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Development of the Khao Khwang Fold and Thrust Belt: Implications for the geodynamic setting of Thailand and Cambodia during the Indosinian Orogeny

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ABSTRACT

The Indosinian Orogeny in Thailand is often viewed as having developed between strongly linear terranes, which today trend approximately N–S. The terranes were subsequently disrupted by later tectonics, particularly NW–SE trending Cenozoic strike-slip faults. The ENE–WSW to NE–SW striking thrusts and folds in the Khao Khwang Platform area of the Saraburi Group on the SW margin of the Indochina Terrane are not easily explained in the context of this traditional view. Reversal of the clockwise rotation shown to have affected the block north of the Mae Ping Fault zone only enhances the E–W orientation of structures in the fold and thrust belt, and moves the belt further east towards Cambodia. One solution for the trend that fits better with regional understanding from hydrocarbon exploration of the Khorat Plateau is that the Indochina Terrane was actually a series of continental blocks, separated by Permian rifting. During the Early Triassic the early stages of collision (South China-Cathaysian Terrane collision with Vietnam Indochina) resulted in the amalgamation of disparate blocks that now form the Indochina Terrane by closure along the rifts. At the same time or following on from the collision there was closure of the back-arc area between Indochina and the Sukhothai zone. The rift basins, were thrusted and inverted during the early stages of the Indosinian orogeny, and only underwent minor reactivated when later Sibumasu collided with Sukhothai Zone-Indochina Terrane margin during the Late Triassic. The scenario described above requires the presence of a (minor) E–W trending suture in NW Cambodia. Evidence for this suture is suggested by the presence of Permo-Triassic calc-alkaline volcanism.

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1. Introduction

The Indosinian orogenic belt is characterized by various subduction and collision-related events that span the period from around 260 Ma to 190 Ma (see reviews in Lepvrier et al., 2004; Sone and Metcalfe, 2008 and Barber et al., 2011). In Thailand the tectonic belts trend predominantly N–S, including the back-arc suture zone (Nan-Uttardit-Sa Kaeo) and the Palaeo-Tethyean sutures (Inthanon Zone; Fig. 1). It is widely accepted that there was closure of the back-arc basin and collision of the volcanic-arc dominated Sukhothai zone with Indochina during the Early to Middle Triassic, and a later collision between the combined Sukhothai-Indochina block with Sibumasu as the Palaeo-Tethys closed during the Late Triassic-Early Jurassic, (e.g. Fontaine and Workman, 1978; Hahn, 1984; Sone and Metcalfe, 2008; Booth and Sattayarak, 2011; Barber et al., 2011).

Fig. 2 shows a summary of radiometric ages from Sibumau (grey rectangles), and the Indochina and South China Blocks (black rectangles). It is apparent from Fig. 2 that much of the early volcanic and metamorphic events are focused on the Indochina and South China Blocks (particularly Early-Middle Triassic), while the most important deformation affecting the Sibumasu Block is later (about 220–190 Ma). The early phase of deformation will be referred to here as Stage 1, while the second phase as Stage 2.

In terms of the unconformities identified in the Khorat Plateau area of the Indochina Block (Booth and Sattayarak, 2011), the Indosinian I unconformity marks the termination of the most extensive episode of deformation to affect the Permian and older units of the region. The unconformity is overlain by Late Triassic (?Norian) rift-related sediments of the Kuchinarai Group (Booth and Sattayarak, 2011). The Indosinian I unconformity effectively marks the end of Stage 1. The Indosinian II and III unconformities occur during Stage II, but lie within the region that is much less affected by Stage 2 deformation, in comparison with Sibumasu.

The Sukhothai and Inthanon zones are best established in northern Thailand, while in Central and Eastern Thailand (Saraburi, Pak-Chong, Sa Kaeo, Chanthaburi; Fig. 3) the tectonic units and timing of deformation become more ambiguous. Recently Ridd (2012) presented a review of the tectonic zones, and evolution of southeastern Thailand (including the Sa Kaeo Suture zone) and concluded that the timing of collision occurred during Middle-Late

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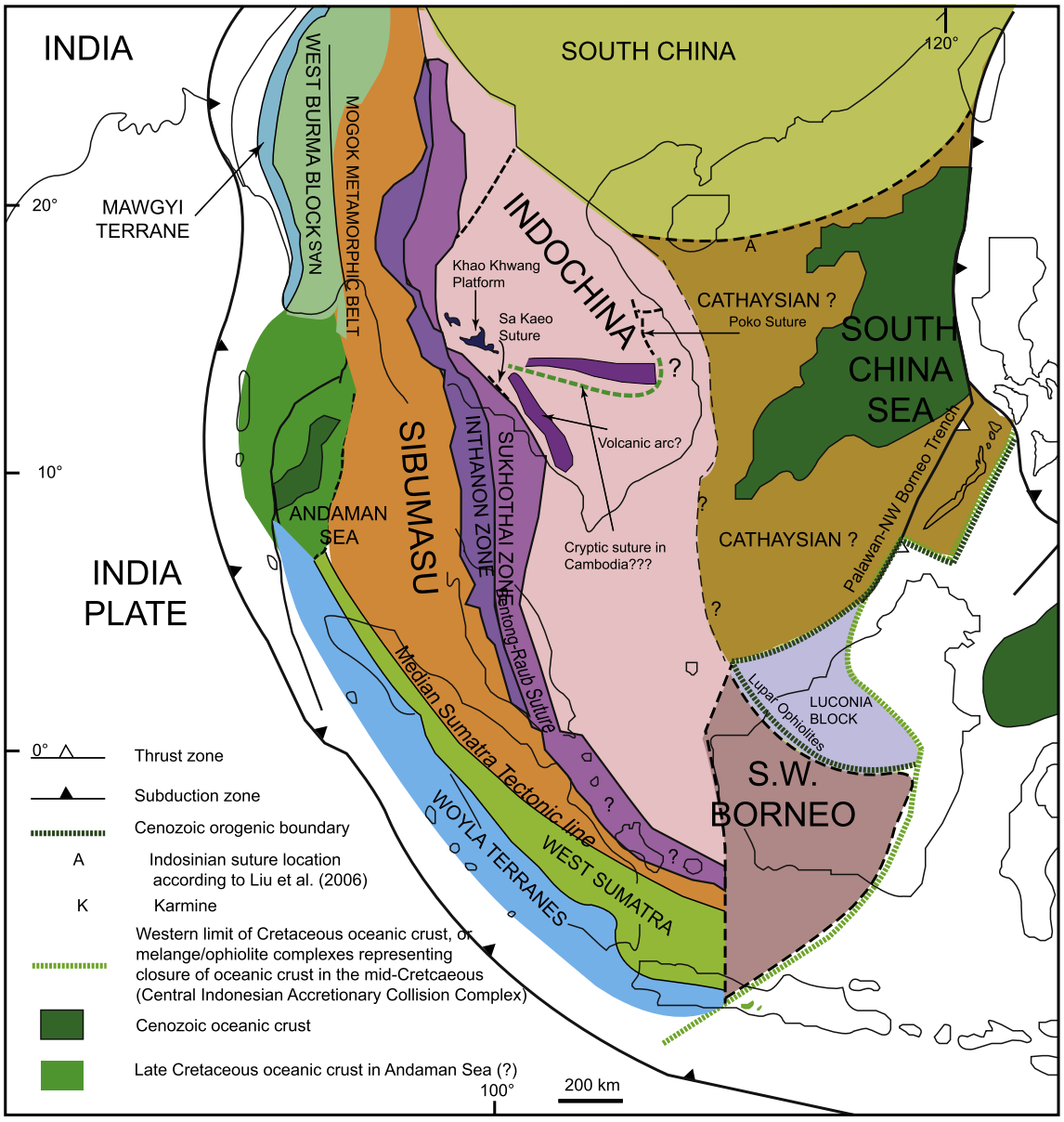

Fig. 1. Regional location map showing Terranes accreted in the Late Palaeozoic and Mesozoic, in part based on Sone and Metcalfe (2008), Barber et al. (2011), and Metcalfe (2011).

Triassic (i.e. predominantly Stage 2), with no evidence for earlier Triassic deformation having a major impact in the area. However, north of the Sa Kaeo Suture zone recent work on the foreland fold and thrust belt of the Saraburi-Pak Chong area has a significant impact on our understanding of the tectonic development of eastern Thailand. This paper discusses how the relationship between the Permian carbonates and clastics of the foreland fold and thrust belt, and the adjacent Khao Yai magmatic belt to the south both improve and challenge our understanding of how the Indosinian orogeny developed.

2. Khao Khwang Platform and Fold and thrust belt

Bunopas (1981) was the first to propose a separate Indochina Block stratigraphic division (Saraburi Group) for the units in the Saraburi-Pak Chong area. Later Hinthong (1985) and Hinthong et al. (1985) defined the stratigraphy still used today, which comprises three main carbonate platform dominated facies (Phu Phe, Khao Khad, and Khao Khwang formations), separated by clastic or mixed siliciclastic and carbonate sequences (Sap Bon, Pang Asok, Nong Pong formations). The deepwater siliciclastic deposits of the Nong Pong Formation probably connect northwards to the deepwater deposits of the Nam Duk Formation, whose depositional basin probably trended N–S (e.g. Ueno and Charoentitirat, 2011). Studies of the sedimentology of the Saraburi Group are few and include those by Pendexter (1980), Dawson (1993), Dawson and Racey (1993), Dawson et al. (1993), Charoentitirat (2002), and Udchachon et al. (2007, 2008). While the presence of folds and faults within the Saraburi Group has been noted (e.g. Dawson and Racey, 1993), and in a regional map the Phu Phe Formation is shown as being overthrust onto the Khao Khad and Sap Bon formations (Hinthong et al., 1985), there are no detailed, published structural studies on the area.

