terrane, from the Mesozoic continental redbeds of the Phu Kradung Formation (Khorat Group). Palinspatic reconstruction, palaeobiogeography and correlation with other occurrences of the genus, in southern China as well as in Vietnam, suggest a middle Jurassic age for the Phu Kradung Formation level yielding the fossil wood. As the dating of this formation is still controversial, our data is an important step towards a better understanding of southeast Asia Mesozoic continental redbeds geological history, palaeoecology and significance for the evolution of the vertebrates.

Key-words: palaeobiogeography; Indosinian terrane; continental redbeds.

1 Introduction

Continental Mesozoic redbeds are an important feature of southeast Asia geology. The stratigraphy of several of them is still, however, poorly constrained. This is partly due to the uniform sedimentation and the lack of characteristic fossils, most of the up to now documented palaeobiota being stratigraphically uninformative terrestrial organisms. Only if better time-constrained, would the great phylogenetical interest of these Mesozoic terrestrial fauna and flora of southeast Asia be fully exploited. Moreover, a better dating of the southeast Asia redbeds would help to understand their formation, classical scenarii being challenged by the evidences that a *ca* 15° clockwise rotation and *ca* 1700 km southeastward translation occurred, starting from the Early Cretaceous (Carter & Bristow, 2003; Singsoupho et al., 2015).

Fossil wood has demonstrated some potential for the dating of southeast Asia Mesozoic redbeds (Philippe et al., 2004, 2011). One of the fossil woods encountered there, belonging to the genus *Xenoxylon*, is distributed all through the Late Triassic – Late Cretaceous interval in the northern hemisphere (Philippe et al., 2009). It usually occurs north of 45°, but there are some exotic data from continental Mesozoic redbeds in South-East Asia (Boureau 1950, Vozenin-Serra & Privé-Gill, 1991; Boonchai et al., 2017). These *Xenoxylon* occurrences are questioning as the genus is supposedly an indicator of mid- to high palaeolatitudes and cool or wet climates (Philippe et al.,

2013; Oh et al., 2015). Frustratingly none of the above mentioned southeast Asia *Xenoxylon* fossils were found in-situ, except for the Vietnamese data, the age of which has been considered dubious (Boureau, 1950).

Here we report the discovery in Thailand of the first in-situ *Xenoxylon* fossil wood for southeast Asia. The southern China and southeast Asia genus record is compiled from a bibliographical survey, and ages are reconsidered. Use of palinspatic reconstruction allows to replace the data in a palaeobiogeographical framework. The stratigraphical and palaeoecological implications are discussed.

2 Materials and Methods

2.1 Field work

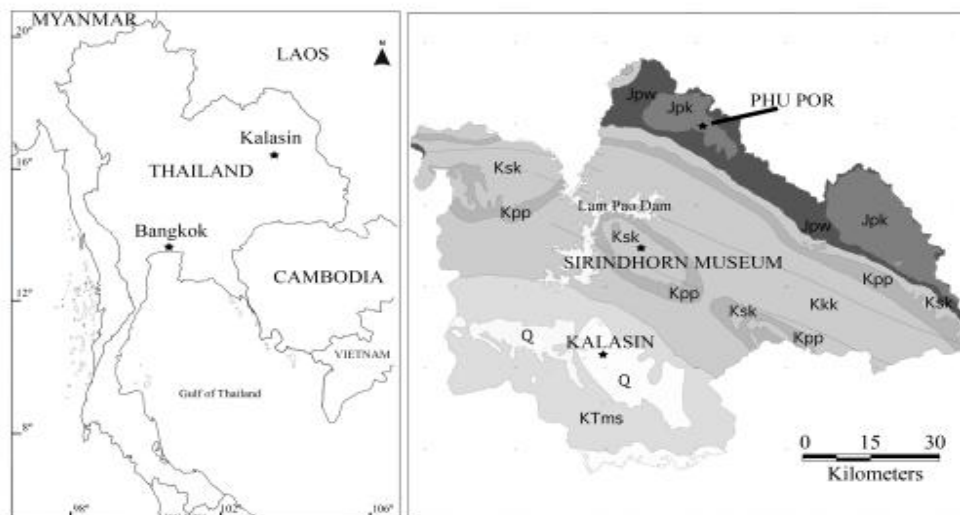


Figure 1a: Location of the Phu Por site in Kalasin Province, Thailand. Abbreviations are for the different formations of the Khorat group: Jpk = Phu Kradung; Jpw = Phra Wihan; Kkk = Khok Kruat; Kpp = Phu Phan; Ksh = Sao Khua (in ascending order). Q is for Quaternary.

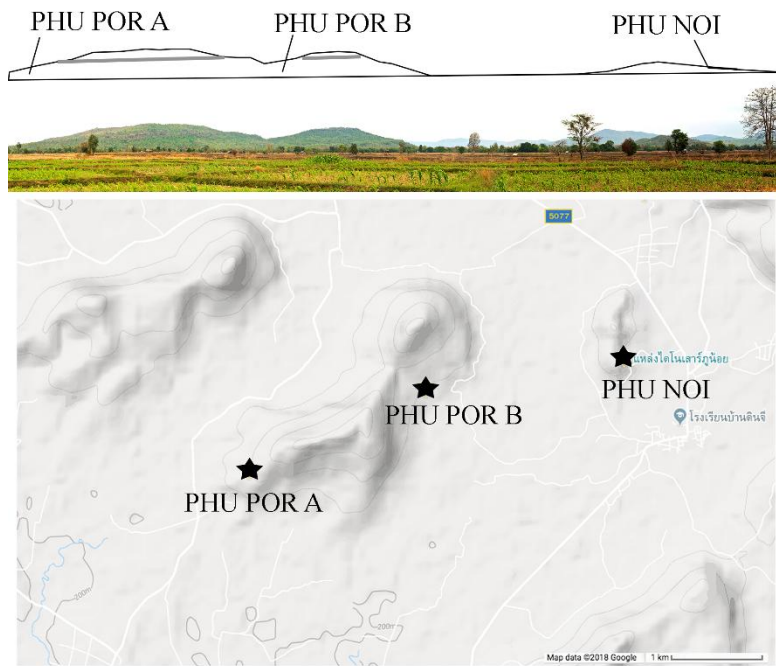


Figure 1b: Correlation between Phu Por and Phu Noi fossil localities. Phu Noi, a prominent dinosaur site, is stratigraphically slightly below Phu Por, and belongs to the same soft beds of the Phu Kradung Formation. The collection sample described in this paper is from “Phu Por site B”, eastern side of the mountain.

