
Chapter 7: Palaeogeographic and tectonic evolution

In SE Asia, there are two major tectonic landmasses, that is, the Indochina and Sibumasu terranes. They are distinguished most clearly by their possessions of Cathaysian and Gondwanan faunal and floral characters, reflecting the biogeographic regions to which they originally belonged. The two terranes became closer to each other at some stages of the Permian to Triassic, and eventually collided after a long-lived vast ocean, the Palaeo-Tethys, was closed in the Late Triassic. Consequently, a wide foldbelt consisting of accretionary complexes and an island arc (Sukhothai-Eastmal Island-arc System) was formed in between Sibumasu and Indochina, stretching through the middle of SE Asia from western Yunnan in the north to the Malay Peninsula in the south. This appears one of the largest-scaled longitudinal tectonic structures in today's SE Asia.

The granitoid provinces, the Palaeo-Tethys Suture Zone, and the Sukhothai-Eastmal Island-arc System and its back-arc basin suture are placed principally along this longitudinal belt. In this chapter, the granitoid distribution, tectonic sutures, and tectonostratigraphic correlation of constitutive terranes during the late Palaeozoic to Mesozoic are analysed. A new interpretation on the tectonic evolution of SE Asia is then proposed with respect to the Palaeo-Tethyan opening and subduction and the accretion of Sibumasu into Asia. Special emphasis is given to Permian geographic changes.

7.1 Suture zone age ranges

Between the Indochina Terrane and the Sibumasu Terrane, there are two lineages of tectonic sutures. One is the Palaeo-Tethys Suture Zone along the Changning–Menglian, Inthanon–Rayong, and Bentong–Raub sutures, and another is a suture of a former back-arc basin (the Jinghong to Sra Kaeo Back-arc Basin) behind the Sukhothai-Eastmal Island-arc System along the Jinghong, Nan, and Sra Kaeo sutures (Fig. 7.1). Geological features with sedimentary records recognised in those regional sutures are outlined in Chapter 2. Here, pelagic or deep-water radiolarian-bearing sediments found in those sutures are reviewed, and their geographic and stratigraphic ranges are summarised in Figures 7.2 and 7.3.

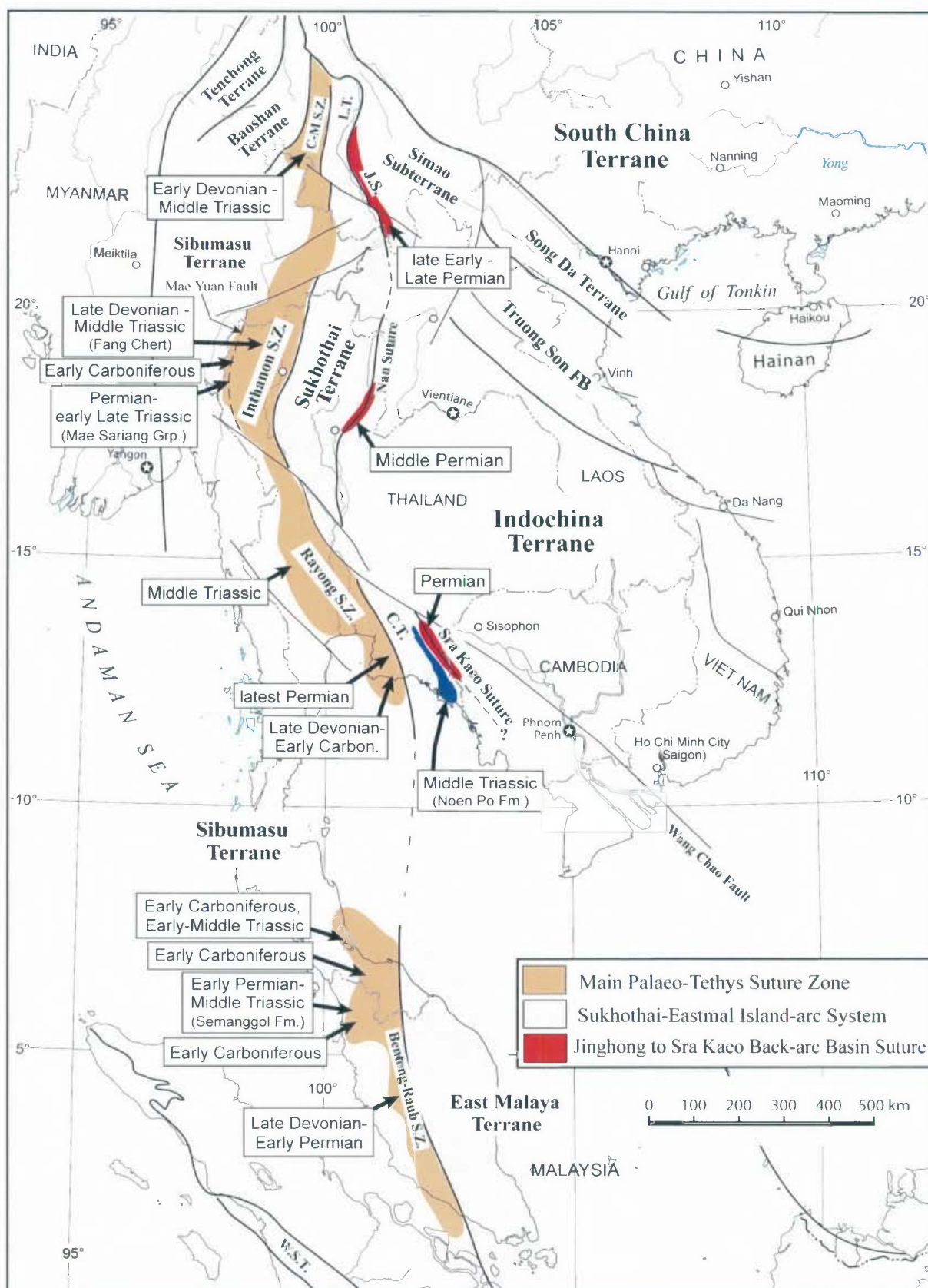


Figure 7.1 SE Asian terrane map showing approximate locations and ages of radiolarian-bearing deep-water sediments found in tectonic sutures of the former Palaeo-Tethys Ocean and the Jinghong to Sra Kao Back-arc Basin. Abbreviations for Yunnan tectonic units; C-M S.Z. = Changning-Menglian Suture Zone, L.T. = Lancang Terrane, J.S. = Jinghong Suture, C.T. = Chanthaburi Terrane. W.S.T. = West Sumatra Terrane.

Overall age ranges of the Palaeo-Tethys Ocean and the Jinghong to Sra Kao Back-arc Basin are compared in Figures 7.2 and 7.3. It is apparent that the two former seaways have distinctly different age ranges. It is also apparent that the Palaeo-Tethys Suture Zone is geographically much wider than the Jinghong to Sra Kao Suture (see Fig. 7.1). The Palaeo-Tethys Suture Zone represents a huge accretionary complex resulted from the long-ranged subduction of the major Devonian–Triassic ocean, whereas the latter suture is for a short-lived Permian back-arc basin.

