Mesozoic red bed sequences from SE Asia and the significance of the Khorat Group of NE Thailand

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Mesozoic red bed sequences from SE Asia and the significance of the Khorat Group of NE Thailand

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Abstract: New geological data are presented and previously published information is reviewed to demonstrate that much of the Khorat Group (Phu Kradung to Khok Kruat Formations) of NE Thailand is Early Cretaceous in age. It is suggested that the Mesozoic red bed sequences of neighbouring Indochina are likely to be of similar age rather than spanning the entire Late Triassic to Early Cretaceous as previously assumed. Moreover, the Lower Nam Phong Formation dated as Late Triassic and previously included as the basal formation of the Khorat Group is now removed from this group, thus creating a hiatus within the Jurassic. There is therefore no clear relationship between the Indosinian Orogeny and the Triassic collision of the Sibumasu (also referred to as Shan-Thai) and Indochina Blocks and the subsequent deposition of the Khorat Group in a Late Triassic–Early Cretaceous thermal sag basin. Jurassic sediments may be absent across much of the Khorat Plateau whereas marine Jurassic sediments to the west and east show no sediments younger than Bajocian. Because sea levels were generally rising in the Middle and Late Jurassic it is likely that the Khorat region was uplifted at this time. It is suggested that the Khorat Group was originally deposited in a foreland basin setting rather than a thermal sag basin following Late Triassic rifting. Moreover, the original site of deposition was to the north in southern China, with the present-day location being the result of movement along the Red River Fault coupled with a clockwise rotation of the Indochina Block (on which the Khorat Group sits) with respect to the South China Block.

The Khorat Group and its lateral equivalents comprise a thick sequence of Mesozoic continental red bed sediments, which were deposited over much of NE Thailand and neighbouring parts of SE and central Laos (around Vientiane, Savannakhet and Pakse) and Cambodia (Fig. 1). It underlies much of the Khorat Plateau in NE Thailand and has an areal extent of around 200 000 km² with a maximum present-day preserved width of around 500 km and maximum preserved sediment thickness of around 4.5 km. Possible coeval red beds also occur in southern Peninsular Thailand (Trang Group) and in Peninsular Malaysia (within the Gagau and Tembeling Groups). Up to 3 km of post-Khorat Group section was removed in NE Thailand by erosion during Tertiary uplift associated with the collision between India and Eurasia and the formation of the Himalayas (Racey et al. 1996, 1997a, b). Although the Khorat Group crops out on the Indochina Block it does partly extend westwards across the Loei–Phetchabun and Sukothai Fold Belts onto the Sibumasu Block, the two blocks having been sutured together since at least the Late Triassic (Figs 1, 2). The Indochina Block comprises eastern Thailand, Laos, Cambodia and Vietnam, and is also referred to in the literature as the Shan-Thai Block (Fig. 2).

The original depocentre of the Khorat Basin appears to have been oriented roughly NW–SE and superficially it has the appearance of a typical sag basin with each formation gradually overlapping the previous formation towards the edge of the basin. The Khorat Plateau has an uplifted western and southern margin (up to 1300 m above sea level) with a mesa-like appearance formed as a result of compressional deformation along its western margin (Loei–Phetchabun Fold Belt), which marks the western margin of the Indochina Block and the approximate boundary between the Indochina and Sibumasu Blocks. The central region of the Khorat Plateau is at present only a few hundred metres above sea level.

The sedimentary fill comprises a non-marine red bed sequence (Khorat Group), which is unconformably overlain by continental evaporites and clastic deposits of the Albian–Cenomanian Maha Sarakham Formation and is overlain by Late Triassic–Early Cretaceous sediments, which include volcanic rocks of the Huai Hin Lat and Lower Nam Phong Formations and Late Palaeozoic marine sediments (Fig. 3). Traditionally the Khorat Group comprises six formations, which are from bottom to top, the Lower Nam Phong Formation, the Huai Hin Lat Formation, the Phu Kradung Formation, the Khok Kruat Formation, the Phu Thok Formation, and the Phetchaburi Formation.
to top: Nam Phong, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan and Khok Kruat (Fig. 3).

Based on seismic and well data the Nam Phong Formation varies in thickness from 2500 m in the central portion of the basin to ≤500 m along its flanks. The formation is clearly divisible on seismic sections into an Upper Nam Phong Formation and Lower Nam Phong Formation separated by an unconformity. The Phu Kradung Formation varies from 1200 m in the basin centre to around 500 m in thickness on the basin flanks. The Phra Wihan Formation varies in thickness from around 50 to 300 m, and the Sao Khua Formation varies widely in thickness from around 100 to
700 m. The Phu Phan Formation is generally 50–100 m thick, and the Khok Kruat Formation shows marked variations in thickness because of erosion, from 200 m in the NW to 850 m in the SE.

The generally accepted model for the region is that the continental collision between the Sibumasu Block and mainland Indochina Block occurred in the Late Triassic (Indosinian Orogeny). Uplift and orogenic faulting associated with this event led to the formation of intermontane thermal sag basins, which were rapidly infilled with Jurassic–Cretaceous continental sediments (Khorat Group and its equivalents) over a broad area from eastern Peninsular Malaysia across the South China Sea into the Khorat Basin of NE Thailand, southern Laos, Cambodia and Vietnam. However, as will

Fig. 2. Inferred location of the key sutures and blocks within the study area (see also Fig. 4).
<table>
<thead>
<tr>
<th>Age</th>
<th>Group</th>
<th>Formation</th>
<th>Key Events</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERT.</td>
<td></td>
<td>Phu Tok</td>
<td>HIMALAYAN OROGENY: Major uplift and erosion of &gt;3km of sediment plus formation of long wavelength folds. 900 - 1000km left-lateral displacement and paleomagnetic data indicate the Khoral Basin was located within Southern China (Sichuan) (see fig. 11).</td>
<td>Aeolian &amp; Fluvial</td>
</tr>
<tr>
<td>LATE</td>
<td></td>
<td>Maha Sarakham</td>
<td>Ridley and isolated intracontinental basin.</td>
<td>Fluvial &amp; Aeolian</td>
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<tr>
<td>CRETACEOUS</td>
<td>Aptian - Cenomanian</td>
<td>Khok Krueat</td>
<td>MID-CRETACEOUS EVENT: Inversion, uplift and erosion plus initiation of Phu Phran uplift to separate Khoral Basin in south from Sakho Nakhon Basin in north.</td>
<td>Hypersaline lake within an arid desert</td>
</tr>
<tr>
<td></td>
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<td>Phu Phran</td>
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<td>Sao Khua</td>
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<td>Phu Krudung</td>
<td>Possible BARREMAN-APTIAN EVENT suggested by paleomagnetic data and marked erosion of Sao Khua Formation.</td>
<td></td>
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<tr>
<td></td>
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<td>Upper Nam Phong</td>
<td>‘CIMMERIAN’ EVENT (Indosinian III orogeny) Marked by Jurassic-Helian unconformity along southern edge of Khoral Basin.</td>
<td>Fluvial braided and meandering rivers</td>
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<tr>
<td>JURASSIC</td>
<td></td>
<td>Huai Hin Lat</td>
<td>MIDDLE NAM PHONG</td>
<td>Indosinian II Orogeny: Major uplift, erosion and penepalation. Inversion of Triassic half-grabens.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Extension and half-graben development.</td>
<td>Lacustrine and fluvial with volcanics in lower part</td>
</tr>
<tr>
<td>TRIASSIC</td>
<td></td>
<td></td>
<td>Indosinian I Orogeny (Late Permian-Mid Triassic): Major uplift, erosion and penepalation.</td>
<td>Shallow marine</td>
</tr>
<tr>
<td>PERMAN</td>
<td></td>
<td></td>
<td>Indosinian I Orogeny (Late Permian-Mid Triassic): Major uplift, erosion and penepalation.</td>
<td>Shallow marine</td>
</tr>
</tbody>
</table>

Fig. 3. Revised stratigraphic column for the Mesozoic of NE Thailand with the main depositional environments and key tectonic events.
be evident from the information presented below, this is probably an oversimplification.

