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# Stratigraphical and palaeobiogeographical significance of fossil wood from the Mesozoic Khorat Group of Thailand

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**Abstract** – Fossil wood from the poorly dated (Jurassic–Cretaceous?) continental sediments of the Khorat Group, northeastern Thailand (Isan) is described. The Khorat Group is widely distributed (Laos, Cambodia and Thailand) and, despite its poorly known age, stratigraphy and palaeoecology, is of importance in understanding the Sibumasu–Indochina collision. The systematics of wood assemblage and palaeobiogeographical analysis reveal strong relationships with Indochina, especially Vietnam, and suggest an age in the range Middle Jurassic to Early Cretaceous. According to wood taphonomy, the corresponding trees grew alongside streams under a rather arid climate, although this became wetter during the deposition of the upper formations of the Khorat Group.

Keywords: Jurassic, Cretaceous, Thailand, fossil wood, palaeobiogeography.

## 1. Introduction

The Khorat Group is a set of continental sediments deposited during Mesozoic times in northeastern Thailand (and parts of adjacent Laos and Cambodia). The deposition of this thick terrestrial succession occurred after the collision of the Sibumasu terrane with the Indochina block (Bunopas, 1982; Metcalfe, 1996; Charusiri, Kosuwan & Imsamut, 1997; Racey *et al*. 1997; Spiller, 2002). As clearly shown by the abundant literature (Iwai *et al*. 1966, 1975; Hahn, 1976, 1982; Heggemann, Kohring & Schlutert, 1990; Racey, Duddy & Love, 1997; Racey *et al*. 1994, 1996; Metcalfe, 1998), the stratigraphy and palaeoecology of the different formations of the Khorat Group is still poorly known. Data about the palaeogeographical evolution and biogeography of the area are, however, highly desirable, as Southeast Asia is a key region for Mesozoic palaeobiogeography. The biogeographical importance of this region has been demonstrated, as for the evolution of various groups of Cretaceous dinosaurs (such as tyrannosaurid, ornithomimosaurid theropods and nemegtosaurid sauropods: Buffetaut & Suteethorn, 1998, 1999), hybodont sharks (at least seven genera, showing affinities with those of Japan, Tibet, Kirghisia and Mongolia but unknown outside Asia: Cuny *et al*. 2001) as well as conifers such as the Araucariaceae and the Podocarpaceae (Vozenin-Serra & Boureau, 1978; Vozenin-Serra, 1983). Moreover, the area may yield an answer to the disputed question of biogeographical relationships and exchanges of terrestrial taxa across the Eastern Tethys during the Jurassic and Cretaceous periods (Vozenin-Serra, 1977; Vozenin-Serra & Salard-Chelbodaeff, 1994; Franchesci & Vozenin-Serra, 1997; Yin Hongfu, 1997; Philippe *et al*. 1999). Finally, the timing of the Sibumasu–Indochina collision is still a matter of debate, and the Triassic model (Metcalfe, 1996) is challenged (Stokes, Lovatt Smith & Soumphonphakdy, 1997). Biogeographical and stratigraphical inferences from terrestrial biota are relevant to the discussion of these points (Tong, Buffetaut & Suteethorn, 2002).

Fossil wood has been commonly reported from the Khorat Group for quite a long time (Högbom, 1913; Colani, 1919), but has been little studied up to now, with only one genus recognized, namely *Araucarioxylon* (Kobayashi, 1960; Asama, 1982). More emphasis has been put on fossil leaf flora (Iwai *et al*. 1966; Kon'no & Asama, 1973), despite these being poorly preserved. Fossil wood is, however, a reliable and informative record of terrestrial biota. As a result of renewed prospecting and field collecting, we have examined hundreds of fossil wood specimens, distributed through the Khorat Group. Fifty-six determinations have been

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Figure 1. Indochina Peninsula with principal outcrop of the Khorat Group (shaded area).

| AGE | | | GROUP | FORMATION |
|---|---|---|---|---|
| Cretaceous | Early | Aptian | KHORAT | Khok Kruat |
| | | Barremian to Aptian | | Phu Phan |
| | | | | Sao Khua |
| | | ? Late Jurassic to Barremian | | Phra Wihan |
| | | | | Waritchaphum |
| Jurassic | Late | | | Phu Kradung |

Figure 2. Stratigraphy of the Khorat Group, northeastern Thailand (adapted from Lovatt Smith & Stokes, 1997, and Mouret, 1994).

performed. We report here these preliminary results and analyse their stratigraphical and biogeographical significance.

## 2. Material

Fossil wood was collected all over the Khorat Plateau, also known as Isan (Fig. 1), in the vicinity of Udon Thani (17°02′ N, 12°45′ E), in Kao Yai National Park (14°31′ N, 102°06′ E) and in the Phu Phan Range (16°31′ N, 104°18′ E; 16°22′ N, 104°23′ E; 17°30′ N, 102°50′ E; 16°20′ N, 103°55′ E; 16°16′ N, 104°05′ E; 16°38′ N, 103°52′ E; 16°41′ N, 104°09′ E; 16°24′ N, 104°21′ E). As the better outcrops for the Khorat Group are in the Phu Phan Range, we focused on this area, mainly in the Khao Wong and Tat Phut Wong anticlines. We attempted to obtain fossil wood from all the different formations (Fig. 2), but failed to obtain any samples from the two upper formations (Khok Kruat and Phu Phan) and from the base of the Phu Kradung Formation. Following Mouret's proposal (1994), in this paper we recognize the Waritchaphum Formation. This formation accommodates the pale sandstones formerly included in the upper part of the Phu Kradung Formation. Interestingly, this formation yielded jet, thermally evolved lignite and wood epigenized by iron hydroxides, whereas the underlying reddish sandstones of the Phu Kradung Formation contain only silicified woods and few lignitic ones.

Despite the fact that fossil wood is common in the Khorat Group, pieces with preserved anatomy are rather scarce. Of the approximately three hundred specimens examined, sixty-one were selected, of which fifty-six could be determined. The wood is either silicified or lignitized, and no charcoal was recognized with certainty. Lignite pieces are dark in colour, with a glossy shine, which indicates that they underwent some thermal evolution (the same was noted for palynomorphs: Mouret *et al*. 1993). Large samples of jet have been found, especially at the transition from Waritchaphum to Phra Wihan formations. The fossil wood occurs in pieces ranging in size from twigs and branchlets to large trunks over a metre in diameter and even stumps.