	Palaeo-Tethys Ocean	Jinghong to Sra Kao Back-arc Basin
Western Yunnan	Changning–Menglian Suture Zone (Mid. Devonian to late Mid. Triassic) (*Early Devonian turbidites)	Jinghong Suture (late Early to Late Permian)
North Thailand	Inthanon Suture Zone (Late Devonian to late Middle Triassic) (*early Late Triassic in Mae Sariang Grp.)	Nan Suture (late Middle Permian)
East to western Thailand	Rayong Suture Zone (= southern Inthanon Suture) (Late Devonian to Middle Triassic)	Sra Kao Suture Thung Kabin Mélange (Early to early Late Permian) (*Middle Triassic in Noen Po Fm.)
Malay Peninsula	Bentong–Raub Suture Zone (s.s.) (Late Devonian to late Early Permian) Extended zone in NW Peninsular Malaysia & southern Thailand (late Early Permian to late Middle Triassic) (*Late Triassic cherts in Kodiang Lst.)	suture lying in the South China Sea? (data not available)
Overall age ranges	Mid. Devonian to late Mid. Triassic (main oceanic phase) *Early Devonian (initial opening stage) *Late Triassic (post-closure?)	Early to Late Permian (unequivocal suture sediment in mélange) *Middle Triassic (a regional remnant basin after closure)

Figure 7.2 Age ranges of deep-water or pelagic sediments found in each suture of the former Palaeo-Tethys Ocean and the Jinghong to Sra Kao Back-arc Basin, indicated by available radiolarian data. Mark* indicates ages of particular sediments which are not attributable to as true oceanic deposits.

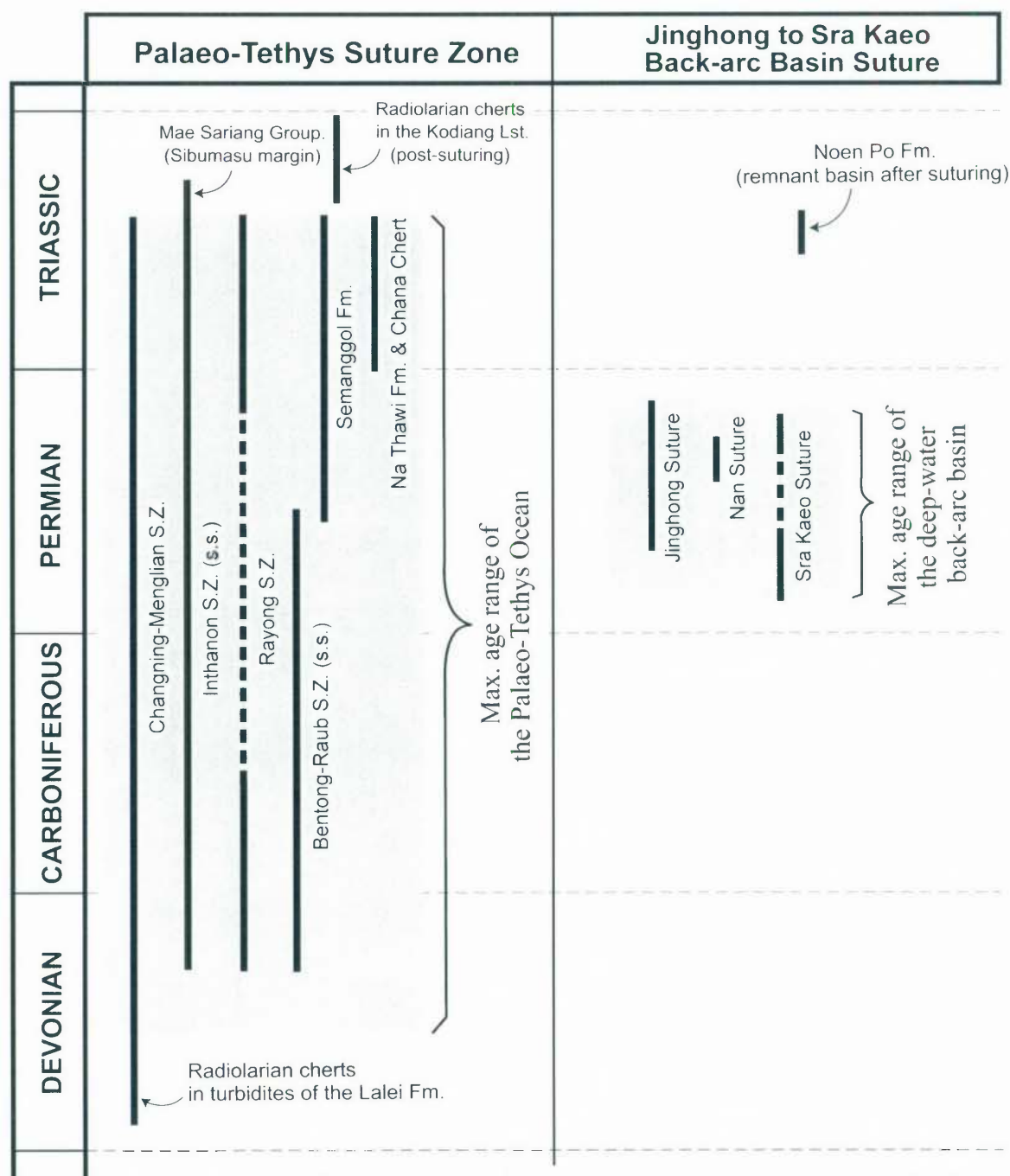


Figure 7.3 Stratigraphic range chart of the Palaeo-Tethys Ocean and the Jinghong to Sra Kao Back-arc Basin in SE Asia.

7.1.1 Palaeo-Tethys Suture zones

As a whole, radiolarian-bearing deposits of the Early Devonian through to the Late Triassic are present in the Palaeo-Tethys Suture Zone in SE Asia. However, as summarised below, unequivocal pelagic sediments referable to the Tethyan oceanic deposits are restricted to a

range from the Middle Devonian to the late Middle Triassic. This is the most likely age range of the Palaeo-Tethys Ocean that existed in between the Indochina and Sibumasu terranes. The Early Devonian and the Late Triassic sediments show more proximal facies than pelagic cherty deposits; they were probably deposited in the rift basin or continental margin. They are not regarded as true Palaeo-Tethys deposits.

Of all the Palaeo-Tethys sutures defined in Chapter 2, the Changning–Menglian Suture Zone in SW Yunnan preserves the best stratigraphic records indicating the longest history of the wide ocean. Radiolarian-bearing oceanic sediments recovered in this suture zone range from the Devonian to the Triassic. The Early Devonian Lalei Formation near Menglian bears cherty layers with an *Eoalbaillella lilaensis* radiolarian assemblage (Feng and Liu, 1993a; Feng and Ye, 1996). As discussed in Chapter 2, however, this formation is turbiditic, and is unlikely a true oceanic deposit (Qinglai Feng, pers. commun., 2005). The oldest radiolarian cherts with unequivocal pelagic facies are recognised in Middle Devonian sediment (see Fang et al., 1996). This marks the oldest Palaeo-Tethyan oceanic deposit in SE Asia. These Devonian records suggest that the rifting and initial spreading of the Palaeo-Tethys probably started in the Early Devonian, and its oceanic stage began from the Middle Devonian. The latest oceanic sediment in the Changning–Menglian Suture Zone is represented by Ladinian (Middle Triassic) cherts with the *Triassocampe deweveri* radiolarian zone (see Feng and Ye, 1996).

In the Inthanon Suture Zone, oceanic sediments of Late Devonian to Middle Triassic ages are present (see Chapter 2 for details). The Fang Chert represents typical Palaeo-Tethyan oceanic deposits, and ranges in age from Late Devonian through to Middle Triassic (Caridroit, 1993; Caridroit et al., 1990; Feng et al., 2004; Sashida et al., 2000a; Sashida et al., 1998; Sashida et al., 1993). Another radiolarian-bearing unit of the Mae Sariang Group bears Permian and Early–Late Triassic radiolarians (Caridroit et al., 1993; Kamata et al., 2002). Kamata et al. (2002) concluded that the Triassic cherts of the Mae Sariang Group were not formed in a pelagic environment, but on the continental margin of the Sibumasu Terrane. Therefore, the Late Triassic chert of the Mae Sariang Group cannot be recognised as the youngest Tethyan oceanic deposit. It may have been deposited in a remnant basin of the Palaeo-Tethys at a syn- to post-collisional stage, as the ocean closed in the Late Triassic. The latest oceanic sediment of the Inthanon Suture Zone is referred to the Ladinian of the Fang Chert, which is represented by the *Triassocampe deweveri* radiolarian zone.