For a more detailed summary of the lithologies and environments of deposition of the various formations making up the Khorat Group the reader is referred to Racey et al. (1996). The biostratigraphy of the Khorat Group, especially the palynology and its importance in dating these formations, has been discussed in detail by Racey & Goodall (2009).

Terranes and sutures

As shown by Metcalfe (1996) mainland SE Asia comprises a complex mosaic of allochthonous terranes that accreted throughout the Late Palaeozoic to Mesozoic (Fig. 4). The exact timing of these collisions and the relationship between the various tectonic fragments is by no means certain and has been the subject of much debate (Cooper et al. 1989; Metcalfe 1996, and references therein).

**Fig. 4.** Regional blocks and sutures referred to in text (after Metcalfe 1996). EM, East Malaysia; WB, West Burma; SWB, SW Borneo; S, Semitau Terrane; HT, Hainan Island terranes; L, Lhasa Terrane; QT, Qiangtang Terrane; QS, Qamdo–Simao Terrane; SI, Simao Terrane; SG, Songpan Ganzi accretionary complex; KL, Kumlun Terrane; QD, Qaidam Terrane; AL, Alashan Terrane. Dashed line between Indochina and EM marks the approximate southern boundary of the Indochina Block.
There are three major cratons or blocks of relevance to the current study area. The northern margin of the study area is marked by the South China Block, bordered to the immediate south by the Indochina Block, which in turn is bordered to the west and SW by the Sibumasu Block (Fig. 4).

The Indochina Block is bounded to the NE by the Song Ma Suture (Red River Fault Zone), to the NW by the Nan–Uttaradit Suture, which is partly coincident with the Dien Bien Phu Fault, and to the south by the Wang Chao and Three Pagodas sinistral strike-slip faults (dashed line in Fig. 4). The Sibumasu Block is bordered on its western side by the Western Burma block along the Sagaing Fault Zone (also referred to as the Shan Boundary Fault). The South China Block is bounded to the north by the Qinling mountains (Qinling–Dabie Suture), to the west by the Tertiary Long Men Shan Thrust Belt and to the SW by the sinistral Xian-Shui-He (Ailaoshan Suture) and Song Ma Suture (Red River Fault).

**Geological history (Figs 3 and 4)**

The Indochina and South China Blocks collided during the Early Carboniferous, the boundary being marked by the NW–SE-trending Song Ma Suture (Metcalfe 1996). Within this paper two main Indosinian Orogenies are recognized, following Mouret (1994) and Booth (1998). Interestingly, two Indosinian phases are also recognized in China (Tin 1992) although these are related to different collisions (Wan & Zhu 1991). The Sibumasu and Indochina Blocks collided during the Indosinian I Orogeny in the Late Permian–Triassic along the NNE–SSW-trending Nan–Uttaradit Suture, which continues southwards as the Phtetchabun Fold Belt and in Peninsular Malaysia as the Bentong–Raub Suture. Continued movement northwards of these two plates resulted in subduction between the blocks and a major period of uplift, erosion, peneplanation and thrusting (thin and thick skinned). However some workers (e.g. MacDonald & Barr 1984), observed that the volcanic rocks of this age in the Nan area of northern Thailand more closely resemble volcanic arc basalts than true obducted oceanic crust, and if correct this would suggest that there was no significant obduction of an intervening oceanic basin, at least not along this part of the suture between Sibumasu and Indochina. MacDonald & Barr (1984) suggested that the suture could be further east beneath the thick Mesozoic cover and that the collision between Sibumasu and Indochina was oblique. The Song Da Suture is considered to represent a region of Permo-Triassic rift basins that ceased in the Late Triassic with subsequent reactivation of this suture as a major strike-slip zone in the Late Mesozoic to Early Cenozoic (Metcalfe 1996). During the Late Triassic a series of intracontinental rift basins developed across NE Thailand extending into western Laos. These generally trend WNW–ESE, except in the region of the Phu Phan Uplift (a mid-Cretaceous inversion feature), where they trend north–south. These are filled with fluvial–lacustrine sands, silts and mudstones of the Late Triassic (Carnian–Norian) Huai Hin Lat Formation. Within the Khorat Plateau region a second major tectonic event of only slightly younger Late Triassic age is observed on seismic sections separating the Huai Hin Lat Formation from the Late Triassic Lower Nam Phong Formation. This event is herein referred to as the Indosinian II Orogeny and represents a second period of uplift, erosion and peneplanation with more localized thin-skin thrusting (Booth 1998). The end of the Triassic is marked by an unconformity, which on seismic sections in the Khorat Plateau region separates the Lower from the Upper Nam Phong Formation (Cimmerian/Indosinian III event). This event represents an unconformity or hiatus with the subsequent deposition of overlying Khorat Group fluvial sediments of the Upper Nam Phong, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan and Khok Kruat Formations, which are dated as ?Late Jurassic to Early Cretaceous. A possible Kimmeridgian (Cimmerian) event is also identified in Vietnam (Tien 1991) and this may be contemporaneous with the Yanshan I compression recognized in China (Mouret 1994).

The top of the Khorat Group is marked by an unconformity between the Aptian Khok Kruat Formation and the Albain–Cenomanian continental evaporitic Maha Sarakham Formation. This unconformity represents a mid-Cretaceous inversion, which is also recognized to the north in Laos (Lovatt-Smith et al. 1996). This inversion led to the development of the Phu Phan Uplift in NE Thailand and to the subsequent formation of a rimmed basin across much of the Khorat Basin into which the Maha Sarakham Formation was deposited. This was followed by the deposition of fluvial and aeolian sediments of Latest Cretaceous–Early Tertiary age (the Phu Tok Formation). The unconformity at the base of the Maha Sarakham Formation is broadly coeval with the Yanshan II Phase of orogeny recognized in China (Mouret 1994).

The continuing collision of India with Asia during the Tertiary resulted in extensive dextral movement along the Song Da Suture, causing South China to move southeastwards along the suture over implied distances of several hundred kilometres (Sato et al. 1999). It also resulted in general uplift and inversion of the Khorat Plateau (as supported by its present elevation and apatite fission-track data; see below). Such dextral slip may have caused a clockwise rotation of the Khorat Plateau such that the current location of
the Khorat Basin may not reflect its original relative geographical location, with the possibility that much of the Khorat Group could have been deposited originally as far away as southern China (see Carter & Bristow 2002, and section below on Palaeomagnetic data).

