Tectonic implications of the Nan Suture Zone and its relationship to the Sukhothai Fold Belt, Northern Thailand

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Abstract

The Nan Suture and the Sukhothai Fold Belt reflect the processes associated with the collision between the Shan-Thai and Indochina Terranes in southeast Asia. The Shan-Thai Terrane rifted from Gondwana in the Early Permian. As it drifted north a subduction complex developed along its northern margin. The Nan serpentinitic melange is a thrust slice within the Pha Som Metamorphic Complex and in total this unit is a Late Permian accretionary complex containing offscraped blocks from subducted oceanic crust of Carboniferous and Permian age. The deformational style within the Pha Som Metamorphic Complex supports a west-dipping subduction zone. The Late Permian to Late Triassic fore-arc basin sediments are preserved in the Sukhothai Fold Belt and include a near continuous sedimentary record, at least locally. The whole sequence was folded and complexly thrust in the Late Triassic as a result of the collision. Late syn- to post-kinematic granites place an upper limit of 200 Ma on the time of collision. Post-orogenic sediments prograded across the suture in the Jurassic.

1. Introduction

The tectonic evolution of the northern Thailand region has been a subject of interest and controversy in recent years. Much of the debate has centred on the geometry and timing of terrane accretion in this part of Southeast Asia. In most discussions the Nan (or Nan-Uttaradit) Suture has been identified as the terrane boundary and much of the discussion has been limited by this perception. However, the whole of the Sukhothai Fold Belt (Fig. 1) is related to this margin, and the plate tectonic evolution of northern Thailand is much better constrained when the fold belt is considered as a whole. The structural and metamorphic evolution of key rock units within the Sukhothai Fold Belt constitute the main part of this paper. This data was produced from a detailed structural study of a section across northern Thailand from Lampang to the Sirikit Dam (Fig. 2). Existing tectonic models for this part of Southeast Asia are tested in the light of this new structural and metamorphic data.

1.1. Current tectonic models

The common view among geoscientists concerned with the tectonic evolution of Southeast Asia is that mainland Southeast Asia (south of the Red River Fault Zone) was formed by amalgamation of the Shan-Thai and Indochina Terranes (Fig. 1). These two terranes have been thought to be part of Gondwana in the Early Palaeozoic (Ridd, 1971; Burrett, 1974; Audley-Charles, 1983; Burrett and Stait, 1985, 1986). The glaciomarine siliciclastic rocks of the Early Permian Phuket Group of southern Thailand, Shan-Thai Terrane are direct correlates of the Gondwana glacial stratigraphy. These correlations, and the faunal provinciality in associated rocks, require that the Shan-Thai Terrane did not rift from Gondwana until the Early Permian (Metcalfe, 1988; Hills, 1989; Shi and Waterhouse, 1991).

Plate tectonic models accounting for the collision between the Shan-Thai and Indochina Terranes have been proposed by a number of workers. The general agreement among these models is that there was a palaeo-ocean basin between the two terranes in the Late Palaeozoic. The suture between these two terranes is commonly drawn along the “Nan River Ophiolite Belt”. This belt is thought to extend southwards to the Sa Kao Suture (Bunopas, 1981) and across the Gulf of Thailand into Peninsular Malaysia where a similar feature known as the Bentong-Raub ophiolite line has been recognised (Stauffer, 1974; Bunopas, 1981). Nevertheless, the geometry and timing of collision has been controversial.

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The geometry of plate convergence prior to collision has been interpreted as:


3. A pair of subduction zones dipping in opposite directions, i.e. towards both the west and the east, as suggested by Gatinsky et al. (1978), Thanasuthipitak (1978), Bunopas (1981), Bunopas and Vella (1983), Cooper et al. (1989) and Hutchison (1989).

The timing of collision of the Indochina and Shan-Thai Terranes has been interpreted as:


2. Late Permian–Early Triassic (Stauffer, 1974; Thanasuthipitak, 1978; Ridd, 1980; Metcalfe, 1986; Hayashi, 1988; Cooper et al., 1989), and


This wide diversity of interpretation reflects the complicated tectonic evolution of the region, the lack of detailed geological knowledge and the strong focus on the Nan Suture itself without sufficient regard to the surrounding Sukhothai Fold Belt. The analysis below synthesises the geology, including that of the Sukhothai Fold Belt into a coherent picture of the whole belt.