The Rayong Suture Zone (the southern extension of the Inthanon Suture Zone) covers the Rayong region in East Thailand through to the Kanchanaburi region in western Thailand.

Deep-water radiolarian cherts of the Late Devonian or Early Carboniferous, the latest Permian, and the Middle Triassic have been recorded. The records are not as complete as the Inthanon Suture Zone (s.s.) in the north, but the inferred age range (Late Devonian to Middle Triassic) is as long as those of other Palaeo-Tethyan sutures.

In the traditional Bentong–Raub Suture Zone (s.s.) of Peninsular Malaysia, cherts and mudstones/shales bearing radiolarians range in age from the Late Devonian (Famennian) through to the latest Early Permian (Kungurian) (Jasin and Ali, 1997a; 1997b; Spiller, 1996; Spiller, 2002; Spiller and Metcalfe, 1995). Note that no post-Early Permian deep-water sediment is present in the Bentong–Raub Suture (s.s.). Nevertheless, some younger Permian and up to the late Middle Triassic oceanic sediments have recently been found in southernmost Thailand and NW Peninsular Malaysia, where the greater part of the Bentong–Raub Suture Zone is recognised, as noted below.

In NW Peninsular Malaysia, the lower chert member of the Semanggol Formation in Malaysia yields radiolarians of the late Early Permian (Kungurian) up to the Middle Triassic (Ladinian) (Jasin, 1997; Jasin et al., 2005a; Jasin et al., 2005b; Sashida et al., 1995; Spiller, 2002; Spiller and Metcalfe, 1995). The latest horizon is evident with the *Triassocampe deweveri* radiolarian zone (Ladinian). However, it is still uncertain whether the entire Semanggol Formation can be assignable to an oceanic deposit, as pointed out by Metcalfe (1996; 2000) and Metcalfe et al. (1999, p. 267). The Semanggol Formation was possibly formed in a more or less similar depositional setting to the Mae Sariang Group noted above, and their sites were rather proximal to the Sibumasu continental margin. Some authors (Metcalfe et al., 1999; Sashida et al., 1995; Sashida and Igo, 1999) hesitated to include the Semanggol Formation to the Palaeo-Tethys deposits. They concluded a Late Permian to Early Triassic closure of the Palaeo-Tethys Ocean in the Malay Peninsula, the suturing age earlier than mainland SE Asia. However, the *T. deweveri* radiolarian zone was recently confirmed by Sashida et al. (2000b) in the Chana Chert of southernmost Thailand, which is definably a Palaeo-Tethyan oceanic deposit (Fig. 7.4). Therefore, even though the Semanggol Formation may not be a true oceanic deposit, it is now evident that the Palaeo-Tethys Ocean between the Sibumasu and East Malaya terranes did not close until the Ladinian. This age is consistent with information gained from other suture zones to the north. An early Late Triassic closure of the Palaeo-Tethys along the Bentong–Raub Suture Zone (s.l.) is likely.

In addition, Late Triassic radiolarian cherts were reported from the upper Kodiang Limestone by Jasin et al. (1995) and Jasin and Harun (2001b). Sashida and Igo (1999) and Sashida et al. (1999) interpreted that the Late Triassic Kodiang Limestone was formed in a

continental margin of the Sibumasu not in the Palaeo-Tethyan Ocean (Fig. 7.4). Metcalfe (2000) interpreted that the Late Triassic Kodiang Limestone was formed in a remnant basin after the main closure of the Palaeo-Tethys. The latter view is supported in this study, and the Late Triassic Kodiang cherts are not recognisable as an element of the Tethyan oceanic deposit.

Early Carboniferous (Tournaisian) radiolarian cherts were present in Pokok Sena of Kedah, NW Peninsular Malaysia (Jasin and Harun, 2001a) and in Saba Yoi to Kabang of southernmost Thailand (Sashida et al., 2002). As discussed in Chapter 2, they are chert layers intercalated within more clastic units of the Kubang Pasu Formation and the Yaha Formation, respectively. The two formations are laterally equivalent, formed on the Sibumasu continental margin, but they are not part of Palaeo-Tethyan oceanic deposits. Nevertheless, Tournaisian cherts of more definite pelagic facies are present in Langkap, Negeri Sembilan along the traditional Bentong–Raub Suture Zone (Jasin and Ali, 1997b), justifying the presence of Early Carboniferous Tethyan oceanic record in this regional suture.

In summary, the overall stratigraphic range of the Palaeo-Tethys sediments in the Malay Peninsula is from the Late Devonian (Famennian) to the late Middle Triassic (Ladinian). This is comparable to those of the Changning–Menglian, Inthanon, and Rayong suture zones recognised in Yunnan and mainland Thailand. All three sections of the Palaeo-Tethys Suture zones in Yunnan, Thailand, and the Malay Peninsula reveal similar stratigraphic ranges for the ocean that existed up to the Ladinian. Of them, the Changning–Menglian Suture Zone has the oldest record beginning from the Middle Devonian. As a whole, the Palaeo-Tethys Ocean recognised in SE Asia was in existence from the Middle Devonian through to the late Middle Triassic. It is interpreted from deep-water sedimentological data outlined above that the Palaeo-Tethys probably started its rifting and initial spreading in the Early Devonian, and its fuller oceanic stage started from the Middle Devonian. It probably gained its greatest width as a vast ocean during the Carboniferous. A major closure of the ocean took place in the early Late Triassic, although, in some areas of the Bentong–Raub Suture, the suturing may have started a little earlier.

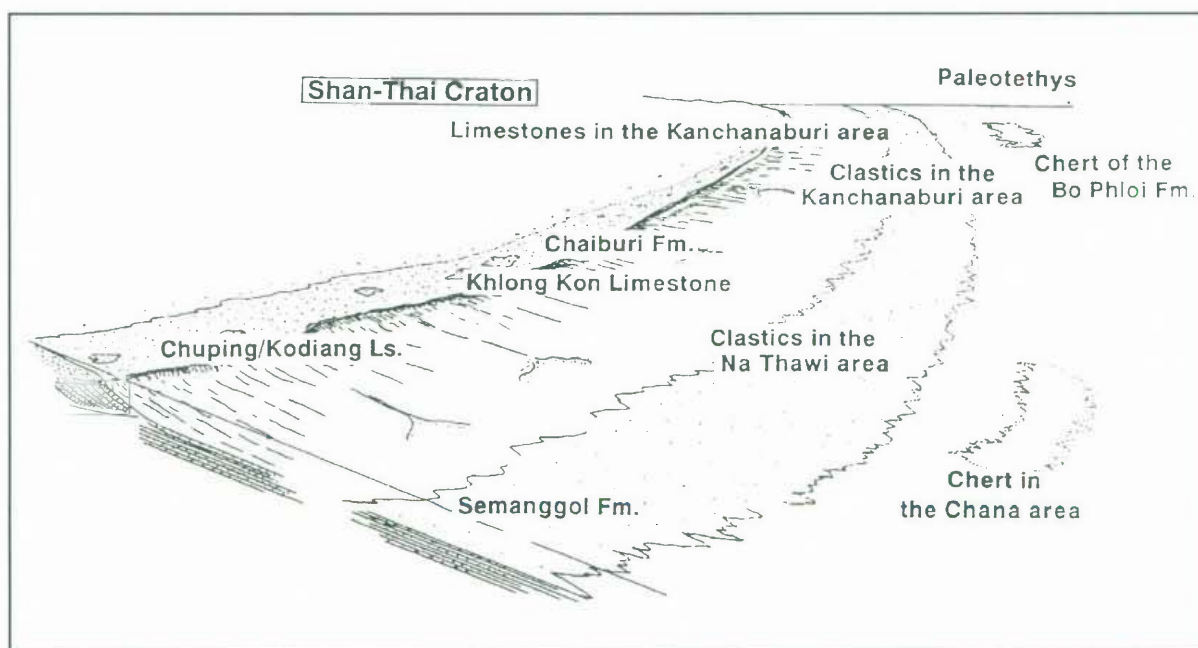


Figure 7.4 Schematic palaeogeographic reconstruction of Sashida et al. (1999, fig. 5) for depositional environments of Middle Triassic sedimentary units found in western Thailand to NW Peninsular Malaysia. It shows lithological facies changes for those units from shallow to deep water in the Sibumasu (Shan-Thai in the figure) continental margin towards the Palaeo-Tethys Ocean, and their lateral equivalents over the area.