Stratigraphy

Khorat Group, NE Thailand

Many previous workers have assumed that the Nam Phong Formation, which ‘traditionally’ forms the basal part of the Khorat Group, is Late Triassic and that the Early, Middle and Late Jurassic are represented by the overlying Phu Krading, Phra Wihan and Sao Khua Formations respectively, with the remainder of the group (Phu Phan and Khok Kruat Formations) assigned to the Early Cretaceous. Early stratigraphic studies of the Khorat Group mainly used plant fossils coupled with guesswork to assign ages to the various formations. Subsequent age dating has been based mainly on vertebrates from the Phu Krading and Sao Khua Formations (Buffetaut et al. 1993), many of which have subsequently been shown to range into the Early Cretaceous (see Racey et al. 1994, 1996; Racey & Goodall 2009; Buffetaut et al. 2006, 2009, and references therein). Palynological data now suggest an Early Cretaceous (Berriasian to Aptian) age for the Phu Krading to Khok Kruat Formations, although the lowermost part of the Phu Krading and Upper Nam Phong Formations could in part be Jurassic (most probably Late Jurassic), as discussed by Racey & Goodall (2009). These revised ages mean that a significant hiatus must exist between the Lower Nam Phong and Upper Nam Phong Formations, and that the former should therefore no longer be considered to be part of the Khorat Group. The Lower Nam Phong Formation on seismic sections occurs below the base Khorat unconformity and should therefore be excluded from the Khorat Group (J. E. Booth, pers. comm.).

Many oil company geologists who have studied seismic sections across the region consider this unconformity, referred to in Figure 3 as the ‘Cimmerian Event’ (Indosinian III orogeny), to mark the boundary between an ‘upper’ Nam Phong and a ‘lower’ Nam Phong Formation, the ‘lower’ comprising mainly sandstone.

Racey et al. (1994, 1996) presented new palynological evidence that reassigned the Phra Wihan and Sao Khua Formations to the Early Cretaceous and the Phu Krading to the Late Jurassic to Early Cretaceous. Racey & Goodall (2009) have recently acquired additional palynological data that further support this reassignment and also indicate that most of the Phu Krading Formation is Early Cretaceous. In recent years several new vertebrate discoveries have also led to a revision of the ages of the formations such that they are now more in line with the palynological dating (see Buffetaut et al. 2006, 2009). Although common mention has been made of Jurassic vertebrates in many papers, the recent publications of Buffetaut et al. (2006, 2009, and references therein) indicate that the Phra Wihan to Khok Kruat Formations are now considered to be Early Cretaceous in age whereas the vertebrate dating suggests that the Phu Krading Formation is Late Jurassic (Tithonian) or Early Cretaceous in age.

Indochina ‘red beds’

Within the broader context of Indochina, Mesozoic continental red beds form two main ‘groups’ identified by the early French workers in the 1930s. These comprise the ‘Terrain Rouge’, which consists of gently folded sandstones, marls, shales and red–purple claystones that vary markedly in thickness from 100 to 2000 m. This interval is also referred to as the ‘Indosinias Moyennes’ or ‘Middle Indosinias’. In older literature it was assigned to the Late Triassic to Middle Jurassic. However, Workman (1977) considered this interval to be equivalent to the Phu Krading Formation of NE Thailand, which at that time was considered to be Early Jurassic (now thought to be mainly Early Cretaceous), and that it rested unconformably on folded Triassic or older rocks. In central Vietnam fossil wood of Middle Jurassic–Early Cretaceous age has been recorded in this group (by Hutchison 1989). There are older references indicating the presence of upper Carnian–Norian marine intercalations in the lower part of the Terrain Rouge in northern Laos (Fromaget 1937; Saurin 1950) and ?Norian–Liassic in eastern Cambodia (Saurin 1935) but these may not actually be part of the Terrain Rouge sensu stricto; for example, Saurin (1944) and Fontaine (1964) noted that the Terrain Rouge in central Vietnam rested unconformably on marine Liassic sediments.

The second younger group occurs over most of southern Indochina and is referred to as the ‘Grès Supérieurs’ (also known as the Indosinias Supérieures or Upper Indosinias); it comprises mainly light grey, often cross-bedded, coarse-grained (sometimes conglomeratic) quartz-rich sandstones with intercalations of shale and coal. In southern Cambodia around Kampot and the Bokor Massif the Grès Supérieurs rest on the Terrain Rouge and comprise 160–400 m of conglomerate and sandstone overlain by 200 m of finer-grained sediments containing Early Cretaceous plants (Hutchison 1989). Workman (1977) subdivided the Indosinias (Grès) Supérieures into a lower member, which he tentatively correlated with the Phu Krading and Phra Wihan Formations (and possibly also the Sao
Khua but in a much more proximal, i.e. sandier and coarser-grained facies), and an upper member, which he considered broadly equivalent to the Khok Krut and Maha Sarakham Formations of NE Thailand. The lower member comprises thick sequences of sandstone in the Cardamome Mountains and Bolovens Plateau regions of central and northern Laos and SW Cambodia, is up to 1000 m thick and contains some interbeds of conglomerate, marl and occasional lignite seams. Early Cretaceous pollen has been identified from the upper part of this lower member (SNMGP (Service National des Mines de la Géologie et du Pétrole) 1972–1973). In eastern Cambodia, Laos and neighbouring parts of Vietnam these lower member sandstones overlie (?unconformably) marine upper Liassic (Sinemurian–Toarcian) sediments. The upper member is restricted to the area around Savannakhet eastwards, and this has yielded Early to mid-Cretaceous plants from near Saravanne and reptile bones and freshwater bivalves from Muong Phalane (Hoffet 1939). These bones were originally dated as Senonian by Hoffet (1939) but are now known to be Aptian and equivalent to the Khok Krut Formation of NE Thailand (Buffetaut et al. 2005).

It is interesting to note that Jurassic marine facies across Indochina are apparently restricted to the Liassic, with the youngest interval identified being Toarcian (end of the Early Jurassic) at Ban Don on the Sre Pok in Vietnam, which has yielded the ammonites Hildoceras quadratum and Grammoceras lanenoisi (Workman 1977). Neither of these taxa have been recorded from the Liassic sequences of western Thailand.

Peninsular Thailand and Peninsular Malaysia ‘red beds’

In SW Peninsular Thailand on the western side of the Bentong–Raub and Nan–Uttaradit suture non-marine red beds of the Middle Jurassic to Upper Cretaceous Trang Group crop out. These comprise the following four formations (from bottom to top): Khlong Min, Lam Thap, Sam Chom and Phu Phin (Meesook et al. 2002). As noted by Racey & Goodall (2009), the palynomorph assemblages recovered to date from these formations, although limited, show marked similarities to those of the Khorat Group of NE Thailand, although in some cases they are stratigraphically younger and include samples dated as Albian–Cenomanian, Berriasian–Albian and early Barremian–Berriasian.

In eastern Peninsular Malaysia east of the Bentong–Raub suture, an area that also formed part of the Indochina landmass, the lower part of the Tembeling Group (Kerum Volcanic series and Lanis Conglomerate Formations) is considered equivalent to the Terrain Rouge and its upper part (the Mankin Sandstone and Termus Shale Formations) is considered equivalent to the Grès Supérieurs. Elsewhere in Peninsular Malaysia the Tebak Formation and the Gagua Group (comprising the Badong Conglomerate and the Lotong Sandstone Formations) are considered to be broadly equivalent to the Grès Supérieurs (Hutchison 1989). The Tebak Formation in SE Peninsular Malayasia has yielded Early Cretaceous fossil plants, and the flora of the underlying Tembeling formation is similar and may for the most part be assigned to the Early Cretaceous (Smiley 1970a, b). In NE Peninsular Malaysia also on the eastern side of the Bentong–Raub Suture, red conglomerates and subordinate sandstones, siltstones and shales of the Badong Conglomerate are overlain by the Lotong Sandstone, which comprises cross-bedded sandstones with some rhyolite and coal interbeds (Hutchison 1989). These two formations form the Gagua Group, which has yielded Late Jurassic–Early Cretaceous plant fossils comparable with those of the Tebak Formation. Palynomorphs including abundant Corollina spp. with rare Aequitriradites cf. verrucosis have been recovered from plant-bearing beds within the Lotong Sandstone of the Gagua Formation with A. cf. verrucosis indicating an Early Cretaceous age (Smiley 1970a, b). Within the Termus Shale and Mangkin Sandstone Formations of the Tembeling Group, Jirin & Morley (1994) recorded a palynomorph assemblage comprising Corollina, Exisipollenites, Ephedrites, Cycadopites, Cicatricosisporites, Eucommidites and Clavatipollenites to which they assigned an Early Cretaceous age. Moreover, the occurrence of Clavatipollenites in the Termus Shale Formation indicates a Barremian age whereas its absence in the underlying Mangkin Sandstone Formation may indicate that the latter is pre-Barremian.