Phu Por (Fig. 1a&b ; Phu Phan mountain range, Baan Na Bon area, Kham Muang District , Kalasin Province, Thailand) is an important locality for Mesozoic palaeontology (Cuny et al., 2014). Numerous petrified tree trunks have been found there, weathered out from the sandstone matrix, but still in-situ. There are some large logs, more than 2 m long, as well as smaller fragments found scattered all over the area (Fig. 2), especially at two sites on the two sides of Phu Por Hill, respectively Phu Por A and Phu Por B (Fig. 1b). In 2015 and 2016 a team from the Palaeontological Research and Education Centre (PRC), Mahasarakham University, surveyed the petrified wood sites, raising public awareness in petrified wood conservation with local Baan Na Bon community and collected some wood samples from Phu Por B (16.930326, 103.702724; Fig 1, 2). Phu Por is close to the site of Phu Noi, one of the most famous dinosaur sites, where numerous dinosaur fossils similar to those of Jurassic Chinese dinosaur, *Sinoraptor* and *Mamenchisaurus* were found (Buffetaut et al., 2014; Cuny et al., 2014).



Figure 2: Weathered out silicified logs at Phu Por site B.

Phu Por sites A and B belong to the same level, which overlay the fauna yielding those cropping out in Phu Noi (Fig. 3). The two sites are lithostratigraphically similar and belong to the lower part of the upper Phu Kradung Formation (Cuny et al., 2014). The age of these levels is controversial. Racey & Goodall (2009) propose an Early Cretaceous age for most if not all of the Phu Kradung Formation, based on palynomorphs. However, the Phu Kradung Formation could be at least partly Jurassic in age (Meesok & Sha, 2010). Indeed fauna and microfauna clearly have Jurassic affinities, at least in the zone 3 (Cuny et al., 2014), of the Phu Kradung Formation, which includes the Phu Noi levels as well as the wood-yielding Phu Por B levels.

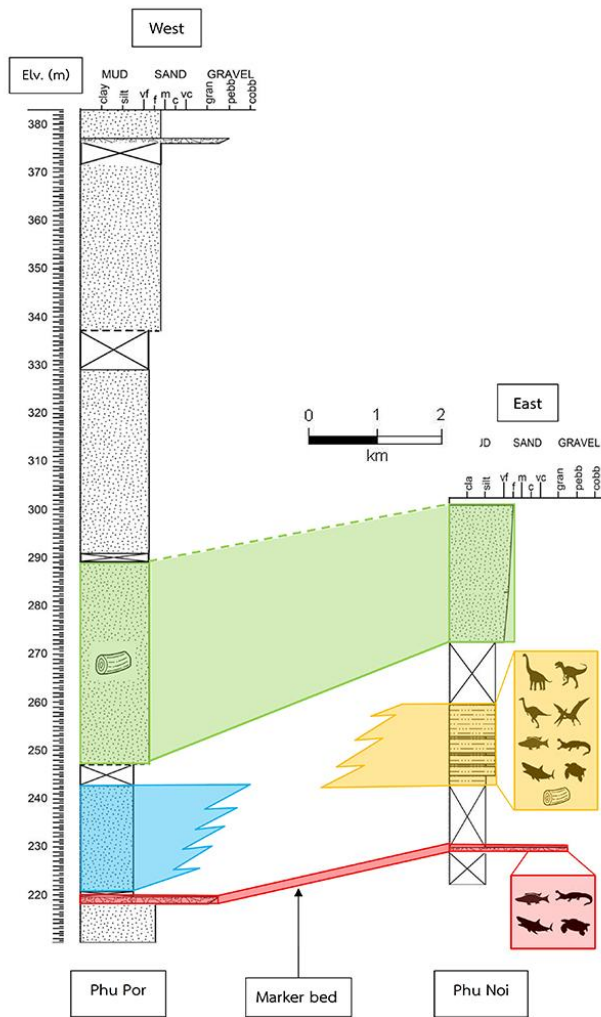


Figure 3: Lithostratigraphical and geometrical relationships of the Phu Por (A and B) and Phu Noi sites. The wood yielding level at Phu Por overlays the famous fauna rich Phu Noi levels. The blank levels, marked with an oblique cross, do not crop out.

2.2 Laboratory

Wood samples were cut and partially prepared at PRC. The thin sections were then prepared at the Université Claude Bernard Lyon 1, France, using standard petrographic ground method, including grinding with silicon carbide powders and mounting on slides with Thermoplastic, before microscopic investigation. Slides were examined with a Leica DN1000 microscope, photographed with a Leica ICC50HD camera, and images managed with Leica Application Suite.

The collected samples are stored in the collection of PRC.

3 Results

3.1 Systematic palaeontology

Two taxa were recognized among our material (Table 1).

Table 1: List of studied samples (Phu Por B locality, Kham Muang District , Kalasin Province, Thailand) and their identification.

| Samples | Identification |
|----------|--------------------------------------|
| PP 15-01 | <i>Brachyoxylon serrae</i> |
| PP-15-02 | Undetermined |
| PP-15-03 | Undetermined |
| PP-15-04 | Undetermined |
| PP-15-05 | <i>Xenoxylon phyllocladoides</i> |
| PP 16-01 | <i>Brachyoxylon serrae</i> |
| PP-16-02 | cf. <i>Brachyoxylon</i> |
| PP-16-03 | <i>Brachyoxylon serrae</i> |
| PP-16-04 | <i>Brachyoxylon serrae</i> |
| PP-16-05 | <i>Brachyoxylon serrae</i> |
| PP-16-06 | <i>Brachyoxylon serrae</i> |

Most samples (6 out of 11) are assigned to *Brachyoxylon serrae* Philippe, Suteethorn & Buffetaut, a taxon already reported several time from the Phu Kradung Formation, both in Thailand and in Laos (Philippe et al., 2011, 2014). Samples PP-15-02, PP-15-03 and PP-15-04 are too poorly preserved to be identified. Only sample PP-15-05 is described below.

Order: Pinales

Family: unknown

Genus: *Xenoxylon* Gothan

Xenoxylon phyllocladoides Gothan, Verh. Russ.-Kais. Mineral. Gesell. 44: 454, fig. 4. 1906.

Type: as the Gothan's type material is lost, a neotype was proposed and illustrated by Philippe et al. (2013). It originates from the Bathonian of Poland.

Description of the material (Figure 4):

A tracheidoxyl with growth-rings. Late wood narrow, sharply differentiated from the early wood, limited to 2-4 layers of radially much flattened tracheids. Axial parenchyma and resin canals not observed. Tangential walls of tracheids unpitted. Rays composed of one type of cell only (homocellular), the marginal cells not to only slightly broader than the inner ones. Rays 1 to 10 cells high (mean = 4.74; SD = 2.7; n = 37). Pitting on the radial walls of the tracheids of the “*phyllocladoides*” type (Philippe et al., 2013), with mostly uniseriate obround contiguous pits. Locally radial pits are in much flattened xenoxylean clusters. Biseriate pits are either opposite or alternate. Sanio’s rims not observed. Early wood cross-field pits single, large, subquadrate to obround unborded oopores, late wood cross-field pits quadrate oopores.