7.1.2 Jinghong to Sra Kaeo Back-arc Basin Suture

In contrast to the Palaeo-Tethys Suture Zone, a suture line of the former Jinghong to Sra Kaeo Back-arc Basin is considerably narrower in geographic extent. It also has much shorter-ranging stratigraphic records of deep-water deposition than the Palaeo-Tethys Suture Zone, confined to the Permian. The suture line lies between the Sukhothai-Eastmal Island-arc System and the Indochina Terrane along the Jinghong Suture in Yunnan to the Nan and Sra Kaeo sutures in Thailand (Fig. 7.1). Its southerly continuation is not clear, most likely lying in southern Cambodia and further in the Malay Basin of the South China Sea, as discussed in Chapter 2.

The newly named Jinghong Suture of Yunnan is defined as the northern extension of the Nan to Sra Kaeo suture. It has yielded three radiolarian assemblages of different Permian ages; late Early Permian chert of the Longdonghe Formation (Feng et al., 2000), late Middle or earliest Late Permian red cherts of the Daxinshan Formation (Feng et al., 2002), and early Changhsingian (Late Permian) cherts in Bangsha of the Jinghong region (Feng and Liu, 1993b). The last find marks the youngest deep-water deposit of the entire Jinghong to Sra

Kaeo Back-arc Basin. Those cherts are often interbedded with volcanoclastics. No pre- or post-Permian deep sea is evident in the Jinghong Suture.

In the Nan Suture of northern Thailand, records of deep-water sediments are extremely limited, as only Middle Permian cherts are known. It has previously been recognised as a representative section of the closed Palaeo-Tethys Ocean (e.g. Bunopas, 1981; Hada et al., 1997), but such an interpretation is undermined by a lack of stratigraphically sufficient evidence. Hada et al. (1997) reported late Middle Permian bedded red chert from the Nan Mine area; this is the only example of a deep-water cherty sequence known in this suture. Thus, a sedimentary record to prove the existence of such a long-lived major ocean as the Palaeo-Tethys is insufficient. The Permian chert in the Nan Suture, on the other hand, is in good harmony with stratigraphic records of the Jinghong Suture to be the same back-arc basin origin (see Fig. 7.3).

In addition, Hada et al. (1997) reported a single specimen of the Middle Triassic radiolarian *Triassocampe* sp. found in a red-chert clast reworked in the continental redbeds, Khorat Group, in the Nan area. Hada et al. (1997) interpreted this to be part of the Devonian–Triassic Palaeo-Tethyan deposits in the Nan Basin. However, as discussed in Chapter 2, it is still uncertain whether the Middle Triassic clast is *in situ*, because no host Triassic sequence is confirmed in the Nan Suture. The clast may alternatively have been derived and transported from the Palaeo-Tethyan Suture Zone (e.g. Inthanon Suture Zone to the present west), where Middle Triassic cherts (e.g. Fang Chert) are present. Consequently, only the Middle Permian sequence of the Nan Mine is unequivocally accepted for a deep-water deposit of the Nan Basin.

In the Sra Kaeo Suture to the south, Permian radiolarian cherts are found in close association with ophiolitic suites of the Thung Kabin Mélange (Hada et al., 1997). The radiolarian cherts recovered range in age from Sakmarian to Kungurian (Early Permian) (Hada et al., 1997) and from Capitanian to Wuchiapingian (late Middle to early Late Permian) (Sashida et al., 1997). Thus, the Sra Kaeo Suture preserves the oldest and longest deep-water depositional records (Early to the early Late Permian) of all the back-arc basin sutures. This may suggest that the back-arc basin opened a little earlier for the Sra Kaeo Basin than the Jinghong and Nan basins to the north. That is, the Chanthaburi Terrane as part of the Sukhothai-Eastmal Island-arc System emerged from the Indochina Terrane as early as the Sakmarian.

In addition, Middle Triassic radiolarian-bearing cherts and black shales of the Noen Po Formation (= the Chanthaburi Chert-clastic Sequence of Hada et al., 1997) are distributed

over a hinterland of the Chanthaburi Terrane adjacent to the Sra Kaeo Suture, as outlined in Chapter 2. Hada et al. (1997) interpreted those Triassic cherts as part of the Sra Kaeo Palaeo-Tethys oceanic deposits. However, the Noen Po Formation is not regarded as sediment of the Sra Kaeo Suture in this study. The Noen Po Formation was probably formed in a regional inter- or intra-arc basin within the Chanthaburi Terrane, which must have been relatively deep in the Middle Triassic. This perhaps resulted from plutonic uplift of adjacent areas in the Chanthaburi arc. It may alternatively be a remnant depression of the Permian Sra Kaeo Back-arc Basin. This, however, is less likely because the geographic distributions of the Permian Thung Kabin cherts and the Triassic Noen Po sediments are separable, as seen in Hada et al. (1997) (see Fig. 2.14). There is no deep-water sedimentary sequence filling the gap between the Permian and Middle Triassic sediments. Thus, the two sedimentary units are diachronous. The Triassic Noen Po Formation is not regarded as an element of the Sra Kaeo Suture; a differing view to that of Hada (1997).

In summary, unequivocal deep-water sedimentary records for the Jinghong to Sra Kaeo Back-arc Basin are confined to the Permian, as the maximum overall range is from the Sakmarian to the early Changhsingian (Fig. 7.3). This indicates that the back-arc basin was much shorter-lived than the Palaeo-Tethys Ocean. It is evident that the Sra Kaeo Basin already gained a substantial depth in the Sakmarian. This implies that the back-arc basin must have started to open a little earlier, perhaps in the Asselian. That is, the Sukhothai-Eastmal Island-arc System started to separate from the Indochina Terrane in the very early Permian. This Early Permian opening is in good agreement with the Early Permian initial magmatic age of the Sukhothai-Eastmal Island-arc System (I-type granitic Eastern Province). It is probable that the back-arc basin attained its greatest width during the Middle Permian. It closed and was uplifted by the Triassic. In addition, there are still some inconsistencies in stratigraphic range among the three regional back-arc basins. The Sra Kaeo Basin already opened in the Sakmarian, while the opening of the Nan Basin may have been delayed to the Middle Permian. Such regional variations in degree of back-arc basin development are plausible. Nevertheless, available data are not sufficient to make a confident interpretation.

7.2 Granitoid provinciality and ages

Three granitoid provinces of different geochemical characters were recognised in SE Asia by Cobbing et al. (1986); they were termed the Western Province (S- and I-type granites), the Main Range Province (S-type), and the Eastern Province (I-type) (Fig. 7.5). This subdivision was later modified slightly in Cobbing et al. (1992), yet the fundamental concept of the first model has been widely accepted by many later works (e.g. Barr and Macdonald, 1991; Gasparon and Varne, 1995; Krähenbuhl, 1991; Metcalfe, 2005). Those three granitoid provinces are also characterised by having distinct chronological ranges of their plutonic activities, reflecting differences in their tectonic settings and histories.

