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An alternative plate tectonic model for the Palaeozoic–Early Mesozoic Palaeotethyan evolution of Southeast Asia (Northern Thailand–Burma)

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Abstract

An alternative model for the geodynamic evolution of Southeast Asia is proposed and inserted in a modern plate tectonic model. The reconstruction methodology is based on dynamic plate boundaries, constrained by data such as spreading rates and subduction velocities; in this way it differs from classical continental drift models proposed so far. The different interpretations about the location of the Palaeotethys suture in Thailand are revised, the Tertiary Mae Yuam fault is seen as the emplacement of the suture. East of the suture we identify an Indochina derived terrane for which we keep the name Shan–Thai, formerly used to identify the Cimmerian block present in Southeast Asia, now called Sibumasu. This nomenclatural choice was made on the basis of the geographic location of the terrane (Eastern Shan States in Burma and Central Thailand) and in order not to introduce new confusing terminology. The closure of the Eastern Palaeotethys is related to a southward subduction of the ocean, that triggered the Eastern Neotethys to open as a back-arc, due to the presence of Late Carboniferous–Early Permian arc magmatism in Mergui (Burma) and in the Lhasa block (South Tibet), and to the absence of arc magmatism of the same age East of the suture. In order to explain the presence of Carboniferous–Early Permian and Permo-Triassic volcanic arcs in Cambodia, Upper Triassic magmatism in Eastern Vietnam and Lower Permian–Middle Permian arc volcanites in Western Sumatra, we introduce the Orang Laut terranes concept. These terranes were detached from Indochina and South China during back-arc opening of the Poko–Song Ma system, due to the westward subduction of the Palaeopacific. This also explains the location of the Cathaysian West Sumatra block to the West of the Cimmerian Sibumasu block.

Keywords: Southeast Asia; Palaeodomains; Orang Laut terranes; Palaeopacific; Palaeotethys; Back-arc type Neotethys

1. Introduction

Thailand and adjacent areas are interpreted as being the product of the collision between several microcontinents. The Cimmerian Sibumasu block (Metcalfe, 1984) lies in the westernmost part of Thailand, West of the Mae Yuam fault. To the East of it is located the Inthanon zone, considered to be of Northern Palaeotethyan affinity. The latter is considered by Ueno and Hisada (2001) to represent nappes displaced from the East, overthrusting a basement of Cimmerian (Sibumasu) affinity, on the basis of the presence of Ordovician limestone and sandstones, interpreted as typically Cimmerian (see discussion later). To the East of the Inthanon zone, East of the "cryptic suture" of Barr and MacDonald (1991) or Chiang Rai tectonic line (considered by many authors as the main Palaeotethys suture), is located the Sukhothai zone, associated with volcanic features (Lampang volcanics) and separated from the Indochina block by the Nan-Uttaradit Suture Zone.

In this paper we would like to propose an alternative model in which the Inthanon and the Sukhothai zones are both part of a block detached from Indochina due to the opening of the Nan basin, in Carboniferous or Permian time (Fig. 1). From that, we would like to propose southward subduction of the Eastern part of the Palaeotethys under Gondwana and under the Gondwana-derived Eastern Cimmerian blocks. Finally, we would like to propose the existence of the Orang Laut terranes, a band of terranes detached from Indochina/South China during the Early Permian due to the subduction of the Palaeopacific Ocean.

The assumption that the Inthanon and Sukhothai zones form a terrane detached from Indochina at the opening of the Nan basin is based on the fact that the Chiang Rai line does not

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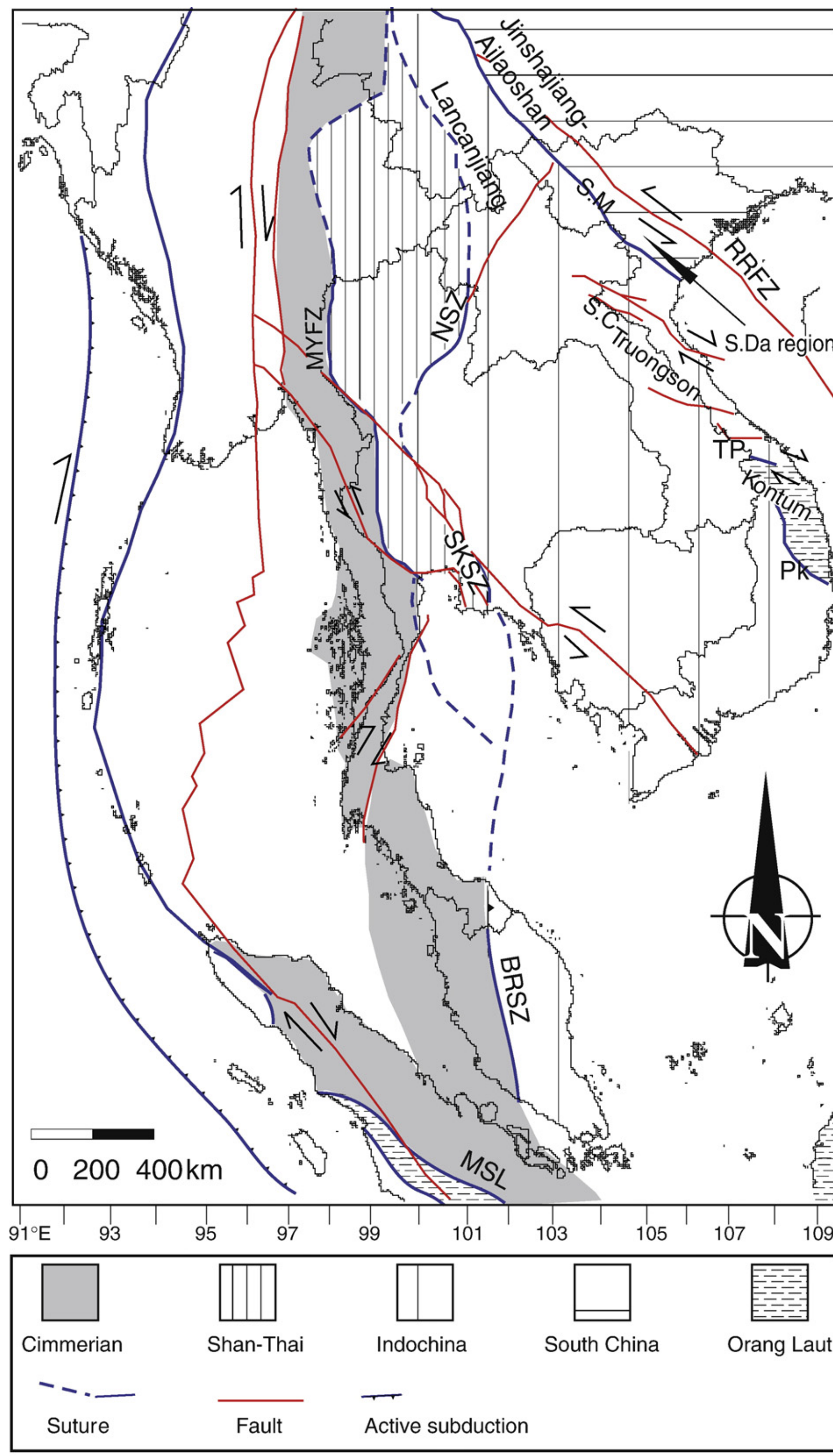

Fig. 1. Tectonic map of Thailand and adjacent regions showing the Cimmerian, Shan–Thai, Indochina, South China and Orang Laut palaeodomains, as well as their limits. BRSZ: Bentong Raub Suture Zone; MSL: Medial Sumatra Line; MYFZ: Mae Yuam Fault Zone; NSZ: Nan-Uttaradit Suture Zone; Pk: Poko Suture; RRFZ: Red River Fault; SKSZ: Sa Kaeo Suture Zone; SM: Song Ma Line; TP: Tamky-Phuok Son suture.

represent a suture, or at least not the main Palaeotethys suture, which is likely to be located somewhere along the Mae Yuam fault. We assume that the Inthanon zone does not represent nappes displaced from the East, but part of the long-lived Northern margin of the Palaeotethys Ocean. Even if the term Shan–Thai has originally been used to define the Cimmerian domain, we propose to use this term to name the Indochina derived block detached during the opening of the Nan basin, as this block is located in the Eastern Shan states of Burma and in Thailand, and to use only the term Sibumasu for the Cimmerian block, West of the Mae Yuam fault, regarded as the only Palaeotethys suture at that time.

2. Review of the possible Palaeotethys sutures in Northern Thailand

Different emplacements have been proposed to locate this suture in the past years (Fig. 2), regarding whether or not the Inthanon and Sukhothai zones are a part of Sibumasu. In Thailand, three possible emplacements for this suture have been proposed, from East to West: the Nan-Uttaradit Suture (Bunopas and Vella, 1978), the Chiang Mai–Chiang Rai volcanic belt (Barr and MacDonald, 1991), and the Mae Yuam fault (this work). Bunopas and Vella (1978) and Bunopas (1981) separated Thailand palaeogeographically into two zones: the Western Shan Thai block and the Eastern Indochina block, divided by the Nan-Uttaradit Suture Zone, considered to be the Palaeotethys suture. Metcalfe (1984) introduced the term Sibumasu for the areas including the Shan States (Burma), the Western part of peninsular and mainland Thailand, the Eastern part of Sumatra and the Western part of the Malay peninsula. Barr and MacDonald (1991) proposed a model in which the Palaeotethys suture is located along a “Cryptic suture” North of Chiang Mai. In their model, the Lampang belt would represent the volcanic arc associated with subduction of the Palaeotethys. Ueno (1999) divided Thailand into four zones, namely, from West to East, the Sibumasu Block, the Inthanon zone, the Sukhothai zone and the Indochina block (Fig. 3), but in his model the Palaeotethys suture is located along the Cryptic suture and thus the Inthanon zone is seen as a nappes pile displaced from the Eastern of the suture towards the West and covering a Cimmerian basement (Ueno and Hisada, 2001).

It has to be stated that the suture between two palaeogeographic entities is not necessarily shown by the presence of ophiolites. In fact, as shown by Stampfli and Borel (2002) for the Tethyan region, the majority of ophiolitic sutures are due to obduction processes and not to subduction. It is the case for the ophiolites around the Neotethys suture, which mainly witness the obduction of back-arc basins and not so much the subduction of the main ocean. Hence, the boundary between two terranes is best shown by the juxtaposition of two regions that show different geological histories until the moment of their docking. As the Palaeotethys suture must be located between the Cimmerian blocks and the Indochina block (or an Indochina derived block), the period when those two entities were in a very different position was the Late Carboniferous–Early Permian. In fact, during that period, the Cimmerian blocks were still attached to Gondwana, which was undergoing glaciation, while Indochina was lying in an intertropical position as shown by the presence of coral limestone and coaly sandstones. This fact is now widely accepted and has been demonstrated by many authors (e.g. Ueno, 1999; Myo Min et al., 2001; Ueno and Hisada, 2001; Ueno, 2002, 2003a).

Physiographically, Thailand is characterized by two mountain ranges: the Western range, which continues southwards into the Tenasserim division in Burma, and the Sukhothai fold belt to the East. The two ranges are separated by the central alluvial plain, where Bangkok is located. To the East of the Sukothai fold belt is found the Khorat plateau, which occupies most of northeastern Thailand (Isan) towards the Mekong river.