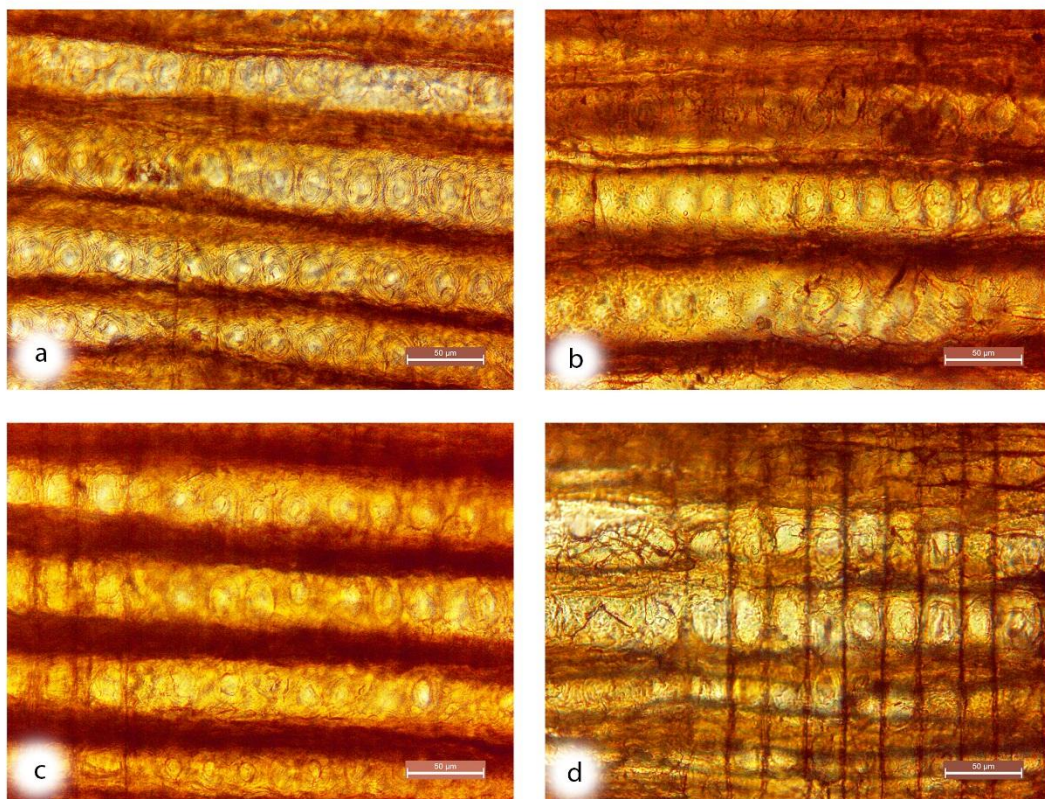


Figure: 4: All views from sample PP-15-05, kept in PRC collection, Thailand; all views from radial section; a) uniseriate mixed type of radial pitting, pits elliptic to obround; b) xenoxylean pitting, with much wider than high pits on the radial wall of tracheids; c) mixed type of radial pitting, including some xenoxylean pits and spaced

pits, and a ray with large fenestriform oopores, early wood; d) *Xenoxylon* typical cross-field pitting in the early wood.

Identification:

Co-occurrence of xenoxylean radial pitting, *phyllocladoides* type of radial pitting and large fenestriform oopores in cross-field is typical for *Xenoxylon phyllocladoides* (Philippe et al., 2013). Here cross-fields are never as radially elongated as for *Xenoxylon huttonianum* (Witham) Philippe & Hayes. The lack of axial parenchyma and radial pitting features discard *Xenoxylon hopeiense* Chang

3.2 Occurrences of *Xenoxylon* in SE Asia (South of 30°N, modern latitude), a survey

The genus was first quoted for southeast-Asia by Boureau (1950). This occurrence is based on two samples which were collected on the ground, weathered from the rock of the “Série de Tho-Lam”, apparently not reworked in alluvial deposits, close to Nong-Son coal mine, south-west of “Tourane” in Quang-Nam Province (Vietnam, Boureau, 1950). The coal mine is still active at this location, Quế Trung commune, Quế Sơn district, Quảng Nam province (15.716308, 108.0310147). Stratigraphically the samples originate from redbeds overlying marine levels with ammonites dated as Hettangian. According to Khuc et al. (2005) this wood level belongs to the Ban Co Fm, which they date as Middle Jurassic. However, these redbeds are now considered as an independent unit of the Tho Lam Gr., namely the Huu Chanh Fm (Thanh & Khuc, 2011). The Huu Chanh Fm. conformably overlays the ca. 150 m thick Khe Ren Fm, the basis of which contains ammonites dated as Sinemurian - Toarcian (Khuc & Cariou 1998; Meister et al., 2000; Thanh & Khuc, 2011). The upper boundary of the ca. 500 m thick Huu Chanh Fm is unknown, and fossil woods are within the upper part. North of the Nong Son basin the Bai Dinh Fm was recently described (Thanh & Khuc, 2011), where similarly marine sediments grade into red beds, yielding a Jurassic palynoflora. On the basis of its stratigraphic relationships the Huu Chunh Fm is assigned to the Middle-Jurassic.

Later on, the genus *Xenoxylon* was repeatedly reported from Mekong alluvial deposits (Vozenin-Serra & Privé-Gill, 1991; Boonchai et al., 2017), always south of Vientiane (Laos). Although these samples were not in-situ, the relatively high

occurrence hints to a sub-local source, not yet determined, from within the Khorat group.

More recently the genus *Xenoxylon* was documented from China southern provinces of Yunnan and Henan (Miao et al., 1989; Liu et al., 2001; Feng et al., 2015). There are also some occurrences from the Late Triassic of Southern China (see Tian et al., 2016), which are not discussed here. In Henan, the *Xenoxylon* wood reported by Miao et al. (1989) comes from the Yima coal mine. These levels are assigned to the Yima formation, with *Coniopteris* and *Phoenicopsis*, an assemblage which is considered typical for Middle Jurassic strata, possibly Bajocian to early Bathonian (Kang, 1988; Zhou & Zhang, 1989). Pollen assemblages also suggest a middle Jurassic age for the Yima coal (Zhang, 1965). More recent work suggests that part of the Yima coal might be partly Late Jurassic in age (Zeng et al., 1995). Until now no palaeontological data allows to safely put aside that at least part of the Yima coal could be Callovian in age.

In Yunnan, Liu et al. (2001) found *Xenoxylon* in the Lanping – Shimao Basin, drained by the Bijang River, a tributary of the Mekong. The geological level is a copper-ore known as the Jinman copper layer, belonging to the upper part of the Huakaizuo Formation (Ji & Li, 1998; Liu et al., 2002). This copper layer is supposedly late Mid-Jurassic in age (Wang & Lu, 1991), and metallogenesis took place later, during the Tertiary (Liu et al., 2001 ; Feng et al., 2015). More recent investigations suggested an early Late Jurassic age (Zhang et al., 2012).