The Western Granitoid Province occurs in peninsular Thailand and Myanmar over the western part of the Sibumasu Terrane. It is characterised most importantly by having Cretaceous S-type granites with high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (up to 0.740) and minor I type granites. Cobbing et al. (1986) indicated granite ages of 82 to 98 Ma. In general, the simplest explanation for the petrogenesis of S-type granites with very high Sr ratios is the involvement of partial melts of continental crust (Beckinsale et al., 1979, p. 535). They have been generally interpreted as products of the Neo-Tethyan closure and collision and a subsequent orogeny (e.g. Krähenbuhl, 1991; Mitchell, 1977).

Major plutonic activities in the Main-Range Granitoid Province and the Eastern Granitoid Province are older than the Western Province, and are more or less related to the Palaeo-Tethyan subduction and closure. The main igneous constituents of the Main-Range Province comprise S-type granitoids of the early Late Triassic to late Early Jurassic (230–180 Ma) (see Cobbing et al., 1986; Krähenbuhl, 1991). They were produced by the collision of Sibumasu to the Sukhothai-Eastmal arc terranes and the partial subduction of Sibumasu continental crust. Thus, the petrogenesis of the Main-Range Province's S-type granitoids can be explained by partial melting of the Sibumasu crust beneath the obducted Palaeo-Tethys accretionary complex (e.g. Hutchison, 1989; Metcalfe, 2000; Mitchell, 1977) (Figs 7.8–7.10). In fact, the bulk of the Main-Range Province granites are closely associated with the Palaeo-Tethys Suture Zone in geographic extent, acting as stitching plutons between the subducted part of Sibumasu and the obducted Tethyan accretionary prism. The early magmatic age of the Main-Range Province (i.e. 230 Ma, early Late Triassic) suggests that the initial collision (i.e. the closure of the Palaeo-Tethys) already took place by then.

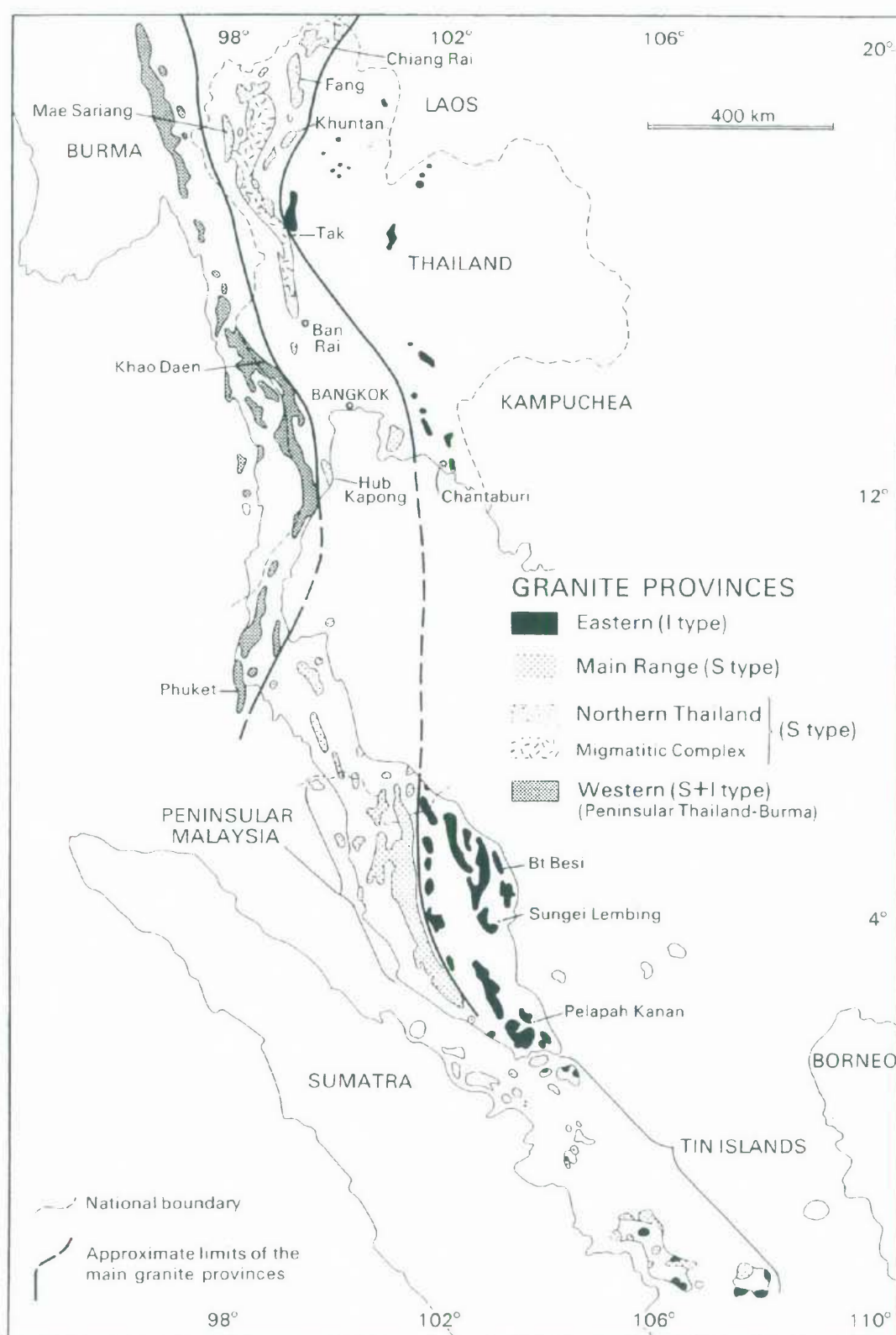


Figure 7.5 Distribution of granite provinces within the SE Asian tin belt proposed by Cobbing et al. (1986, fig. 1). Note that their Eastern Province includes granites of both the Sukhothai-Eastmal arc terranes and the Loei-Phetchabun Volcanic Belt of the Indochina Terrane).