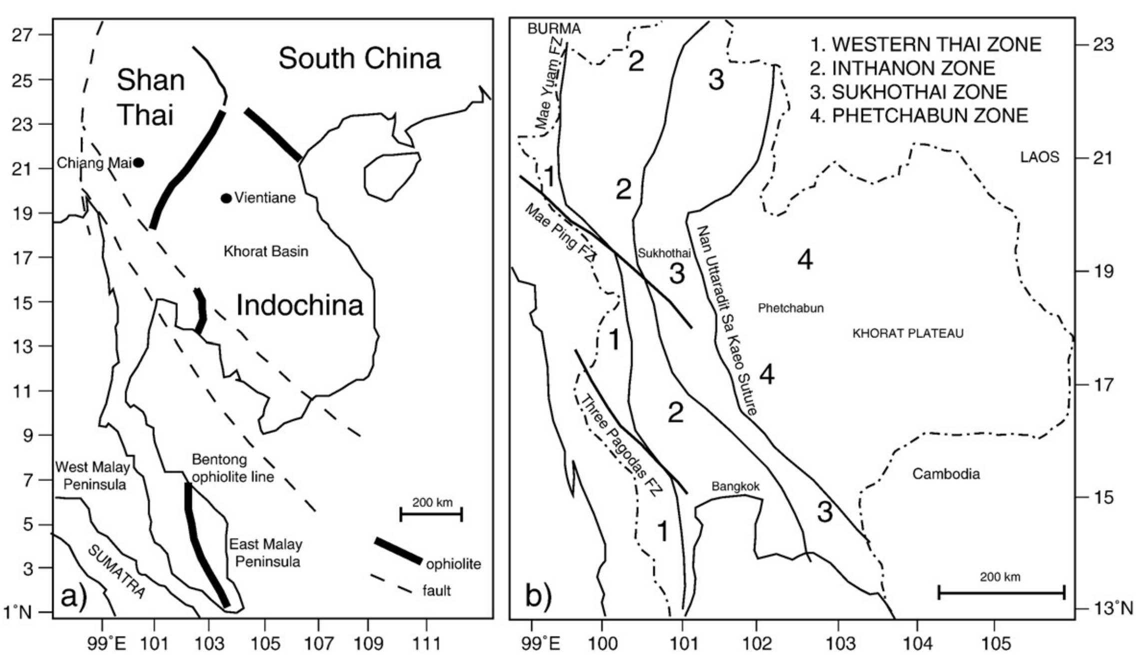

Fig. 2. a) The subdivision of Thailand by Bunopas (1981) in which the “Palaeotethys suture is located along the Nan-Uttaradit Suture Zone. After Bunopas (1981); b) the subdivision of Thailand after Barr and MacDonald (1991) in which the Palaeotethys suture is located between the Inthanon zone (2) and the Sukhothai zone (3), along the “cryptic suture”. After Barr and MacDonald (1991).

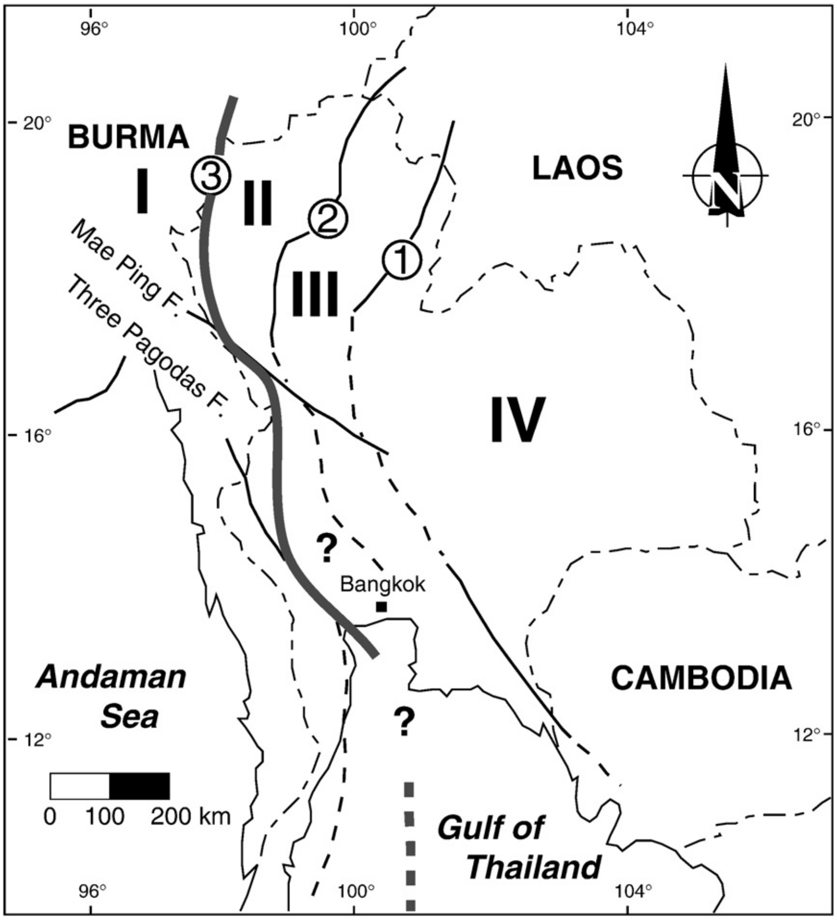

Fig. 3. The subdivision of Thailand by Ueno. Modified from Ueno (2003a).

The review presented here is based on data compilation and fieldwork. The field data resulting from fieldwork are given by Ferrari (2007), while here we focus on the reinterpretation of the existing data (including ours) in a plate tectonic point of view. We will shortly introduce the different areas and discuss the arguments in favour or against the attribution of this Asia–Gondwana divide. Fig. 4 shows the position of the localities cited in this section, on a tectonic map.

2.1. The Nan-Uttaradit ophiolitic suture zone

The Nan-Uttaradit ophiolitic belt is exposed in the easternmost part of Northern Thailand along the Nan River, at the Eastern margin of the Sukothai fold belt, between the “Sukothai zone” and the “Indochina block” of Ueno (1999). During the past decades it has been studied by several authors (e.g. Bunjitradulya, 1978; Thanasuthipitak, 1978; Barr et al., 1985; Barr and MacDonald, 1987; Ferrari, 2007) and was interpreted as a suture zone between the Shan–Thai terrane (in its first definition) and the Indochina plate. This suture zone was seen by many authors as the main Palaeotethys suture, but recent works have shown that this is not the case (Ueno and Hisada, 2001).

The oldest rocks exposed in the Sukothai fold belt are those of the Pha Som Metamorphic Complex (Singharajwarapan and Berry, 1993, 2000), composed of different blocks ranging in composition from volcanic rocks to meta-greywacke, limestone, piemontite-quartz schists, radiolarian cherts and a serpentinite melange. The age of the radiolarites ranges from Early Permian to Middle Triassic (Hada et al., 1999). The opening of the basin probably took place in the Late Carboniferous–Early Permian, based on different age dating of cherts (Fig. 5).

The time and mainly the modality of the Nan-Uttaradit Basin closure are still subject to controversy. Amphiboles in the metamorphosed “ophiolite” from the Sirikit Dam area, studied by Helmcke (1985) using the K/Ar method, were dated at 344 ± 22 Ma, while Barr et al. (1985) found ages of 269 ± 12 Ma for greenschist metamorphism by K/Ar dating on actinolite. However, the presence of Upper Permian to Middle Triassic radiolarites implies that a basin still existed at that time. Hence, the final closure of the Nan-Uttaradit Basin must have taken place prior to the deposition of the Carnian–Norian molasse described by Luddecke et al. (1991) along the highway Rong Kwang-Nan.

As there is evidence for a compressive event in the Loei Area, at the Devonian–Carboniferous boundary (Chonglakmani and Helmcke, 2001), proved by data on the basement of the Khorat Basin (Kozar et al., 1992), the 344 Ma amphiboles are likely to represent the closure of a former basin. In fact, in the Loei area, there is evidence for arc magmatism dated at 374 ± 33 Ma and for MORB at 360 ± 11 Ma (Intasopa and Dunn, 1994). However, these ages have to be considered carefully, as

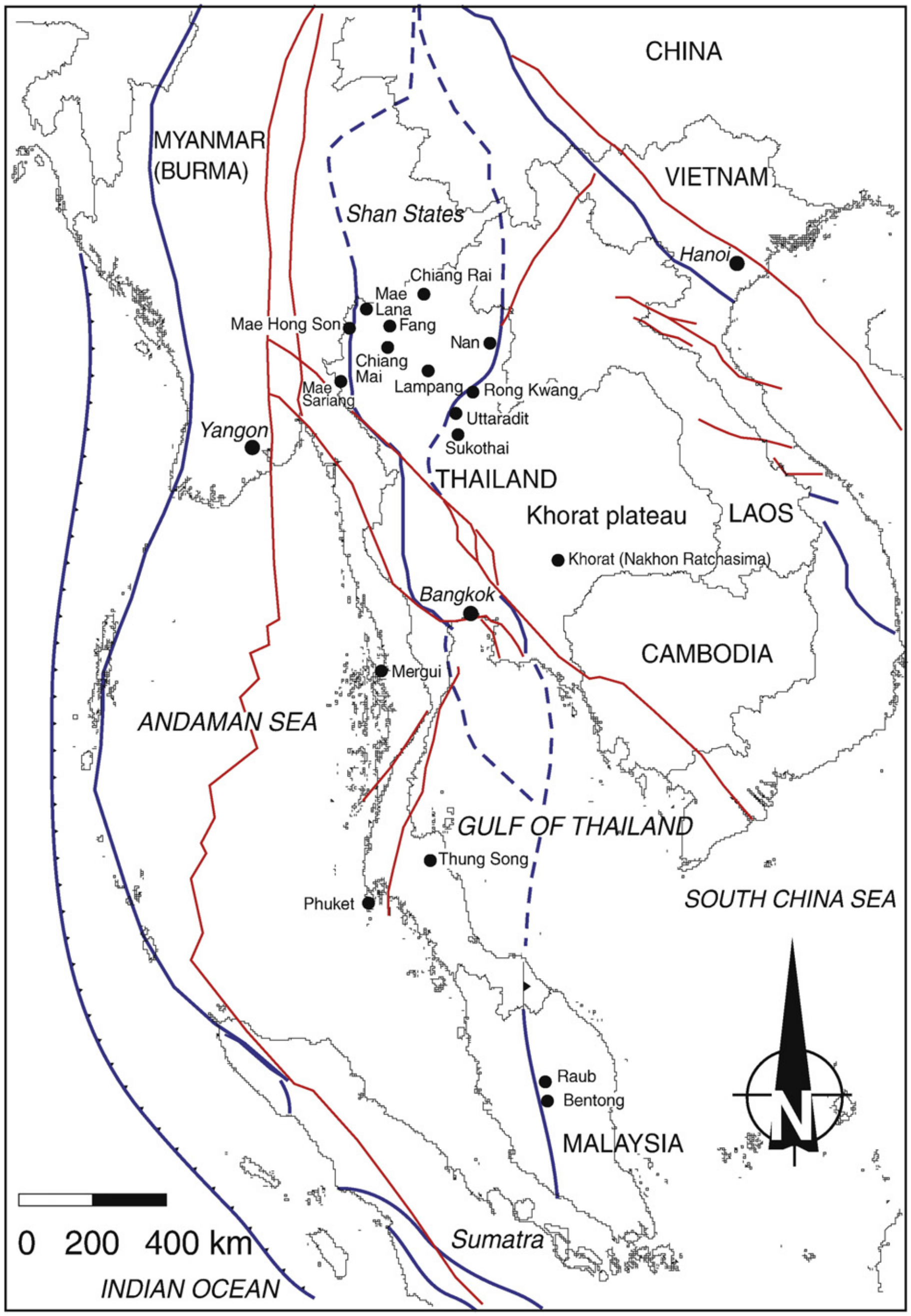

Fig. 4. Map of Southeast Asia with the limits of the Terranes the localizations of the localities cited in the text.

they are derived from K–Ar and Sr–Nd techniques, which often give older ages than modern methods. The ages of 269 ± 12 Ma for greenschist metamorphism obtained by Barr et al. (1985) possibly represent the obduction age of one part of the Nan basin (Ferrari, 2007), as the basin continued to exist until the Early Permian.