The techniques used for investigation are the classical thin-section technique for silicified wood and SEM for lignitic and haematized samples. Parlodion® (purified pyroxylin) casts were also used for some lignite. SEM was performed at the CMEABG of Université-Lyon-1, France, with a Geol-35-CF under 10 kV accelerating voltage and with gold/palladium coating.

Nomenclatural and taxonomical positions are those of Philippe (1993) and Bamford & Philippe (2001). All samples are kept in the collection of the Laboratoire de Paléobotanique of University Lyon-1, the original logs still being *in situ* in Thailand. Bibliographical data are very few. Previously, wood had only been identified from the Phu Kradung Formation: *Araucarioxylon* sp. was identified by Ogura (Kobayashi, 1960), Ban Kut Bot, Phu Phan Range; in 1982, Asama identified silicified wood from the same locality as *Araucarioxylon japonicum* Shimakura; a large fossil trunk from Phu Tang Kwian was later assigned to *Araucarioxylon* sp. without thin-sections (Srisuk, pers. comm. 2000).

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Table 1. Wood taxa recognized for the Khorat Group

| | Phu Kradung | Waritchaphum | Phra Wihan | Sao Khua |
|---|---|---|---|---|
| *Agathoxylon saravanensis* | 14 | 6 | 3 | 1 |
| *Brachyoxylon boureauii* | 4 | 0 | 0 | 0 |
| *Brachyoxylon orientale* | 15 | 0 | 0 | 0 |
| *Brachyoxylon sp. nov.* | 4 | 4 | 0 | 0 |
| Indeterminable | 3 | 1 | 1 | 1 |
| Total analysed | 40 | 10 | 4 | 2 |

Number of samples of conifer fossil wood analysed and determinations for each formation of the Khorat Group. No data from Phu Phan and Khok Kruat formations.

A composite trunk, constructed from different wood pieces from the Upper Phu Kradung Formation, on display at the Phu Faek footprint site, is labelled 'Podocarpaceae' by park rangers.

## 3. Results

The xylological results are summarized in Table 1. Four wood morphospecies were recognized (Fig. 3). They show little differentiation, and it was often difficult to attribute a wood to a taxon, in particular when radial pitting is poorly preserved. Several samples were thus not determined. It was necessary to observe at least 20–30 tracheids with preserved uniseriate pitting, 10–20 tracheids with biseriate pitting, as well as 10–20 cross-fields, to decipher the affinities of a wood sample. This similarity is unusual and raises the question of the possible conspecificity of these four taxa. We did not observe any intermediate, however, providing enough pitting was preserved.

*Agathoxylon saravanensis* (Serra) nov. comb.

1966*b* *Araucarioxylon saravanensis* Serra, pp. 22–8, figs 5–10, pl. II.

Samples attributed to this taxon: MP1223, 1224, 1233, 1234, 1236, 1238, 1241, 1242, 1252, 1253, 1254, 1255, 1279, 1282 (Phu Kradung Fm.); MP1219, 1220, 1269, 1270, 1278, 1301 (Waritchaphum Fm.); MP388, 1272, 1274 (Phra Wihan Fm.); MP1275 (Sao Khua Fm.).

This tracheidoxyl does not have particularly striking features. Uniseriate radial pitting is composed of long chains of slightly compressed to rounded pits, with rare short spaces in between pits. While biseriate, the pits either build two longitudinal chains which are not contiguous, or a more classical row of alternating compressed pits. Oculipores are few, rarely more than six, and usually included in an elliptic border. Thai woods fit well with the Lao material described as *Araucarioxylon saravanensis*. *Araucarioxylon* is, however, an invalid generic name (Philippe, 1993), and according to its xylological features this taxon is referred to the genus *Agathoxylon*. Some of the samples are similar to the *Araucarioxylon* sp. described by Vozenin-Serra & Privé-Gill (1989) from a Plio-Pleistocene fluvial deposit of southern Isan, suggesting that this later wood may have been reworked from the Khorat Group.

*Brachyoxylon boureauii* Serra

1966*a* *Brachyoxylon boureaui* Serra, pp. 77–86, text-figs 20–9, pls V–VIII.

Samples attributed to this taxon: MP1240, 1249, 1250, 1251, all from the Phu Kradung Formation.

This taxon's most striking feature is the number (up to 37 per field) and small size of its oculipores. The radial pitting is mostly uniseriate, with pits in long continuous chains of slightly compressed pits, sometimes biseriate and then sub-opposite to clearly alternate. The biseriate pit pairs are never exactly opposite, although some poorly preserved pairs may look so. The uniseriate radial pits never display the strong compression found in *Brachyoxylon orientale* (Serra) nov. comb. A taxon with these features, *Brachyoxylon boureauii*, has already been described from the base of the 'Grès Supérieurs' in Cambodia.

*Brachyoxylon orientale* (Serra) nov. comb.

1969 *Protopodocarpoxylon orientale* Serra, pp. 7–11, text-figs 1–9, pls VII–IX.

1969 *Protopodocarpoxylon paraorientale* Serra, pp. 11–13, pls X, XI.

1982 *Araucarioxylon japonicum* Shimakura, in Asama, pp. 61–3, pl. XI, figs 1–10.

1990 *Protopodocarpoxylon orientale* Serra, in Vozenin-Serra & Pons, p. 117, pl. V, figs 4–6; pl. VI, fig. 1.

Samples attributed to this taxon: MP1225, 1226, 1227, 1229, 1230, 1231, 1235, 1239, 1243, 1244, 1263, 1264, 1265, 1280, 1283 (Phu Kradung Fm.).