Lithologically similar red bed sequences of presumed Mesozoic age have also been encountered in hydrocarbon exploration wells in the offshore Gulf of Thailand although to date these have yielded only rare, poorly preserved, long-ranging Mesozoic palynomorphs (pers. obs.).

Jurassic–Cretaceous sequences of mainland SE Asia (Fig. 5)

Vientiane Basin–Sayabouri–Nakhon Thai Basin

The Vientiane Basin represents the northern extension of the Khorat Basin into southern Laos, where the Phu Kradung to Khok Krut Formations are represented by the lithologically similar Nam
Fig. 5. Lithostratigraphy and possible correlation of Late Triassic to Late Cretaceous sequences of NE Thailand with those of the surrounding region.
Set, Phu Phanang, Ban Ang, Champa and Ban Thalat Formations, which rest unconformably on a Triassic rift sequence (Huai Hin Lat Formation equivalent) and are unconformably overlain by a continental evaporitic sequence (Thangon Formation, which is equivalent to the Maha Sarakham Formation in NE Thailand).

Stokes et al. (1996) observed that the Pak Lay Fold Belt, which borders the western side of the Vientiane Basin, comprises a compressively deformed imbricate wedge of Late Carboniferous to Late Jurassic sediments and associated Triassic to Late Jurassic lavas, agglomerates and tuffs. They concluded that volcanic arc-related activity occurred during subduction prior to collision and the age of this collision can therefore be no older than Late Jurassic. They recorded a palynological assemblage of Corollina spp., Callialasporites dampieri, Cerebropollenites mesozoicus, Uvaesporites spp. and Peripollenites elatoides to which they assigned a Middle to Late Jurassic age. However, this assemblage could equally well extend into the Early Middle to Late Jurassic. They concluded that volcanic arc-related activity occurred during subduction prior to collision and the age of this collision can therefore be no older than Late Jurassic. They recorded a palynological assemblage of Corollina spp., Callialasporites dampieri, Cerebropollenites mesozoicus, Uvaesporites spp. and Peripollenites elatoides to which they assigned a Middle to Late Jurassic age. However, this assemblage could equally well extend into the Early Cretaceous. Radiometric dating of extrusive basalt yields Bajocian and Kimmeridgian ages whereas intrusive granites were dated as Aptian (Stokes et al. 1996) with younger ages in the west. Stokes et al. (1996) concluded that subsequent major erosion was followed by the deposition of the ‘Khorat Group’, which oversteps this truncated Carboniferous–Late Jurassic sequence (and would therefore suggest an age for the ‘Khorat Group’ of no older than Late Jurassic). Granites were intruded in the mid-Cretaceous and these may have been associated with the inversion of the Khorat Basin prior to deposition of the Late Cretaceous Phon Hong Group (comprising the Thangon and Saysomboun Formations) in the Vientiane Basin (Stokes et al. 1996). The Pak Lay–Phetchabun Fold Belt was inverted and eroded during the mid-Cretaceous and possibly also during Tertiary compression, removing the Cretaceous cover from this region.

The Nakon Thai–Sayabouri Basin is located on the western side of the Nan–Uttaradit Suture and extends from the area around Nan in northern Thailand northwards into westernmost Laos and contains a Khorat Group red bed fill.

**Savannakhet Basin**

The Savannakhet Basin represents the eastwards extension of the Khorat Basin into SW Laos and has a broadly similar stratigraphy (Fig. 5). The sequence comprises non-marine Late Triassic synrift clastic rocks of the Apok Formation (Huai Hin Lat Formation equivalent) overlain by alluvial sediments with westward-directed palaeocurrents, of the Bangbouyang Formation (Nam Phong Formation equivalent). These are unconformably overlain by lacustrine to quasi-marine or lagoonal sandstones, mudstones and limestones of the Lamo Formation (Phu Krading Formation equivalent), which pass upwards into mud-dominated fluvial or alluvial red beds of the Salavan Formation, which becomes depositionally more proximal up-section, passing into stacked massive sheet and channelled sandstones (Phu Krading Formation equivalent in its lower part becoming sandier and more like the Phra Wihan Formation in its upper part). This is overlain by the Bangfai Formation (Phu Phan Formation equivalent), which comprises pale-coloured medium-grained to pebbly quartz–feldspathic sandstones deposited in a proximal braided river setting. The absence of an obvious intervening red muddy–silty equivalent of the Sao Khua Formation seen in NE Thailand may be explained by the fact that this basin is closer to the sediment source area, causing a marked thinning (and ‘partial erosion’) of the Sao Khua equivalent interval creating an effective ‘merging’ of the distinctive sandstone-dominated ‘Phra Wihan’ and ‘Phu Phan’ Formation equivalents into a single formation referred to here as the Bang Fai Formation. This in turn is overlain by a sequence of argillaceous sediments with thin sandstones and occasional evaporites deposited in a playa lake setting with fluvial influence and referred to the Champon Formation, which is assumed to be equivalent to the Khok Kruat and possibly in part the Maha Sarakham Formations.

**Western Thailand (west of suture)**

In western Thailand (Mae Sariang–Kanchanaburi Basin area) the marine Mae Moei Group rests unconformably on Triassic marine sediments (Fig. 5). It comprises undifferentiated Early Jurassic (dating based on foraminifers and calcareous algae), and late Toarcian–early Bajocian sediments based on ammonites (Chonglakmani 1982; von Braun & Jordan 1984; Fontaine & Suteethorn 1988; Meesook & Grant-Mackie 1996). Sediments of late Middle Jurassic age (Bathonian–Callovian) and latest Late Jurassic (Kimmeridgian–Tithonian) have not been recorded. Marine sedimentation had ceased by the Late Jurassic and the Mae Moei Group along this western margin of the Sibumasu Block is unconformably overlain by inferred Cretaceous continental red beds of the Kalaw Formation (von Braun & Jordan 1976). This would support the idea of uplift and erosion during the Late Jurassic–Early Cretaceous (Cimmerian) and may be correlatable with the Kimmeridgian orogeny in eastern Burma, where Jurassic Loian Beds are unconformably overlain by Kalaw red beds of inferred Late Jurassic–Early Cretaceous age (Thein 1973). This Cimmerian event was
accompanied by widespread granite emplacement (Klompe 1962; Kobayashi 1984).

Southern Laos, Cambodia and south Vietnam

Key studies in this area are those by Fontaine (1962), Workman (1977) and Tien (1991). The Jurassic is represented by the Tholam and Bandon Suites, which rest unconformably on a variety of Precambrian to Triassic rocks. A Lower Jurassic (Hettangian–Toarcian) to Middle Jurassic (Aalenian–Bajocian) marine sequence is known from southern Laos, Kampuchea and South Vietnam whereas the Bathonian–Callovian is ‘missing’ (as in Western Thailand) and the inferred Upper Jurassic is represented by red beds (Tien 1991). These red bed sequences could be Khorat Group equivalent (?Phu Krading). Jurassic limestones in southern Laos and Vietnam are interbedded with non-marine ?Phu Krading equivalent clastic rocks and overlain by pale-coloured sandstones (possibly equivalent to the Phra Wihan Formation).