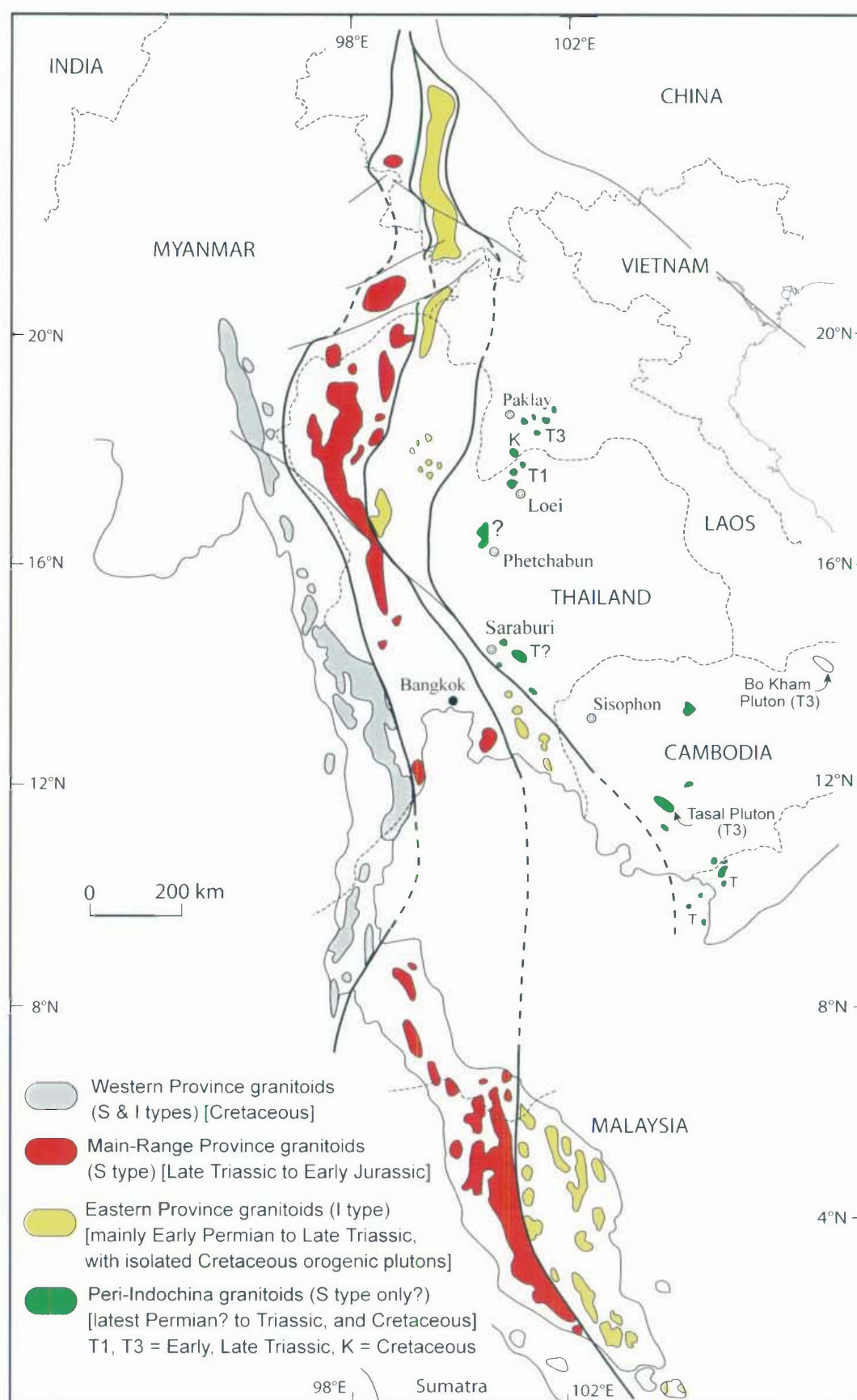


Figure 7.6 Revised classification of granitoid provinces in SE Asia (revised after Cobbing et al., 1992; Metcalfe, 2005, fig. 14), with peri-Indochina granitoids. Ages are indicated for those of the peri-Indochina granitic rocks (see text for sources).

	Western Province	Main-Range Province	Eastern Province	Peri-Indochina granitoids
Main granite types	S and I	S	I	S only?
Granite ages (Ma)	82–98 Late Cretaceous	180–230 early Late Triassic – Early Jurassic	190–290 early Early Permian – latest Triassic 70–80 Late Cretaceous	255, 213, 195, 117 latest Permian – Late Triassic, mid-Cretaceous

Figure 7.7 Comparison chart of four granitoid provinces in SE Asia (data compiled from Cobbing et al., 1986, Cobbing et al., 1992, Krähenbuhl, 1991, Charusiri et al., , 1992, 1993; for the peri-Indochina granitoids newly defined, data gained from Intasopa & Dunn, 1990, Lasserre et al., 1970, Lasserre et al., 1972, Stokes et al., 1996).

The Eastern Granitoid Province of Cobbing et al. (1986) was originally defined to include those granites, which are now recognised in the Sukhothai, Chanthaburi, and East Malaya terranes and in the Loei–Phetchabun Volcanic Belt of the western Indochina Terrane over the Nan to Sra Kaeo Suture line (see Fig. 7.5). However, the Eastern Province is revised here to consist only of granitic rocks of the Sukhothai-Eastmal magmatic arc, and thus those of the Lancang Terrane in Yunnan, represented by the Lincang Batholith, are included (Fig. 7.6). Thus, those minor plutons in the western Indochina Terrane over the Loei–Phetchabun Volcanic Belt are here excluded from the Eastern Province. As will be discussed later, they are defined as peri-Indochina granitoids, which principally constitute a Mesozoic plutonic zone of orogenic origin. The eastern boundary of the Eastern Province is redefined to be equivalent to the Jinghong, Nan to Sra Kaeo Suture. The granitoids in the Eastern Province refined are I type and magmatic arc origin, and are mainly Permian to Triassic in age, with occasional Cretaceous intrusions.

The arc magmatism of the Eastern Province was induced by the eastward subduction of the Palaeo-Tethys beneath the margin of the Indochina Terrane originally proposed by Mitchell (1977) and followed by some other authors (Figs 7.8–7.10). It started at about 280 Ma in the Early Permian, and continued until the end of the Triassic at 290 Ma (Cobbing et al., 1986). It is here interpreted to have formed the Sukhothai-Eastmal Island-arc System during the Permian and then the continental arc during the Triassic. The arc magmatism ceased shortly after the Palaeo-Tethys subduction was completed in the early Late Triassic.

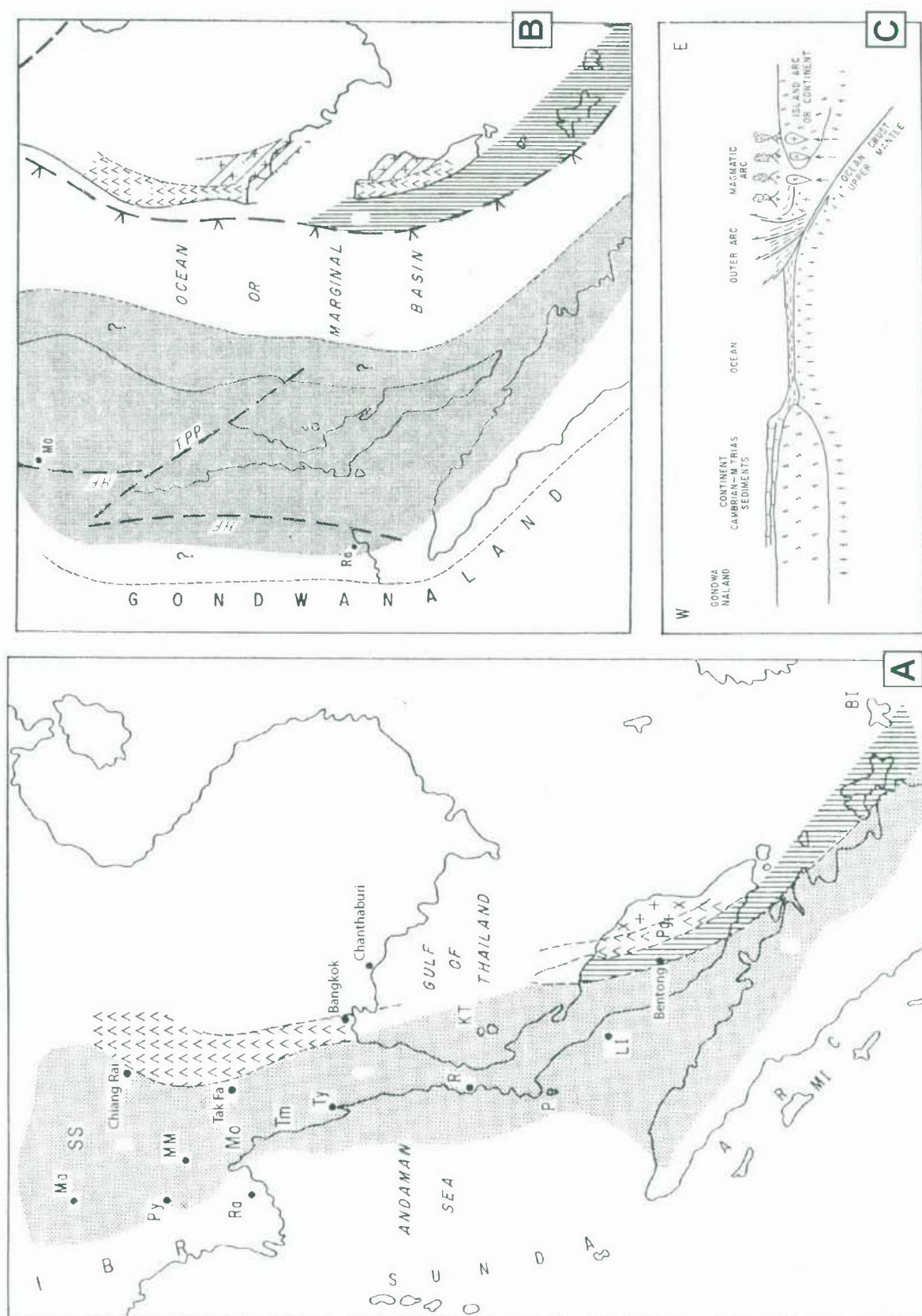


Figure 7.8 Tectonic concept of Mitchell (1977, figs 2-4) for SE Asia. (A) Tectonic zones (his fig 2). (B) Schematic Late Permian geographic reconstruction (his fig 3). (C) Cross-section of the Late Permian geography (his figure 4).