The detailed structural geology of the Khao Khwang Platform is a work in progress, and the stratigraphic detail required to

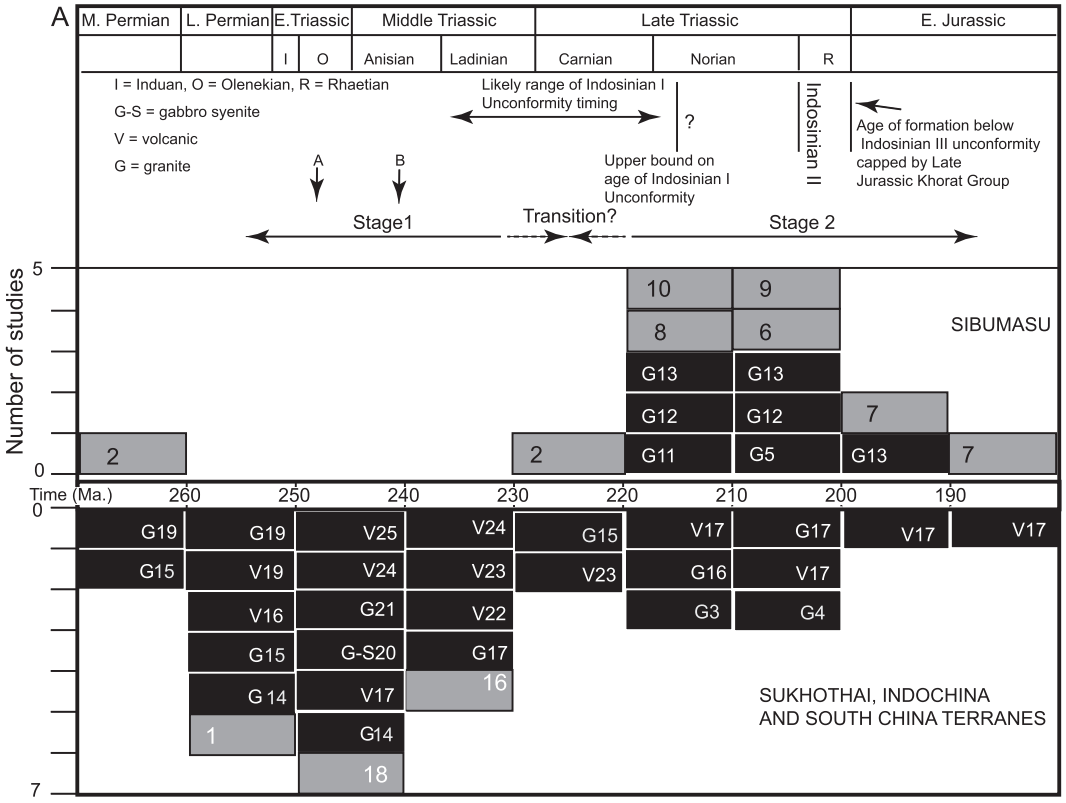

Fig. 2. Histograms showing the occurrence of igneous and metamorphic events related to the Indosinian Orogeny in Thailand, Malaysia and Vietnam. (A) radiometrically dated igneous events (mostly Ar/Ar mica and U–Pb zircon ages). (B) U–Pb dated metamorphic events in Thailand and Vietnam. The black and grey rectangles denote dated igneous (black) and metamorphic (grey) events for 10 my time periods. The upper rectangles are for western Thailand, Peninsular Thailand and Malaysia, (i.e. west of the Bentong-Raub suture, or Sibumasu). The lower rectangles are for the Sukhothai zone, Indochina Block in Eastern Thailand, and Vietnam, and the South China Block in Vietnam. A = nappes in NE Vietnam older than 248–245 Ma (Roger et al., 2012), B = Khao Khwang Fold and Thrust Belt older than 240 Ma. 1 = Nan River Volcanic Belt, N Thailand, Barr and Macdonald (1987); Singharajwarapan and Berry (2000). 2 = Khao Phra, Peninsular Thailand, Hansen and Wemmer (2011). 3 = Khao Luk Chang area, SE Thailand, Hansen and Wemmer (2011). 4 = Khao Kiew granites, Charusiri et al. (1993). 5 = Tak granite, W. Thailand, Hansen and Wemmer (2011). 6 = Umpang Gneiss, W. Thailand, Hansen and Wemmer (2011). 7 = Lansang gneiss, W. Thailand, Hansen and Wemmer (2011). 8 = Ban Tak biotite gneiss, W. Thailand, (Hansen and Wemmer, 2011). 9 = Doi Suthep, NW Thailand, Barr et al. (2010). 10 = Mae Wang, NW Thailand, Barr et al. (2010). 11 = Phuket granite, Peninsular Thailand, Searle et al., (2010). 12 = Penang, Malaysia, Liew and Page (1985). 13 = Main Range plutons, Malaysia, Liew and Page (1985), Searle et al. (2012). 14 = Eastern Malaya plutons, Singapore, Hotson et al. (2011). 15 = Eastern Malaya plutons, Malaysia, Liew and McCulloch (1985). 16 = Chonburi-Klaeng area, E. Thailand, Geard (2008). 17 = Klaeng area SE Thailand, Geard (2008). 18 = Nam Co Formation, Song Ma suture zone, Vietnam, Lepvrier et al. (2008). 19 = Phan (2000). 20 = Vietnam, Tran Trong et al. (2008). 21 = Phia Bioc intrusion, Vietnam Roger et al. (2012). 22 = Chiang Khong volcanic suite (Sukhothai Zone, N. Thailand), Barr et al. (2006). 23 = Lampang Group, N. Thailand, Srichan et al. (2008). 24 = Western Loei area, NE Thailand, Salam et al. (2008). 25 = Western Loei (Chatree gold mine), NE Thailand, James and Cummings (2007).

construct regional cross-sections has yet to be established. However recent work is shedding more light on the structural styles. A detailed description of recent work describing the basic structure is planned (Morley et al., in prep). This section provides an overview of what is currently known. The general stratigraphic scheme shows several carbonate platform-dominated sequences that pass laterally into clastic-dominated ones (Fig. 4). Seismic reflection data from the Khorat Plateau area shows that the Permian basins are rift-related, controlled by extensional faults, and that carbonates tend to occupy the high, intra-basinal areas, while clastics or mixed clastics and carbonates fill the basins (Booth and Sattayarak, 2011). The map-view distribution of these rift basins is shown in Fig. 3. It is to be expected that a similar syn-depositional fault control existed in the Khao Khwang Platform area, but at present this control cannot be demonstrated. Around the southern margin of the Khao Khwang Platform/northern margin of the Saraburi-Khao Yai volcanics, and around granite intrusions the carbonates are extensively metamorphosed to marble.

The Permian carbonates developed in the area are grouped as the Khao Khwang Platform, hence the region of deformation is referred to as the Khao Khwang Fold and Thrust Belt. The region is characterized by WNW–ESE to NE–SW trending folds and thrusts that form an arcuate belt (Fig. 5). There are a number of quarries in the region, which provide excellent exposures, as well as some natural exposures and road cuts. The quarries range in size from a few 100 m long to about 4 km long (quarry locations are shown in Fig. 5). Enough is now known to outline the general structural characteristics of the fold and thrust belt. The types of structure present include low-angle thrusts, which are kilometres long. Where shales are present in the high deformation zone is typically 10–30 m thick, implying high displacement. Stratigraphic separation is estimated to be in the order of 100's m. These characteristics suggest displacements in the order of kilometres. These thrusts are rarely exposed but three major ones are found in quarry A, and in quarries in Saraburi (Figs. 6 and 7, Table 1). Some thrusts can also be inferred from outcrop relationships from natural exposures. Generally structures are approximately north-verging, but in some areas, particularly the quarries around Highway 21 (Fig. 5), south-verging structures are also significant (Figs. 6a and 7b). The well-bedded limestones are commonly folded and in the quarries adjacent to Highway 21, are a number of well-developed fault bend fold, fault propagation fold and detachment fold geometries (Fig. 6). In many areas shortening by flexural-slip folding has clearly reached its upper limit, because late structures such as conjugate tension gashes cross-cut fold limbs.