Peninsular Malaysia

Peng (1983) recorded ?Late Jurassic to Early–Middle Cretaceous non-marine red beds from the eastern side of the Bentong Raub Suture forming the Tebak Formation and Gagua Group, and similar age red beds are known (Jirin & Morley 1994) from the upper part of the Tmbeling Group (Mangkin Sandstone and Termus Shale Formations) (Fig. 5). Interestingly, the Lower and Middle Jurassic appear to be absent and the Triassic is mainly marine. This suture probably represents the southwards continuation of the Nan–Uttaraditt Suture, which separates the Sibumasu and Indochina Blocks.

Tectonic models for the evolution of the Khorat Basin

The formation and evolution of the Khorat Basin is generally poorly understood and has been the subject of much debate. Saurin (1956) first suggested the presence of two orogenies within this region, an Indosinian (late Triassic) and a ‘Cimmerian’ (late Jurassic to Early Cretaceous), and Klompe (1962) suggested that the boundary between these two orogenies was located along the western margin of the Khorat Plateau. Baum et al. (1970) concluded that the boundary was further to the west along the north–south-trending Chiang-Mai ‘Geanticline’. The later ‘Cimmerian’ Orogeny was accompanied by the widespread emplacement of granites. Early tectonic models assumed that the Khorat Group was deposited as molasse related to the Indosinian Orogeny; that is, the Late Triassic collision between Sibumasu and Indochina (Bunopas & Vella 1978; Hutchison 1989). The model most frequently applied to the area is that of Cooper et al. (1989), who suggested that the Khorat Group was deposited in a thermal sag basin following Late Triassic extension related to the crustal collapse of an overthickened crust produced by the Indosinian Orogeny.

More recently, Lovatt-Smith et al. (1996) interpreted the Khorat Basin as being a foreland basin deposited at the front of a Jurassic Orogenic Belt created by the Song Ma and Song Da sutures to the north or NE, which broadly parallel the axis of the Khorat Basin and mark the suture between the southern China Block and Indochina. Racey et al. (1994, 1996, 1997) concluded that although the Nam Phong Formation could have in part been deposited during thermal subsidence following Triassic extension the same model could not be applied to the overlying Phu Krading to Khok Kruat Formations owing to the presence of a hiatus spanning a large part of the Jurassic. However, the unconformity is now considered to fall within the Nam Phong Formation (as discussed above) and separates a Lower Nam Phong Formation of Late Triassic age from an Upper Nam Phong Formation of probable Jurassic (?Late Jurassic) age. Lovatt-Smith et al. (1996) noted that there is little evidence on seismic data for major syndepositional faulting in the Khorat Basin, suggesting that the stretching factor was low. On regional seismic lines Khorat Group formations have a mainly layer-cake appearance with no significant topographic features for the sediments to infill; that is, they appear typical of deposition in a thermal sag driven setting.

From the regional perspective Metcalfe (1996) concluded that from the Late Permian–Triassic onwards the various blocks that now form much of SE Asia began to collide and accrete in a series of four events. First, the South China and Indochina Blocks collided, followed by the collision and accretion of the Qiantang and Sibumasu Blocks to the Indochina Block in the Triassic. The Indochina Block then became sutured to South China in the NE along the Song Ma and Song Da Sutures and to the Sibumasu Block in the west along the Nan–Uttaraditt Suture. Finally, in the Early Cretaceous the Lhasa Block, and then in the Late Cretaceous the West Burma Block collided and accreted with the Qiantang–Sibumasu terrane (Metcalfe 1996). Of particular relevance to the Khorat Plateau region is the collision between the Sibumasu–Qiantang Blocks and Indochina in the mid-Triassic with associated late kinematic granites in NE Thailand dated at 200 Ma (end Triassic).
marking the final stages of this collision (Singharajwarapan & Berry 2000). This Triassic event is typically referred to as the Indosinian Orogeny and was originally thought to have formed the thermal sag basin into which the Khorat Group was deposited. However, there are several problems with this interpretation, many of which are discussed below, including the significance of the revised age dating of the Khorat Group, regional palaeogeographical considerations, sediment provenance and palaeo-current data, to list a few.

Significance of the Khorat Group

The following sections outline some of the key features of the Khorat Group and age-equivalent sequences elsewhere in mainland SE Asia and discuss the bearing of these observations on the new ages for the group outlined by Racey & Goodall (2009) and their significance in understanding the geological evolution of the region. A key factor here is that if the revised ages are correct and there is a major hiatus in the Jurassic, then what is the evidence from other geological data for this ‘event’?

Age dating

Revised age dating based on palynology by Racey & Goodall (2009, and references therein) indicates that the Phu Krading to Khok Krurat Formations are mainly Early Cretaceous (Berriasian to Aptian) in age. A Late Jurassic age for the lowermost part of the Phu Krading Formation cannot be completely ruled out, as the lowermost part of the Phu Krading Formation lacks the key Early Cretaceous palynomorph *D. etruscus* but also has not yielded any Jurassic-restricted palynomorphs.

Moreover, recent vertebrate discoveries (see Buffetaut et al. 2006, 2009) within the Sao Khua Formation (previously reported to be Late Jurassic) are now considered to be Early Cretaceous, and those from the Phu Krading Formation previously thought to be Early Jurassic are now considered to be Late Jurassic to Early Cretaceous, based on their degree of evolution and similarity to other similar assemblages from SE Asia.

The age of the Nam Phong Formation is more problematic. Limited palynological data from the Phu Horm-1 well presented by Racey & Goodall (2009) suggest that the Upper Nam Phong Formation cannot be older than Pliensbachian (middle Early Jurassic) based on the presence of *C. turbatus*, but is unlikely to extend into the Early Cretaceous (based on the absence of the Early Cretaceous marker *D. etruscus* seen throughout most of the overlying Phu Krading Formation). Consequently, the age of the Upper Nam Phong Formation could fall anywhere between the Pliensbachian and the end of the Jurassic.

Because the Lower Nam Phong Formation is bounded by unconformities it cannot according to the code of lithostratigraphic nomenclature be assigned to the same formation as the Upper Nam Phong Formation. Consequently, either the Lower Nam Phong or Upper Nam Phong should be given a new formation name.

Palaeogeographical reconstructions; regional correlation

If the Khorat Group was mainly Jurassic (a view still held by some Thai geologists) then it is difficult to explain the absence of marine influence and deltaic sediments within the group, as it is bordered by marine Jurassic sediments to the east and west. Although bivalves have been reported from the Phu Krading Formation, no convincing specimens of marine taxa have yet been illustrated. It could be suggested that the Khorat Group ‘delta’ portion of this fluvial system is located further south in the Gulf of Thailand and is now obscured by a thick cover of Tertiary sediments. However, two observations are against this model. First, there are well penetrations within the Gulf of Thailand that have penetrated Mesozoic non-marine red beds and, second, similar Late Jurassic–Early Cretaceous non-marine red bed sequences occur even further south in eastern Peninsular Malaysia.