The other Yunnan *Xenoxylon* wood is from Laobaiyan, in Huize county (Feng et al., 2015). It originates from the middle part of the lower unit of the Shaximiao Fm. (this lower unit being sometimes known as the Xiashaximiao Fm.), which is lithostratigraphically assigned to the Middle Jurassic (Liu et al., 2001). A Bajocian to Bathonian age was assigned to the upper unit of the Shaximiao Fm. by Li et al. (2011) but later Lu et al. (2015) bracketed the Shaximiao Fm between 175 and 156 My. On the basis of zircon Wang et al. (2018) dated the Xiashaximiao Fm. at 159 ± 2 Ma, thus a younger age than previously proposed. Hence it is probably wise to remain cautious and to assign a broad late Middle Jurassic – early Late Jurassic age for this *Xenoxylon* data.

4 Discussion

4.1 Palinspatic reconstruction

Indochina accreted to southern China at the end of the Triassic (Faure et al., 2014). Post Rhaetian data of *Xenoxylon* for southeast Asia and southern China are plotted on a modern map (Figure 5A). Then, Indosinian plate is graphically translated 1700 km northwestward along the Ailao Shan – Red River fault system and rotated 15° anti-clockwise (Singsoupho et al., 2015), in order to reconstruct what could have been the mid-Cretaceous palaeogeography Figure 5B).

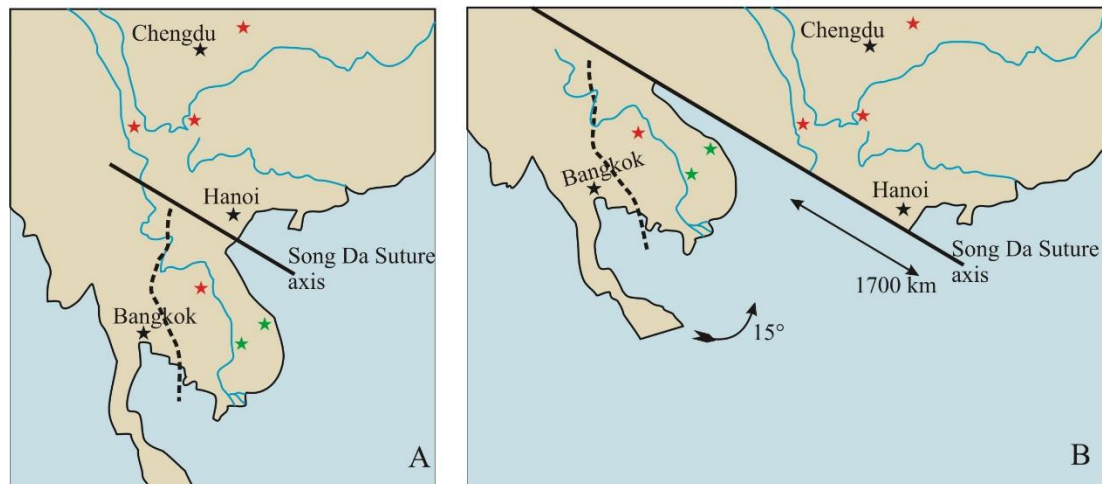


Figure 5: *Xenoxylon* record in South-China and Southeast Asia; red stars for in-situ samples, green stars for data based on reworked samples. A on a modern geographical background. B on a palinspatic reconstruction for the Jurassic based on Singsoupho et al. (2015) results. Our reconstruction considers Sibumasu terrane (west of the dotted line) as already accreted, which is still partly controversial.

On figure 5A *Xenoxylon* occurrences have a meridian distribution, a rare case for a plant species, however on figure 5B they have a more classical distribution, as a latitudinal belt. This belt was located, according to Charusiri et al. (1997) or Metcalfe (2013), at 20°N (palaeolatitude), however, other reconstructions put the Khorat Basin center of gravity during the Mid-Jurassic at 23.8°N or even 25°N (Singsoupho et al., 2015; Carter and Bristow, 2003). Ziegler et al. (1996) position the Sichuan basin at 37°N during the Late Jurassic. In Europe at that time the genus *Xenoxylon* was documented from 33°N to 70°N (Philippe et al., 2017).

4.2 Stratigraphic implications

The palaeobiogeographical reconstruction evidences suggest therefore that, instead of being scattered over southeastern Asia without a clear logic, *Xenoxylon* occurrences are concentrated in a large basin, dominated by fluvial and lacustrine silicoclastic sedimentation during most of the Mesozoic, including Sichuan basin and Khorat basin. In these two basins *Xenoxylon* is a rare find. It is thus tempting to consider that all the corresponding occurrences are coeval. If a mid-Jurassic to early Late-Jurassic age is admitted for the Vietnamese and the Chinese occurrences (Table 2), then the Thai data is probably of the same age.

Table 2: Age of the different *Xenoxylon* data in southeast Asia and southern China

| | Vietnam | Henan | Yunnan 1 | Yunnan 2 |
|-----------|---------------|--|---|--|
| reference | Boureau, 1950 | Miao et al., 1989 | Liu et al., 2001 | Feng et al., 2015 |
| Age | Mid Jurassic | Mid Jurassic, possibly early Late Jurassic | latest Mid Jurassic or earliest Late Jurassic | Late Mid Jurassic to early Late Jurassic |

It is worth noting that a number of *Xenoxylon* occurrences are reported from the Tethys northern margin: Afghanistan (Sitholey, 1940); Iran (Nadjafi in Philippe & Thévenard, 1996); Georgia (Delle, 1960). To all these data, often associated to coal deposits (Vaez-Javadi, 2018), are assigned a Middle Jurassic age. Northward, in Asia as in Europe, *Xenoxylon* is known through all the Jurassic (Philippe et al., 2009). Worldwide, *Xenoxylon* is found south of 45°N (palaeolatitude) associated to *Brachyoxylon*, as here in Thailand, only during the Bathonian – Early Oxfordian interval (Oh et al., 2015).

During the Mesozoic Western Europe and Eastern Asia had very different palaeogeographies. While the former was a low-lying archipelago for most of the time interval, Eastern Asia was much more continental, with several high mountain ranges (for a reconstruction see Philippe et al., 2014). Keeping this limitation in mind, it is now well established that in Europe, during the Jurassic, the southern limit of *Xenoxylon* range oscillated much (Figure 6; Philippe et al., 2017).