This is perhaps the most difficult taxon to recognize among these Thai woods. Radial pitting is very variable. Uniseriate radial pits are generally contiguous, either round, compressed, or even strongly flattened (as illustrated by Serra, 1969, text-fig. 3). Spaces in between pits are rare. Biseriate pitting is common, with opposite pairs, sub-opposite pairs, or, much more rarely, alternate rows. Uniseriate pits as well as biseriate pairs, when opposite, can be included in a rim that

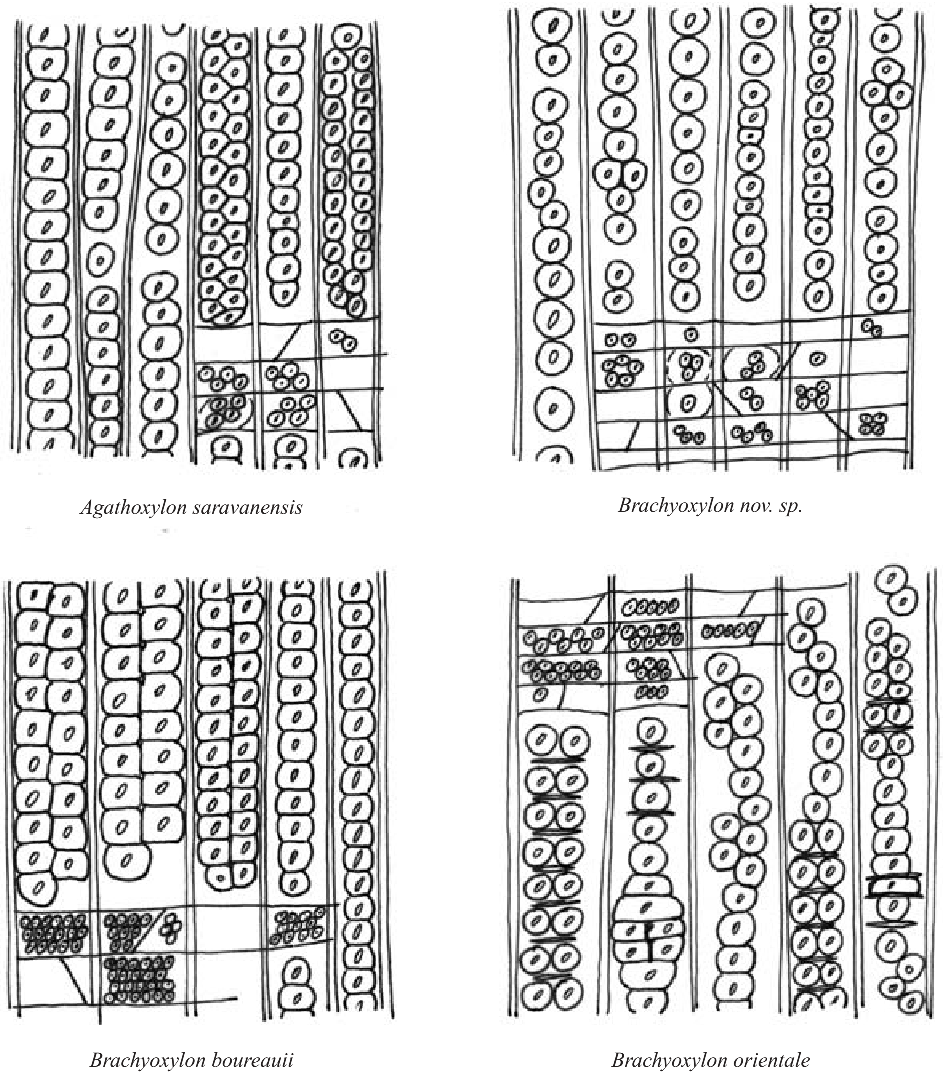


Figure 3. Synthetic radial view of the encountered wood taxa.

mimics Sanio's bar. Radial pitting is often podocarpoid, that is, with pits jutting out from the others, oblique contact in between two contiguous pits, and short clusters of lop-sided uniseriate pits among rows of biseriate ones. Oculipores are more numerous than in *Agathoxylon saravanensis* (Serra) nov. comb. which otherwise is quite similar to this taxon. The cross-fields regularly display a typical pattern of bright but low fields with 2(3) rows of 4–5 oculipores (as illustrated by Serra, 1969, pl. VII, fig. 7). We agree with Vozenin-Serra & Pons (1990) that the samples from East Shandong (China) assigned to *Dadoxylon* (*Araucarioxylon*) *japonicum* Shimakura by Sze, Li & Hsu (1963) could belong to another taxon, their radial pitting displaying a somewhat different pattern. We propose here the new combination *Brachyoxylon orientale* for the Thai wood, because this taxon cannot be assigned to *Protopodocarpoxylon* (Philippe, Zijlstra & Bamford, 2002) due to its araucarioid cross-fields.

*Brachyoxylon* nov. spec.

1963 *Brachyoxylon rotnaensis* Mathiesen, in Serra, pp. 469–82, pls I–III, text-figs 1–5. Non *Brachyoxylon rotnaensis* Mathiesen (a taxonomical synonym of *Simplicioxylon hungaricum* Andreanszky).

Samples attributed to this taxon: MP1228, 1245, 1247, 1248 (Phu Kradung Fm.); MP1221, 1222, 1276, 1292 (Waritchaphum Fm.).

The radial pitting with 20 % to 30 % of spaced and round pits clearly distinguishes this taxon from the other three taxa. Biseriate pits are not common, forming (1) 2–3 (4) contiguous opposite pairs. Like Serra (1963, pl. III, fig. 2) we observed the transition from a single strongly compressed radial pit to a pair of opposite pits. Oculipores are quite numerous, up to 12, and sometimes included in an elliptic border (apparently in compression wood). Tangential pits were observed (MP1228). Resin plugs are frequent.

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A sample from Laos with similar features was attributed to *Brachyoxylon rotnaensis* Mathiesen by Serra (1963), a taxon originally described from the Liassic of Denmark. This Danish sample was later related to *Simplicioxylon hungaricum* Andreanszky, whereas the Lao sample described in Serra (1963) was excluded from this taxon (Philippe, 1995). The Lao sample and ours form a distinct xylological unit, which will be described as a new species, as soon as Serra's material can be revised (work in progress).