The final subduction has probably taken place towards the present-day East; in fact, in the Loei region, there is evidence of arc magmatism dated at 238 ± 4 Ma and 237 ± 12 Ma by the $^{40}Ar/^{39}Ar$ method (Intasopa, 1993). The Lampang Volcanic series, to the West of the Nan Suture, have been correlated to the Lincang–Jinghong volcanic belt in Yunnan (Yang et al., 1994; Barr et al., 2000), which, as demonstrated by Heppe (2004), is not a volcanic arc but the witness of bi-modal embryonic rift volcanism. Indeed, the Lampang series have been deposited in a basin, formerly considered to be of intramontane type (Helmcke, 1982; Chonglakmani and Helmcke, 1989). The volcanites have been interpreted to be subduction-related, without a possible distinction between an arc and a back-arc setting (Barr et al., 2000). The age of these series (U–Pb method) is of 240 ± 1 Ma (Barr et al., 2000). Due to the ages of the Lampang series, we interpret this volcanism as subduction-related, due to the subduction of part of the Palaeotethys under the Shan–Thai block during the Middle Triassic (see Section 5). The abortion of the back-arc is due to the inversion of the tectonic regime at the time of the collision between Shan–Thai/Indochina and the

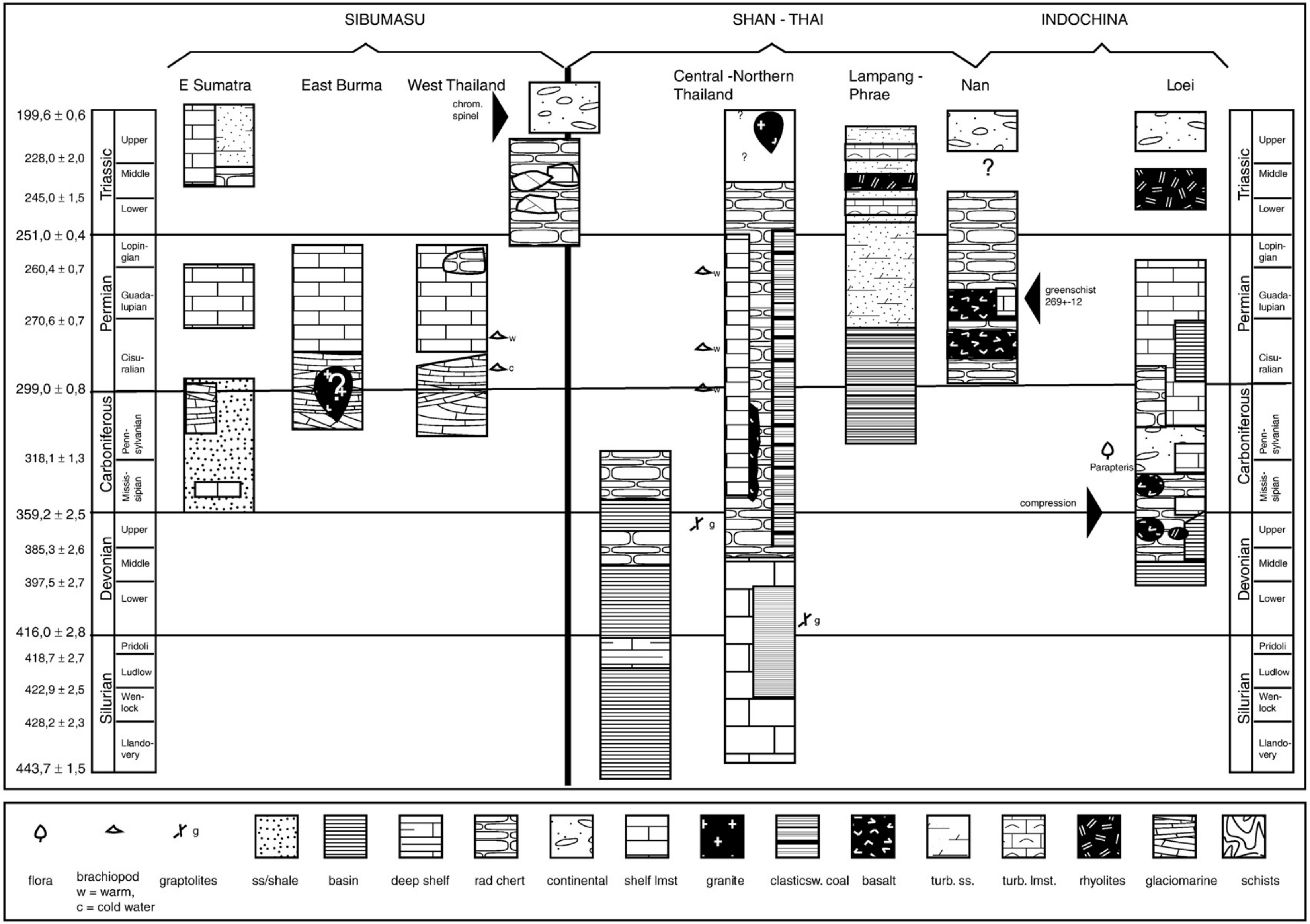

Fig. 5. Synthetic stratigraphic columns of the different domains in Northern Thailand, Southern Burma and Northern Sumatra. Data from Caridroit et al., 1990; Luddecke et al., 1991; Charusiri et al., 1992; Mitchell, 1992; Ratanasthien, 1992; Vachard et al., 1992; Baird et al., 1993; Dawson, 1993; Intasopa, 1993; Sashida et al., 1993; Fontaine et al., 1994; Intasopa and Dunn, 1994; Shi and Archbold, 1995; Fontaine and Salyapongse, 1997; Panjasawatwong et al., 1997; Ueno and Igo, 1997; Sashida et al., 1998; Charoentitirat and Ueno, 1999; Chonglakmani, 1999; Fontaine and Salyapongse, 1999; Kobayashi, 1999; Mantajit, 1999; Ueno, 1999; Barr et al., 2000; Fontaine et al., 2000; Sashida et al., 2000a,b; Singharajwarapan and Berry, 2000; Chonglakmani and Helmcke, 2001; Kamata et al., 2002; Sashida and Salyapongse, 2002; Barber and Crow, 2003; Panjasawatwong et al., 2003; Ueno, 2003b; Feng et al., 2004a,b; Hisada et al., 2004; Zhou and Liengjarern, 2004; Kobayashi et al., 2006; Ferrari, 2007. Time scale according to Ogg (2004).

Cimmerian blocks. Some of the granites of the Eastern Belt of Cobbing et al. (1986) may have the same origin (see discussion about the granites in Section 2.2).

2.2. The Chiang Mai volcanic belt and the Chiang Rai Line ("cryptic suture")

The Chiang Mai volcanic belt is a scattered zone of Permo-Carboniferous volcanic rocks, extending from Chiang Rai, to the northeast, to the Thai–Burmese border, in the Mae Hong Son region. It is located between the "Inthanon zone" and the "Sukhothai zone" of Ueno (1999), but mainly within the Inthanon zone as the basalts are also found between Chiang Mai and Mae Hong Son. This belt has been interpreted in different ways in the last decades. Hutchinson (1975) interpreted it as an "uncertain ophiolite", Bunopas and Vella (1978), as well as MacDonald and Barr (1978) attributed the volcanics to a remnant volcanic arc. Later on, Barr et al (1990) interpreted the belt as consisting essentially of basalts, related to an intraplate continental rifting phase and not subduction-related. Metcalfe (2002) named part of this belt (near Chiang Mai and Chiang Dao) "Chiang Mai Suture", but, as noticed by Ueno (2002), this name was used by Cooper et al. (1989) to define a line which corresponds more to the Chiang Rai line.

The Chiang Rai line, which corresponds to the "Cryptic suture" of Barr and MacDonald (1991) is the zone that separates the Inthanon zone from the Sukothai zone of Ueno (Ueno, 1999, 2002, 2003a). It is composed of scattered mafic rocks with some ultramafite, in the region of Chiang Sen and Mae Chan. Its continuation to the South of Chiang Mai is quite obscure and has been inferred to lie between the central and the eastern granitic provinces of Cobbing et al. (1986) (Fig. 6).

The stratigraphy of the Inthanon zone is characterized by a thick sedimentary sequence from the Ordovician to the Jurassic (Fig. 5). In general, from the Silurian to the Triassic, the sedimentation is typical of siliciclastic marine basins, with the deposition of graptolite shales, radiolarian cherts and clastic sediments containing coal and plant remnants. The typical sections showing this sedimentation are mainly located along the road 107 from Chiang Mai to Fang. In the past, the Devonian to Triassic cherts belonging to this series were referred as the "Fang Chert" (Bunopas, 1981).

During the Silurian and Devonian, shallow marine sediments, containing brachiopods, were coexisting with basin sediments (see Fig. 5 and references herein). From the Visean to the Late Permian the detrital sedimentation was accompanied by the deposition of platform limestone and the presence of basaltic rocks of the Chiang Mai volcanic belt (at least in the Visean, as shown by Ferrari, 2007). The limestones are often found in association with the basalts, overlying them: it is the case in Mae Lana, North of Mae Hong Son, and in a quarry 15 km to the NE of Chiang Mai (Ferrari, 2007). In the other cases the basal contact of the limestone is not visible. The limestones contain no quartz grains, indicating that they were protected from the surrounding detritism, probably because they were deposited on top of the basalts, which were forming islands. In fact, according to Barr et al. (1990), the basalts of this belt were set in a continental intraplate context; as the rest of the sedimentation is basinal (siliciclastic sediments and radiolarites), it is likely that the volcanics formed islands within these basins, on top of which the platform limestone developed. We performed Nd–Pb isotopic studies to confirm this setting (Ferrari, 2007).

As the marine ages and the fauna found in this zone are more typical of Northern Palaeotethyan deposits, rather than Gondwanan (Ferrari, 2007) it is likely that it represents the ancient long-lived Northern passive margin of the Ocean, or a rim basin of the latter, in which deep marine and shallow marine sediments were deposited from the Silurian to the Triassic.

Ueno and Hisada (2001) and Ueno (2003a) expressed the possibility that the series of the Inthanon zone may have been emplaced there as tectonic nappes displaced from the East.

There is no doubt that the strata are deformed, especially in the Western part of the zone, where overturned strata have been observed. Near the Mae Yuam Fault, overturned fold limbs exhibit turbidites of the Triassic–Jurassic Mae Sariang Formation showing reverse graded bedding that underlie series equivalent to those of the Inthanon zone. Nevertheless, the possibility of West directed nappe tectonics is mainly based on the assumption that the Chiang Rai line represents the main Palaeotethys suture (and thus warm water Late Carboniferous to Early Permian fauna to the West of it must come from the East) and on the basis of the presence of Ordovician limestone similar to the Thung Song limestone of southern peninsular Thailand, considered to be typically "Cimmerian". We think that the latter argument cannot be taken as an evidence, because during the Ordovician both Indochina and Sibumasu were located on the Eastern part of Gondwana, on similar latitudes, thus there is no reason for an Ordovician feature to be considered as typically Cimmerian or Indochinese, as the Palaeotethys did not open until Silurian or Devonian times.