In western Thailand, within the marine Mae Moei Group, late Toarcian, Aalenian–Bajocian and Oxfordian ammonites were noted by Chonglakmani (1982), and Beauvais & Fontaine (1993) noted the presence of the coral *Montiivalita numismalis*, a taxon considered a marker for the Bathonian. Meesook & Grant Mackie (1993), in a study of the marine Jurassic faunas of western Thailand, noted that previous reports of Late Jurassic (Oxfordian) ages could not be supported and that the faunas were mainly Toarcian–Bajocian; that is, latest Early to middle Middle Jurassic (see also Meesook & Grant-Mackie 1996). Further west in eastern Burma, Bender (1983) also recorded marine Jurassic sediments. To the east in southern Laos, Kampuchea and central Vietnam, Early and Early–Middle Jurassic sediments have also been noted, but here
the inferred Late Jurassic sediments are red beds and are associated with Kimmeridgian basalts (Hofet 1933; Hoffet & Le Maitre 1939; Fontaine 1962; Tien 1991). Interestingly, throughout most of these areas the Callovian and Oxfordian, and possibly most of the Late Jurassic, appears to be missing. All microfossils (pollen and spores) and macrofossils (vertebrates and bivalves) found to date in the Khorat Group are interpreted as non-marine (Racey et al. 1994, 1996) and would not therefore fit with a marine delta model of any age (Jurassic or Cretaceous). Moreover, no evidence of marine diagenesis or sedimentary structures or trace fossils have been noted in Khorat Group sediments to date.

Recent vertebrate data
Buffetaut et al. (2006) have recently noted that the vertebrate fauna from the Phu Kradung Formation of NE Thailand is very similar to that from the Upper Shaximiao Formation of Sichuan in southern China which is assigned a Late Jurassic age. Buffetaut et al. also noted that the fauna of the Sao Khua Formation is in part similar to that of the Napai Formation from Guangxi in southern China, and the Khok Kruat Formation vertebrates are very similar to the Aptian–Albian forms from China. E. Buffetaut (pers. comm.) suggested that in terms of time there is a wider gap between the Phu Kradung and Sao Khua vertebrate assemblages than between those of the Sao Khua and Khok Kruat assemblages. This may indicate that if the Khok Kruat Formation is Aptian then it is more likely that the Sao Khua Formation is Barremian (the inference being that the Phu Kradung Formation would be earliest Cretaceous (Berriasian) or Latest Jurassic (Tithonian).

Sedimentation rates
If the Khorat Group was mainly Jurassic in age then it is difficult to explain how red bed sedimentation could have continued uninterrupted from Late Triassic to Early Cretaceous time over an interval of c. 90 Ma with no major breaks or unconformities yet only accumulated around 4500 m of sediment (a rate of 49 m Ma\(^{-1}\)), which appears low for this type of depositional system. On the other hand, if the Khorat Group, including the Upper Nam Phong Formation, is mainly confined to the Late Jurassic–Early Cretaceous and was deposited over a 49 Ma interval (excluding the Lower Nam Phong Formation dated as Late Triassic) then this represents a sedimentation rate of c. 92 m Ma\(^{-1}\), which appears to be more realistic.

**Palaeocurrents**

Palaeocurrent data for the Khorat Plateau from outcrops presented by Heggemann et al. (1994) and Racey et al. (1996) indicate that the Nam Phong Formation had both eastward- and westward-directed palaeocurrents (Fig. 6), whereas in the Phu Kradung to Phu Phan Formations they are mainly directed towards the SE and west (Figs 7–9), implying sediment sourcing from the NE and east. The Khok Kruat palaeocurrents tend to be directed towards the west (Fig. 10). Thus, based on palaeocurrents, the Nam Phong Formation differs from all the overlying formations that traditionally make up the Khorat Group, possibly because of the continued influence of Triassic extensional faults causing uplift and erosion. Of the palaeocurrents shown only the three data points from the western margin of the Khorat Plateau are known to be from the Lower Nam Phong Formation and therefore of Late Triassic age, though interestingly these are all directed eastwards. It is not clear in the field whether the other data shown are from the Upper or Lower Nam Phong Formation.

Mouret (1994) noted that the pale-coloured sandstones (Phra Wihan and Phu Phan Formations) thicken ‘upstream’ towards the NE with a concomitant thinning of the interbedded floodplain-dominated red beds of the Phu Kradung and Sao Khua Formations. This he noted is coupled with an increase in the size and abundance of quartz pebbles in the same direction. Mouret (1994) suggested that the sandstones are probably diachronous and may be younger in Thailand than in Vietnam to the east. He further suggested that early Kimmeridgian tectonics in north and south Vietnam predates the onset of deposition of the pale-coloured sandstones of the Phra Wihan Formation, which would agree with the revised Early Cretaceous age for this formation. Heggemann (1994) also suggested that the Khorat Group sequence changes from being more proximal in the east to distal in the west of the Khorat area.

The Vientiane Basin and Pak Lay area to the north have been studied by Lovatt-Smith & Stokes (1997) and Stokes et al. (1996), respectively. The Mesozoic red bed fill in this basin effectively represents the northern part of the Khorat Basin although the formation names change to use Lao terminology (Fig. 5).

Palaeocurrents in the Salavan and Lamo Formations, which are broadly equivalent to the Phu Kradung and Phra Wihan Formations (Fig. 5), in the Savannakhet Basin of Laos to the immediate east of the Khorat Basin are dominantly towards the SW and west (Figs 7 and 8). An unconformity
Fig. 6. Palaeocurrent data for the Late Triassic Nam Phong Formation and its equivalents. (Note a dominance of both eastward- and westward-directed palaeocurrents.) Data sources: Hegemann et al. (1994); A. Racey et al. (unpubl. data).
Fig. 7. Palaeocurrent data for the latest Jurassic? to Early Cretaceous Phu Kradung Formation and its equivalents. Palaeocurrents appear to be dominantly coming from the north to NE. Data sources as for Figure 6.
Palaeocurrent data for the Early Cretaceous Phra Wihan and Sao Khua Formations and their equivalents. Palaeocurrents appear to be flowing mainly from the NE, with some also from the east. Data sources as for Figure 6.
Fig. 9. Palaeocurrent data for the Early Cretaceous Phu Phan Formation and its equivalents. Sediment transport directions are dominantly from the NE, with a minor component from the east. Data sources Hegemann et al. (1994), Racey et al. (1994, 1996) and A. Racey et al. (unpubl. data).
Fig. 10. Palaeocurrent data for the Early Cretaceous Khok Kruat Formation. Although outcrops of this formation are limited, thus restricting the amount of palaeocurrent data for interpretation, the dominant sediment transport direction appears to have changed to being from the west.
or disconformity at the top of the Salavan Formation is associated with a change in provenance, with palaeocurrents flowing mainly to the SW within the overlying fluvial sandstones of the Bang Fai Formation (Phu Phan equivalent) as shown in Figure 9. Mouret et al. (1993) and Mouret (1994) have also suggested the presence of a minor unconformity at the base of the Phu Phan Formation based on changes in lithology and palaeocurrents coupled with seismic stratigraphy.

Fig. 11. Distribution of Mesozoic red bed sequences of Late Triassic to Early Cretaceous age and the effect of major lateral displacement along the Red River Fault system coupled with a clockwise rotation of Indochina relative to China. This, coupled with other data discussed in the text, suggests that the original source area for the Khorat Group may have been far to the north in southern China as initially suggested by Carter & Bristow (2002).
Because the main palaeocurrents in the Khorat Group flowed towards the west and SW, it is difficult to envisage how these could have been associated with the Indochina–Sibumasu collision in the Late Triassic with subsequent uplift and erosion throughout the ‘Jurassic’, as we would expect a significant number of palaeocurrents to also flow towards the east and NE; that is, sediment would be shed from both sides of the suture or collision.