## 4. Discussion

### 4.a. Stratigraphy

From a stratigraphical point of view all the taxa recognized were already found in adjacent Indochina (Vietnam, Cambodia, Laos). There, they all belong (Vozenin-Serra & Boureau, 1978) to the 'Gisements de la Série Rouge, Série de Tho Lam', more accurately to the informally named 'Grès supérieurs', and have not been recorded in older strata. The age of these 'Grès supérieurs' is, unfortunately, poorly constrained (Corsin & Desreumaux, 1972). It is worth noting that the taxa recorded in the Liassic (post-Pliensbachian?: see Vozenin-Serra & Franchesci, 1999) strata of Indochina, namely *Araucarioxylon laosense* Vozenin-Serra (1978), *Xenoxylon latiporosum* (Cramer) Gothan and *Ginkgoxylon quangnanmense* Serra (1967*a*), are all absent from our record. Overlying these Liassic strata, the poorly dated 'Terrains rouges' also yielded some wood in the Nong Son area (Vozenin-Serra & Boureau, 1978). All four taxa recognized there (Fig. 3) are absent from the Isan wood flora, either at the generic level (*Protophyllocladoxylon* and *Baieroxylon*) or at the specific level (*Agathoxylon colanii* and *Brachyoxylon brachyphylloides*). If this is not for palaeoecological reasons, it could be that, in accordance with the Liassic 'style' of their wood flora, the 'Terrains Rouges' in Vietnam are actually older than the Khorat Group, possibly latest Liassic to Early Middle Jurassic. Such an age would fit partly with the Middle to Late Jurassic age proposed for the 'Terrains Rouges' in Cambodia on palynological evidence (Corsin & Desreumaux, 1972, p. 209).

*Agathoxylon saravanensis* was first dated as Liassic (Serra, 1966*b*), because it occurs in the same locality of Saravane province from which Serra identified *Brachyoxylon rotnaensis* Mathiesen, a taxon first known from the Liassic of Denmark. This later attribution is, however, no longer accepted (Philippe, 1995). The Saravane xyloflora has exactly the same composition as the Thai Waritchaphum Formation: *Agathoxylon saravanensis* (Serra) nov. comb. and *Brachyoxylon* nov. spec.

*Brachyoxylon boureauii* has been described from Treng, Cambodia, at the base of the 'Grès Supérieurs' (Serra, 1969). Interestingly enough we recorded it in Isan only from the oldest formation of the Khorat Group, the Phu Kradung Formation.

*Brachyoxylon orientale* is the only taxon which has been found in well-dated strata. It was reported from the Lower Aptian of southern Tibet (Vozenin-Serra & Pons, 1990), on the Lhasa block, a terrane that became accreted to the Asian mainland at the beginning of the Cretaceous (Metcalfe, 1998). Amazingly, this wood is recorded in Isan only from the lowest formation. In the Thô-Châu archipelago, *Brachyoxylon orientale* was probably (see Serra, 1969, p. 6) found in the 'Grès supérieurs', together with *Protelicoxylon asiaticum* (Serra) Philippe. The latter has not been recorded yet in Isan. Also quite similar to *Brachyoxylon orientale*, as stated above, are the woods from Shandong reported as *Dadoxylon* (*Araucarioxylon*) *japonicum* in Sze, Li & Hsu (1963). These Chinese woods are dated as Late Jurassic (Cheng, Hu & Fang, 1995).

The Phu Kradung Formation wood flora includes the same woods (*Agathoxylon saravanensis* and *Brachyoxylon* sp. nov.) as that collected in Saravane (Laos). On the basis of satellite imagery, the Lao locality had been correlated with the Phu Kradung Formation by Workman (1981).

The safest inference that can be drawn from this is that palaeoecology played a significant role in the Isan fossil wood record. From our data we can only bracket the age of the studied formations of the Khorat Group (Phu Kradung to Sao Khua) in between the Bajocian (as the taxa occurring in the Liassic–lower Middle Jurassic of Indochina are all absent from our record and as the taxa we recorded have never been found elsewhere in Liassic–lower Middle Jurassic strata) and the Albian (as no Angiosperm wood has been found). We have no record, however, from the basal Phu Kradung strata, and these may yield different woods. Such woods would be very interesting, because the base of the Phu Kradung is not yet dated exactly, despite its relevance for the dating of Southeast Asia tectonic evolution (Racey *et al*. 1997).

### 4.b. Palaeobiogeography

From the biogeographical point of view, the Isan wood record has strong relationships with that from the 'Grès Supérieurs' of Indochina (Fig. 4). By the time of Khorat Group deposition, terrestrial biota in Indochina had Laurasian affinities, demonstrated, for example, by the occurrence of *Goniopholis* in Isan (Buffetaut & Ingavat, 1983) or that of *Xenoxylon* in Vietnam (Boureau, 1950). The wood flora of the 'Grès Supérieurs' and Khorat Group is, nevertheless, peculiar. Woods display peculiarities (like small clusters of strongly compressed radial pits included in a normal araucarian row, transition from a single compressed radial pit to a pair of pits, or pair of opposite pits included in an elliptic rim) that are not

| AGE | Thailand (Khorat) | Lao PDR | Cambodia | Vietnam |
|---|---|---|---|---|
| Aptian | Khok Kruat Fm.<br>no data | Ban Thalat Fm.<br>@Muong Phalane - "bois abiétinéens" | no data | |
| Barremian to Aptian | Phu Phan and Sao Khua Fms<br>*Agathoxylon* | Champa and Ban Ang Fms<br>no data | Upper "Grès supérieurs" | |
| Latest Jurassic to Barremian | Phra Wihan and Waritchaphum Fms<br>*Agathoxylon*, *Brachyoxylon* | Phu Phanang and Nam Set Fms<br>@ Saravane - *Agathoxylon*, *Brachyoxylon* | no data | @Thô-Châu - *Brachyoxylon*, *Protelicoxylon* |
| ?Middle to Late Jurassic | Phu Kradung Fm.<br>*Agathoxylon*, *Brachyoxylon* | @Muong Phin - *Agathoxylon* | Lower "Grès supérieurs"<br>@Treng - *Agathoxylon*, *Brachyoxylon* | no data |
| Late Liassic to Middle Jurassic | no data | no data | reworked in Mekong terraces<br>*Agathoxylon*, *Baieroxylon*, *Xenoxylon* | "Terrains rouges"<br>@Nong-Son - *Agathoxylon*, *Brachyoxylon*, *Protophyllocladoxylon* *Baieroxylon* |
| Middle Liassic | no data | no data | | Liassic shales<br>@Quang-Nam - *Araucarioxylon*, *Gingkoxylon*,*Xenoxylon* |