2.3. The Mae Yuam fault zone

The Tertiary Mae Yuam fault is located in the westernmost part of Northern and Central Thailand. It trends North–South, passing near the cities of Mae Hong Son and Mae Sariang and possibly extends to Southern Thailand, East of Phuket. The fault separates the Inthanon zone, to the East, from the Sibumasu block of Ueno (1999). According to Bunopas (1981), the geology along the fault, in Northern Thailand, is characterized by the presence of sediments going from the Ordovician to the Cenozoic. Its main feature is the Triassic–Jurassic Mae Sariang Group, composed of limestone, bedded cherts, shales and sandstones. Various sections in the surroundings of the Mae Hong Son–Mae Sariang road show the following sequence: bedded chert, bedded chert with limestone blocks, turbiditic sandstone and arkosic sandstone, conglomerate. The arkosic sandstones and the conglomerates are clearly deposited in continental–epicontinental environments. Fine grained distal turbiditic sandstones have been found all along the fault, but the thickness of the series is difficult to estimate. The stratigraphic position of these turbidites under the continental sediments allows us to express the possibility that they are part of a flysch sequence, but this has yet to be demonstrated. Indeed,

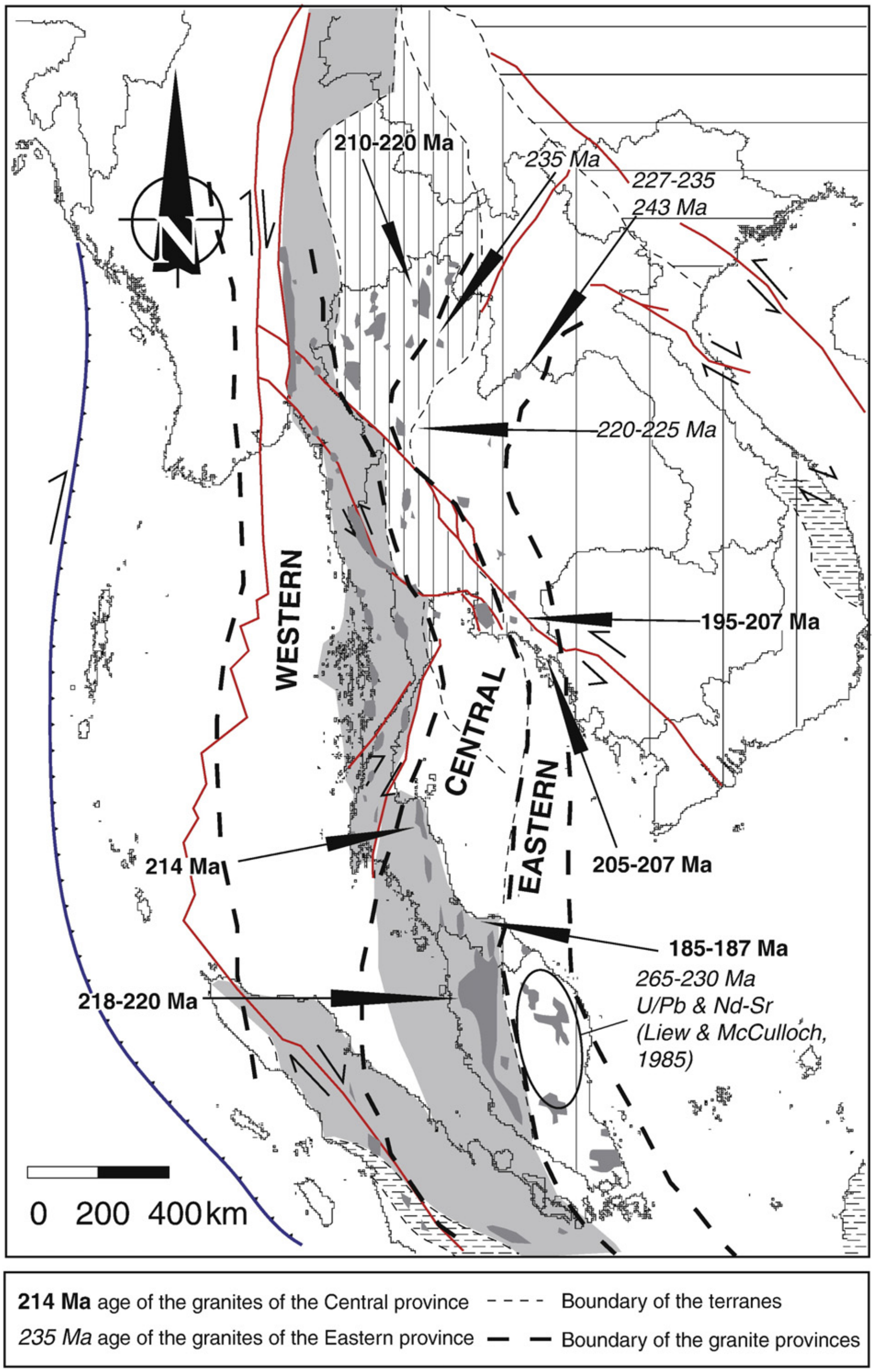

Fig. 6. The Western, Central and Eastern granite provinces, based on Charusiri et al. (1993); Ages: $^{40}Ar/^{39}Ar$ (Charusiri et al., 1993), apart for these of the East Malaya arc (Liew and McCulloch, 1985). The symbols for the terranes are the same as in Fig. A.

there are no ophiolitic rocks cropping out in the region, but there is no doubt that the fault represents the divide between the Cimmerian and the Northern Palaeotethyan domains, due to the marked difference between the Eastern side (Inthanon) and the Western side (Sibumasu) of it, as noticed by many authors.

As already mentioned, the Carboniferous and Permian of the Inthanon zone contain tropical deposits, with corals, fusulinids and warm water brachiopods; Myo Min et al. (2001) pointed out the fact that the fault represents the westernmost extension of these Late Carboniferous tropical facies as well as the easternmost extension of the glaciomarine ("pebbly mudstone") deposits, typical of the Latest Carboniferous–Early Permian strata of the Sibumasu Block. The pebbly mudstones are mainly found within the Phuket Group, in Southern Thailand, the Taungoo area, in Burma, West of Mae Hong Son, the Mergui series, in Southern Burma, the Singha Group in Eastern Peninsular Malaysia and the

Tapanuli Group in Sumatra. They sometimes contain detrital diamonds, showing close isotopic affinity with diamonds from the Argyle lamproite in Australia (Griffin et al., 2001; Win et al., 2001) and indicating a connection between the two areas during the deposition of the diamictites. The fact that all the diamonds seem to derive from the same source is also a good indication for the location of the block, during the Carboniferous, near Australia in the Gondwana Continent.

These major differences between both sides of the Mae Yuam fault zone clearly indicate different positions of both blocks during the Late Carboniferous and until at least the Middle Permian (Myo Min et al., 2001). The Western Sibumasu side has a typical Gondwanan history, with a transition from high to low latitudes, while the Eastern Inthanon side shows no major variations in a climatic point of view. This strongly suggests that the Palaeotethys suture s.s., between the Cimmerian block of Sibumasu and the Indochina derived Shan Thai block, is located along the Mae Yuam fault zone. The same differences in depositional environments are found in Sumatra (e.g. Barber and Crow, 2003), where Late Carboniferous–Lower Permian glacio-marine deposits are also present (see Section 3.2).

As stated above, an oceanic suture is not necessarily witnessed by the presence of ophiolites, as it seems to be the case for the Mae Yuam region. Nevertheless, Hisada et al. (2004) found detrital chromian spinels within the clastic rocks of the Triassic Mae Sariang Group. The chemistry of the spinels suggests that they derive from ophiolitic rocks, indicating that the latter were exposed in the region during the deposition of the Mae Sariang molasse. Of course there is still the possibility that the spinels come from elsewhere, but their presence within the molasse is a fact that must be taken into consideration.

Another point is the position of the Tertiary Mae Yuam fault zone. This late strike-slip fault undoubtedly separates the Sibumasu block from the Inthanon zone which contains typical Northern Palaeotethyan sediments. If it does not represent the Palaeotethys suture, it means that, as suggested by Ueno and Hisada (2001), the Inthanon zone is composed of a Cimmerian basement covered by nappes of Northern Palaeotethyan origin displaced from the present-day East. Nevertheless, as it is a strike-slip, nearly vertical fault, it is more likely that it developed in the proximity of a suture zone (following the geometry of the plate boundary) rather than at the front of an eroded tectonic nappe-pile.

2.4. Extension of the Palaeotethys suture to the South: the Bentong Raub Suture Zone

The Palaeotethys suture extends to the South through the Bentong Raub Suture Zone, which extends from southernmost peninsular Thailand to Raub and Bentong in the Malay Peninsula, East of Malacca. It forms a North–South trending line of approximately 20 km in width bordering the Main Range Granitoids of Peninsular Malaysia, and comprising mélange, ribbon cherts, schists and serpentinized mafic to ultramafic bodies. Metcalfe (2000) presented an overview of the suture zone including data about its stratigraphic, tectonic and magmatic features. To the West of the suture the stratigraphy presents typical Cimmerian characteristics, such as the Lower Permian glacio-marine Singha Formation, whereas to the East the series are of Cathaysian affinity, with typical flora and warm climate indicators for the Lower Permian (Metcalfe, 2000). The age of the oceanic ribbon cherts preserved within the suture ranges from Middle Devonian to Middle Triassic, and the ages of the limestone and chert clasts within the mélange range from Early Carboniferous to Early Permian. These ages are typically Palaeotethyan, and it makes no doubt that the Bentong Raub Suture is the divide between the Cimmerian and the Cathaysian domains. The orogenic deformation, according to Metcalfe (2000), initiated during the Late Permian–Early Triassic.

The East Malaya volcanic arc is found to the East of the suture and is composed of Middle to Upper Permian andesites and Triassic acid volcanics. The volcanites were accompanied by the granitoids of the Eastern Belt, interpreted as representing an ensialic plutonic arc. The age of the granitoids ranges from 265 to 230 Ma (Liew and McCulloch, 1985), but, as cited in Metcalfe (2000), Darbyshire (1988) found only Triassic ages. Metcalfe (2000) supposed that the age of this volcanic arc is likely to extend down into the Carboniferous, but this assumption is not supported by any data, and must therefore be confirmed. This arc is classically regarded as being related to the northwards subduction of the Palaeotethyan oceanic lithosphere. However, the absence of equivalent arc magmatism northward, as well as the possible absence of Lower Permian vulcanites could suggest that subduction before that time did not take place, or that part of the arc disappeared. We interpret this arc as resulting from the subduction of part of the Palaeopacific Ocean. As shown in Section 4, this is not in contradiction with the fact that the Bentong–Raub suture is the divide between Sibumasu and Indochina as, in this case, Eastern Palaeotethys and Western Palaeopacific have to be seen as a system and not as two completely separated entities.

3. Two key regions: Sumatra and Northern Vietnam

Sumatra and Northern Vietnam are two key areas for the understanding of the Palaeozoic–Mesozoic tectonic evolution of Southeast Asia. In Sumatra, Cathaysian units containing Early Permian arc association are located to the SW of typical Cimmerian units characterized by diamictites. A good review of the geology of the island as well as of the tectonic models has been given by Barber and Crow (2003). In Northern Vietnam, in the Truong Son belt and in the Kontum massif, high temperature metamorphism occurred in the range of 250–240 Ma (Lepvrier et al., 2004); the collision along the Song Ma line is classically interpreted as the northward subduction of Indochina beneath South China and could be related to the opening–closing of the Song Da rift. The latter was then affected by a Late Triassic phase of shortening.