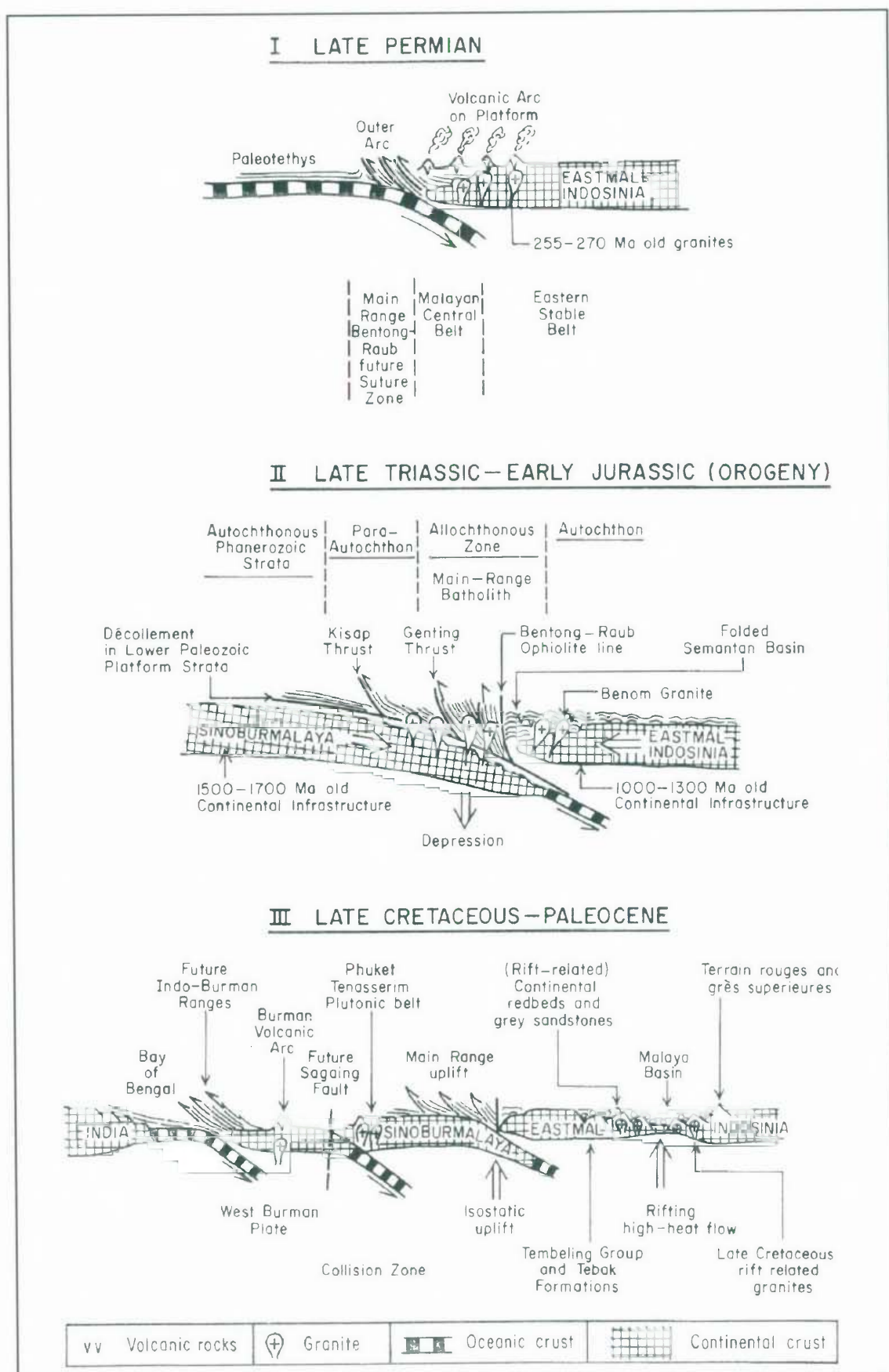


Figure 7.9 Tectonic interpretation of Hutchison (1989, fig. 5.12) for Malay Peninsula, developed from the concept of Mitchell (1977).