**Palaeomagnetic data**

The palaeomagnetic data of Yang & Besse (1993) suggest that only a minor rotation of Thailand has occurred with respect to South China in the Tertiary. Yang & Besse noted a large discrepancy between the poles for Indochina and other published data for the South China Block for both the Triassic–Jurassic and Jurassic–Cretaceous boundaries and calculated that 1500 ± 800 km of post middle Cretaceous left lateral slip has occurred along the Red River and Xian–Shui–He fault zones with an approximately 14 ± 7° clockwise rotation of Indochina relative to South China (Fig. 11).

The North China Block, South China Block, Yunnan and Indochina were probably in contact with each other since the Late Triassic and then they moved slowly northwards relative to Eurasia until the Cretaceous (Enkin *et al.* 1992; Yang *et al.* 1992). The calculated relative pole positions for both the Khorat and Yunnan Basins show no significant change in latitude during the Late Triassic to Early Cretaceous whereas post-Cretaceous displacement between the Khorat Basin of NE Thailand and both the central Yunnan Basin and South China Block is implied. Yang & Besse (1993) noted that the various blocks to the west of the stable South China Block (e.g. around Markam (Si Mao Basin), the Song Pan Ganze area and the Yunnan Basin) all display similar strong clockwise rotations, suggesting that they, like Indochina, were subsequently displaced, probably along left lateral strike-slip faults (the Xian–Shui–He and Red River Faults or their predecessors) as narrow tectonic slivers. This tends to broadly support the general extrusion model for the Tertiary collision of the Indian Plate with Eurasia proposed by Peltzer & Tapponier (1988).

**Fig. 12.** Variations in rock fragment type between the various formations of the Khorat Group and the Triassic Huai Hin Lat and Nam Phong Formations. The Huai Hin Lat and Nam Phong Formations (stippled) show a marked volcanic component compared with the remainder of the Khorat Group. Within the Phu Kradung to Phu Phan field the area overlapping with the Nam Phong and Huai Hin Lat fields dominantly belongs to the Phu Kradung Formation. The Khok Kruat Formation appears to have a different composition from the other formations.
Carter & Bristow (2002), using palaeomagnetic data from Yang & Besse (1993) and subsequent estimates of left lateral Tertiary displacement of between 500 and 1300 km (from Leloup et al. 1995; Sato et al. 1999) along the Indochina–Sibumasu suture, have shown that in palaeogeographical restorations the pre-extrusion location of the Khorat Basin was more probably within South China close to the Sichuan Foreland Basin.

Insamut et al. (1995) undertook a palaeomagnetic study of the Late Cretaceous–Early Tertiary Phu Tok Formation red bed sequence, which overlie the Albian–Cenomanian Maha Sarakham Formation in northern Thailand. Their data suggested that the Phu Tok Formation was deposited at a palaeolatitude of 20–30°N (i.e. close to southern China). Moreover, they interpreted a clockwise rotation of the palaeopoles for ‘Indochina’, which suggests at least a 1000 km sinistral displacement along the Red River Fault, possibly associated with the collision between India and Eurasia, further supporting the extrusion model for the Himalayas collision.

Provenance

Racey et al. (1996) noted that, based on thin-section modal analysis and whole-rock chemistry of outcrop samples, the Huai Hin Lat and Nam Phong Formations contained a significant volcanic component unlike the overlying formations (Fig. 12). The Nam Phong Formation samples are most probably from the Lower Nam Phong Formation, which has in part yielded Rhaetian palynomorphs. In terms of trace element chemistry the Nam Phong and Huai Hin Lat Formations show a depletion in Fe₂O₃ + MgO and an enrichment in Na₂O possibly indicative of a calc-alkaline volcanic component (Fig. 13). A minor albeit very diluted volcanic component was also noted by Racey et al. (1996) for the lower part of the overlying Phu Kradung Formation, which may either represent a minor contemporaneous volcanism at this time or minor reworking of Nam Phong lithologies. The Phu Kradung to Phu Phan Formations are dominated by metamorphic quartz (in contrast to the underlying Nam Phong Formation). Racey et al.

![Fig. 13. Variations in whole-rock chemistry between the various formations of the Khorat Group and the Triassic Huai Hin Lat and Nam Phong Formations. The depletion in Fe₂O₃ + MgO and enrichment in Na₂O for the Nam Phong and Huai Hin Lat Formations (stippled) supports a partial calc-alkaline volcanic origin for these sediments, as suggested in Figure 12. The Khok Kruat Formation contains more feldspar (supported by Fig. 14), and hence has a higher Na₂O content, suggesting a change in provenance for this uppermost formation of the Khorat Group.](image)
(1996) originally suggested that the bulk of these sediments (Phu Kradung to Phu Phan Formations) may have been derived from the Kontum Massif to the east with some input from the Louangphabang and Truongson Belts and Rao Cao Massif to the north and NE (i.e. the Annamitic Mountain Belt).

However, Carter & Bristow (2002) have suggested that the palaeogeographical position of the Khorat Basin in Early Cretaceous times was more probably much closer to the Sichuan Foreland Basin to the north; this is situated to the immediate south of the Qinling Orogenic Belt, which may have provided a more likely sediment source area for the Khorat Group sediments. The Qinling Orogenic Belt would form a suitable mature hinterland, being dominated by 250 Ma granitic–plutonic, rocks and this would support the petrographic data of Racey et al. (1996), which indicated that much of the Khorat Group was dominated by metamorphic quartz and metamorphic rock fragments, suggesting sourcing from an area of regionally metamorphosed crystalline basement. The Khok Kruat Formation at the top of the Khorat Group has a broadly similar provenance but additionally contains a large proportion of detrital feldspar, indicating a possible igneous component as shown in Figure 14. The Khok Kruat Formation also differs from the underlying formations of the Khorat Group in having westerly directed palaeocurrents (Fig. 10) and in showing minor evidence of possible marine influence based on the presence of bi-directional ripple trains, which may indicate partial deposition in a marine-influenced sand flat, although the formation is dominantly fluvial in aspect.

If there were a Late Jurassic–Early Cretaceous ‘Cimmerian’ event or collision then one might expect to see some evidence of contemporaneous volcanism at around Phu Kradung times. However, detrital mineralogy (and palaeocurrents) suggests that sediment sourcing was mainly from the east and NE (i.e. away from any potential continuing collision to the west, and is dominated by metamorphic quartz. Racey et al. (1997b), in a fission-track study of the Khorat Group, noted thatapatites within the Phu Kradung, Phra Wihan and Phu Phan Formations were relatively rich in chlorine (up to 3 wt%), suggesting a partial volcanic source (chlorine-poor apatites would indicate a metamorphic or granitic source, which we know existed to the east and NE and supplied much of

![Fig. 14. Variations in quartz, lithic fragments and feldspar content between the various formations of the Khorat Group and the Triassic Hual Hin Lat and Nam Phong Formations. Most of the formations significantly overlap in this figure although the Khok Kruat Formation stands out as being significantly enriched in feldspar.](image-url)
the sediment to the Khorat Basin). The chlorine-rich apatites were observed to be fairly euhedral, possibly indicating derivation from a nearby volcanic source. Moreover, many of the apatites collected from the Phu Phan Formation near the centre of the Khorat Plateau (sample Ap8 in fig. 1 of Racey et al. 1997b) showed many dislocations, a feature commonly observed in ‘chilled’ apatites from a tuffaceous source (I. Duddy, pers. comm.). Combined these observations on the apatites may indicate minor near-contemporaneous volcanism at this time (i.e. latest Jurassic to Early Cretaceous).