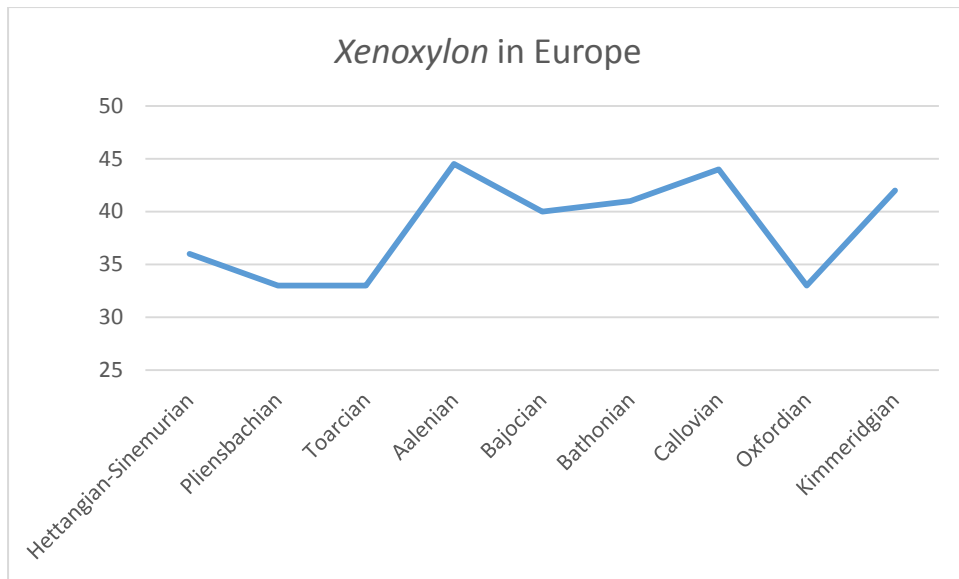


Figure 6: Palaeolatitude of the southernmost limit of the *Xenoxylon* range in Europe during the Jurassic; data from Philippe et al. (2017).

These oscillations were probably under global climate determinism and, although Asian palaeogeography was different, surely also impacted Asian *Xenoxylon* distribution. For the Jurassic of Europe, it is in the Late Pliensbachian and early Oxfordian that *Xenoxylon* reached his southernmost limit. It is thus possible that the southern Asia *Xenoxylon* data could be dated as Oxfordian. Although it might seem somewhat contradictory with the dates given in Table 2, it is much more parcimonious than to suppose a Liassic age.

The genus *Xenoxylon* is well distributed in the Jurassic of China, north of Qinling-Dabie range (Philippe et al., 2009; Oh et al., 2015). A cooling or wetting event might have temporarily extended southward the southern limit of this genus, from its northern strongholds, through the Qilian-Qinling Orogenic Belt (Bao et al., 2014) and down to the Khorat basin.

The Callovo-Oxfordian cooling event identified in Europe (Dromart et al., 2003), and which is recorded by *Xenoxylon* there (Figure 6), is a good candidate for the climatic oscillation which drove *Xenoxylon* as south as Thailand, Laos and Vietnam. Zeng et al. (1998) hypothesized, on the basis of three palynoflora from Yima coal mine, that the timing of climatic oscillations might have been different in southern China as compared to Siberia or Europe, with a mid-Jurassic warming starting earlier. It does not, however, dismiss the possibility of synchronous cold snaps later on, e.g. at the end of the Middle Jurassic.

In addition, the shark fauna recovered from Phu Noi also points to a middle Jurassic age. The unusual shark dermal denticles from this site were indeed until then only known from the Khlong Min Formation in southern Thailand, which was dated as Bathonian-Callovian in age (Cuny et al., 2009; Cuny et al., 2014) whereas *Jiaodontus*, another hybodont recovered at Phu Noi, was so far restricted to the Oxfordian of northwestern China (Klug et al., 2010). The presence of these two taxa supports therefore the Callovo-Oxfordian age suggested by the presence of *Xenoxylon* in the overlying beds. The rest of the Phu Noi shark fauna, being composed of stratigraphically long-ranging taxa, cannot help to more precisely discuss the age of the site (Cuny et al., 2014).

4.3 Red beds palaeoecological interpretation

Thai redbeds are usually interpreted as deposited under uniform hot and dry climates (Horiuchi et al., 2012). This was questioned, however, by Jiang et al. (2015) and it might be possible that at least part of these redbeds deposited under wetter and cooler climate than the usually supposed one.

The huge amount of large silicified logs, with large growth-rings, encountered in some parts of the Khorat groups, is hardly compatible with a dry and hot climate.

After Philippe and Thévenard seminal study (1996), several contributions confirmed that the wood genus *Xenoxylon* is bound to moist setting, with not limiting water availability (Philippe et al., 2009, 2013; Jeong et al., 2014; Oh et al., 2015; Tian et al., 2016; Tramoy et al., 2016).

From the Phu Kradung Formation of the Khorat group, *Shimakuroxylon*, another palaeobiogeographically significant genus, was reported (Philippe et al., 2014). This genus is endemic to a zone bearing a southern type of flora. There is no safe Jurassic data for *Shimakuroxylon*. In the Upper Jurassic of Japan, however, *Xenoxylon* and *Shimakuroxylon* are never encountered together, but associated to very different leaf flora types, namely the Ryoseki vs. Tetori types (Kimura, 1987). Whereas *Xenoxylon* points out a wet and possibly cool climate, *Shimakuroxylon* was associated to warm tropophilous climate.

The apparent lithological uniformity of Khorat Group redbeds thus possibly hides different palaeoecological setting for its deposition. This seems to support Jiang et al.'s hypothesis according to which several of the lithological features of this formation could possibly be determined by post-deposit events.

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Captions

Figure 1a: Location of the Phu Por site in Kalasin Province, Thailand. Abbreviations are for the different formations of the Khorat group: Jpk = Phu Kradung; Jpw = Phra Wihan; Kkk = Khok Kruat; Kpp = Phu Phan; Ksh = Sao Khua (in ascending order). Q is for Quaternary.

Figure 1b: Correlation between Phu Por and Phu Noi fossil localities. Phu Noi, a prominent dinosaur site, is stratigraphically slightly below Phu Por, and belongs to the same soft beds of the Phu Kradung Formation. The collection sample described in this paper is from “Phu Por site B”, eastern side of the mountain.

Figure 2: Weathered out silicified logs at Phu Por site B.

Figure 3: Lithostratigraphical and geometrical relationships of the Phu Por (A and B) and Phu Noi sites. The wood yielding level at Phu Por overlays the famous fauna rich Phu Noi levels. The blank levels, marked with an oblique cross, do not crop out.

Figure 4: All views from sample PP-15-05, kept in PRC collection, Thailand; all views from radial section; a) uniseriate mixed type of radial pitting, pits elliptic to obround; b) xenoxylean pitting, with much wider than high pits on the radial wall of tracheids; c) mixed type of radial pitting, including some xenoxylean pits and spaced pits, and a ray with large fenestriiform oopores, early wood; d) *Xenoxylon* typical cross-field pitting in the early wood.

Figure 5: *Xenoxylon* record in South-China and Southeast Asia; red stars for in-situ samples, green stars for data based on reworked samples. A on a modern geographical

background. B on a palinspatic reconstruction for the Jurassic based on Singsoupho et al. (2015) results. Our reconstruction considers Sibumasu terrane (west of the dotted line) as already accreted, which is still partly controversial.

Figure 6: Palaeolatitude of the southernmost limit of the *Xenoxylon* range in Europe during the Jurassic; data from Philippe et al. (2017).

Table 1: List of studied samples (Phu Por B locality, Kham Muang District , Kalasin Province, Thailand) and their identification.