1.2. Regional geology

The oldest rocks recognised in the Sukhothai Fold Belt (Permo-Carboniferous) are in the Pha Som Metamorphic Complex along the eastern margin. Permian turbidites and limestones (Phrae Group) are distributed mainly in the central and eastern part of the Sukhothai Fold Belt (Fig. 2). Permio-Triassic volcanic and volcanioclastic rocks occur in two areas, in the Lampang-Phrae area (i.e. the central part of the Sukhothai Fold Belt) and in the Sirikit Dam area close to the boundary between the Sukhothai and the Loei fold belts. Triassic turbidite sequences (the Lampang Group) in the Lampang and Phrae areas conformably and unconformably overlie the Permo-Triassic volcanic rocks and the Permian turbidite sequence. In the Sirikit Dam area (Figs. 2 and 3), continental red beds of Middle Jurassic age (the Phra Wihan Formation) unconformably overlie folded Triassic turbidites (the upper part of the Nam Pat Group).

Preliminary geochemical data from volcanic rocks in the Loei Fold Belt, to the east of the Nan Suture, support subduction-related arc volcanism in that area, but Intasopa and Dunn (1994) showed that these volcanic rocks have diverse tectonic settings of eruption and range in age from Late Devonian to Triassic. The present evidence suggests that most of the volcanic rocks in the Loei volcanic province are older than the Sukhothai Fold Belt and are probably related to an older arc. Indochina probably formed by amalgamation of the Kontum Terrane and the Truongson region (Fig. 1) perhaps as late as Early Triassic (Lepvrier et al., 1997). A Late Permian–Early Triassic collision matches the stratigraphic break in the Loei Fold Belt where Early to Middle Triassic strata are missing. The Permian marine strata in this fold belt are unconformably overlain by largely lacustrine, deltaic and fluvial clastic sediments of the Upper Triassic (Norian) Huai Hin Lat Formation (Chonglakmani and Sattayarak, 1978). We assume here that the structural and volcanic relationships in the Loei Fold Belt may be related to an Early Triassic collision between parts of the Indochina Terrane and therefore they cannot be used to...
constrain the key characteristics of the collision between the Indochina and Shan-Thai Terranes.

2. The Sukhothai Fold Belt

2.1. Pha Som Metamorphic Complex

The oldest rocks recognised in the Sukhothai Fold Belt, particularly the eastern part, is the Pha Som Metamorphic Complex (Singharajwarapan and Berry, 1993). This unit is composed of a number of fault-bounded blocks of rocks with highly variable composition. Major elements of the complex include volcanic rocks, greywacke-dominated meta-sedimentary units, piemontite–quartz schist and a serpentinite melange unit (including the Nan ophiolite association) each with a discrete sedimentary and deformational history.

The metasedimentary rocks consist of metagreywacke and minor phyllite. Singhharajwarapan (1998) discussed the modal and whole rock composition of the metagreywackes. He noted that they have high detrital plagioclase, high La/Th and high Sc and concluded that they were derived from a continental volcanic arc. The range in greywacke compositions is very similar to the range in the Torlesse and Caples Terranes in New Zealand.
The metagreywacke can be divided into three textural groups, equivalent to textural zones 1 to 3 of Bishop (1972) in the Torlesse Group of New Zealand. The Pha Som Metamorphic Complex has four deformation phases (Singharajwarapan, 1994). S₂ is the dominant cleavage with widespread transposition of bedding and rare relict S₁. Locally, mylonitic textures are found associated with the most intense cleavage zones. S₂ dips moderately to the northwest and a locally developed L₂ stretching lineation plunges shallowly to the WNW (Fig. 4c, e). The structural vergence and other kinematic criteria, for the D₂ event, indicate eastward tectonic transport. The D₃ and the D₄ asymmetrical angular folds and related thrusts in this complex are much less intense and correlate with structures present in the overlying Permo-Triassic turbidites. The metamorphism of the Pha Som metagreywacke occurred under pumpellyite–actinolite facies conditions, i.e. 3–6 kbar and 300–400°C. Barr and MacDonald (1987) reported marginal blueschist facies assemblages 70 km to the north, within lithologies correlated with the Pha Som metagreywacke. Peak metamorphism is contemporaneous with D₂ deformation.