Figure 4. Chronological distribution of fossil wood flora from the Jurassic and Early Cretaceous of Southeast Asia. A synthesis based on Boureau (1950), Boureau & Serra (1961), Colani (1919), Serra (1966*a*,*b*, 1967*a*,*b*, 1968, 1969, 1970), Vozenin-Serra (1971, 1978) and Vozenin-Serra & Privé-Gill (1991, 1994) and our new results. Stratigraphy from Mouret (1994) and Lovatt Smith & Stokes (1997).

encountered elsewhere in the world, as far as we know. A geographical or ecological isolation with some floral endemism is thus probable after the Aalenian in Indochina. This endemism makes difficult the biostratigraphical correlation with the other wood flora known from Eastern Asia. As *Brachyoxylon orientale* has been observed in the Aptian of Tibet, and probably older strata of Thailand and Vietnam, this isolation must have been disrupted around Barremian/Aptian time.

Despite being limited, the wood record suggests biogeographical isolation of Indochina from the end of Liassic to Early Cretaceous times. This scenario fits well with the results from vertebrates, based mainly on dinosaurs and hybodont sharks (Buffetaut & Suteethorn, 1998, 1999). The agreement of the two sets of evidence indicates that the isolation concerned the whole terrestrial ecosystem.

For Southeast Asia outside the Indochina block, Jurassic–Cretaceous wood is known only from western Burma and southern China. Only one wood specimen was reported from Burma, in the vicinity of Lake Inle (Sahni, 1938), and this had been related to *Xenoxylon* (Philippe & Thévenard, 1996). The locality, dated as Jurassic, belongs to the Sibumasu terrane, which may have been already bound to eastern Thailand in the Late Triassic (Metcalfe, 1998). There are some wood data from southern China in Shangtung, Fengtien and Hunan (Gothan & Sze, 1933; Hsü, 1950; Sze, Li & Hsu, 1963), but these are located much further north and probably belonged to a different palaeofloristic province. In the Soegi Island (south of Singapore), a coniferous wood species is reported (Roggeven, 1932) from a locality attributed to the Triassic. This age, along with the age of some other fossil woods from Borneo or Malacca mentioned in the same work, is poorly supported, however. Another occurrence of doubtful age (Permian–Cretaceous) that may be compared to Isan woods is the *Araucarioxylon telentangensis*, described by Idris (1990) from southern peninsular Malaysia, but its protologue is not clear. In her 1919 paper, Colani, in addition to Triassic woods from Vin-Phuoc (Vietnam), also mentioned some *Agathoxylon* that could be Jurassic–Cretaceous in age from Luang-Prabang (northern Laos) and Khône Island (on the Mekong River in southern Laos). Unfortunately these

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woods are too poorly described to be compared with those from Thailand. To sum up, the wood record in adjacent areas is to be revised, but interesting comparisons can be expected.

#### 4.c. Sedimentology and palaeoecology

The xylological singularity of the Waritchaphum Formation supports it being distinguished from the typically reddish underlying Phu Kradung Formation strata. According to our record, two taxa (*B. boureauii* and *B. orientale*) disappeared from the record by Waritchaphum times, while only one (*A. saravanensis*) is subsequently recorded in the two younger formations. It could be argued that the number of samples taken into account for Phra Wihan and Sao Khua formations is limited. In both Phu Kradung and Waritchaphum formations, however, *A. saravanensis* is not dominant. Thus its exclusive (or relative?) dominance in Phra Wihan and Sao Khua is probably indicative of some palaeoecological change. Xylologically the Waritchaphum Formation is more related to the Phra Wihan Formation than to the Phu Kradung Formation.

Some imprints were found at Tad-Thong, Phu-Phan Range, in the Phu Kradung Formation (work in progress), including leafy twigs of Coniferales. The leaf cuticle shows xerophytic features like scaly leaf margins and papillate subsidiary cells, indicative of a warm and dry climate.

It is striking how silicified wood is limited to the Phu Kradung Formation. In these strata silicified trunks are commonly found, some reaching as much as 1.2 m in diameter and 15 m in length. In the Ban Thung Chuak locality we found these trunks included in their matrix. The latter is full of small lignitic fragments, and looks similar to the other plant-bearing strata of the younger formations of the Khorat Group we observed (Waritchaphum, Phra Wihan and Sao Khua). Silicified wood can be found in these younger formations, although the woods are rare and small. Silicification of this type (that is, in a siliciclastic flood plain) occurs in a subarid climate (Lefranc & Guiraud, 1990; Pailler *et al*. 2000). The near-absence of large silicified logs in the Waritchaphum and subsequent formations, when compared with their abundance in the Phu Kradung Formation, could be interpreted as a transition to a wetter climate during Waritchaphum times. This fits with other interpretations (Hahn, 1982; Mouret *et al*. 1993; Heggeman, 1994) and could also explain why in the Phu Kradung Formation *sensu lato*, most vertebrate remains are located towards the top (Le Lœuff *et al.* 2002), wetter climate meaning higher plant biomass and more food availability. Subsequent levels with silicified wood in the Phra Wihan and Sao Khua formations (Ward & Bunnag, 1964) could then be interpreted as short arid intervals. If it is admitted that the climate was somewhat arid, the size of the complete trunks as well as the growth-ring brightness could appear paradoxical. The only hypothesis to remove this paradox is that the tree grew alongside streams. Modern analogues are known, such as in the Okavango delta of Botswana.