Table 2: Age of the different *Xenoxylon* data in southeast Asia and southern China

Figure 1a
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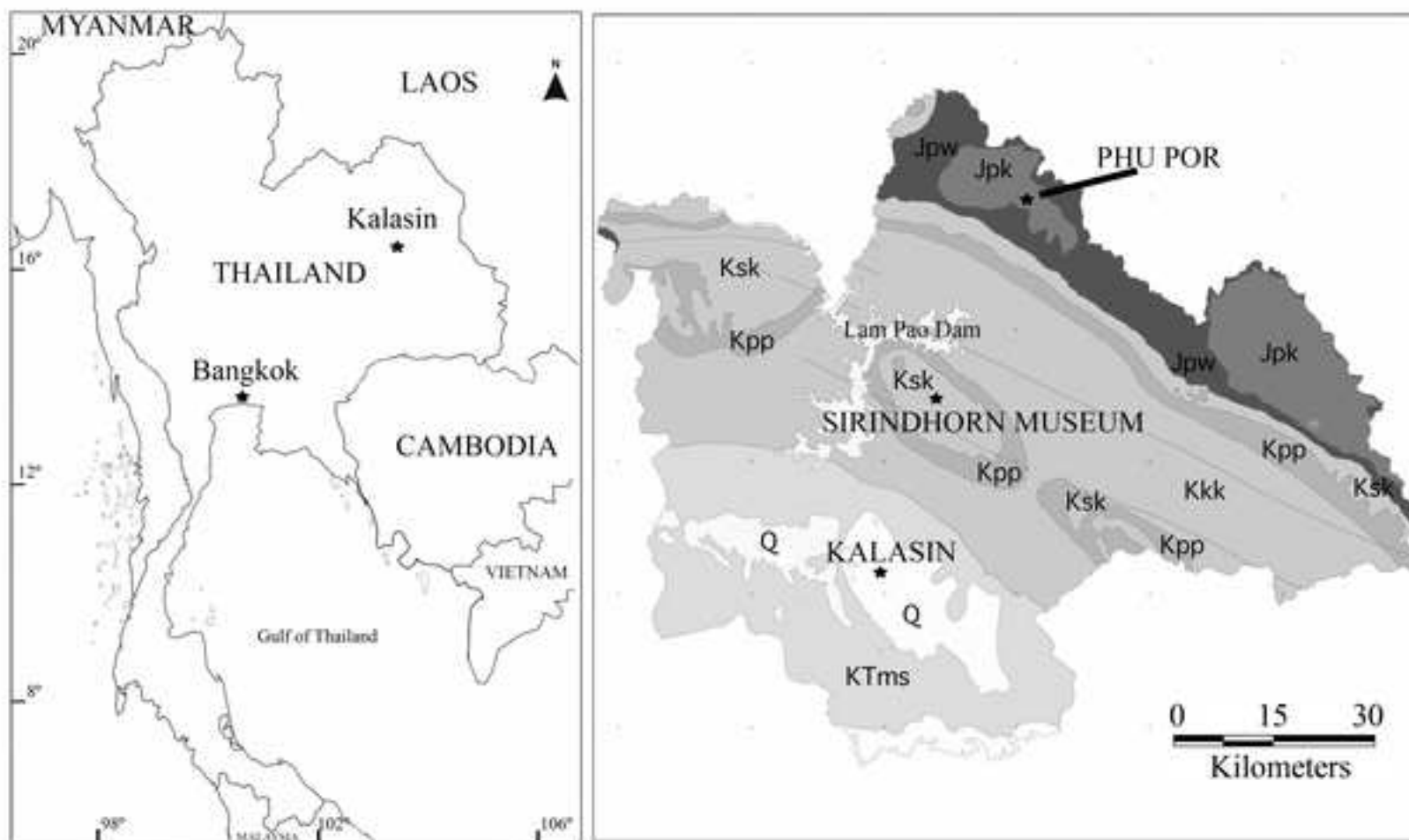


Figure 1b
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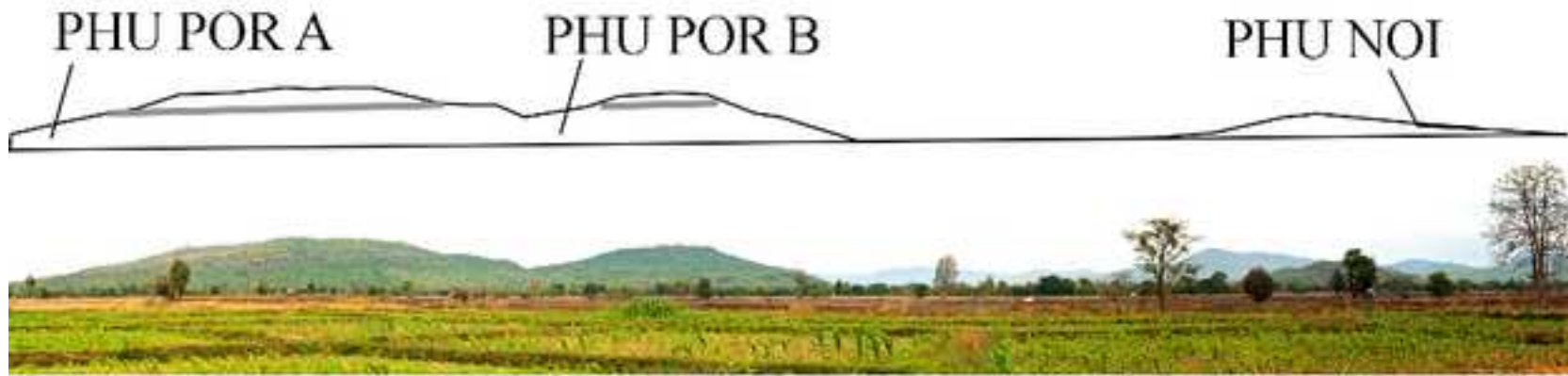