3.1. Sumatra

In Sumatra, units of Gondwanan affinity are clearly distinguished from the units of Cathaysian affinity (Fig. 7). In Northern Sumatra, northeast of the Sumatran fault, the

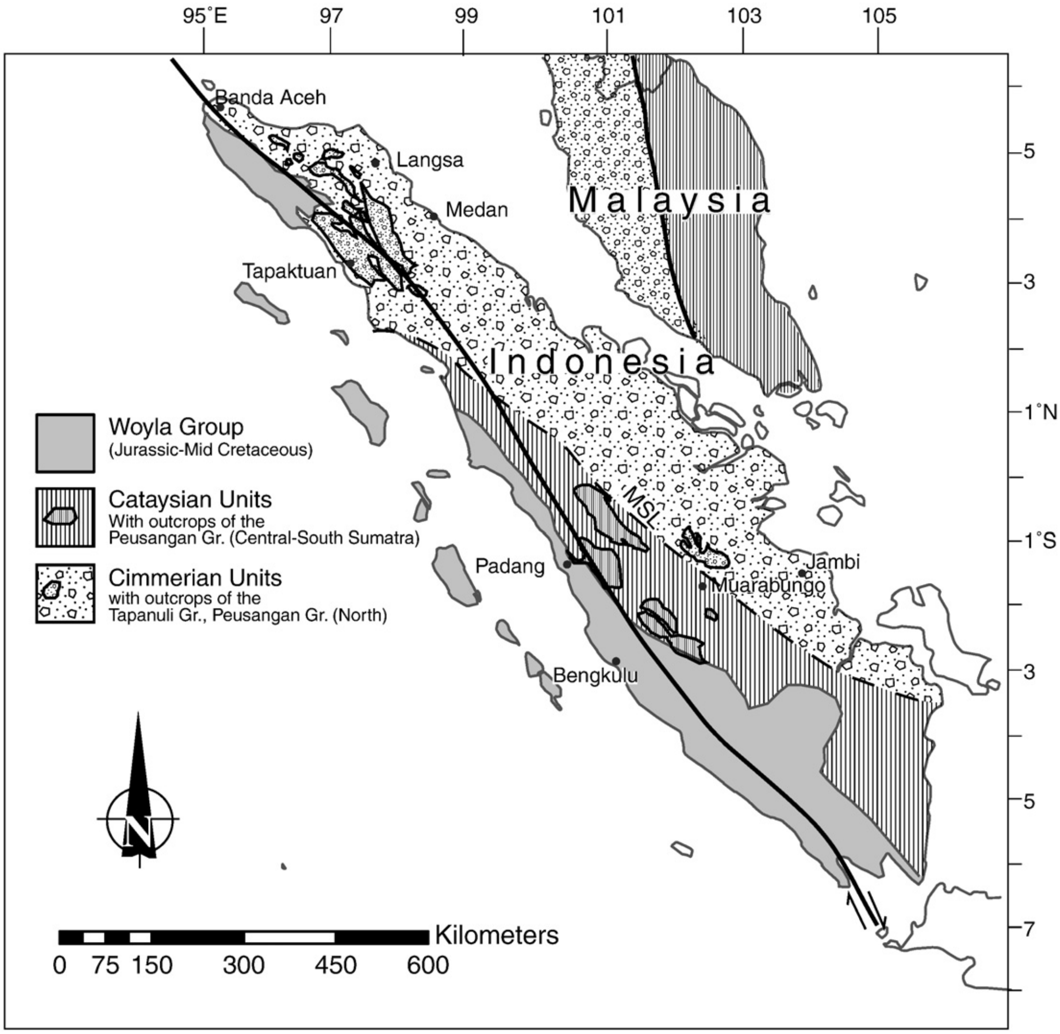

Fig. 7. Map of Sumatra showing the location of the outcrops showing Cimmerian affinity, Cathaysian affinity and the Jurassic–Cretaceous Woyla Group. Redrawn after Barber and Crow (2003).

Palaeozoic series are all part of the Sibumasu block. The Carboniferous–Early Permian Tapanuli Group is composed of Visean massive limestone, interpreted by Fontaine and Gafoer (1989) as deposited in a temperate climate (Alas formation), diamictites (Bohorok Formation), and clastic sediments (Kluet Formation). The attribution of this Group to Sibumasu is made on the basis of the presence of the glaciomarine sediments of the Bohorok Formation and of the Late Carboniferous–Early Permian Pangururan Bryozoan Bed, correlated with the Early Permian Bryozoan Bed in Phuket. Barber and Crow (2003) compared the series of the Tapanuli Group with those of the Bonaparte Gulf in northwestern Australia, demonstrating their similitude, and giving further evidence for the appartenance of Northern Sumatra to the Sibumasu Block and for the proximity between Australia and Sibumasu (on Gondwana) until the opening of the Neotethys. The Permian–Triassic Peusangan Group is composed of Middle to Late Permian and Triassic limestone (Situtup, Kaloi and Batumimil Formations) and Middle–Late Triassic cherts and rhythmites (Kualu Formation). The upper part of the Kualu Formation is composed of *Halobia*-bearing sandstones. Neither latest Permian nor Early Triassic rocks have so far been found in Northern Sumatra. The Kualu formation has been correlated to the Semanggol Formation in the northwestern part of the Malay Peninsula, interpreted as part of Sibumasu.

In Central Sumatra, the geology is similar to the Northern part of the island. Within the Tapanuli Group, the Mentulu Formation, composed of tilloids, was directly correlated with the Bohorok Formation. However, the Visean Kuantan limestone, to the Southwest of the Mentulu Formation, correlated with the Alas formation, is regarded as Cathaysian. In fact, as stated by Fontaine and Gafoer (1989), the depositional environment of the Kuantan Formation is tropical whereas the Alas formation was deposited in a temperate climate. For this reason, the Kuantan limestone was interpreted as part of a Cathaysian terrane (West Sumatra Block). The boundary between the West Sumatra Block and the Sibumasu terrane is assumed to be represented by the Medial Sumatra Line of Hutchinson (1994). In Central Sumatra this line is found as a NW-SE trending belt of intensely folded chlorite, tremolite, muscovite and quartz schists identified as the Pawan and Tanjung Puah members of the Kuantan Formation.

In contrast to Northern Sumatra, the Peusangan Group of Central Sumatra is characterized by Permo-Triassic Cathaysian units. The Late Asselian to Sakmarian Menkarang Formation is characterized by tropical marine fauna and by the “Jambi flora” which, according to Vozenin-Serra (1989), consists entirely of Cathaysian species. Within the Peusangan Group, there are volcanic arc assemblages (Palepat and Silungkang formations) associated with Early Permian limestone containing corals and fusulinids. The Permian association of Central Sumatra is interpreted as lying unconformably on the Kuantan Limestone (Barber and Crow, 2003) and as being part of the Cathaysian West Sumatra Block. As in Northern Sumatra, no latest Permian–Early Triassic rocks have been described. The Triassic Tuhur Formation is correlated with the Kualu Formation of Northern Sumatra. It contains a limestone member, partly conglomeratic, which recycles clasts of Mid- to Late Permian fusulinid limestone, indicating a Late Permian–Middle Triassic unconformity. Barber and Crow (2003) interpret the Late Permian–Early Triassic gap as a period of uplift, where Mid–Late Permian limestone situated on horst blocks were eroded. This phase would have been followed by a phase of extension, where the deep water cherts and shales of the Kualu and Tuhur Formations were deposited. In their interpretation, the similitude of the Middle and Late Triassic deposits of the Kualu and Tuhur formations indicates that Sibumasu and West Sumatra were contiguous at that time.

In Southern Sumatra, even if the outcrops are scarce, the series are equivalent to those of Central Sumatra, with a northeastern Cimmerian part and a southwestern Cathaysian part, where *Gigantopteris* flora has been described.

The fact that the Cathaysian units of the West Sumatra block are located to the West of the Sibumasu block is interpreted by Hutchinson (1994) as the result of a Cenozoic strike-slip movement along the Median Sumatra Tectonic Zone, which, as suggested by Barber and Crow (2003), is likely to represent the trace of a suture. Crow (2005) cited the presence of serpentinites within the Median Sumatra Zone. Barber and Crow (2003) regard this strike-slip fault movement as Late Permian–Early Triassic due to the similitude between the Middle to Late Triassic sequences of West and East Sumatra. Concerning the initial position of the West Sumatra block, they inferred it not to be adjacent to East Malaya, because there the arc magmatism took place from Middle to Late Permian (Early Triassic?) whereas in Sumatra it ceased in Mid-Permian times.

3.2. Vietnam: Truong Son belt and Kontum Massif

The territory of Vietnam is formed by two continental blocks, Indochina to the southwest and South China to the northeast. The divide between the two blocks was traditionally represented by the Tertiary Red River Fault (Tapponnier et al., 1990) or along the Song Ma suture (Hutchinson, 1975) also called Song Ma line (Şengör and Hsü, 1984) in Northern Vietnam. This suture is composed of mafic and ultramafic rocks represented by intensely sheared lenses of serpentinized peridotite and pyroxenite of the Pac Nam Formation, and by gabbro and gabbro-amphibolite of the Bo Xinh complex. The timing of the amalgamation of South China with Indochina is still controversial. Classically, the collision was assumed to have taken place during the Devonian–Early Carboniferous (Gatinsky, 1986; Gatinsky and Hutchinson, 1987), or the Visean (Hutchinson, 1989) resulting in the formation of a continent called East Asian continent. On the other hand, the presence of Devonian fresh-water fishes, typical of South China, South of the Song Ma line (Thanh et al., 1996) is an argument in the direction of a Devonian terrestrial connection between both blocks, even if some species of fresh-water fish have a marine stage. Şengör and Hsü (1984), even if accepting an Early Carboniferous docking, inferred the main orogenic event to have taken place during the Late Triassic, along the Song Da zone, situated between the Song Ma Suture and the Red River Fault.

Other authors (Lepvrier et al., 2004 and references herein) consider that the Song Da zone more likely represents an intracontinental rift. We also share this point of view. This zone consists of volcanic rocks represented by the Lower Permian andesitic–basaltic to picritic–andesitic–basaltic Cam Thuy Formation and the Upper Permian–Early Triassic komatiitic–basaltic and trachybasaltic–trachyandesitic–trachydacitic Viet-nam Formation. The volcanites are intercalated with Permian–Early Triassic terrigenous–carbonate sediments. Lepvrier et al. (2004) interpret the Song Da zone as a back-arc opened during the Permian due to the subduction of Indochina beneath South China. In fact the same authors dated the metamorphism ($^{40}Ar/^{39}Ar$ method) at 250–240 Ma, implying that the collision along Song Ma took place during the Early Triassic. We also share this interpretation about the timing of the collision along the Song Ma Suture.

Further to the South, North and West of the Kontum Massif are located two other suture zones: the Tamky–Phuok Son zone and the Poko Suture, which also contain ophiolitic remnants. In these areas as well, metamorphism has been dated at 250–240 Ma (Lepvrier et al., 2004). The presence of an Early Triassic tectonothermal event and the palaeontological evidences for a Devonian terrestrial connection between South China and Indochina, as well as the evidences for an extensional phase during the Early Permian (Song Da rift) allow us to propose that the Song Ma basin opened more or less coevally with the Nan basin in Thailand, during the Late Carboniferous–earliest Permian, isolating the Indochina block from the rest of Eastern Asia, including South China (see discussion later). In fact, as the West Sumatra block was displaced westwards after the collision of Sibumasu with Indochina (Barber and Crow, 2003), there must have been a mechanism for this displacement. The mechanism is possibly the opening of an Early Permian back-arc (on the basis of the age of the arc volcanism in Western Sumatra), represented by the Poko suture, and related to the subduction of the Palaeopacific Ocean beneath East Asia. The opening of that basin is also interpreted to be responsible for the strike-slip opening of the Song Ma basin. The terranes displaced by this Poko back-arc would comprise the Kontum Massif, Palawan, West Borneo (Kalimantan) and West Sumatra. In fact, in West Borneo arc volcanism is found at least during the Late Triassic (Hutchinson, 1989), represented by the Serian

Volcanics, and, along the Eastern Vietnam coast and in Cambodia, Hutchinson (1989) illustrates Carboniferous–Lower Permian and Permo-Triassic volcanic arcs on his maps. We propose to name these blocks "Orang Laut terranes", because they are now located on the route taken since 4000 B.C. by the Orang Laut Sea Gypsies, who started from Taiwan to reach Eastern Vietnam, Borneo, Sumatra and Burma.

4. Methodology for the plate reconstructions

In the next section we will propose a model for the tectonic evolution of Southeast Asia. Our model differs from models that have been so far proposed, and was made on the basis of our field observations, compiled literature about the whole Southeast Asia and then inserted into a plate tectonics oriented model in which plate movements are constrained on global reconstructions. A chronostratigraphic scheme is proposed in Fig. 8, in which the main events that affected Southeast Asia are represented with their timing.