The piemontite-bearing quartz schists represent metamorphism of hemipelagic or pelagic chert with high-Mn contents (Singharajwarapan, 1994). They occur as a thrust-bound structural unit about 5 km long by 0.5 km wide exposed within the Sirikit Reservoir. The Nan ophiolite association is tectonically enclosed in the metasedimentary packages. It is composed of blocks of mafic–ultramafic rocks and minor sedimentary rocks in a sheared serpentinite matrix. Blocks in a serpentinite melange (the ophiolite association) have somewhat different metamorphic history. Amphibolite blocks are the result of amphibolite facies metamorphism before incorporation in the accretionary complex. Other blocks of sedimentary origin are not visibly metamorphosed. Although no detailed studies have been carried out, the mineralogy of the melange matrix is consistent with greenschist facies metamorphism.

Hess and Koch (1975) proposed a Permo-Carboniferous age for the Pha Som metasedimentary rocks on the basis of regional stratigraphy. The greywackes are unconformably overlain in part by ?Permian sedimentary rocks (Bunopas, 1981). A metamorphic age of 269 Ma (early Late Permian), based on a K–Ar radiometric dating of actinolite–quartz schist, was suggested by Barr and MacDonald (1987). The Nan ophiolite association contains a range of blocks that place an older age limit on the deformation. The ⁴⁰Ar/³⁹Ar amphibole ages of the amphibolite blocks range from 338 to 256 Ma (Panjasawatwong and Crawford, 2000).
A volcanic breccia within the melange has a Permo-Carboniferous depositional age (Hahn, 1985). A Late Permian chert block was reported by Hada et al. (1999). These data suggest that the probable age range of blocks within the ophiolite association is Carboniferous to Late Permian. In summary, a Late Permian age for the assembly of the Pha Som Metamorphic Complex is suggested on the basis of included blocks, K/Ar dating of metamorphic minerals and stratigraphic relationships. The Upper Cretaceous K–Ar radiometric ages on white mica reported by Ahrendt et al. (1993) are incompatible with the presence of unmetamorphosed Jurassic stratigraphy that unconformably overlies the Pha Som Metamorphic Complex and they are interpreted here as the result of resetting during Cretaceous reactivation.

The recognition of subduction-related accretionary complexes in old terrains has typically been linked to the presence of broken formation, melange with exotic blocks and blueschist facies metamorphism (Lash, 1985). Barr and MacDonald (1987) reported melange and marginal blueschist facies metamorphism along the Nan Suture and interpreted this as evidence for an intra-arc origin for Nan ophiolite association. Mn-rich cherts are a common association in accretionary prisms (Leggett et al., 1982) and these have been report both as blocks with the serpentinite melange and as thrust slices of metamorphosed piemontite–quartz schist within the complex. Many accretionary prisms are dominated by arc-sourced turbidites (Ingersoll, 1988). Where these are included in the accretionary complex by offscraping at the toe of the prism they are dominated by melange, but in other areas the accretionary prism is composed of intensely deformed but largely coherent meta-greywacke (Sample and Fisher, 1986; Fisher and Byrne, 1992; Miller and Gray, 1996). Singharajwarapan and Berry (1993) argued that the early deformation events in the Pha Som greywackes are very similar to the structure reported within coherent blocks of greywacke on Kodiak Island (Sample and Fisher, 1986) and the Otago schists, New Zealand (Bishop, 1972).