It is more difficult to find good exposures through the clastic-dominated Sap Bon, Pang Asok and Nong Pong formations. However, the seven good exposures (4 road cuts, 3 quarries) through

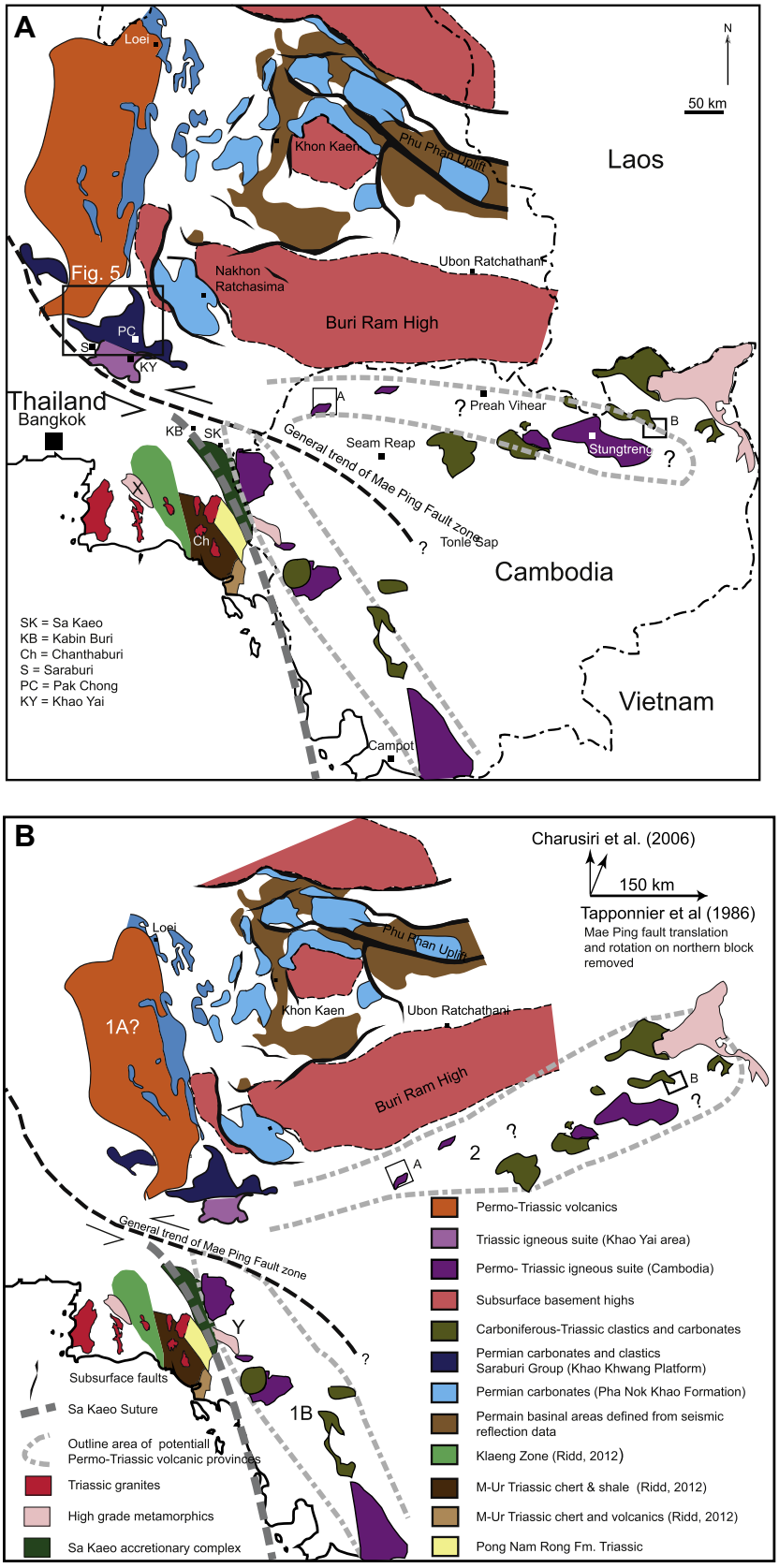

Fig. 3. (A) Regional distribution of key Permo-Triassic tectono-stratigraphic units both from the surface and subsurface (compiled from Booth and Sattayarak, 2011; Ridd, 2012; Ueno and Charoentitirat, 2011; Barr and Charusiri, 2011). (B) Same map as A, but with 150 km Cenozoic sinistral translation of the block north of the Mae Ping Fault removed. The displacement amount is from Tapponnier et al. (1986) and the resulting rotation is consistent with the palaeomagnetic results obtained from the Khorat Group by Charusiri et al. (2006). A = mining concession of Liberty Mining International, Andong Bor, Banteay Meanchey, B = Banlung project.

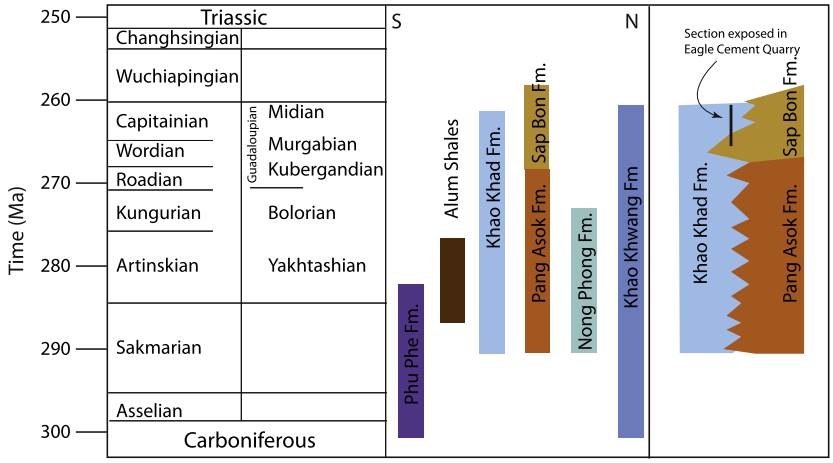

Fig. 4. Ages and stratigraphic names for the formations of the Saraburi Group (modified from Ueno and Charoentitirat, 2011).

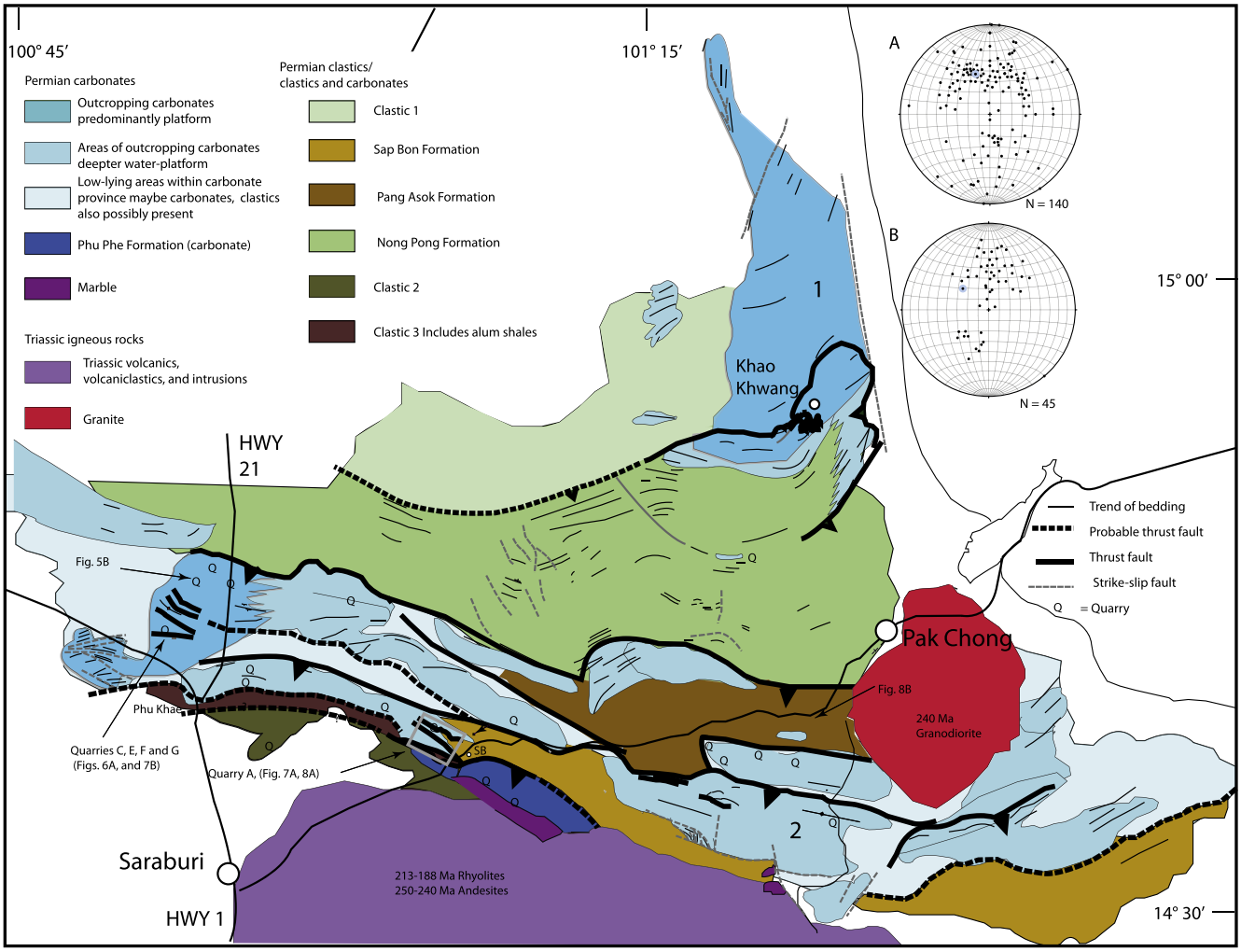

Fig. 5. Geological map of the Khao Khwang Fold and Thrust Belt region. Considerably modified from the original map in Ueno and Charoentitrat (2011), based on fieldwork and satellite interpretation. Modification of the map is still work in progress. (A) Stereonet of poles to bedding for the region, (B) Stereonet of poles to thrusts with displacements at least 10+ m. The bias towards northerly vergence is evident in the plots (upper hemisphere). 1 = area of carbonates that correspond with the Khao Khwang Formation, 2 = WNW–ESE to E–W trending zone of carbonates attributed to the Khao Khad Formation. SB = Sap Bon village.

these formations known to the authors show predominantly upright to steeply inclined fold axes, with a similar fold style. In the Pang Asok Formation axial planar cleavage is well developed and has spawned a local tile-making industry (Fig. 8B). The restricted area of Alum Shale outcrops around quarry A (Table 1) also shows well developed cleavage that is axial planar to tight,