Stampfli and Borel (2002) developed a new plate reconstruction method which represents a distinct departure from classical continental drift models. These new plate models for Palaeozoic and Mesozoic times (Ordovician to Cretaceous) integrate dynamic plate boundaries, plate buoyancy factors, ocean spreading rates, subsidence patterns, stratigraphic and palaeobiogeographic data, as well as major tectonic and magmatic events. Lithospheric plates are constructed through time by adding/removing oceanic material (symbolized by synthetic isochrones) to major continents and terranes. This approach offers a good control on plate kinematics and geometries, and provides new constraints for plate tectonic scenarios.

From the plate models presented in Stampfli and Borel (2002, 2004) a revised set of reconstructions (still under construction) is being developed using GIS software, covering most of the planet with the exception of large oceans such as Panthalassa, and extending from Late Neoproterozoic to Tertiary times. The major changes with respect to the previous publications is the use of more than 300 terranes properly defined in terms of their geodynamic significance, in an effort to create a geodynamic database to assess the validity of the plate models.

We present here parts of the new plate models for the Far-East, starting with a Late Cambrian peri-Gondwana fit of all major continental blocks (Fig. 9a). The position of blocks such as Indochina and related terranes is still poorly constrained at that time. However, the plate models in space and time provide important clues on the potential location of these blocks around

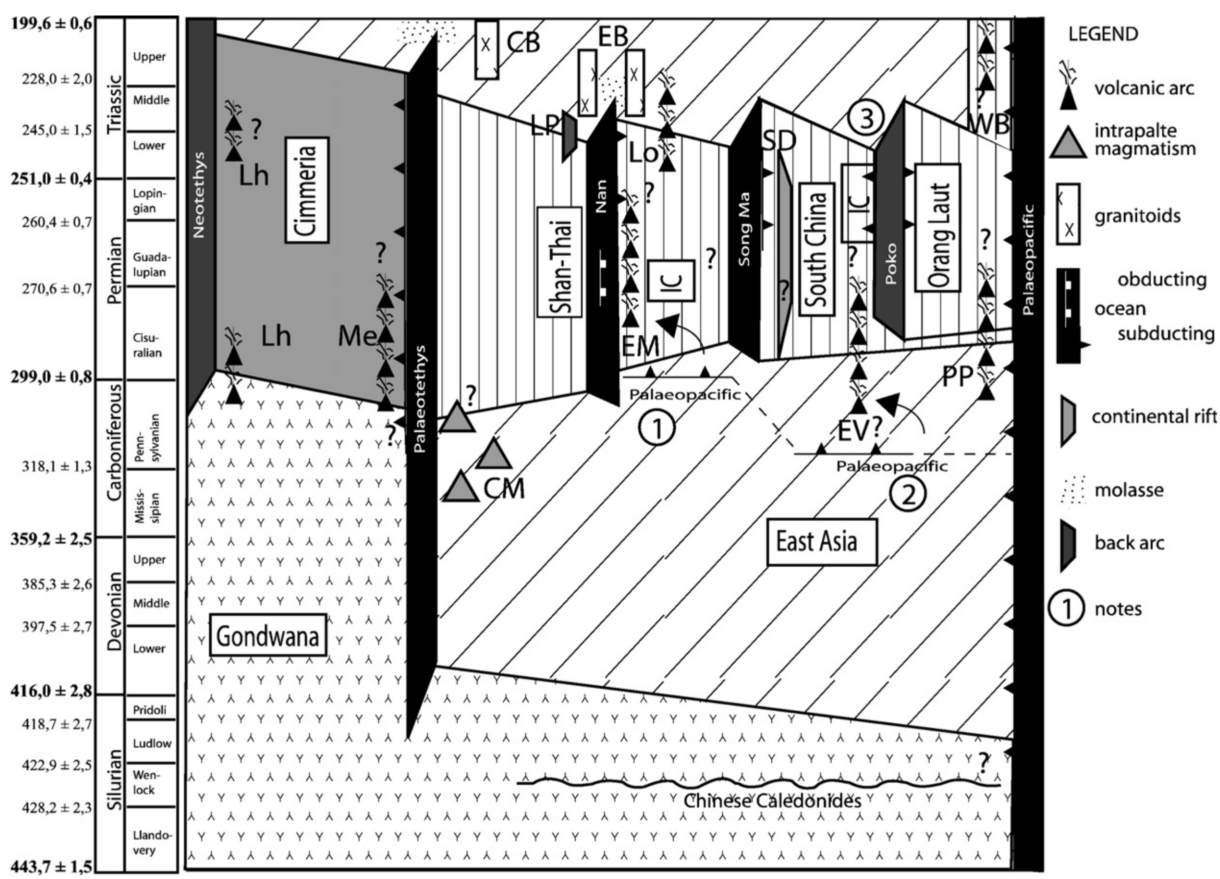

Fig. 8. Chronostratigraphic scheme showing the timing of the geodynamic events that affected Sibumasu, Shan Thai, Indochina, South China and Orang Laut from the Silurian to the Late Triassic. CB: Central granitoid belt; CM: Chiang Mai intraplate basalts; EB: Eastern granitoid belt; EM: East Malaya volcanic arc and granitoids (emplaced on Indochina, resulting from the subduction of the Palaeopacific Ocean under Indochina); EV: Eastern Vietnam (volcanic arc resulting from the subduction of the Palaeopacific Ocean); IC: Indochina; Lh: Lhasa; Lo: Loei arc; LP: Lampang-Phrae; Me: Mergui; PP: Peusangan–Palepat; SD: Song Da; WB: Western Burma;. Notes: 1), 2): arcs resulting from the subduction of the Palaeopacific; 3) The Orang Laut terranes are in upper plate position with respect to Indochina, and in lower plate position with respect to South China. Time scale according to Ogg (2004).

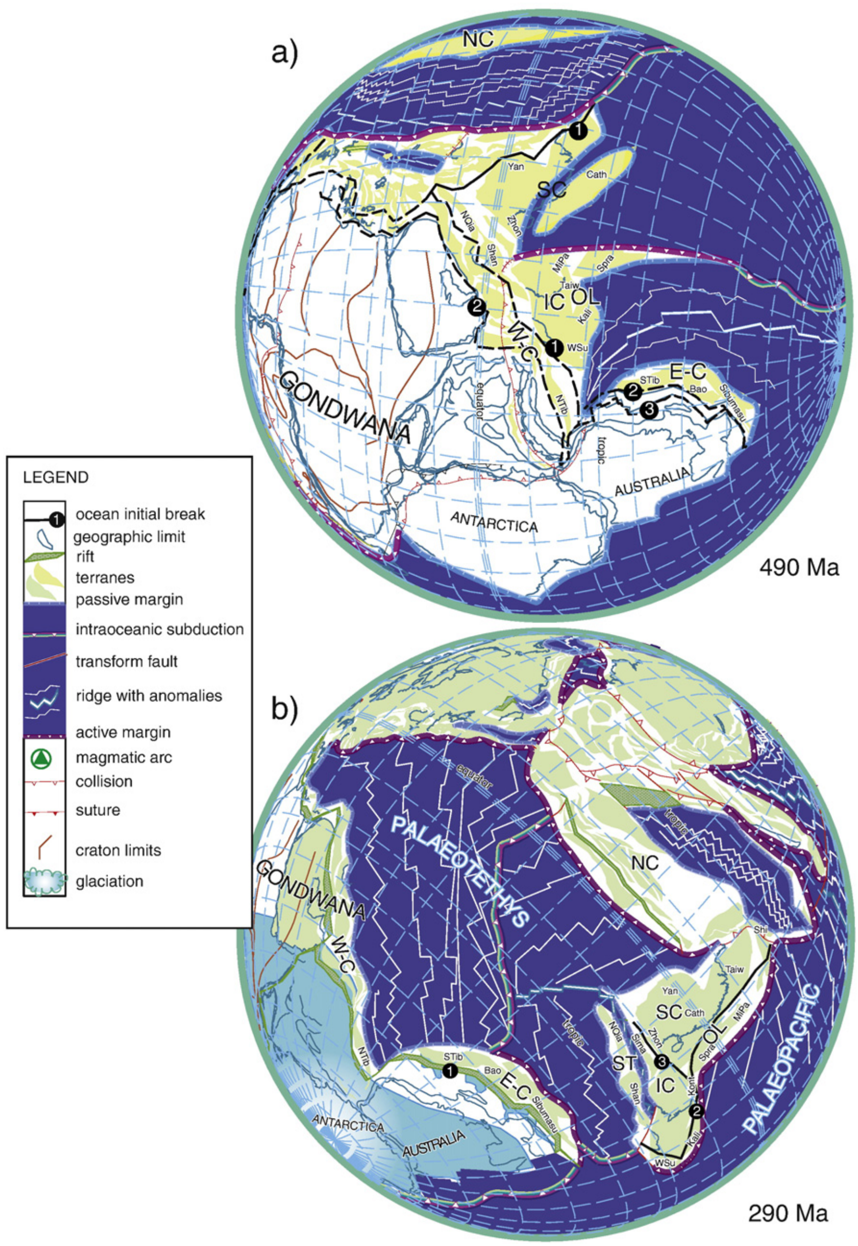

Fig. 9. a) Geodynamic reconstruction at 490 Ma (Latest Cambrian). The initial breaks correspond to 1: Palaeotethys, 2: Neotethys and 3: Argo oceans. S–T: Shan–Thai, OL: Orang Laut. b) Geodynamic reconstruction at 290 Ma (Sakmarian). Initial breaks correspond to 1: Neotethys, 2: Poko, 3: Song Ma and 4: Argo oceans. Terranes: Bao: Baoshan; Cath: Cathay; Kali: Kalimantan; Kont: Kontum; MiPa: Mindoro–Palawan; NTib: NQuia: North Quiantang; North Tibet; Shi: Shimanto–Chichibu; Sima: Simao; STib: South Tibet (Lhasa); Spra: Spratley; Taiw: Taiwan; WSu: West Sumatra; Yan: Yangtze; Zhon: Zhongza. The legend is also valid for Figures G and H. See text for explanation.

Gondwana. Also, we took into account major palaeobiogeographical data, such as the presence in Northeast Thailand of the Eurasian *Paripteris* flora, described by Laveine et al. (1993). Then, a set of models extending from Early Permian to the Late Triassic is presented in Figs. 9b–11b. The geological information, as reviewed in the present paper, was used to constrain the geodynamic character of plate boundaries (e.g., active margin polarity, intra-oceanic subduction zone as a source for obduction, lower/upper plate position of continental blocks during collision). Then, the plate model was checked for consistency in terms of plate velocity and timing of terrane assembly (Fig. 12).

Besides the two large Palaeotethyan and Neotethyan oceanic domains (one replacing the other during the Triassic) many oceanic back-arc type oceans opened around the Indochinese block, as well as along the Palaeotethys active margin. They are sometimes erroneously considered as Neotethyan because of the Triassic to Jurassic age of their sutures, but most of these had no direct connection (neither geographic nor geological) with the peri-Gondwanan Neotethys Ocean, and should therefore be called with their local names (e.g., Nan).