Figure 2
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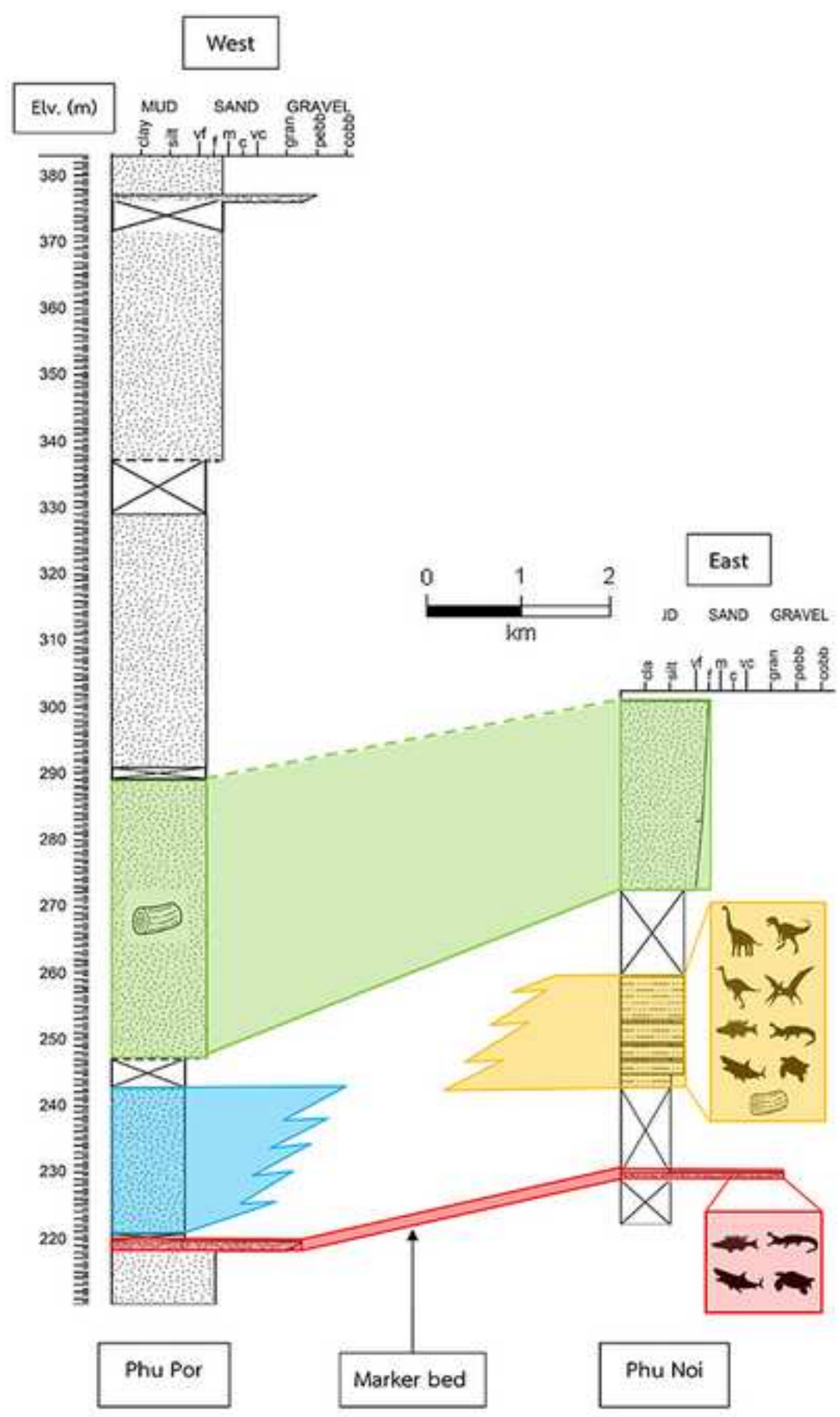


Figure 4
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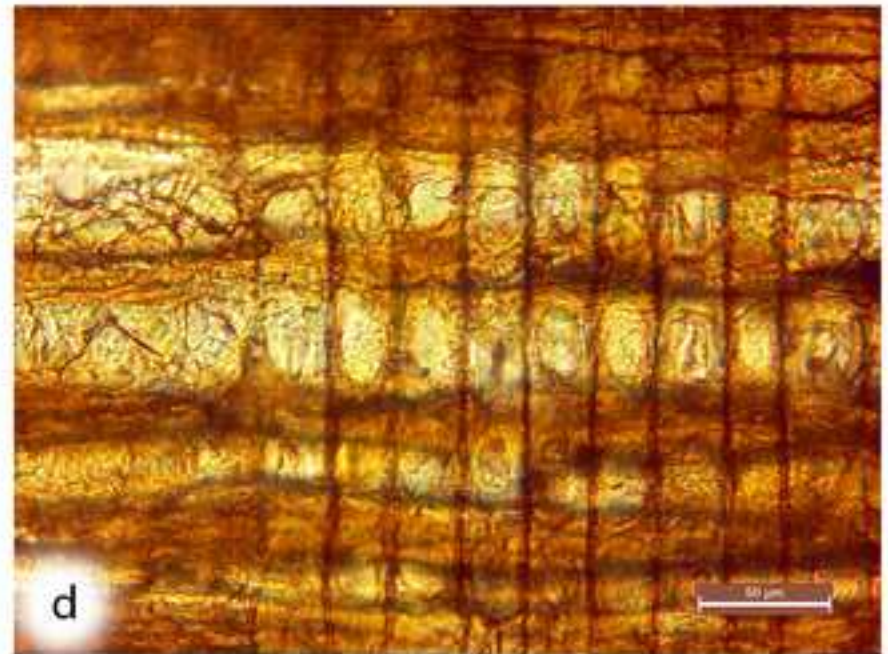
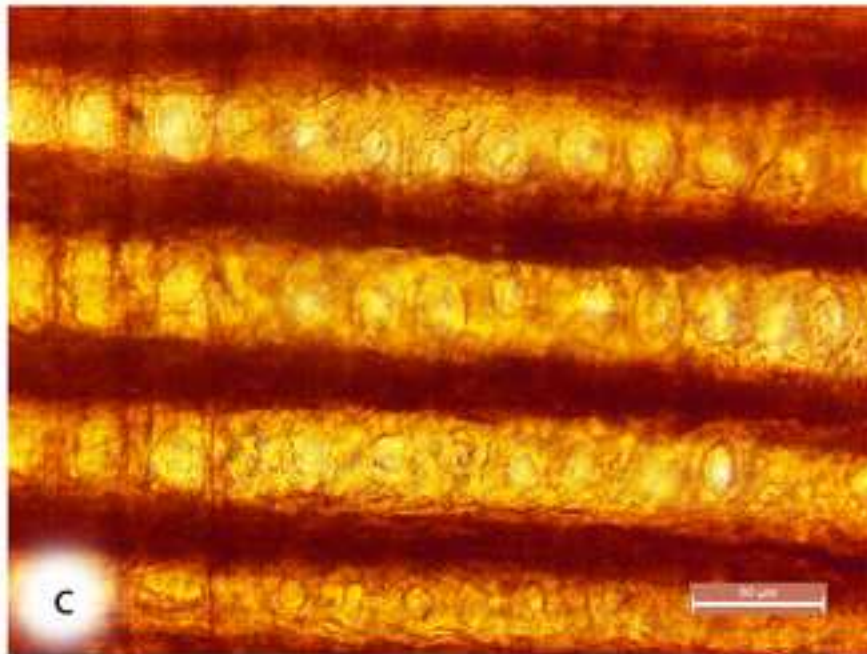
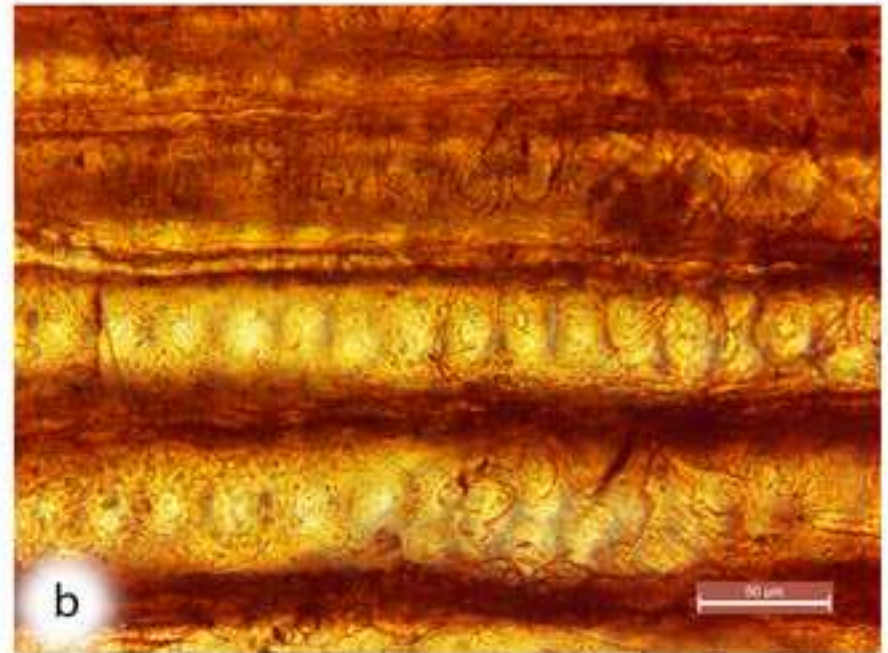
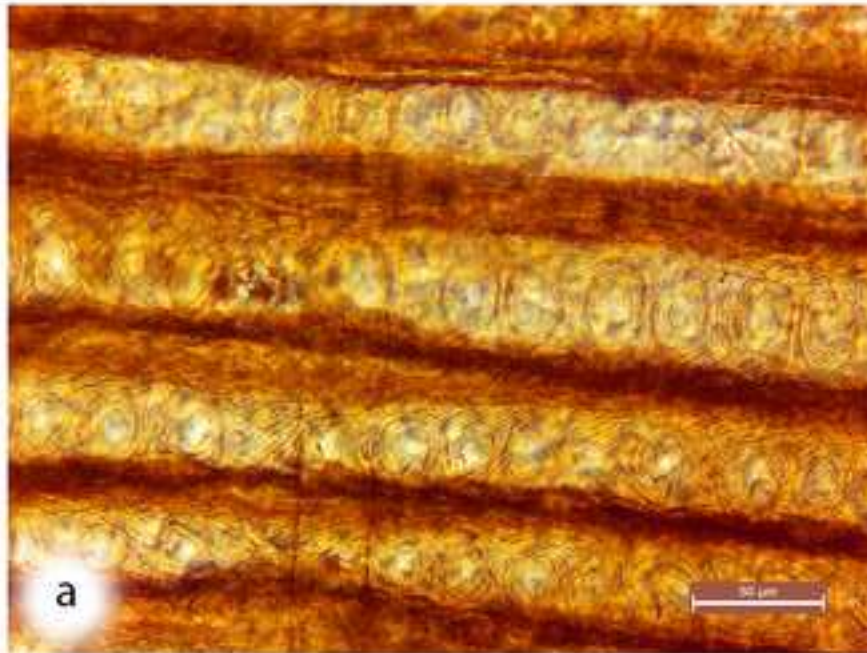