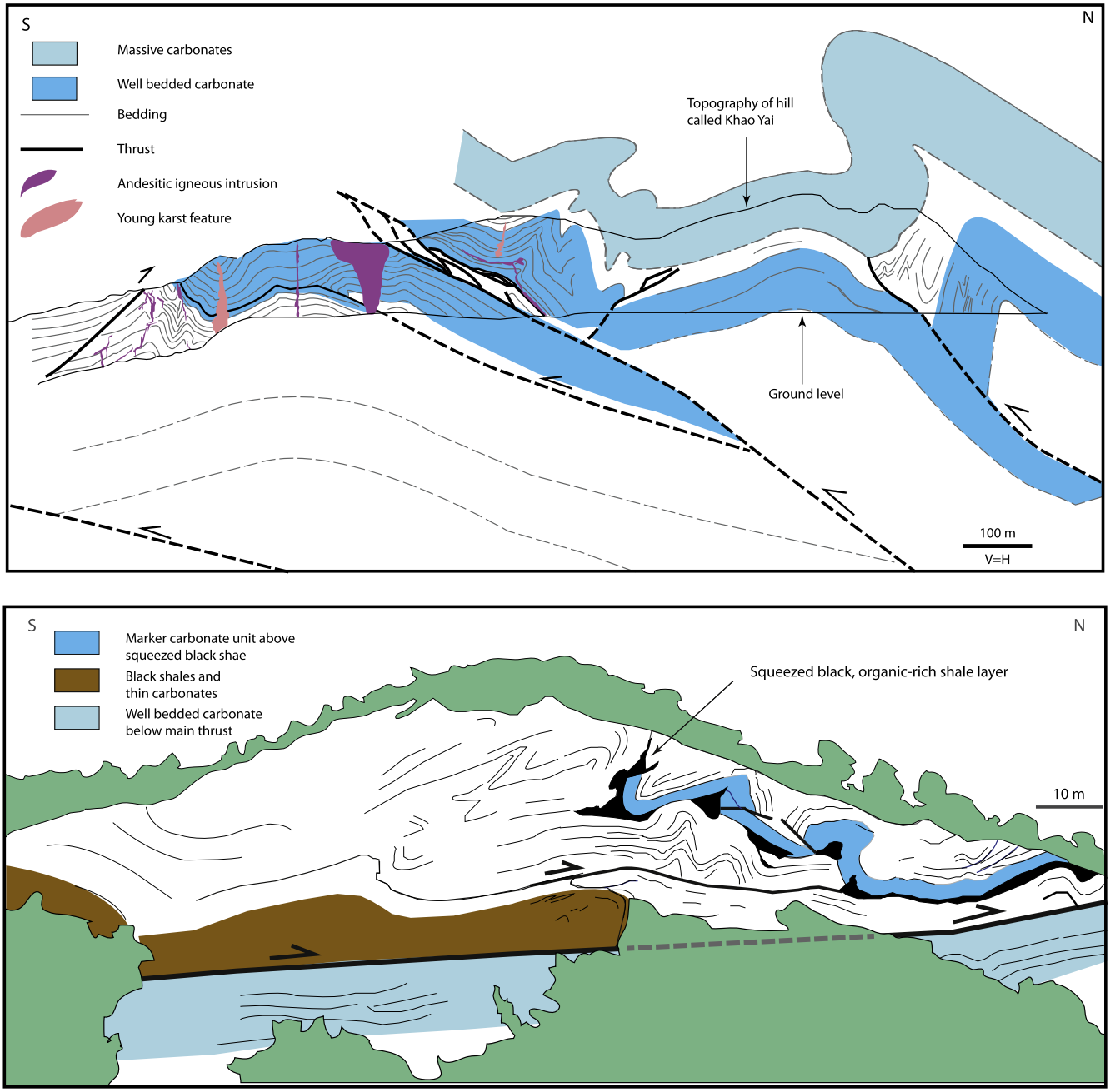

Fig. 6. Cross-sections of large quarry outcrops in the Saraburi Highway 21 area, see Fig. 5 and Table 1 for locations). (A) Cross section of predominantly south-verging structures across the extensively quarried hill (across quarries E, F and G, Table 1). (B) North verging major thrust, with fault bend fold in hangingwall. Secondary folds are partially a result of detachment and squeezing along shale horizons, Quarry H.

north vergent folds seen in light green tuffaceous beds within the shales (Fig. 8A).

Palaeo-stress measurements (Fig. 9) and the general trend of folds, thrusts and cleavage indicate N–S to NNE–SSW maximum horizontal stress directions and point to generally N–S convergence. Later deformation (timing poorly established but possibly Indosinian II and/or early Cenozoic) has produced oblique structures including NNE–SSW trending folds, and type 1 and 2 fold interference patterns (Graseman et al., 2004). NW–SE to E–W trending sinistral strike-slip faults are also present in some areas.

The region is anomalous with respect to the N–S trends of the Inthanon and Sukhothai zones, yet it represents the best developed example of foreland fold-and-thrust-belt-type deformation associated with the Indosinian Orogeny in Thailand. Consequently it is important to explain why the Khao Khwang Fold and Thrust Belt developed. Does the E–W trend of the fold and thrust belt represent a minor bend in the old continent margin, an inverted basin trend, or a tectonically significant departure from the regional N–S trends?

3. Relationship of the Khao Khwang Platform to Permian deposits of the Khorat Plateau area

Further north and northeast of the Khao Khwang Platform extensive areas of Permian carbonates and clastics are present that were deposited in an intra-continental setting in rift basins and their adjacent high areas (Booth and Sattayarak, 2011). The

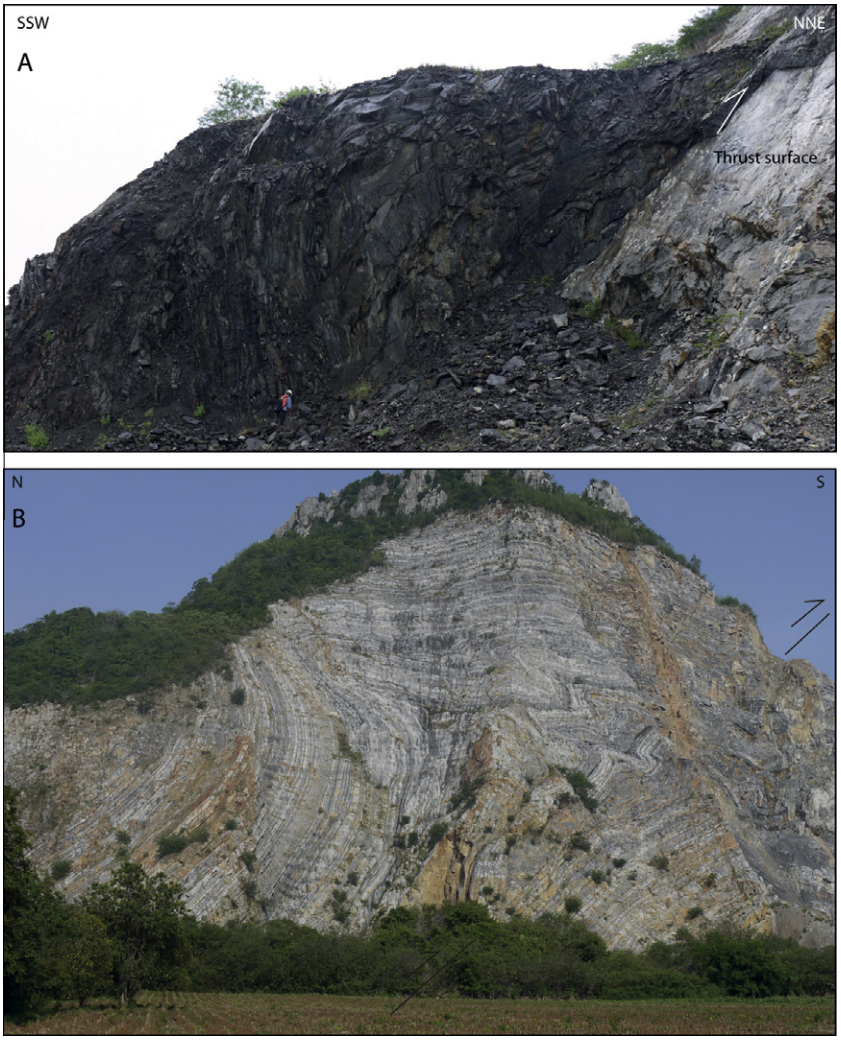

Fig. 7. Photographs of large-scale structural features within the Saraburi Group (see Fig. 5 and Table 1 for locations). (A) Shales with thin sandstone beds of the Sap Bon Formation thrust over Khao Khad Formation carbonates to the NNE. The thrust probably has a displacement in the order of a few kilometres, and a complex antiformal duplex (but with many out-of-sequence thrusts) is formed in the hangingwall. Main thrust plane 290°40°S, striations variable, most dominant set 160°25°SSE (quarry A). (B) North tilted, south-transported detachment folds on west side of Khao Yai hill, off Highway 21 (quarry C, Table 1). This hill is on the opposite (western) side of the hill shown in section Fig. 6A.

Table 1
List of quarries described in this paper with location coordinates.