The Pha Som Complex includes most of the features typically used to identify an accretionary complex. There are exotic lithologies within a serpentinitic melange, Mn-rich cherts and a high strain greywacke association with an arc provenance, and dominated by a shallowly dipping foliation associated with intense transposition. Extensive areas of broken formation have not yet been found near the Nan Suture, but they have been reported along the Sa Kaeo Suture 500 km to the south, on the boundary between

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**Fig. 4.** Lower hemisphere equal area projection of structural data from: the Permo-Triassic sedimentary rocks (a) Poles to bedding; (b) Poles to cleavage; and the Pha Som Metamorphic Complex (c) poles to dominant cleavage (S2); (d) poles to S3; (e) L2 stretching lineation; (f) fold axes and crenulation lineations associated with D3. Contours at 1, 2, 4, 8 and 16% per 1% area.
the Shan-Thai and Indochina Terranes (Hada et al., 1999). The metamorphism in the metagreywackes is not convincingly high pressure in character, but it is very similar to the metamorphism in the Otago Schist, New Zealand (Kawachi, 1975; Kawachi et al., 1983). On this basis we conclude that the lithology, deformation history, and metamorphism of the Pha Som Metamorphic Complex are consistent with those observed in ancient and modern accretionary complexes in many parts of the world. As S2 is the dominant foliation that we correlate with accretionary processes, the eastward transport associated with this structure is interpreted to indicate an originally west-dipping subduction zone dipping under the Shan Thai Terrane.

2.2. Permo-Triassic volcanic rocks

The Pak Pat Volcanics (Fig. 2) occur as a belt of volcanic rocks forming a high ridge between the Nan River in the west and Nam Pat Group in the east. This volcanic unit is overthrust on the west by metagreywacke and phyllite of the Pha Som Metamorphic Complex along the Phu Khon Kaen thrust (Fig. 3) and by the ophiolite association farther to the north. In the east, it is unconformably overlain by conglomerate beds, Huai Lat Formation (lowest formation of the Nam Pat Group). The volcanic rocks are variably deformed. The Pak Pat Volcanics belong to the subalkali series with probable medium to low-K suggesting oceanic island arc affinities (Singharajwarapan, 1994). The Huai Lat Formation is Lower to Middle Triassic in age (Bunopas, 1981; Lüddecke et al., 1991) which places an upper limit on the age of these volcanic rocks.

The tectonic setting of eruption of the Permo-Triassic felsic to intermediate volcanic rocks in the Lampang-Phrae area (referred to here as the Doi Luang volcanics, Fig. 2) is inferred, on the basis of field observations and petrography, to have formed in a continental arc environment (Singharajwarapan, 1994). The Doi Luang volcanics are 1000–1500 m thick and characterised by massive volcanioclastic rocks. The dominant rock types are grey to green rhyolitic to dacitic tuffs with minor green to reddish purple volcanic breccias. Coherent rhyolite and dacite are restricted to thin layers within these massive volcanioclastic sequences. Bedding is rare, but is recognisable where interbeds of mudstone and tuffaceous sandstone are present.

The Doi Luang volcanics overlie the Upper Permian Huai Thak Formation (Phrae Group) and underlie the Lower Triassic Phra That Formation or the Pha Kan Formation (Lampang Group). The geochemical signatures of these volcanics is unknown but the predominance of volcanioclastic rocks over the lavas, and the felsic to intermediate composition suggest that the Doi Luang volcanics erupted in a continental arc.

2.3. Permo-Triassic turbidite sequences

Permian turbidite and limestone (the Rong Kwang Formation, part of the Phrae Group; Fig. 2) has a faulted contact with the Pha Som Metamorphic Complex (Fig. 3). The Phrae Group was deposited in a forearc basin (Bunopas, 1981). The 2000 m thick, Permian Rong Kwang Formation consists typically of dark grey to black shale (grading to slate) and massive limestone. Interbeds of sandstone and shale are rare. The shale is generally massive, locally laminated, and has moderately- to strongly-developed cleavage. In the study area, the contact between the Rong Kwang Formation and the Pha Som Metamorphic Complex is faulted. Outside the study area, the Rong Kwang Formation is reported to be underlain conformably by the Mae Sai Formation which in turn rests unconformably on the Pha Som Metamorphic Complex (Bunopas, 1981).

The Triassic turbidite sequences (Lampang Group) in the Lampang and Phrae areas overlie the Doi Luang volcanics and the Rong Kwang Formation (Phrae Group). Although in some areas the boundary is an unconformity, in the eastern part of the Sukhothai Fold Belt, the contact between the Lampang Group and Rong Kwang Formation is conformable, indicating continuous deposition through the Permain–Triassic boundary. This observation supports previous reports of continuous marine sedimentation from the Permian into the Triassic (Junhavat and Plyasins, 1978; Hahn, 1985). Chonglakmani and Helmcke (1989) argued against the idea that the Triassic Lampang Group was deposited in a forearc-basin environment in a pre-collisional setting. They interpreted the depositional environment of the Lampang Group as a series of post-collisional shallow intramontane molasse basins.