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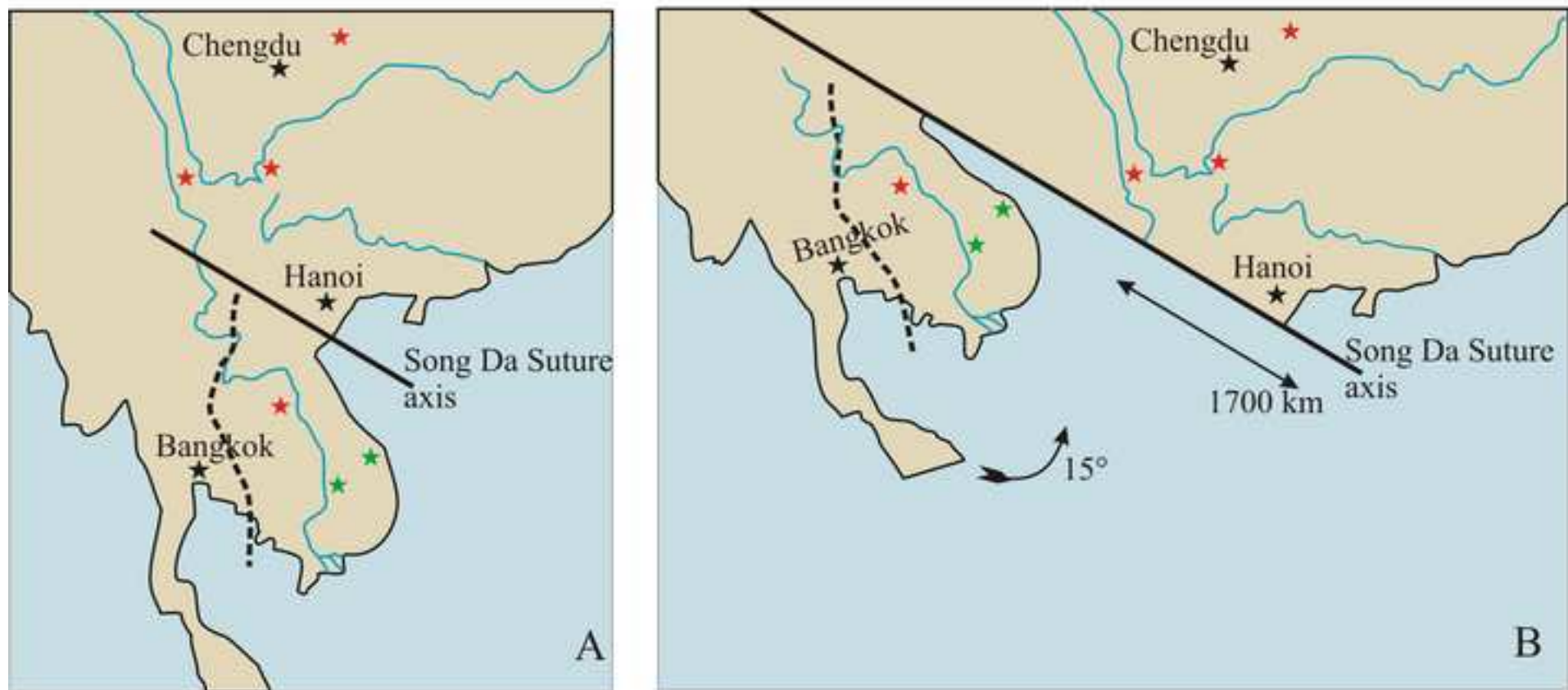


Figure 6
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