Quarry A = Siam Cement Quarry	14°38′44N	101°04′30E
Quarry B = Abandoned slate quarry, Pak Chong	14°39′22N	100°22′29E
Quarry C = Khao Yai Quarry 1, Saraburi	14°42′10N	100°52′57E
Quarry D = Sila Sakol Pattana Co Ltd., Pak Chong	14°37′36N	101°21′49E
Quarry E = Khao Yai Quarry 2, Saraburi	14°41′55N	100°53′05E
Quarry F = Khao Yai Quarry 3, Saraburi	14°42′06N	100°53′10E
Quarry G = Khao Yai Quarry 4, Saraburi	14°42′16N	100°53′10E
Quarry H = Abandoned quarry, Saraburi	14°43′55N	100°53′51E

geometry of these basins is well defined by industry seismic reflection data acquired across the Khorat Plateau. These basins range from being undeformed by Indosinian deformation, through inversion, to being strongly folded and thrusted (Kozar et al., 1992; Booth and Sattayarak, 2011). The orientations of structures in the basis in varied and can be interpreted as a function of both varying orientations of the inverted normal faults, and changing stress directions with time, in particular there are significant NNE–SSW and E–W folds and thrusts trends in these basins (Fig. 2). The Khao Khwang Platform area is related to the basins of the Khorat Plateau area but is somewhat different in that the platform lies close to the SW edge of the Indochina Block marked by the Sa Kaeo Suture. Consequently it is likely that the Khao Khwang Platform was deposited on the continental margin of Indochina, and not in an interior basin. This view is complicated by the presence of the Cenozoic Mae Ping Fault zone between the Khao Khwang Platform and the Sa Kaeo Suture (Fig. 2), and how much translation has occurred along the strike-slip fault to attain the present day configuration. The impact of the Mae Ping Fault zone is discussed in Section 6.

4. Extent of the Loei-Petchabun volcanic belt

The Loei-Petchabun volcanic belt comprises a region of diverse igneous rock types and ages that extends from Loei in the north to Khao Yai (or Saraburi) and Sa Kaeo in the south (Fig. 3). The geology of the belt has recently been reviewed by Barr and Charusiri (2011). The belt contains some Devonian and Carboniferous volcanics (including possible sea floor spilites; Intasopa and Dunn, 1994; Panjansawatwong et al., 1997, 2006; Charusiri et al., 2002), as well as Permo-Triassic volcanics and intrusives. The Permo-Triassic igneous rocks comprise calc-alkaline basalts, andesites and rhyolites, agglomerates and pyroclastic rocks are common

Fig. 8. Photographs of deformed clastics within the Saraburi Group (see Fig. 5 for locations). (A) Alum Shales, southern part of quarry A (Table 1), the light coloured tuffaceous layers are tightly to isoclinally folded in places. In shales where no tuffaceous layers are present all trace of folding and original layering is lost, and the tectonic cleavage is dominant. Cleavage orientation approximately 266°50°S. (B) Pang Asok Formation, anticline crest traversed by high-angle axial planar cleavage in quarry B (Table 1). Cleavage orientation ~090°80°–90°N and S depending upon location.

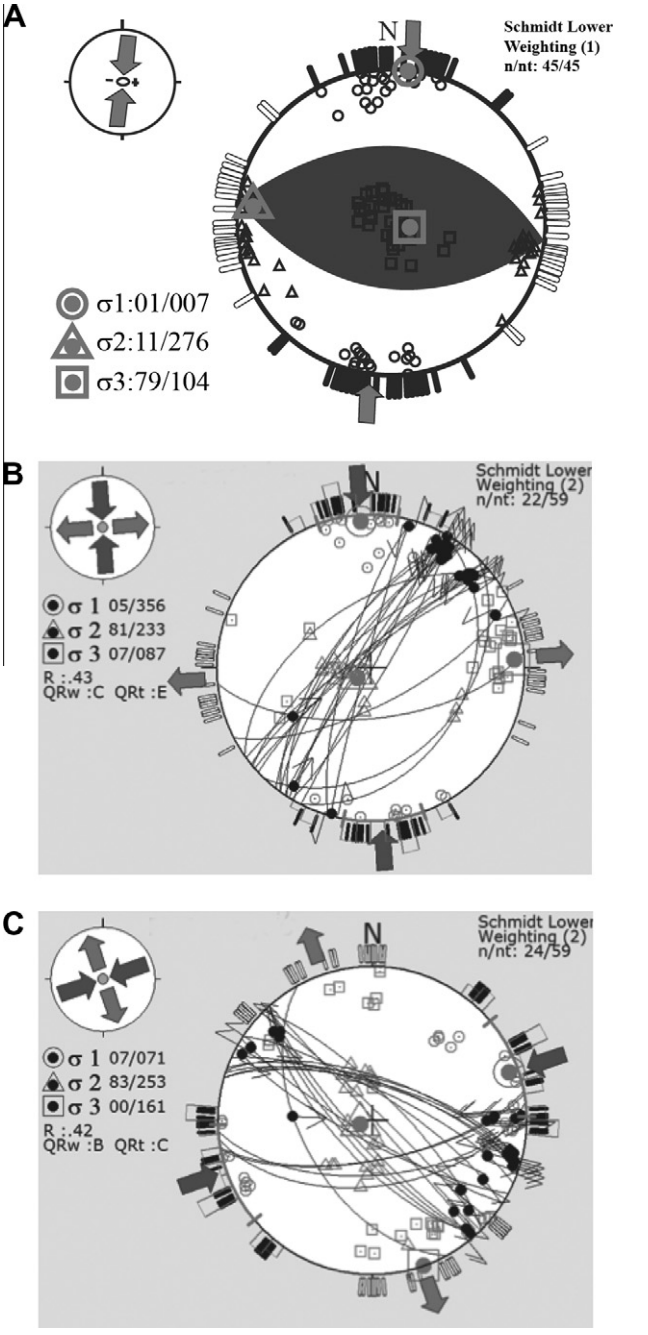

Fig. 9. Examples of palaeostress determined from populations of mostly minor faults from quarries. (A) quarries E, F, and G, stage 1 deformation (Table 1), (B) Quarry D. Early Triassic deformation, stage 1 deformation (Table 1), there are a few E–W trending thrust faults in the data set, and more numerous NE–SW trending minor sinistral strike-slip faults. Weighting has been applied in favour of the thrusts, which are larger-displacement features, though still probably only exhibiting tens of metres offset. (C) Later deformation (probably either Indosinian II, or Palaeogene), superimposed on structures related to B).

(Barr and Charusiri, 2011). The volcanics appear to be predominantly of early Triassic age, (~235–250 Ma, Intasopa, 1993; Jungyusuk and Khositanont, 1992; James and Cummings, 2007) and are interpreted by a number of workers to have formed in a volcanic arc setting (Kamvong et al., 2006; Marhotorn et al., 2008; Nakchaiya et al., 2008). However, Sone and Metcalfe (2008) argued that the Loei-Phetchabun granitoids (mostly of Triassic age) have an S-type affinity, and that the magmatic belt developed as a consequence of crustal thickening caused by back-arc compression and later by Sibumasu-Indochina collision. Although Barr and Charusiri (2011) note that geochemically the Loei-Phetchabun volcanic belt is compatible with Triassic subduction, in these old sequences it is difficult to discriminate between a subduction setting, and that suggested by Sone and Metcalfe (2008).

Recent U–Pb dating of zircons by Meffre et al. (in prep.) for the Saraburi-Khao Yai area indicate the presence of 213–188 Ma rhyolites, which overlie 250–240 Ma andesites, together with 250–240 Ma and 210–200 Ma granites. In terms of the Indosinian phases of deformation identified in the Khorat Plateau, the 250–240 ages correspond with the Stage 1 (Fig. 2), while the 213–188 Ma ages correspond with Stage 2 (Fig. 2). Since a 240 Ma granodiorite post-dates deformation in the Pak Chong area (Fig. 5), deformation in the Khao Khwang Fold and Thrust belt must have occurred sometime between the latest Permian and 240 Ma. Andesite-dacite dykes and sills are common features in the Khao Khwang fold and thrust belt. In most cases they cross-cut folds, and cross-cut or follow thrusts, indicating they were intruded after deformation. However, in some cases dykes are offset by thrusts. Hence magmatic activity began during deformation, but continued and increased in activity after deformation ceased. Following the general scheme of orogenic development proposed by Sone and Metcalfe (2008) closure of a marginal back-arc basin and collision of a Sukhothai Belt-related island arc fragment with Indochina is the likely cause for the formation of the Khao Khwang fold and