The resulting picture of the Tethys realm in Permo-Triassic time in the Far-East is, therefore, quite complex, made of numerous small oceans. Many of these oceans are, in most

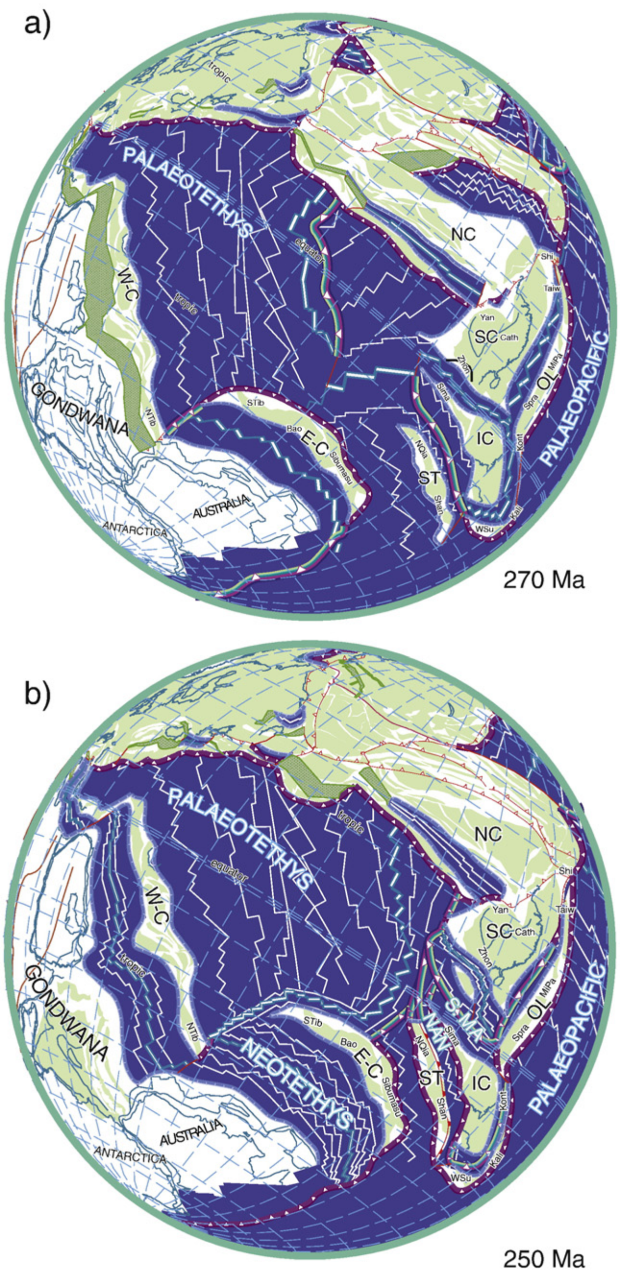

Fig. 10. a) Geodynamic reconstruction at 270 Ma (Late Lower Permian); b) Geodynamic reconstruction at 250 Ma (Lower Triassic). Legend and terranes as in Fig. 9. See text for explanation.

cases, at the origin of the many ophiolitic remnants found around Indochina, whereas older oceanic domains totally disappeared without leaving large remnants of their sea-floors.

5. Palaeozoic–Early Mesozoic geodynamic evolution

5.1. Silurian to Early Carboniferous: the opening of Palaeotethys and the Early Carboniferous extensional phase

In Thailand and adjacent areas, the absence of sections showing typical syn-rift deposits makes the dating of the opening of the Eastern Palaeotethys Ocean quite imprecise. During the Silurian, the coeval deposition of basin and shelf sediments on the Shan–Thai block (Fig. 5) tends to indicate passive margin geometry with tilted blocks forming basins and highs, and suggesting that extension began at that time.

It is possible that the Northern passive margin of Palaeotethys was quite wide and that the oceanisation began more to the North. In fact, in the region of Loei, Upper Devonian ocean floor tholeiites are dated by Intasopa and Dunn (1994) at 361 ± 11 Ma by Sr–Nd isotopic systems. However, there is a Lower Carboniferous angular unconformity between the Loei Group and the Saraburi group in the Khorat plateau (Mouret, 1994; Chonglakmani and Helmcke, 2001) which, as cited by Chonglakmani and Helmcke (2001), could be followed by a rifting phase or newly started subsidence, allowing the Saraburi group to deposit. So, the basalts of Loei, could either be in relation with this

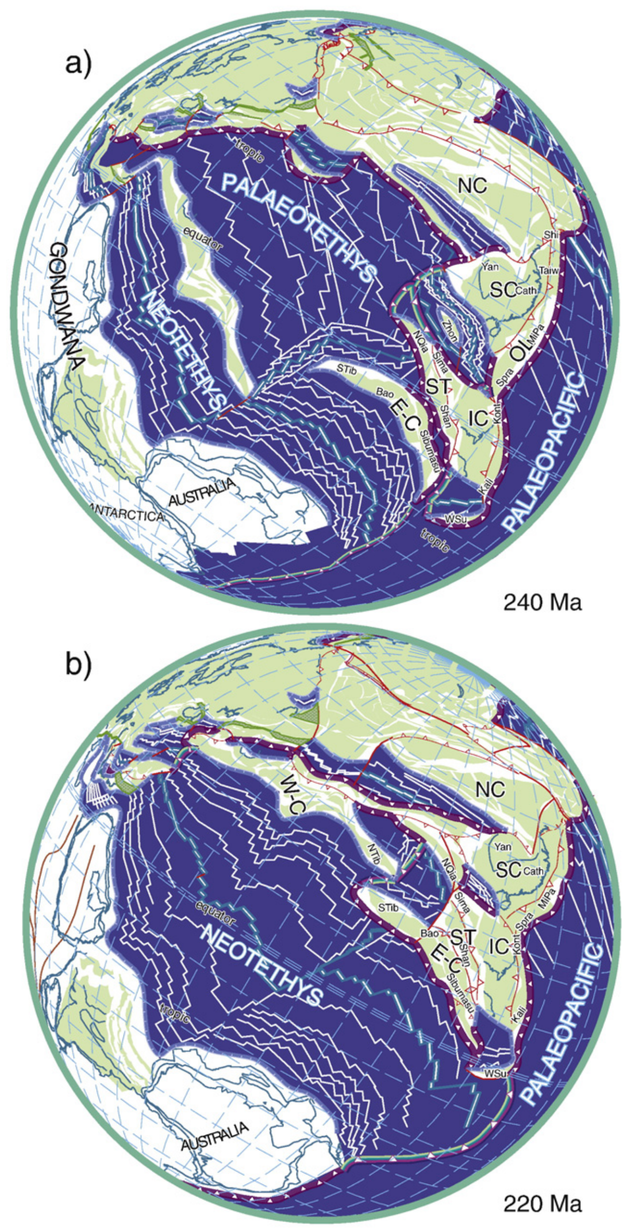

Fig. 11. a) Geodynamic reconstruction at 240 Ma (Middle Triassic); b) Geodynamic reconstruction at 220 Ma (Upper Triassic). Legend and terranes as in Fig. 9. See text for explanation.

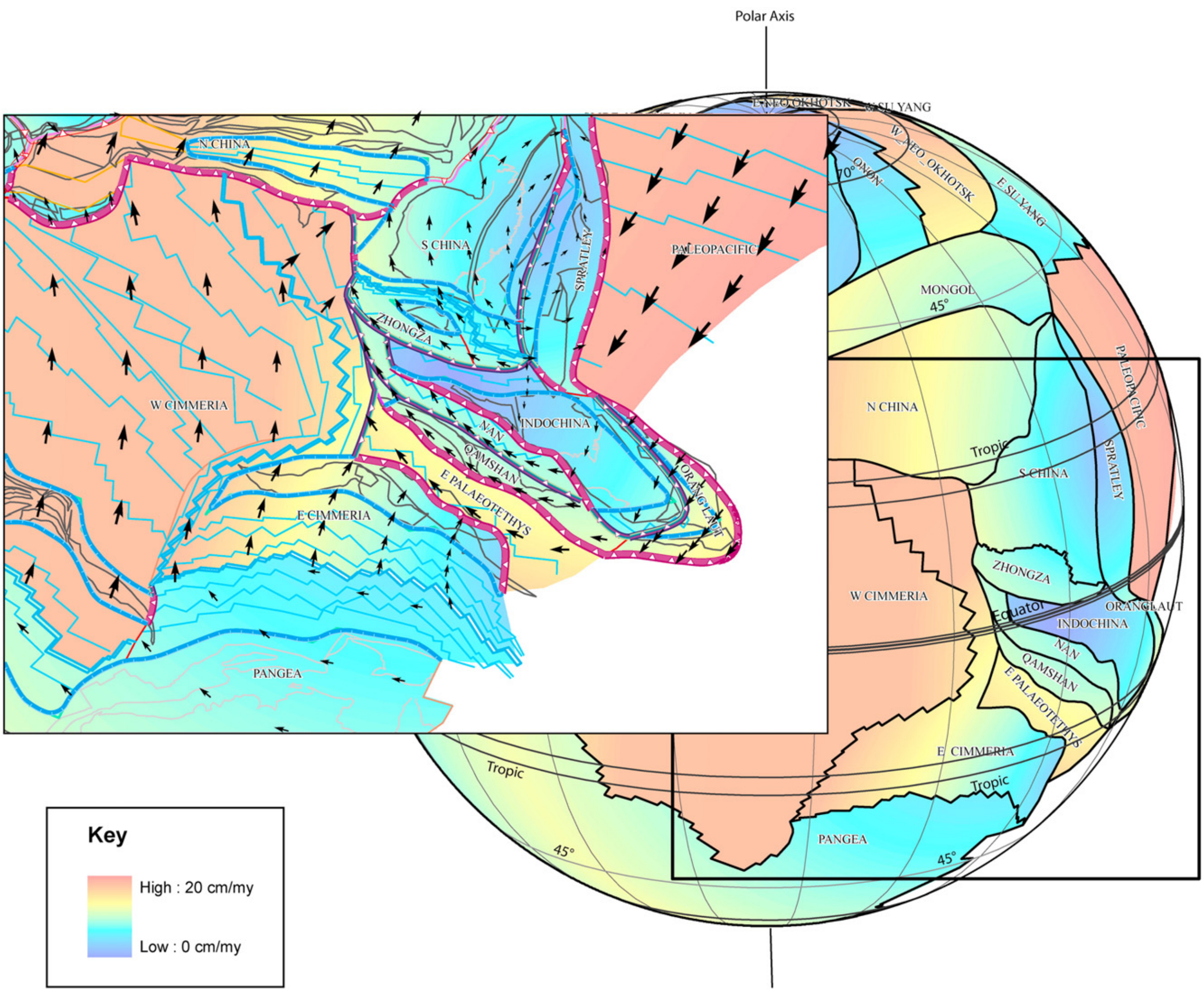

Fig. 12. Late Permian kinematics model representing, in the final position, the average velocity (in cm/my) of each plate between 270 Ma and 250 Ma. The rotation rates of the plates are calculated in a pseudo-absolute reference frame (relative to a fixed magnetic pole). The color variation and the arrow size variation represent the speed evolution from its minimum near the rotation axis to its maximum along the rotation equator. Arrows orientation indicates the direction of the movement. The reference frame is based on paleomagnetic data of Baltica (Torsvik and Cocks, 2005). It is called "pseudo-absolute" because paleo-poles are replaced on the actual North Pole position with an assumed minimum displacement of the reference plate (Baltica) between each stage.

phase, or represent a former (aborted) branch of Palaeotethys, as the validity of the dating of the basalts by Sr–Nd isotopic systems can be questioned.

The presence of such features as the basalts in Loei, the angular unconformity in Saraburi, and other coeval events are very important for the understanding of the tectonic evolution of the region. In fact, westward, on the Shan Thai block (as intended in this paper), the continental intraplate magmatism of the Chiang Mai belt began during the Visean, as shown by the oldest limestone found on top of the basalts. These features can indicate an extensional phase, during which the faults of the Northern Palaeotethyan passive margin were reactivated, creating new basins and allowing the emplacement of basalts. The thickness of the Carboniferous sediments in the Chiang Mai region is in agreement with this interpretation. This phase of extension can possibly be related to subduction of the Palaeopacific which, later during the Permian, was responsible for the opening of the Song Ma–Poko system (see Section 5.3).

In the Shan States of Burma, Bender et al. (1983) describe a Devonian–Carboniferous hiatus that Wu (1993) puts into relation with the "basin and range morphology of northwestern Thailand". In the Truong Son belt of Central Vietnam and in the Song Ma area, an angular unconformity has been mentioned at the base of the Visean (Morgunov, 1970; Fontaine and Workman, 1978). These two can be seen as related to a Devonian opening of Palaeotethys.