Radiometric dating of detrital micas from the Phu Kradung and Phra Wihan Formations gives a Devonian–Carboniferous age of 330–380 Ma for the last intrusive or metamorphic event affecting the source area (Heggemann et al. 1994). This suggests that the source area for the micas was granitic or high-grade metamorphic rocks, with the likely source area proposed by Heggemann et al. (1994) being the Devonian–Carboniferous ‘Variscides’ of North–Central Vietnam and Laos, although the Qinling Orogenic Belt in southern China to the north could also be a potential source area. This would not agree with the idea of a Mesozoic metamorphic event (‘Indosinian’) in the sediment source area as proposed by Bunopas & Vella (1978), Ridd (1978) and Maranate & Vella (1986). However, this is based on a limited database of only two samples, one from the Phu Kradung Formation and one from the Phra Wihan Formation.

**Volcanism–radiometric dating**

K–Ar ages of igneous rocks reported by Stokes et al. (1996) from the Pak Lay Fold Belt area have shown the presence of folded and thrust Jurassic rocks including basalts dated at 152.5 ± 6.3 Ma (Late Jurassic–Kimmeridgian) and 167.2 ± 5.2 Ma (Middle Jurassic–Bajocian). Moreover, Stokes et al. have also redated the Ban Samxong granite (previously considered to be Triassic) which partially intrudes these Jurassic sequences as 117 ± 3.0 Ma (i.e. Aptian). Consequently, there was some extrusive volcanism in the region in the Late Jurassic, whereas Aptian granites may have been associated with the mid-Cretaceous inversion event shown in Figure 3.

**Diagenesis**

Petrographic studies of the Khorat Group have revealed a complete absence of marine cements, with the calcite and ferroan calcites observed being of clear pedogenic origin. All diagenetic processes observed in this sequence were indicative of deposition in an arid to semi-arid continental clastic setting (Canham et al. 1996). Early reports of ‘limestones’ within the Phu Kradung and Sao Khua Formations are now referred to calcretes, and early reports of marine bivalves and ichthyosaurs have been discounted (see Racey et al. 1996, for details).

**Fission-track analysis**

Carter et al. (1995) used fission-track dating to date the Phra Wihan Formation at 125 ± 20 Ma (basal Berriasian to Albian). However, this was based on a single sample (T90/17). Assuming the analysis for separating single grain ages is correct, their data indicate a possible age range of 165–85 Ma (Bathonian–Santonian). Six other zircon samples from the Phra Wihan and Phu Kradung Formations were also shown by Carter et al. to have a significant spread in single grain ages, although no information on the youngest age mode of these samples was presented. No other results were discussed in detail, although a younger age mode of 133 ± 13 Ma (159–107 Ma, Callovian–Albian) was claimed for the Khok Krut Formation and 160 ± 6 Ma (172–148 Ma, Aalenian–Tithonian) for a Sao Khua sample, but no further data were provided to support these age assignments.

Racey et al. (1997b) processed 16 outcrop samples forapatite fission-track analysis from the Phra Wihan, Phu Kradung and Phu Phan Formations, of which four yielded no apatite and a further four samples had low apatite abundance. An additional seven outcrop samples from Laos were also analysed. The samples showed that temperatures of 120 °C had been exceeded during burial and that cooling had commenced from Early–Mid Tertiary (65–45 Ma) with cooling possibly starting c. 10 Ma earlier in the Savanakhet Basin of Laos to the east. Although it was not possible to calculate a palaeoeeothermal gradient at the time of maximum palaeotemperature, the application of any realistic heat flow value would indicate the erosion of at least 3.5 km of section since early to mid-Tertiary, with much of this occurring in the mid–late Tertiary (35–25 Ma). This amount of erosion is in line with the 3–3.5 km of erosion of post Phra Wihan sediments in the vicinity of the Phu Phan Anticline since the Palaeocene suggested by Mouret et al. (1993) based on the truncation of at least 3200 m of section observed on various seismic lines in the area.

**Sea-level changes**

Mouret et al. (1993) have attempted to correlate parts of the Khorat Group with sea-level shifts, correlating the distinctly coarser and sandier Phu Phan Formation with a relative sea-level fall at 128.5 Ma (Barremian) and the Phra Wihan Formation with a relative sea-level fall at 177 Ma (Aalenian). These dates would not fit with the new
vertebrate and palynology dating. However, there is a wide range of tectonic and climatic factors that can cause a change in fluvial style leading to the deposition of these coarser, higher energy, more quartz-rich formations, and there is additionally no direct field evidence for incision caused by base-level changes.

Seismic data

Within the general literature there has been much confusion over the term Indosinian, with some workers using it to refer to Permian and others to Triassic events. Much of this confusion has arisen from a failure to recognize that there are two separate closely spaced Triassic orogenic events as indicated by seismic data from the Khorat Plateau area (J. E. Booth, pers. comm.). The first, referred to as ‘Indosinian I’ occurs at the top of the Permian sequence, prior to Triassic rifting and deposition of the Carnian–Norian Huai Hin Lat Formation (assigned to the Kuchinarai Group by subsurface workers). This represents major inversion and uplift of the entire basin with associated deep erosion and peneplanation together with the development of thick- and thin-skinned thrust systems within the Permian. A second event or unconformity referred to as ‘Indosinian II’ separates the Huai Hin Lat Formation from a Rhaetian ‘Lower Nam Phong unit’. This represents a second period of inversion and uplift of the basin with local folding and thin-skinned thrusting. These two Indosinian orogenies are separated by a period of extension during which deep half-grabens were formed across much of the region and filled with fluvial and lacustrine sediments and volcanic rocks of the Huai Hin Lat Formation. A third unconformity (Cimmerian or Indosinian III) may also be recognized at the end of the Triassic between the ‘Lower Nam Phong’ and ‘Upper Nam Phong’ Formations, and is recognized as a significant angular unconformity along the southern edge of the basin and as a non-conformity elsewhere in the basin.

To the east of the area, in western Laos, a major Cimmerian uplift event is also seen on seismic sections (E. Fenk, pers. comm.), although here there is some uncertainty as to the exact placement of the Nam Phong Formation with respect to this unconformity in that it could be picked above or below base Khorat Group.

Yin & Harrison (1996) have identified a Late Jurassic orogeny in southern China (mistakenly referred to as Indosinian), and a similar Kimmeridgian age event is also recognized in Vietnam.

Conclusions

There is mounting evidence, as outlined herein, that much of the Khorat Group is Early Cretaceous in age and is separated by a hiatus spanning much of the Jurassic from the Late Triassic. In addition, there is strong evidence from biostratigraphy, provenance and subsurface data (seismic) that the Lower Nam Phong Formation should be excluded from the Khorat Group. A foreland basin setting for the Khorat Group, most probably associated with flexural subsidence at the front of a ?late Jurassic orogenic belt, would be more in keeping with the observed broad lateral extent, relative uniform thickness and mineralogical maturity of the Phu Kradung to Khok Kruat Formations. This model would also better fit the calculated sedimentation rates when the revised Early Cretaceous age for much of the Khorat Group is considered. The mechanism for basin formation is still unclear but some (e.g. Carter & Bristow 2002) have suggested that a mechanism for this marked Early Cretaceous erosion may have been the collision between the Lhasa Block and Eurasia, with a possible sediment source area being the Qinling Orogenic Belt to the north in China.

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