## 5. Conclusions

The new data challenge the common view of Khorat Group wood assemblages as uniform and uninformative. Stratigraphical correlations are drawn with adjacent countries and biogeographical relationships are discussed. We now have a firm basis to compare the Jurassic–Cretaceous wood record east and west of the Nan-Uttaradit ophiolitic zone. A newly discovered locality in the Khlong Min Formation (Middle Jurassic?) of southern peninsular Thailand, containing both silicified and lignitized wood, is of great potential importance. There are also indications of wood flora from the Mae Sot Basin (Stokes, pers. comm.). Moreover, interesting results could be expected from comparisons of Jurassic–Early Cretaceous terrestrial biota on both sides of the Song Ma/Song Da suture. Unfortunately, Early Cretaceous flora from southernmost China are poorly known (Sun, 1995) and the closest basin with published fossil wood data from this time interval is in Shandong (Gothan & Sze, 1933; Cheng, Hu & Fang, 1995). These are currently under review (work in progress).

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## References

Asama, K. 1982. *Araucarioxylon* from Khorat, Thailand. *Geology and Palaeontology of South-East Asia* **23**, 57–64.

Bamford, M. & Philippe, M. 2001. Gondwanan Jurassic–Early Cretaceous homoxylous woods: a nomenclatural revision of the genera with taxonomical notes. *Review of Paleobotany and Palynology* **113**, 287–97.

Boureau, E. 1950. Contribution à l'étude paléoxylologique de l'Indochine. I: présence du *Xenoxylon latiporosum* (Cramer) Gothan dans le Lias du Centre-Annam. *Bulletin du Service géologique de l'Indochine* **29**, 1–16.

Boureau, E. & Serra, C. 1961. Sur les structures normales et traumatiques d'un bois mésozoïque du Cambodge, le *Brachyoxylon saurinii* n. sp. *Revue Générale de Botanique* **68**, 373–93.

BUFFETAUT, E. & INGAVAT, R. 1983. *Goniopholis phuwiangensis* nov. sp., a new mesosuchian crocodile from the Mesozoic of North-Eastern Thailand. *Géobios* **16**, 79–91.

BUFFETAUT, E. & SUTEETHORN, V. 1998. The biogeographical significance of the Mesozoic vertebrates from Thailand. In *Biogeography and geological evolution of Southeast Asia* (eds R. Hall and J. D. Holloway), pp. 83–90. Leiden: Backhuys Publishing.

BUFFETAUT, E. & SUTEETHORN, V. 1999. The dinosaur fauna of the Sao Khua Formation of Thailand and the beginning of the Cretaceous radiation of dinosaurs in Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **150**, 13–23.

BUNOPAS, S. 1982. *Palaeogeographic history of western Thailand and adjacent parts of South-East Asia: a plate tectonic interpretation.* Geological Survey of Thailand, Special Paper no. 5, Bangkok, 122 pp.

CHARUSIRI, P., KOSUWAN, S. & IMSAMUT, S. 1997. Tectonic evolution of Thailand: from Bunopas (1981)s to a new scenario. *Proceedings of the International Conference on Stratigraphy and tectonic evolution of Southeast Asia and the South Pacific, Bangkok 19–24 August 1997*, **1**, 414–20. Bangkok, Division of Mineral Resources.

CHENG, Z. W., HU, C. Z., & FANG, X. 1995. Cretaceous stratigraphy and vertebrate faunal sequence in Laiyang–Zhucheng Basin, Shandong, China – as a candidate stratotype of non-marine Cretaceous. *Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biota, Short papers volume*, pp. 97–100. Beijing: China Ocean Press.

COLANI, M. 1919. Sur quelques *Araucarioxylon* indochinois. *Bulletin du Service géologique de l'Indochine* **6**, 5–15.

CORSIN, P. & DESREUMAUX, C. 1972. Découverte d'une flore néocomienne dans les "Grès supérieurs" de Bokor (Cambodge méridional). *Annales de la Société Géologique du Nord* **92**, 199–212.

CUNY, G., SUTEETHORN, V., BUFFETAUT, E. & OUAJA, M. 2001. Freshwater hybodont sharks in the Aptian–Albian of Tunisia and Thailand. *The Palaeontological Association Newsletter* **48**, A9.

FRANCESCHI, D. DE & VOZENIN-SERRA, C. 1997. La flore du Trias supérieur vietnamien. Implications paléogéographiques. *Comptes Rendus de l'Académie des Sciences Paris IIa* **324**, 333–40.

GOTHAN, W. & SZE, H. C. 1933. Über fossile Hölzer aus China. *Memoirs of the National Research Institute of Geology Academia Sinica* **13**, 87–104.

HAHN, L. 1976. Stratigraphy and palaeogeography of the non-marine Mesozoic deposits in Northern Thailand. *Geologisches Jahresbericht* **21**, 155–69.

HAHN, L. 1982. Stratigraphy and marine ingressions of the Mesozoic Khorat Group in northeastern Thailand. *Geologisches Jahresbericht* **43**, 7–35.

HEGGEMAN, H. 1994. Sedimentäre Entwicklung der Khorat-Gruppe (Ober Trias bis Paläogen) in NE- und N-Thailand. *Göttingerarbeiten zur Geologie und Paläontologie* **63**, 146 pp.

HEGGEMANN, H., KOHRING, R. & SCHLUTERT, T. 1990. Fossil plants and arthropods from the Phra Wihan Formation, presumably Middle Jurassic of northern Thailand. *Alcheringa* **14**, 311–16.

HÖGBOM, B. 1913. Contributions to the geology and morphology of Siam. *Bulletin of the Geological Institute University Uppsala* **12**, 65–128.

HSÜ, J. 1950. Two coniferous woods, *Xenoxylon* and *Cupressinoxylon*, from South Hunan. In *Palaeobotany in India* (eds B. Sahni and R. V. Sitholey), p. 24. Journal of the Indian Botanical Society no. 29.

IDRIS, M. B. 1990. *Araucarioxylon telentangensis*, a new species of fossil coniferous wood from the Ulu Endau area, Johore, Malaysia. *Journal of Southeast Asian Earth Sciences* **4**, 55–9.

IWAI, J., ASAMA, K.,VEERABURUS, M. & HONGNUSONTHI, A. C. 1966. Stratigraphy of the so-called Khorat Series and a note on the fossil plant-bearing Paleozoic strata in Thailand. *Geology and Palaeontology of Southeast Asia* **2**, 179–96.