Sandstone of the Triassic Nam Pat Group, from east of the Sirikit Dam (Fig. 2), is very similar to that in the Lampang Group. The sandstone overlies a conglomerate unit (the Huai Lat Formation) which Lüddecke et al. (1991) concluded was derived from a Triassic andesitic continental volcanic arc, not a shallowing trench as implied by Bunopas (1981). The compositional characteristics of the detrital framework grains and their immature textures indicate that the Nam Pat sandstone was derived from a nearby magmatic arc (Singharajwarapan, 1994). The volcanic source is possibly the andesitic volcanoes that generated the Pak Pat Volcanics.

In conclusion, Late Permian to Norian clastic sediments in the Sukhothai Fold Belt were derived from an arc source. Although many local unconformities occur, there are no discrete stratigraphic breaks within this range that extend across the whole fold belt. Within these sedimentary units there are distinct volcanic rock units of Permian to Triassic age, which can be reasonably interpreted as arc-related, although the present database is not adequate to support this conclusion on the basis of the composition of the
volcanic rocks alone. The trend towards shallower water sequences and more unconformities in the west could indicate that the main arc volcanoes lay to the west in the Early Triassic.

2.4. Jurassic red beds

In the Sirikit Dam area, the open-folded Jurassic (Drumm et al., 1993) continental red beds (the Phra Wihan Formation) unconformably overlie the close-folded Triassic Nam Pat turbidites (Fig. 3). Elsewhere in northern Thailand, the Jurassic–Cretaceous continental red beds (including the Phra Wihan Formation) unconformably overlie the Triassic Lampang Group and the Permian Phrae Group (Fig. 2, Piyasin, 1972). The compositional characteristics of the detrital framework modes indicate that the quartz sandstones of the Phra Wihan Formation were derived from a recycled orogenic source or from a craton interior, suggesting post-orogenic deposition. They were deposited in a braided stream environment.

2.5. Deformation and metamorphism

The deformation of the Phrae and Lampang groups is characterised by upright open folds and thrusts. These strata were subjected to a single phase of folding with associated northeast-striking regional cleavage (Fig. 3). The cleavage is sub-vertical through most of the section but a moderate NW-dipping cleavage is developed in the Nam Pat Group at the eastern end of Section 3 (Fig. 3) and the poles to cleavage in this zone form a discrete concentration compared to the steep dips further west (Fig. 4b). Cleavage intensity increases close to the thrusts. Early thrusting was to the east, and was followed by a phase of backthrusting (Fig. 3). Where the Phrae group is juxtaposed with the Pha Som Metamorphic Complex in Section 2 (Fig. 3), the orientation of cleavage and the style of folding in the Phrae group is similar to S3 and the associated F3 folds in the metagreywacke (Fig. 4b, d). S2 in the metagreywacke is much more intense in style and dips 45° NW. On this basis the regional cleavage in the Permo-Triassic sedimentary rocks is correlated with S3 in the Pha Som Metamorphic Complex.

The metamorphic grade of the Permian and Triassic sequences varies across the belt. This variation is best shown using illite crystallinity (Fig. 5). In the Den Chai area, Section 1, pelitic rocks of the Triassic sequence have an illite crystallinity typical of the anchizone (~250°C). Further east on Section 2, the metamorphic grade of the Permian and Triassic pelites is near the boundary of the anchizone and epizone (~300°C). In the far east the Nam Pat Group has an illite crystallinity typical of the boundary between diagenesis and the anchizone (~200°C) and is immediately overlain by the Jurassic post-orogenic stratigraphy. The Jurassic sedimentary rocks are steeply dipping along this western margin of the Khorat Plateau. Lovatt-Smith et al. (1996) interpreted this folding as the result of strong mid-Cretaceous reactivation. The steep metamorphic gradient east of Sirikit Dam section reflects this reactivation which exhumed the deeper parts of the Sukhothai Fold Belt.