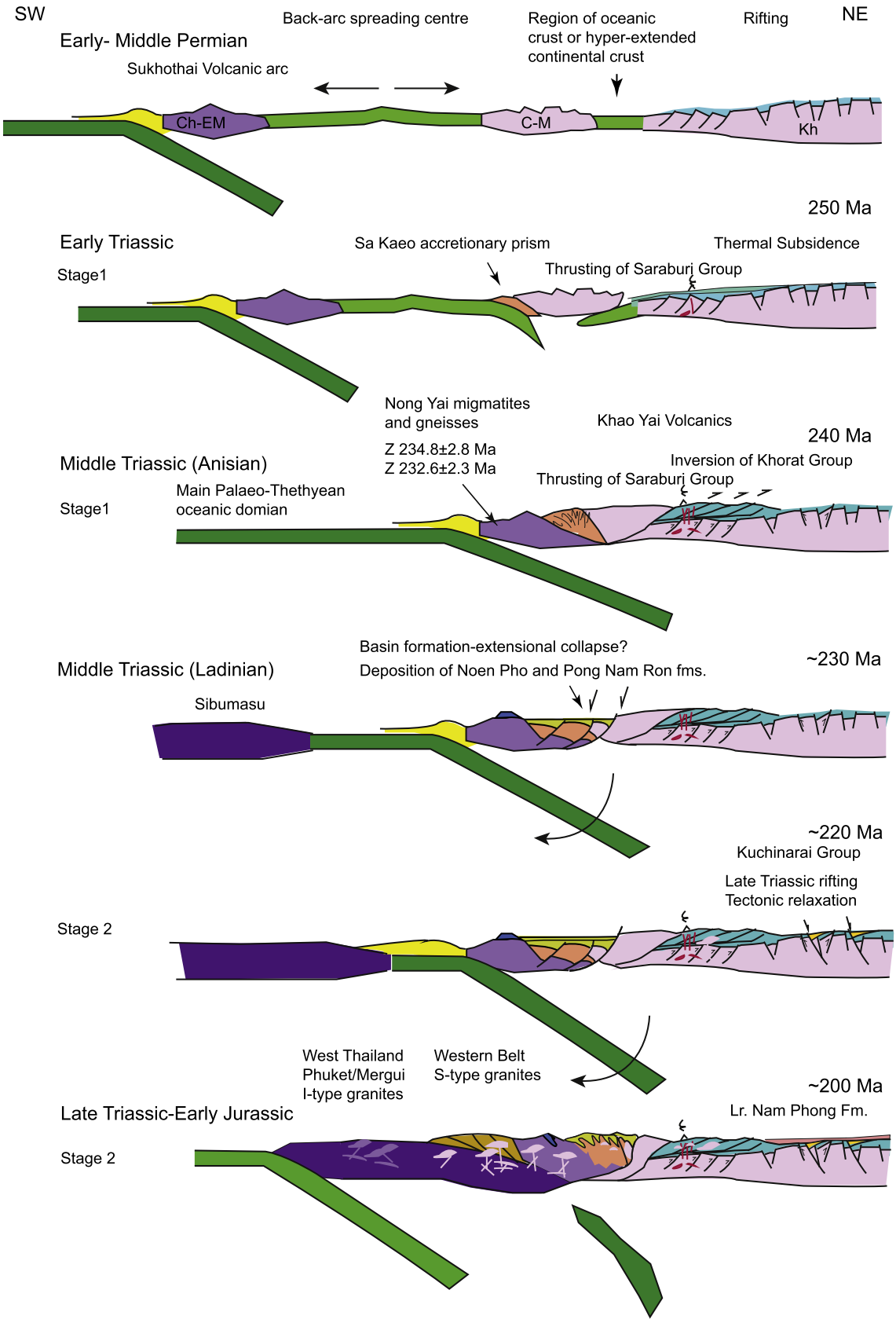

Fig. 10. Schematic plate-scale cross-section showing the tectonic development of the Saraburi-Khorat Plateau area during the Permo-Jurassic development of the Indosinian Orogeny. CH-EM = Chanthaburi-East Malaysia.

thrust belt in the early Triassic. The Saraburi-Khao Yai volcanics are syn- and post-collisional, and they formed on the margin of the Indochina crust. This setting is similar to Sone and Metcalfe's (2008) interpretation of the Loei-Phetchabun belt as a whole.

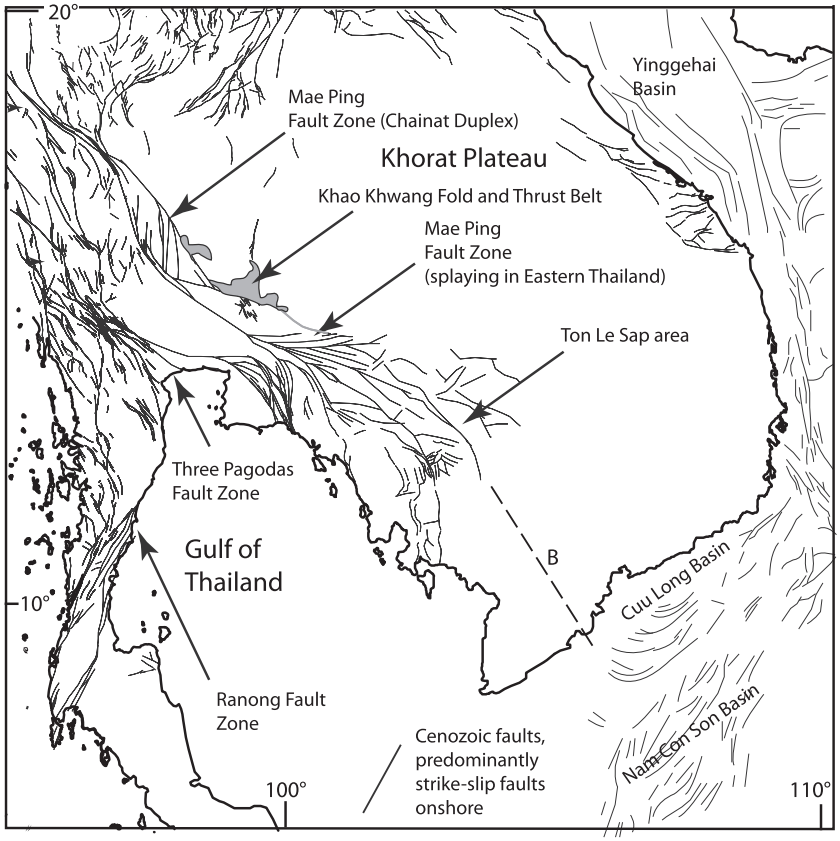

Fig. 11. Regional map of the Mae Ping Fault zone, and other Cenozoic faults illustrating the strongly splaying geometry of the fault as it passes into the Ton Le Sap area. The dashed line marked B shows the trace of the fault required to link the Mae Ping Fault zone with the Cuu Long Basin.

The Khao Khwang fold and thrust belt is the only area where there is reasonably good exposure of the relationships between a major Indosinian fold and thrust belt and the Loei-Phetchabun volcanic belt. But it is probably not representative of the belt as a whole because passing north from Khao Khwang the volcanics lie on the foreland side of the fold and thrust belt and trend overall N–S, while in the Saraburi-Khao Yai area the volcanics lie on the hinterland side, and trend WNW–ESE. It seems appropriate to view the volcanic belt as taking an almost 90° bend to reach the Saraburi area rather than forming a straight N–S belt (Fig. 3).

5. Structural evolution of Eastern Thailand

Ridd (2012) in his review of the geology of Southeastern Thailand noted that the eastern area between Tha Mai and Trat (his Belt IV) was dominated by deepwater Middle-Late Triassic shales, cherts and turbidites, which overlie the block-in-matrix deposits (Thung Kabin mélange) of the Sa Kaeo-Chantaburi Accretionary Complex (Hada et al., 1999; Chutakositkanon et al., 2004; Ueno and Charoentitirat, 2011). The presence of Middle-Late Triassic pelagic chert (Noen Pho Formation), with associated basalts was problematic for Ridd (2012) to explain in the context of an early arc-continent collision (i.e. Stage 1), because the deepwater conditions for deposition of the Noen Pho Formation should not have existed post-collision. Consequently Ridd (2012) proposed cessation of accretion by Middle Triassic times, and subsequent deposition of the Noen Pho and Pong Nam Ron Formations over the mélange. This interpretation is similar to that of Ueno and Charoentitirat (2011). Ridd (2012) inferred that only the Middle to predominantly Late Triassic (i.e. Stage 2) deformation affected the area.

The evidence for folding and thrusting of the Khao Khwang Platform region provides strong evidence that deformation associated with the Stage 1 occurred in Eastern Thailand and contradicts the conclusions of Ridd (2012). Folding and thrusting appears to have largely finished by about 240 Ma as indicated by the intrusion of the post-kinematic granodiorite SE of Pak Chong. Within the amphibolite to granulite metamorphic grade crust of the inferred Sukhothai zone island arc belt, Geard (2008) obtained U–Pb ages from zircons of 234 ± 2.8 and 232 ± 2.3 Ma from the Nong Yai area migmatites and gneisses (area of the Cenozoic Klaeng Fault zone), which require explanation as a metamorphic event associated with closing stages of Stage 1 deformation (Fig. 10). Consequently an alternative explanation for the depositional setting of the Noen Pho and Phong Nam Ron formations must be found. Here it is proposed that extensional collapse of thickened crust following collision caused subsidence that led to development of a deepwater hinterland basin (Fig. 10). Such basins are known in the Mediterranean, in particular the Alboran Sea (Morley, 1993), where volcanism has accompanied rifting and post rift subsidence in deepwater conditions. This is a similar 'successor basin' solution to that proposed by Barber et al. (2011). The Indosinian II collision was focused on west-directed thrusting where the Palao-Tethyean units of the Inthanon Zone were emplaced over the leading edge of Sibumasu (e.g. Sone and Metcalfe, 2008; Fig. 10). Deformation maybe present in the Khao Khwang fold and thrust belt, but it appears to be relatively minor in comparison with Stage 1. The dominance of Indosinian I deformation (i.e. Stage 1) and absence of deformation immediately below the Indosinian II unconformity (i.e. Stage 2) on seismic reflection data across the Khorat Plateau is very clear (Booth and Sattayarak, 2011). There is only local reactivation of some basin bounding faults associated with Indosinian

II (Booth and Sattayarak, 2011). The eastern/northern extent of strong Stage 2 deformation seems to terminate within Belt IV, with inversion of the successor basin, although relatively weak Stage 2 deformation may also affect the Khao Khwang Fold and Thrust Belt (Fig. 10). In this scenario the Triassic magmatism of the Loei-Phetchabun belt is syn- to post-collisional for either Stage 1, or both Stage 1 and Stage 2 (Fig. 10).

In Fig. 10 the Indochina Block is shown as being rifted, and comprising two separate blocks divided by a seaway. This feature has not been shown in previous restorations (e.g. Sone and Metcalfe, 2008; Ridd, 2012). The reasons for its presence are discussed in Section 7. However it is worth noting here that by closing this seaway first between the two Indochina fragments, the collision between the Sukhothai Arc and Indochina can occur later, and match the 234 ± 2.8 and 232 ± 2.3 Ma peak metamorphic ages of Geard (2008) from migmatitic gneisses at amphibolite to granulite facies within the (Cenozoic) Klaeng Fault zone (location X, Fig. 3). Without this delay it becomes difficult to explain how Indochina-Sukhothai Arc collision can generate folding and thrusting of the Khao Kwang Platform prior to 240 Ma, and followed later by peak metamorphism.