IWAI, J., HONGNUSONTHI, A., ASAMA, K., KOBAYASHI, T., KON'NO, E., NAKORNSRI, N., VEERABURAS, M. & YUYEN, W. 1975. Non-marine Mesozoic Formations and fossils in Thailand and Malaysia. *Geology and Palaeontology of Southeast Asia* **15**, 191–218.

KOBAYASHI, T. 1960. Notes on the geologic history of Thailand and adjacent territories. *Japanese Journal of Geology and Geography* **31**, 129–48.

KON'NO, E. & ASAMA, K. 1973. Mesozoic plants from Khorat, Thailand. *Geology and Palaeontology of Southeast Asia* **12**, 149–71.

LEFRANC, J.-P. & GUIRAUD, R. 1990. The Continental Intercalaire of northwestern Sahara and its equivalents in the neighbouring regions. *Journal of African Earth Sciences* **10**, 27–77.

LE LŒUFF, J., KHANSUBHA, S., BUFFETAUT, E., SUTEETHORN, V., TONG, H. & SOUILLAT, C. 2002. Dinosaur footprints from the Phra Wihan Formation (Early Cretaceous of Thailand). *Compte-rendus Palevol* **1**, 287–92.

LOVATT-SMITH, P. & STOKES, R. 1997. Geology and petroleum potential of the Khorat Plateau Basin in the Vientiane area of Lao P. D. R. *Journal of Petroleum Geology* **20**, 27–50.

METCALFE, I. 1996. Pre-Cretaceous evolution of SE Asian terranes. In *Tectonic evolution of SE Asia* (eds R. Hall and D. J. Blundell), pp. 97–122. Geological Society of London, Special Publication no. 106.

METCALFE, I. 1998. Palaeozoic and Mesozoic geological evolution of the SE Asian region: multidisciplinary constraints and implications for biogeography. In *Biogeography and geological evolution of Southeast Asia* (eds R. Hall and J. D. Holloway), pp. 25–41. Leiden: Backhuys Publishing.

MOURET, C. 1994. Geological history of northeastern Thailand since the Carboniferous. Relations with Indochina and Carboniferous to Early Cenozoic evolution model. *Proceedings of the International Symposium on stratigraphic correlation of Southeast Asia, Bangkok 15–20 Nov. 1994*, pp. 132–58. Bangkok, Department of Mineral Resources.

MOURET, C., HEGGEMANN, H., GOUADAIN, J. & KRISADASIMA, S. 1993. Geological history of the siliciclastic Mesozoic strata of the Khorat Group in the Phu Phan Range area, northeastern Thailand. In *Proceedings of the International Symposium on the biostratigraphy of mainland Southeast Asia: Facies and palaeontology* (ed. T. Thanasupthipitak), pp. 23–49. Chiang Mai, Chiang Mai University.

PAILLER, D., FLICOTEAUX, R., AMBROSI, J.-P. & MEDUS, J. 2000. Les bois fossiles mio-pliocènes de Nkondo