The metamorphic event is related to the single cleavage-forming event. K–Ar dating of fine mineral fractions of shale/slate of the Lampang group indicates that the cleavage
formed between 188–220 Ma (Ahrendt et al., 1993). The cleavage (Fig. 4) was found in Middle Carnian–Early Norian sedimentary rocks (~220 Ma) but is absent from the Middle Jurassic Phra Wihan Formation.

2.6. Granite

Granitic intrusions in Thailand were shown by Beckinsale et al. (1979) to have intrude in the Late Permian to Late Triassic (244–204 Ma) and in the Cretaceous (130–90 Ma). The Cretaceous event is concentrated in the Western Granite Province and is not related to the Nan Suture (Cobbing et al., 1986). East of the Nan Suture in Thailand and the Raub Suture in Malaysia is the Eastern Granite Province of Cobbing et al. (1986) with a wider range in age of intrusion (280–200 Ma). The granitoids of this province are dominantly monzogranite in composition, mainly I-type and probably related to arc magmatism (Hutchison, 1977; Beckinsale et al., 1979).

The Northern Thailand Migmatite Complex (Cobbing et al., 1986) contains S-type granitoids of Middle to Late Triassic age. The granitoids in the migmatite complex are highly deformed with strong sub-horizontal foliation interlayered with orthogneisses and paragneisses. Other types of granitoids occur as larger batholiths and associated smaller plutons intruding the Palaeozoic and Lower Mesozoic sedimentary sequences. These S-type granites usually have very high 87Sr/86Sr ratios (commonly in the range 0.722–0.734) indicating a crustal origin (Hutchison, 1983). They have a post-kinematic character with respect to the deformed sedimentary country rocks. The distribution of S-type granites in northern Thailand has been inferred to be indicative of widespread Triassic metamorphism and crustal melting related to the collision of the Shan-Thai and Indochina Terranes (Barr and MacDonald, 1991). One granite of this type is shown on Fig. 3, where it post-dates a thrust and the regional cleavage in the Lower Norian Wang Chin Formation. While this particular granitoid has not been dated, Ahrendt et al. (1993) dated the nearby syn- to post-kinematic Khuntan Granite as 201 ± 2 Ma and 212 ± 2 Ma.

The Tak Batholith is anomalous within the Sukhothai Fold Belt. Despite its position west of the Nan Suture, it has most often been linked with the Eastern Granite Province because it includes I-type compositions (e.g. Cobbing et al., 1986). A detailed geochemical study by Mahawat et al. (1990) demonstrated a transition from medium K calc-alkaline early plutons to high K, or even shoshonitic, later plutons. They concluded that this transition is typical of an arc in an unstable environment such as during cessation of subduction. The late plutons intruded at about 215 Ma (Teggin in Mahawat et al., 1990).

3. Discussion

Summary of geological constraints
The most important observations about the geological evolution of the Nan Suture and Sukhothai Fold Belt relevant to any tectonic interpretation are:

1. The Pha Som Metamorphic Complex has the characteristics of an accretionary prism containing Carboniferous to Late Permian blocks and has a probable metamorphic age of Late Permian. The internal evidence is for east-directed thrusting during the formation of the accretionary complex, suggesting a west-dipping subduction zone.
2. Permo-Triassic volcanic and volcaniclastic sequences are widespread within a Late Permian to Late Triassic turbidite and carbonate sequence that was sourced from continental arc volcanics.
3. The Late Permian (Phrae Group) and Triassic (Lampang Group) sedimentary rocks have the same deformation history.
4. The Jurassic–Cretaceous redbed sequences do not contain the dominant folding event in the Sukhothai Fold Belt and are only folded locally.
5. A major change took place in granite composition between Late Permian–Early Triassic I-type granitoids and the Late Triassic–Early Jurassic S-type granitoids in the western part of the Sukhothai Fold Belt. The S-type granites are late syn- to post-kinematic with respect to folding in the Sukhothai Fold Belt.