Stage 2 deformation is related mostly to collision of Sibumasu with the combined Sukhothai-Indochina Terrane. This collision produced the S-type Western Belt granites in Thailand, and West Malaysia Main Range granites (Figs. 2 and 10; e.g. Charusiri et al., 1993; Searle et al., 2012). According to Searle et al. (2012) subduction of the Neo-Tethys beneath Sibumasu also caused intrusion of I-type granites in the areas of East Burma, West Thailand and West Malaysia.

6. E–W trending Khao Khwang Fold and Thrust Belt

The timing of events discussed above fits in general with the tectonic evolution model proposed by Sone and Metcalfe (2008), but their model was essentially dealing with N–S trending tectonic zones and E–W convergence (with respect to present-day orientations). The anomalous E–W trending Khao Khwang Fold and Thrust Belt presents a problem for understanding this general model. Ridd (2012) explains the disruption of the N–S trends entirely by post-collision strike-slip deformation. Of particular concern for the Khao Khwang Fold and Thrust Belt is possible translation and rotation by the Mae Ping Fault which runs about 30–40 km south of the belt (Figs. 3 and 11) and north of the Sa Kaeo Suture.

If Cenozoic displacement on the Mae Ping Fault Zone is large (~150 km sinistral displacement) as proposed by Tapponnier et al. (1986) then the translation of the Khao Khwang Fold and Thrust Belt eastwards with respect to the block south of the fault, also has implications for understanding the origin of the fold and thrust belt. However, passing eastwards the extent of the Mae Ping Fault becomes controversial. Some authors make the fault of regional extent, passing all the way to the NW Borneo margin (e.g. Leloup et al., 2001), while others suggest it dies out into the Cuu Long Basin on the Vietnam margin (Morley, 2002).

The simplest configuration of the Mae Ping Fault zone is to have a NNW–SSE segment running through the Chainat Duplex area, a WNW–ESE segment in the Kabin Buri area, and a NW–SE segment through Tonlel Sap (Fig. 3). Restoration of the sinistral displacement applied to the northern side of the fault moves the Saraburi-Pak Chong fold-thrust belt eastwards and forces rotation of

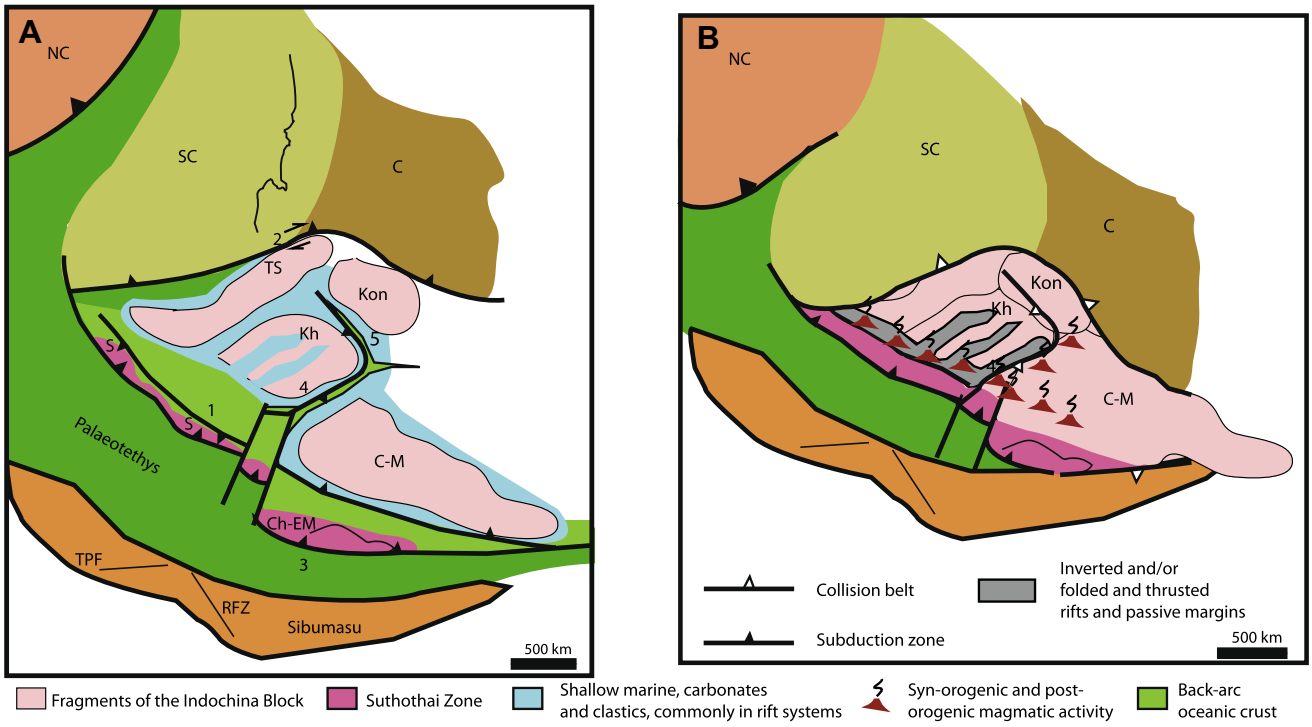

Fig. 12. Map view reconstruction of the plate tectonic setting of SE Asia during the early stages of the Indosinian orogeny, modified from Lepvrier et al. (2004). (A) Early Triassic, (B) Middle Triassic. NC = North China Block, SC = South China Block, C = Cathaysian Block. Indochina Terrane subdivided by rifting into TS = Truong Son, Kon = Kontum, Kh = Khorat, C-M = Cambodia, offshore Malaysia. Sukhothai Block subdivided into: S = Sukhothai, Ch-EM = Chanthaburi-East Malaysia. TPF and RFZ = locations of Three Pagodas and Ranong Fault zones on Sibumasu. 1 = Subduction zone dip to the west (present day; Singharajwarapan and Berry, 2000). 2 = Song Ma suture zone. Eclogites and high-pressure granulites dated at 243 Ma ± 4 Ma (Nakano et al., 2008, 2010) and major nappes in NE Vietnam pre-date Phia Bioc granites (U–Pb ages between 248 and 245 Ma, Roger et al., 2012). 3 = Future Bentong-Raub suture zone which closes first in the east (Metcalfe, 2011). 4 = Site of Khao Khwang Platform at the margin of a rift between the Kh and C–M blocks. The zone wraps around to the future Poko suture (5). Transform offsets in the margin are shown to permit the early eastern collision of Sibumasu with Ch–EM compared with the west.

the northern block around the NNW–SSE to WNW–ESE bend in the Mae Ping Fault as discussed by Ridd (2012). Movement of the northern block relative to a fixed southern block is consistent with the post-mid Cretaceous 35° clockwise rotation of the Khorat Plateau area identified from palaeomagnetic data by Charusiri et al. (2006; Fig. 3B). The restoration moves the Khao Khwang Fold and Thrust Belt to lie north of Palaeozoic metamorphic rocks in Cambodia, which are interpreted to be part of the Indochina Block continental crust (e.g. Sone and Metcalfe, 2008; Fig. 3B location Y).

The simple restoration in Fig. 3B indicates that strike-slip movements actually enhance the problem of explaining the E–W fold and thrust belt in the context of N–S trending major sutures, since the E–W trend is moved further east, and the NE–SW trend of the eastern part of the fold and thrust belt becomes accentuated. However, the assumption of a simple Mae Ping Fault geometry is problematic. Recent gravity and seismic data shows the Mae Ping Fault has a strong splaying geometry in the Tonle Sap Basin, and the fault strongly splays in SE Thailand before reaching Cambodia (Ridd and Morley, 2011). Consequently models that show a long, simple fault traversing a large distance to the NW Borneo margin oversimplify the actual fault geometry to a point where the significance of the splays, as suggesting a region of fault displacement loss, and possibly termination is lost. At best a strand of a complex splaying system reaches the Cuu Long Basin on the Vietnam margin and dies out there (Fig. 11 line B). Probably other strands run NNW–SSE through the easternmost part of SE Thailand (Fig. 11). How displacement can be divided amongst the strands is not at all certain. It seems probable that if there is 150 km sinistral offset on the Mae Ping Fault zone in western Thailand, that displacement is less in SE Thailand, as the fault is dying out into a regional system of complex horse tail-type fault system. Consequently the reconstruction in Fig. 3B represents the highest displacement option, and more likely the actual displacement amount is considerably less.

7. Could an E–W suture run through Northern Cambodia?

For the Khao Khwang Fold and Thrust Belt post-Indosinian strike-slip rotations cannot restore the structure trends to a more N–S direction (e.g. Fig. 3B). Consequently the anomalous E–W orientation of the fold and thrust belt cannot be explained by post-Indosinian deformation and rotation, and needs to be explained in the context of Indosinian tectonics. Additionally the dominant rift structures of the Khorat Plateau, and possibly the Khao Khwang Platform trend approximately E–W. This orientation is at odds with the model of a simple N–S trending margin and suture zone. One explanation of the E–W trends is to postulate an E–W trending continental margin and suture zone that runs south of the fold and thrust belt into northern Cambodia. The possibility of this region being a suture zone was noted by Hutchison (1975, the Siem Reap-Stung Treng 'ophiolite').