5.2. Late Carboniferous–Early Permian: the subduction of Palaeotethys/opening of Neotethys (Fig. 9b)

The data on the Late Carboniferous–Early Permian stratigraphy of the Sibumasu terrane, especially the data concerning the diamonds affinity and the similarities with the series of the Canning (Metcalfe, 2000) and Petrel basins (Barber and Crow, 2003) strongly suggest that its Gondwanan position, prior to the Early Permian opening of the Neotethys Ocean, was adjacent to NW Australia (Fig. 9a).

The Early Permian opening of the Eastern Neotethys and the induced detachment of the Eastern Cimmerian blocks is well constrained in time. Among other data, the observations made by Shi and Archbold (1995) on the brachiopods, the palaeomagnetic data (Van der Voo, 1993; Richter et al., 1999; Metcalfe, 2000), the rapid change from Early Permian glaciomarine sediments to warm water sediments are all in agreement with this interpretation.

More problematic is the interpretation of the modality for the opening of the Neotethys/closure of the Palaeotethys.

In the Western Palaeotethyan domain, northwards subduction of the Ocean has been well established and, by analogy, this interpretation was extended into the Eastern part of the domain. We propose a model based on the presence/absence of volcanic arcs, in which Eastern Palaeotethys subducted southward, under Gondwana. Actually, the subduction of an ocean as wide as the Palaeotethys must have created one or more volcanic arcs along its active margin. As the Sibumasu block detached from Gondwana during the Early Permian, subduction of the Palaeotethys was already active at that time, and continued until the Cimmerian collision, which took place between the latest Permian–Middle Triassic (in the South) and the Middle–Late Triassic (in the North). However, it is still difficult to locate the arc sequences related to the closing of Palaeotethys.

5.2.1. Possible arc magmatism on the Northern (Cathaysian) margin of Eastern Palaeotethys

In Northern Thailand, MacDonald and Barr (1978) assumed the volcanic rocks in the region of Chiang Mai to be subduction-related, but, later, this interpretation was abandoned by Barr et al. (1990) who proved that these rocks represent continental extensional intraplate magmatism. The Lampang Volcanic Belt has also been considered to be a volcanic arc (Barr and MacDonald, 1991), but isotopic U/Pb dating by Barr et al. (2000) gave an Anisian 240±1 Ma age, which is quite late to witness that closure. The same authors interpreted the volcanites as subduction-related, without a possible distinction between an arc and a back-arc setting. Moreover, the Lampang belt is correlated with the Lincang–Jinghong volcanic belt which, as demonstrated by Heppe (2004) represents a bi-modal back-arc rifting and not a volcanic arc (see Section 2.1).

In Southeast Asia three main granitoid belts have been recognized by many authors (Pongsapich et al., 1983; Cobbing et al., 1986; Charusiri, 1989): the Eastern, Central and Western belts, which are part of a 2500 km long and 600 km wide belt that extends throughout Southeast Asia. Different dating techniques gave different results concerning the ages of these granites, but the more reliable are the ones made by $^{40}Ar/^{39}Ar$ method, rather than the ones made by the Rb–Sr and K/Ar techniques, which give systematically older ages. The ages obtained by Charusiri et al. (1993) by the $^{40}Ar/^{39}Ar$ method imply an Early to Late Triassic (245–210 Ma) emplacement for the Eastern Belt, Late Triassic to Early–Middle Jurassic (220–180 Ma) for the Central Belt and Late Cretaceous to Palaeogene (80–50 Ma) for the Western belt. The ages of the granites of the Western belt are too young to be related to the history of the Palaeotethys, and may be related to the closure of the Neotethys Ocean and therefore will not be discussed here. The interpretation of the tectonic setting of granitoid rocks is not easy, and we prefer not to make it on the basis of I- or S-type affinity (Chappell and White, 1974), because, as shown by Barbarin and Bonin (1992), this classification does not necessarily reflect the tectonic setting. On the basis of the ages of the granites, we interpret the Central and the Eastern belt as being emplaced in a syn- to post-orogenic setting. The Early–Late Triassic granites of the Eastern belt are likely to be related to the closure of the Nan basin, and possibly to the rifting along the Lampang Volcanic Belt, while the Late Triassic–Middle Jurassic batholiths of the Central Belt are likely to be related to either slab detachment, subduction of the Neotethys and/or syn- to post-collisional magmatism, as there are good evidences that the Palaeotethys closed in the Late Triassic. It has to be noticed that Charusiri et al. (1993) recognize three different chains of granitoids inside the Central Belt, implying that all the batholiths are not necessarily co-genetic.

In Peninsular Malaysia, East of the Bentong–Raub suture, the East Malaya volcanic arc, as cited above, is of Middle–Late Permian and Triassic age, possibly extending down to the Carboniferous according to the deductions of Metcalfe (2000). The granitoids associated to this arc, which are generally assumed to be part of the Eastern volcanic belt, have been dated at 265–230 Ma by the U–Pb method (Liew and McCulloch, 1985). We think that these granites have a different tectonic setting that the ones of the Eastern belt, on the basis of the diachronism of their emplacement, and their position associated to a volcanic arc directly east of the Palaeotethys suture.

In our model, this region was at the interface between both Palaeopacific and Palaeotethys oceans (Figs. 9b–11a). As witnessed by the cherts, the ages of oceanic material within the suture reflect the age range of the Palaeotethys (Metcalfe, 2000). However, it is not possible in that region to make two separate entities out of both Palaeotethys and Palaeopacific. Thus, we consider the East Malaya volcanic arc as related to the subduction of the Palaeotethys–Palaeopacific system (responsible for the detachment of the Orang Laut terranes) and then to the subduction of the Palaeotethys–Palaeopacific–Nan system (Fig. 9b).

In the Cathaysian West Sumatra block, the Peusangan–Palepat volcanic arc is Early to Middle Permian in age (Barber and Crow, 2003 and references herein). These ages could be related to the subduction of Palaeotethys; however, as Sumatran volcanism stopped in the Middle Permian, we interpret the West Sumatra Block as part of the Orang Laut terranes, detached from the Eastern part of Vietnam at the opening of the Poko back-arc basin (see Section 3.2).

Magmatism in Thailand has been well studied and dated in the last decades, but no Early Permian to Early Triassic arc remnants have so far been found along the Cathaysian margin of Palaeotethys.

5.2.2. Possible arc magmatism on the Southern (Cimmerian) margin of Eastern Palaeotethys–Southwards subduction?

In the Mergui archipelago (Burma), Bender et al. (1983) describe the occurrence of volcanic rocks intercalated in the sediments of the Mergui series. These volcanites consist of tuffs and agglomerates with pumice, volcanic glass, porphyry, rhyolite, volcanic bombs, lapilli and fragments of sediments. They are assumed by the author to be Carboniferous in age but, as the Mergui series are still poorly dated, it is likely that the age of these volcanic series extends into the Permian. In fact, such magmatic event must have a reason and the arc setting is probable. Considering the presence of the Mergui acidic volcanites and the absence of Permian Palaeotethyan arc East of the Palaeotethys suture, we interpreted the Eastern Palaeotethys as having subducted southwards, under the Eastern Cimmerian blocks. In this case, the Eastern Neotethys opened in a back-arc setting (back-arc type Neotethys) in contrast with Western Neotethys which opened by slab-pull (Atlantic type Neotethys). Actually, in the Lhasa Terrane, Pearce and Mei (1988) described two thick sequences of volcanic rocks, dated as Late Carboniferous (South) and Mid-Triassic (North) by the intercalated platform sediments. The Upper Carboniferous volcanites consist of intermediate and acidic lavas, mainly sub-alkaline basalts and andesites. The geochemistry of the lavas exhibits a calc-alkaline volcanic arc setting. We interpret these volcanites as witnessing the presence of a volcanic arc, associated with the southward subduction of the Palaeotethys, in view that the Lhasa block is clearly Cimmerian in nature.

The fact that the Eastern Palaeotethys subducted southward while the Western part subducted northward implies that a plate boundary must have existed between the two parts of the ocean, allowing opposite movement. Thus, in our reconstructions we represented an intra-oceanic subduction zone which, during its evolution, is responsible for the development of a new supra-subduction oceanic ridge by slab roll-back (Figs. 9b–11b).

5.3. Middle Permian to Late Triassic: the Palaeopacific-controlled East Asian tectonics and the closure of Palaeotethys (Figs. 10a and 11b)

On the East Asian continent, in Indochina and South China, the Permian tectonic evolution is controlled by the subduction of the Palaeopacific Ocean. This subduction zone, all along the Eastern Margin of Indochina and South China, is responsible for the detachment of the Cathaysian block, with the consequent opening of the Song Ma–Poko system inducing the separation of the Orang Laut terranes. As described in Section 3.2, the back-arc opening of the Poko basin was interpreted on the presence of coeval arc magmatism in Eastern Vietnam, Borneo and Sumatra. The closure of the Poko–Song Ma system, especially the vergence of the subductions, was interpreted on the basis of structural and magmatic data. In Fig. (10b) the Northern part of the Orang Laut terranes is in upper plate position with respect to South China. In fact, Li (1998) showed the presence of a Middle- to Late Triassic fold and thrust belt in the Eastern part of the South China block, with North-westwards thrust planes, implying lower plate position for South China at that moment.

The Upper plate position of the Southern Orang Laut terranes (Borneo, West Sumatra) is assumed on the basis of the vergence of the subduction of the Nan basin under Indochina, constrained by the presence of the arc volcanites in Loei and in East Malaya. Finally, the North-eastwards subduction of Song Ma is assumed on the basis of the interpretation given by Lepvrier et al. (2004).

Figs. 10b and 11b show the propagation of the Palaeopacific subduction zone under the Shan–Thai block. This explains the presence of the volcanites of the Lampang belt and possibly the presence of part of the granites of the Central and Eastern belts. The final closure of Palaeotethys must have taken place during the Middle Triassic (to the South) to Late Triassic–Lowermost Jurassic, as cited by many authors, on the basis of the ages of the youngest radiolarian cherts and of the Mae Sariang flysch/molasses.

6. Conclusions

Following an overview of existing data and of our own data, we have presented an alternative plate tectonic model for Southeast Asia. Our main effort was to present a model in which all the existing data are taken into account. Some assumptions have been done in order to constrain the model. For instance, as written in point 4, the initial location of the South China block is still poorly constrained. Then, some geological features as the intra-oceanic subduction that separates Western and Eastern Palaeotethys are induced by the plate movement, the plate geometries, and the consistency in the geodynamic evolution of their boundaries. Thus, in order to present this model, we tried to first locate the critical geological objects — passive margins, volcanic arcs, sutures, molasses, flysch sediments etc., by using an interdisciplinary approach which takes into account field observations, palaeobiogeography, geochemistry, geochronology, structural geology etc.

The interpretations presented here highlight several new points about the geodynamic evolution of Southeast Asia as follows:

The first point concerns the redefinition of the term “Shan–Thai block” as a block detached from Indochina during the Early Permian opening of the Nan-Uttaradit Basin. This “Shan–Thai block”, occupying both Inthanon and Sukhothai zones, is considered as entirely East Asian rather than Cimmerian; thus, the suture of the Palaeotethys is considered here as being located along the Mae Yuam Fault.

The second point is the southward subduction of the Eastern Palaeotethys with the consequent back-arc opening of the Eastern Neotethys. This is witnessed by the presence of Upper Carboniferous arc magmatism in the Lhassa Terrane and possible coeval arc magmatism in the Mergui series; on the Indochina block no arc magmatism imputable to the Palaeotethys has been found.

The third point is about the definition of the Orang Laut terranes, a band of terranes detached from Indochina and South China at the Early Permian opening of the Poko and Song Ma basins. These basins were opened as back-arc basins of the Palaeopacific Ocean, as witnessed by the presence of several coeval volcanic arcs in Cambodia, Vietnam, Laos and Sumatra. The introduction of the Orang Laut terranes allows, among other things, to explain the relative position of the Cimmerian East Sumatra block and the East Asian West Sumatra block.

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