3.1. Geometry of plate convergence

A west-dipping subduction zone beneath the eastern margin of the Shan-Thai Terrane and a passive margin on the western edge of the Indochina Terrane is consistent with the presence of the east-facing accretionary complex (the Pha Som Metamorphic Complex) and the Permo-Triassic volcanic rocks (e.g. the Doi Luang volcanics in the Lampang-Phrae area). In addition, it explains the absence of an accretionary complex and the presence of extensive Late Permian platform-carbonates on the western edge of the Indochina Block.

A west-dipping subduction zone does not account for the presence of the Loei volcanic province but the volcanism in this province has a complex tectonic history starting from the Late Devonian and it has recently been interpreted as the result of interaction between the Kontum Terrane and South China Terranes (Intasopa and Dunn, 1994). The ambiguities associated with the Loei province mean that it cannot be used to constrain the geometry of the subduction zone associated with the Nan Suture. The data from the Sukhothai Fold Belt are most consistent with a west-dipping subduction zone before collision.

3.2. Timing of the collision

A “Middle” Permian collision time has been proposed based mainly on the sedimentological and stratigraphical evidence from the Permian sequence in the Loei Fold Belt (e.g. Helmcke and Kraikhong, 1982; Helmcke and Lindenberg, 1983; Helmcke, 1986). These studies emphasise the
contrast in fold styles between the “Lower Permian pelagic and flysch sediments” and the “Middle-Upper Permian molasse sequence” (e.g. Helmcke and Lindenberg, 1983). This collision time is consistent with the age of low-grade metasedimentary rocks in the Pha Som accretionary complex, i.e. the K–Ar age of 269 Ma for actinolite in the Pha Som metasedimentary rocks (Barr and MacDonald, 1987). The direct implication is that the Triassic sediments of the Lampang Group (probably including the Upper Permian part of the Rong Kwang Formation) are post-collisional. The problems with the Middle Permian collision time are: (i) it fails to account for the presence of the Late Permian–Early Triassic arc volcanics in the Sukhothai Fold Belt; (ii) it does not explain the similarities in the deformation and metamorphism of the Permian and Triassic sequences; (iii) there are no syn-collision deformation features visible through the cover sequence; (iv) the large volcanic and minor continental source contribution to the plagioclase-dominated turbidites of the Permian Rong Kwang Formation and the Triassic Lampang Group is not typical of post-collisional sediments.

A Late Triassic age for the collision is most consistent with the evidence presented here. In particular, this collision time is consistent with the similarities in the deformation and metamorphism of the Permian and Triassic sequences, the Late Triassic–Early Jurassic post-orogenic granite intrusions and the distribution of the Jurassic continental redbeds across the Shan-Thai and Indochina Terrane boundary. The problems with this model are the lack of direct evidence for Middle Triassic arc volcanics and that Triassic blocks have not been recorded in the exposed parts of the accretionary complex along the Nan Suture. However, the Tak Batholith may be the intrusive complex formed beneath a Middle Triassic arc volcano and Middle to Late Triassic blocks have been reported from the broken formation in the Sa Kaeo Suture 500 km to the south (Hada et al., 1999).

A Late Permian–Early Triassic collision age is largely based on relationships within the Loei Fold Belt. It is not consistent with the presence of Late Permian–Early Triassic arc volcanics in the Sukhothai Fold Belt. Nor does this model explain the continuous stratigraphic succession from Late Permian to Early Triassic in parts of the Sukhothai Fold Belt. As with the “Middle” Permian collision time, no explanation is provided for the similarities in the deformation and metamorphism of the Permian and Triassic sequences in the Sukhothai Fold Belt.

4. Summary

The Shan-Thai Terrane rifted from Gondwana in the Early Permian. By the Late Permian, an accretionary complex, the Pha Som Metamorphic Complex, accumulated at the margin of the Shan-Thai Terrane above a west-dipping subduction zone. The oceanic crust that was consumed along this margin was largely Permo-Carbonifer-ous in age. A Permo-Triassic arc was developed west of the present Sukhothai Fold Belt but has been partly covered during backthrusting associated with the Late Triassic (?)Norian) collision with the Indochina Terrane. The collision produced a single generation of upright folding and associated thrusting throughout the Sukhothai Fold Belt. Late Triassic (200–215 Ma) S-type granites formed as a result of the collision. In the Early Jurassic, the accumulation of post-orogenic continental redbeds expanded across the Sukhothai Fold Belt.

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