The most prominent suture in the region is the Sa Kaeo suture, which trends NNW–SSE, and hence it can be projected into the Gulf of Thailand, and run parallel to the Raub-Bentong/Inthanon Zone suture. The possible existence of the Siem Reap-Stung Treng 'ophiolite' is largely unacknowledged in more modern literature, except as a trend, without discussion in Fig. 11 of Lepvrier et al. (2004). Cambodia is viewed as being a part of the Indochina Block contiguous with the Khorat Plateau area. Trying to identify any possible suture in northern Cambodia is difficult for two reasons: (1) exposure of Permo-Triassic rocks is very limited, and (2) the geology is simply not well described by modern studies. What intriguingly is mapped, and briefly described for Cambodia is an Late Carboniferous-Triassic age volcano-sedimentary sequence composed of shale, chert, sandstone, marl, limestone, andesite, basaltic andesite, rhyolite, tuff (areas of Stungtreng, Preah Vihear, Siem Reap), andesites, rhyolites, tuffs and agglomerates have also been found in the Campot area (Phan, 2000; Fig. 3). The volcanics have been described as varying in thickness from 300 m to more than 1000 m, high in iron, and Na_2O, low in SiO_2 and Al_2O_3 and falling into the calc-alkaline group of andesites and basalts (Dickens and Tien, 1997). Despite the poor exposures in northern Cambodia in several places along the northern Permo-Triassic volcanic trend (Fig. 3A) reported results of mineral exploration (including shallow coring) in company brochures (e.g. Liberty Mining, http://www.libertymining.com.kh/index.phppage=projects) describe the presence of Permo-Triassic andesitic volcanics and volcanic centres (Fig. 3, localities A and B).

Outcrops of the Carboniferous-Triassic age volcano-sedimentary unit fall into two trends, one in the western part of Cambodia that trends NNW–SSE and runs parallel to the Sa Kaeo suture zone, and another trend that runs E–W through Northern Cambodia. To the west the two volcanic trends meet in NW Cambodia and pass into the Sae Kaeo area of Thailand. Passing eastwards the E–W trend may link up with the Indosinian-age Poko Suture in Vietnam (Lepvrier et al., 2008; Fig. 1). Clearly much work needs to be done on the geochronology and geochemistry of the volcano-sedimentary unit before any conclusions about an E–W suture can be reached, but at least superficially there is a volcanic trend that seems anomalous for an intra-plate setting, and permits the possibility of an E–W suture to be considered.

8. Discussion

There have been no detailed studies on the Indosinian orogeny structural geology in Thailand to confirm the trends defined by regional sedimentary facies trends and igneous belts are matched by structural orientations in deformed sedimentary units. Curiously the two areas that have been studied in some detail for structural trends and sense of displacement both show predominantly E–W trending, north or south verging structures (the Inthanon Zone in Northern Thailand, Hara et al., 2009 and the Khao Khwang Fold and Thrust Belt discussed in this paper). Yet the main trends of the Indosinian Orogeny are viewed as being strongly N–S (e.g. Sone and Metcalfe, 2008) and deviations from this orientation are viewed as being minor, and perhaps caused by post-Indosinian rotations along strike-slip faults. Conversely the Mediterranean displays a number of examples of curved fold and thrust belts that arise due to salient and re-entrants in the colliding margins. The impact of such features has long been discussed for many orogenic belts (e.g. Rankin, 1976; Thomas, 1977, 1983). The most pronounced examples are the Rif–Tell–Betic system in the Alboran Sea, and the Banda Arc in eastern Indonesia, which have resulted from extreme subduction rollback (e.g. Morley, 1993; Rosenbaum et al., 2002; Spakman and Hall, 2010). Whether such models are applicable to segments of the Indosinian orogenic belt is uncertain. But unusual features like the Khao Khwang Fold and Thrust Belt, and the dominance of N–S vergence directions in the Inthanon Zone of northern Thailand (Hara et al., 2009) raise doubts about the simple model of N–S trending sutures.

The complexity of relationships in the Banda Arc is clear warning regarding making simple assumptions about how continental blocks fit within an orogenic belt. Following the termination of oceanic crust subduction the associated accretionary prism stage ended and the Banda Arc is now in an early stage of continent–continent collision (Hall and Wilson, 2000). The irregular nature of the Australian continental margin resulted in the early collisional stage where subduction rollback promoted collision of Australian continental fragments derived from the Papu New Guinea area, in the overriding block, with the Timor area continental block in the downgoing slab (Spakman and Hall, 2010). A deepwater fold and

thrust belt (that could be mistaken for an accretionary prism) lies between the two blocks, overlain by the older accretionary prism stage units (Hall and Wilson, 2000). Hence two continental blocks of the same palaeogeographic affinity could be juxtaposed across a major suture. Subsequent progression of the Australia-Sundaland collision could render such relationships extremely difficult to unravel and must be a concern for our understanding of the Indosinian Orogeny. It also highlights the problem of attributing disruption of perceived simple trends (N–S in the case of the Indosinian Orogeny), as being mostly post-collisional. However, lacking supporting evidence for complex arcuate belts (at present), a simpler explanation for the Khao Khwang Fold and Thrust Belt is proposed below.

Since there are extensive Permian rift basins within the Indochina Terrane of Thailand, it seems reasonable to look for a solution to the orientation of the Khao Khwang Fold and Thrust Belt in the extensional setting. Lepvrier et al. (2004) presented a schematic plate reconstruction for the late Permian that showed the Indochina Terrane as being composed of a number of blocks separated by narrow regions of oceanic crust that were closed during collision. This included a suture zone between a southern Indochina Terrane that includes eastern Malaysia and a Khorat Plateau block. The schematic reconstruction of Lepvrier et al. (2004) is elaborated in Fig. 12.

A basic model for development of the Indosinian Orogeny in Thailand involves early Triassic closure of the Nan-Uttaradit-Sa Kaeo back-arc basin, and collision of the Sukhothai Terrane with Indochina, followed by closure of the Palaeo-Tethys and collision of Sibumasu with combined Sukhothai-Indochina during the Late Triassic (e.g. Sone and Metcalfe, 2008). However, some data suggest that the timing of collisions and direction of palaeo-subduction zones are inconsistent along the strike of the orogenic belt. For example Singharajwarapan and Berry (2000) have argued for a west-dipping subduction zone (modern orientation) beneath the Sukhothai Zone associated with the Nan-Uttardit Suture, while Hara et al. (2006) used variations in Illite crystallinity to deduce a NE-dipping subduction zone for the Sa Kaeo Suture. In northern and central Thailand the age of peak metamorphism is dominantly Late Triassic-Early Jurassic (see review in Hansen and Wemmer, 2011; Fig. 2). Late closure of the Palaeo-Tethys is also indicated by the persistence of deepwater chert deposition within the Inthanon Zone into the Middle Triassic (Hara et al., 2009). However, Metcalfe (2000, 2011) argues that for the Raub-Bentong Suture in Malaysia the data best fits closure of the Palaeo-Tethys by the Early Triassic, although full collision and closure was not achieved until the Late Triassic. The ambiguity in understanding the timing of closure is highlighted by Ridd (in press), who has interpreted the Semanggol Formation and its correlatives in the Thailand-Malaysia border area as showing the Sibumasu-East Malaya collision occurred at the end of the Middle Triassic. Fig. 12 shows one way by which the variations described above can be reconciled. The early Triassic deformation events are largely driven by collision of the South China Terrane with the western and northern part of the Indochina Terrane. Although the significance and existence of this collision zone has been questioned (e.g. Carter and Clift, 2008), recent dating of events, the extensive occurrence of nappes in northern Vietnam, and the presence of high grade Early Triassic metamorphism including eclogites within granulite facies rocks within the Song Ma suture zone point to a significant collision (Nguyen Van Vuong et al. in press; Roger et al., 2012). Both the early collision of the Sibumasu Terrane with eastern Indochina, and South China with western and northern Indochina would have encouraged closure of the inferred oceanic crust-floored rift that separated Cambodian Indochina from Khorat Indochina (Figs. 10 and 12). This led to development of the Khao Khwang Fold and Thrust Belt.

9. Conclusions

The Khao Khwang Fold and Thrust Belt is interpreted as having developed on the southern margin of an Indochina continental fragment during the Early Triassic as part of the Indosinian I orogeny. The present day orientation of the fold and thrust belt is WNW–ESE to NE–SW with the tectonic transport direction predominantly towards the north. Taking into account removal of 150 km of Cenozoic strike-slip displacement on the Mae Ping Fault zone only serves to enhance the E–W orientation of structures in the fold and thrust belt. This contrasts with the general present day setting of the Indosinian terranes that indicate the main structural trends associated with collision of Sibumasu and Indochina should be oriented N–S. Here it is proposed that the Indochina Terrane was a series of continental blocks, separated by Permian rifting that during the early stages of collision (particularly collision of the South China-Cathaysian Terrane with the Vietnam portion of Indochina) during the Early Triassic became amalgamated by closure along the older rifts. At the same time, or following on from the South China-Indochina collision came the closure of the back-arc basin between Indochina and the Sukhothai zone (Figs. 10 and 12). The rift basins, which became thrust, inverted and locked-up during the early stages of the Indosinian orogeny, were only reactivated to a relatively minor degree when later Sibumasu collided with the accreted Sukhothai Zone-Indochina Terrane margin (Fig. 10). It is suggested that the Sa Kaeo suture zone area was initially deformed during the early stages of the orogeny, underwent extensional collapse of thickened crust to form a deepwater basin for Middle Triassic clastics, and was subsequently deformed by the later Sibumasu-Indochina collision (Indosinian II; Fig. 10). The scenario described above requires the presence of a (minor) E–W trending suture in NW Cambodia. Evidence for this suture is patchy and considerably more work is required in this area to establish or eliminate the possibility.

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