(Lac Albert, Ouganda), composition minéralogique et mode de formation. *Comptes Rendus de l'Académie des Sciences Paris IIa* **331**, 279–86.
PHILIPPE, M. 1993. Nomenclature générique des trachéidoxyles mésozoïques à champs araucarioïdes. *Taxon* **42**, 74–80.
PHILIPPE, M. 1995. Bois fossiles du Jurassique de Franche-Comté (nord-est de la France): systématique et biogéographie. *Palaeontographica B* **236**, 45–103.
PHILIPPE, M. & THÉVENARD, F. 1996. Repartition and palaeoecology of the Mesozoic wood genus *Xenoxylon*: palaeoclimatological implications for the Jurassic of Western Europe. *Review of Palaeobotany and Palynology* **91**, 353–70.
PHILIPPE, M., TORRES, T., ZHANG, W. & ZHENG, S. 1999. *Sahnioxylon*, bois mésozoïque à aire disjointe: Chine, Inde et Antarctique occidental. *Bulletin de la Société Géologique de France* **170**, 513–19.
PHILIPPE, M., ZIJLSTRA, G. & BAMFORD, M. 2002. Proposal to conserve the name *Protopodocarpoxylon* Eckhold (Fossil, Gymnospermae, Coniferales) with a conserved type. *Taxon* **51**, 207–8.
RACEY, A., DUDDY, I. R. & LOVE, M. A. 1997. Apatite fission track analysis of Mesozoic red beds from northeastern Thailand and western Laos. *Proceedings of the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific* **1**, 200–9. Bangkok, Department of Mineral Resources.
RACEY, A., GOODALL, J. G. S., LOVE, M. A., POLACHAN, S. & JONES, P. D. 1994. New age data for the Mesozoic Khorat Group of northeastern Thailand. In *Proceedings of the International Symposium on Stratigraphic Correlation of Southeast Asia* (eds Angsuwathana *et al.*), pp. 245–52. Bangkok, Department of Mineral Resources.
RACEY, A., LOVE, M. A., CANHAM, A. C., GOODALL, J. G. S., POLACHAN, S. & JONES, P. D. 1996. Stratigraphy and reservoir potential of the Mesozoic Khorat Group, North Eastern Thailand: part 1, Stratigraphy and Sedimentary Evolution. *Journal of Petroleum Geology* **19**, 5–40.
RACEY, A., STOKES, R. B., LOVATT-SMITH, P. & LOVE, M. A. 1997. Late Jurassic collision in Northern Thailand and significance of the Khorat Group. *Proceedings of the International Conférence on Stratigraphy and tectonic evolution of Southeast Asia and the South Pacific* **1**, 412–13. Bangkok, Department of Mineral Resources.
ROGGEVEN, P. M. 1932. Mesozoisches Koniferenholz (*Protocupressinoxylon malayense* n. s.) von der Insel Soegi im Riouw-Archipel, Niderländisch Ost-Indien. *Proceedings Koninklijke Akademie van Wetenschappen te Amsterdam* **35**, 580–4.
SAHNI, B. 1938. A Mesozoic coniferous wood (*Mesembrioxylon shanense* sp. nov.) from the Southern Shan States of Burma. *Record of the Geological Survey of India* **71**, 380–8.
SERRA, C. 1963. Présence d'un *Brachyoxylon rotnaensis* Mathiesen dans la flore mésozoïque du Bas-Laos. *Compte-rendus du 88° congrès des Sociétés savantes* **2**, 469–82.
SERRA, C. 1966*a*. Etude anatomique et paléogéographique de quelques espèces homoxylées du Sud-Vietnam et du Cambodge. *Archives géologiques du Vietnam* **8**, 59–131.
SERRA, C. 1966*b*. Nouvelle contribution à l'étude paléoxylologique du Cambodge, du Laos et du Viet-nam. *Archives géologiques du Vietnam* **9**, 17–40.
SERRA, C. 1967*a*. Sur un nouveau bois de Ginkgoales récolté dans le Ho-Gia (Province du Quang-nam). *Archives géologiques du Vietnam* **10**, 93–103.
SERRA, C. 1967*b*. *Protophyllocladoxylon koruabense* n. sp., bois fossile du Cambodge. *Compte-rendus du 91° congrès des Sociétés savantes section Sciences* **3**, 201–15.
SERRA, C. 1968. Sur quelques végétaux mésozoïques de la région de Vung-Rua (Province du Quang-Nam). *Archives géologiques du Vietnam* **11**, 1–19.
SERRA, C. 1969. Sur les bois fossiles de l'archipel de Thô-Châu (Golfe de Thaïlande). *Archives géologiques du Vietnam* **12**, 1–15.
SERRA, C. 1970. Etude de structures homoxylées à oopores du Mésozoïque vietnamien. *Archives géologiques du Vietnam* **13**, 61–71.
SPILLER, F. C. P. 2002. Radiolarian stratigraphy of Peninsular Malaysia and implications for regional tectonics and palaeogeography. *Palaeontographica Abteilung A* **266**, 1–91.
STOKES, R. B., LOVATT SMITH, P. F. & SOUMPHONPHAKDY, K. 1996. Timing of the Shan-Thai-Indochina collision: new evidence from the Pak Lay foldbelt of the Lao PDR. In *Tectonic evolution of SE Asia* (eds R. Hall and D. Blundell), pp. 225–32. Geological Society of London, Special Publication no. 106.
SUN, G. 1995. Divisions of non-marine Mesozoic of China and the paleoclimatic implications based on paleobotanical data. *Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biota, Short papers volume*, pp. 1–16. Beijing: China Ocean Press.
SZE, H. C., LI, X. X. & HSU, T. Y. 1963. *Mesozoic plants of China.* Beijing: Science Press, 429 pp.
TONG, H., BUFFETAUT, E. & SUTEETHORN, V. 2002. Middle Jurassic turtles from Southern Thailand. *Geological Magazine* **139**, 687–97.
VOZENIN-SERRA, C. 1971. Notes sur des bois mésozoïques et cénozoïques du Vietnam et du Cambodge. *Archives géologiques du Vietnam* **14**, 1–39.
VOZENIN-SERRA, C. 1977. Sur une pénétration insolite de Gymnospermes australes dans le Sud-Est asiatique au Mésozoïque. *Comptes Rendus de l'Académie des Sciences de Paris, série D* **285**, 1419–21.
VOZENIN-SERRA, C. 1978. *Dadoxylon* (*Araucarioxylon*), *laosense* n. sp., bois homoxylé jurassique du Bas-Laos. *Compte-rendus du 103° congrès national des sociétés savantes, Sciences* **2**, 87–93.
VOZENIN-SERRA, C. 1983. Etat de nos connaissances sur les flores mésozoïques du Sud-Est asiatique. *Compte-rendus du 108° congrès des sociétés savantes, Sciences* **2**, 103–16.
VOZENIN-SERRA, C. & BOUREAU, E. 1978. Sur l'intérêt phytostratigraphique du bassin houiller mésozoïque de Nong-Son – Vinh-Phuoc dans le centre Vietnam et ses rapports avec la phylogénie des espèces. *Comptes Rendus de l'Académie des Sciences de Paris, série D* **287**, 791–6.
VOZENIN-SERRA, C. & FRANCHESCI, D. DE 1999. Flore du Trias Supérieur du Viêtnam (bassins houillers du Quang-Nam et de Hongay). *Palaeontographica, Abteilung B* **249**, 1–62.
VOZENIN-SERRA, C. & PONS, D. 1990. Intérêts phytogénétiques et paléoécologique des structures ligneuses homoxylées découvertes dans le Crétacé inférieur du Tibet Méridional. *Palaeontographica, Abteilung B* **216**, 107–27.

VOZENIN-SERRA, C. & PRIVÉ-GILL, C. 1989. Bois plio-pléistocènes du gisement de Saropée, plateau de Khorat, Est de la Thaïlande. *Review of Palaeobotany and Palynology* **60**, 225–54.

VOZENIN-SERRA, C. & PRIVÉ-GILL, C. 1991. Les terrasses alluviales pléistocènes du Mékong (Cambodge). I Les bois silicifiés homoxylés récoltés entre Stung-Treng et Snoul. *Review of Palaeobotany and Palynology* **67**, 115–32.

VOZENIN-SERRA, C. & PRIVÉ-GILL, C. 1994. Bois pléistocènes du gisement de Binh-Thang, Vietnam. *Palaeontographica, Abteilung B* **232**, 175–95.

VOZENIN-SERRA, C. & SALARD-CHELBODAEFF, M. 1994. Les données paléobotaniques dans le Sud-Ouest Pacifique au Permo-Trias–Leur confrontation aux modèles géodynamiques. *Neues Jahrbuch für Geologie und Paläontologie, Monatsheft* **1**, 54–64.

WARD, D. E. & BUNNAG, D. 1964. *Stratigraphy of the Mesozoic Khorat Group in northeastern Thailand.* Report of investigations no. 6, Division of Mineral Resources, Bangkok, 95 pp.

WORKMAN, D. R. 1981. Study of strata in southern Laos equivalent to the Khorat Group of Thailand using satellite imagery. *Journal of the Geological Society of Thailand* **4**, 1–12.

YIN HONGFU. 1997. An archipelagic view of Tethys. *Proceedings of the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific, Bangkok 19–24 August 1997* **2**, 769. Bangkok, Division of Mineral Resources.