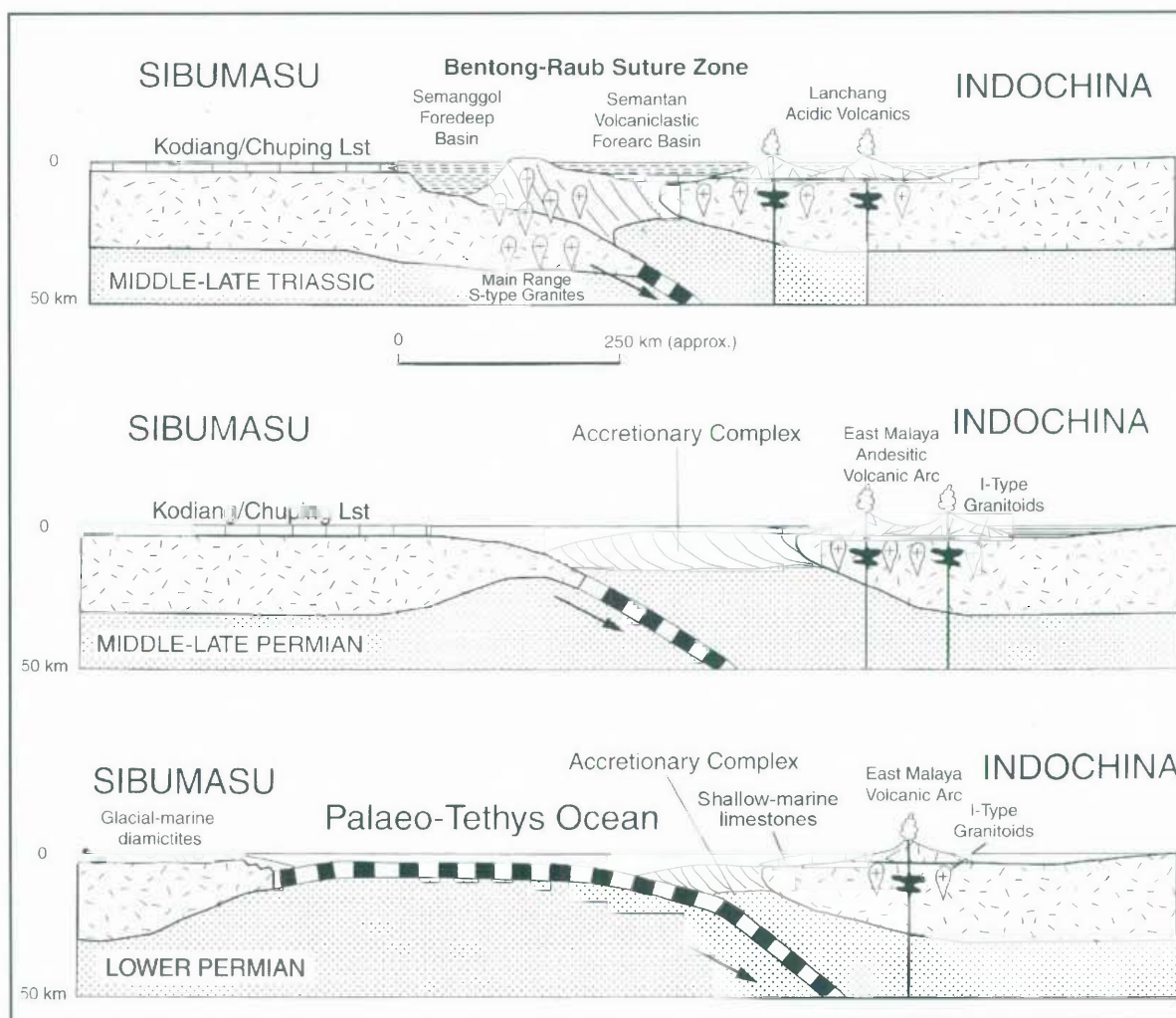


Figure 7.10 Conceptual cross-sections illustrating formation of the Bentong-Raub Suture by subduction of the Palaeo-Tethys Ocean and collision of the Sibumasu and Indochina terranes proposed by Metcalfe (2000, fig. 14).

It is noteworthy that Ueno and Hisada (1999) recognised the Inthanon Zone as the Palaeo-Tethys Suture Zone and the Nan Suture as a closed back-arc basin of the Sukhothai island arc (Fig. 7.11). This is the most convincing interpretation ever proposed for the Palaeo-Tethys subduction of SE Asia. It has the advantage over those similar eastward subduction models of Mitchell (1977), Hutchison (1989) and Metcalfe (2000), which does not figure the development of an island-arc system and a back-arc basin for the Indochina Terrane, shown in Figures 7.8–7.10. The Ueno and Hisada (1999) concept is applicable not only for Thailand but for whole SE Asian development of Indochina to Sibumasu tectonic interactions, and is adapted to the current interpretation.

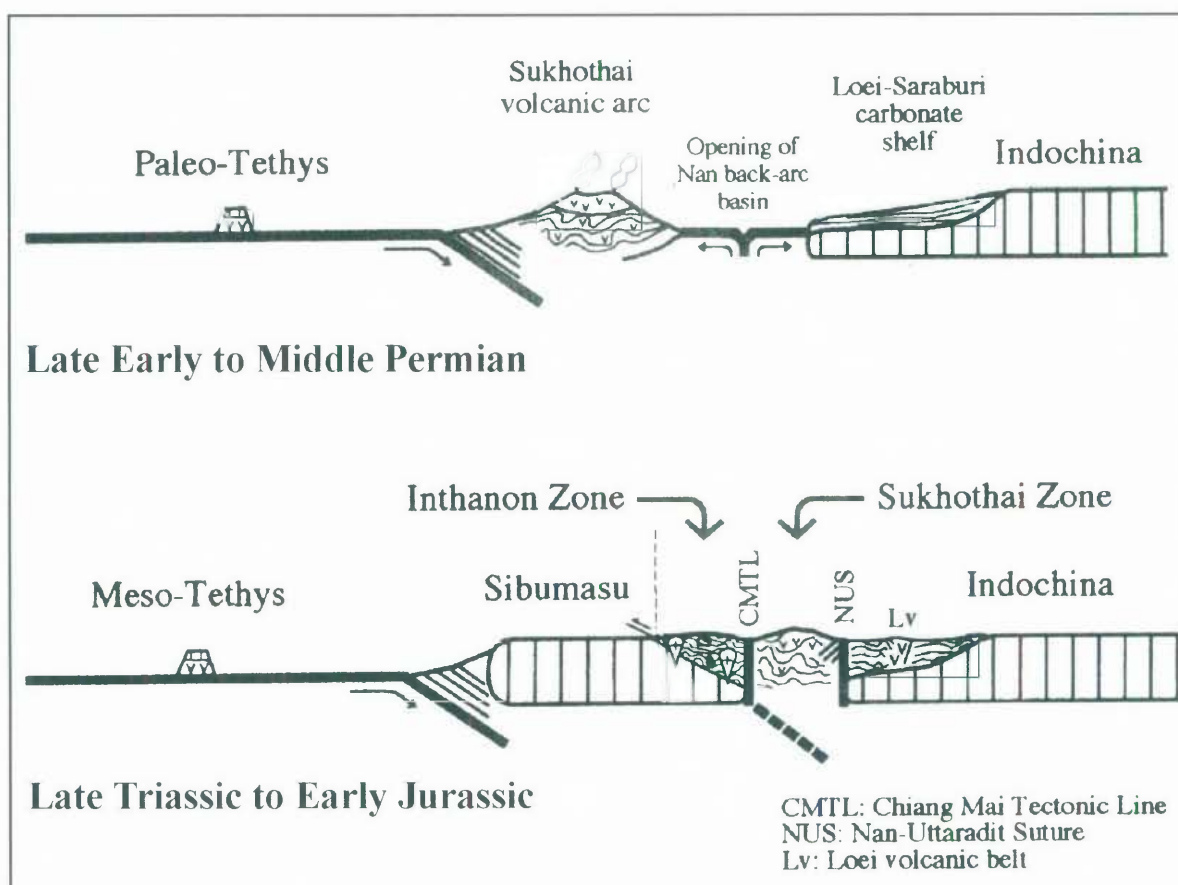


Figure 7.11 Tectonic development of mainland Thailand during the Permian to Jurassic period, proposed by Ueno (1999, fig. 3). Note that the Sukhothai Terrane is depicted to be an island arc with the opening of the Nan Back-arc Basin.

7.2.1 Peri-Indochina granitoids (a possible new granitoid province)

An attempt is here made to shed light on problems of some previous interpretations for the Loei–Phetchabun Volcanic Belt of the western Indochina Terrane. As shown in Figure 7.5, the Eastern Granitoid Province of Cobbing et al. (1986) includes volcanic belts of the Sukhothai, Chanthaburi, and East Malaya terranes and the Loei–Phetchabun Volcanic Belt in central Thailand (western Indochina Terrane). The latter volcanic belt was considered a Permo-Triassic magmatic arc by some authors (e.g. Beckinsale et al., 1979; Bunopas, 1981). Some small plutons of Mesozoic ages are known over the western part of the Indochina Terrane, shown in Figure 7.6. They are here collectively called peri-Indochina granitoids, which are excluded from the Eastern Province, as having different geochemical and chronological characters outlined below.

As noted earlier, granitoids of the revised Eastern Province are exclusively I type of magmatic arc origin (i.e. Sukhothai-Eastmal magmatic arc). Hence, those in the Loei–

Phetchabun Volcanic Belt, as originally included in the Eastern Province, were also considered I type by most authors (e.g. Cobbing et al., 1986; Cobbing et al., 1992; Krähenbuhl, 1991). However, as scrutinised in details below, no evidence comes available to indicate I-type character for granites of the Loei–Phetchabun Volcanic Belt or over the western Indochina Terrane. In general, plutonic bodies of the western Indochina Terrane (i.e. peri-Indochina granitoids) are relatively small and patchily distributed, and do not appear to form a high topographic range, unlike those in the Main-Range and Eastern provinces.

Some authors (e.g. Beckinsale et al., 1979; Bunopas, 1981; Tabakh and Utha-Aroon, 1998) have traditionally regarded the Loei–Phetchabun Volcanic Belt as representing a Permo-Triassic magmatic arc. Bunopas (1981) proposed the Permo-Triassic occurrence of a (eastward) subduction zone within the Nan to Sra Kaeo basin (Palaeo-Tethys Ocean in his concept) beneath the Indochina Terrane (Fig. 7.12).

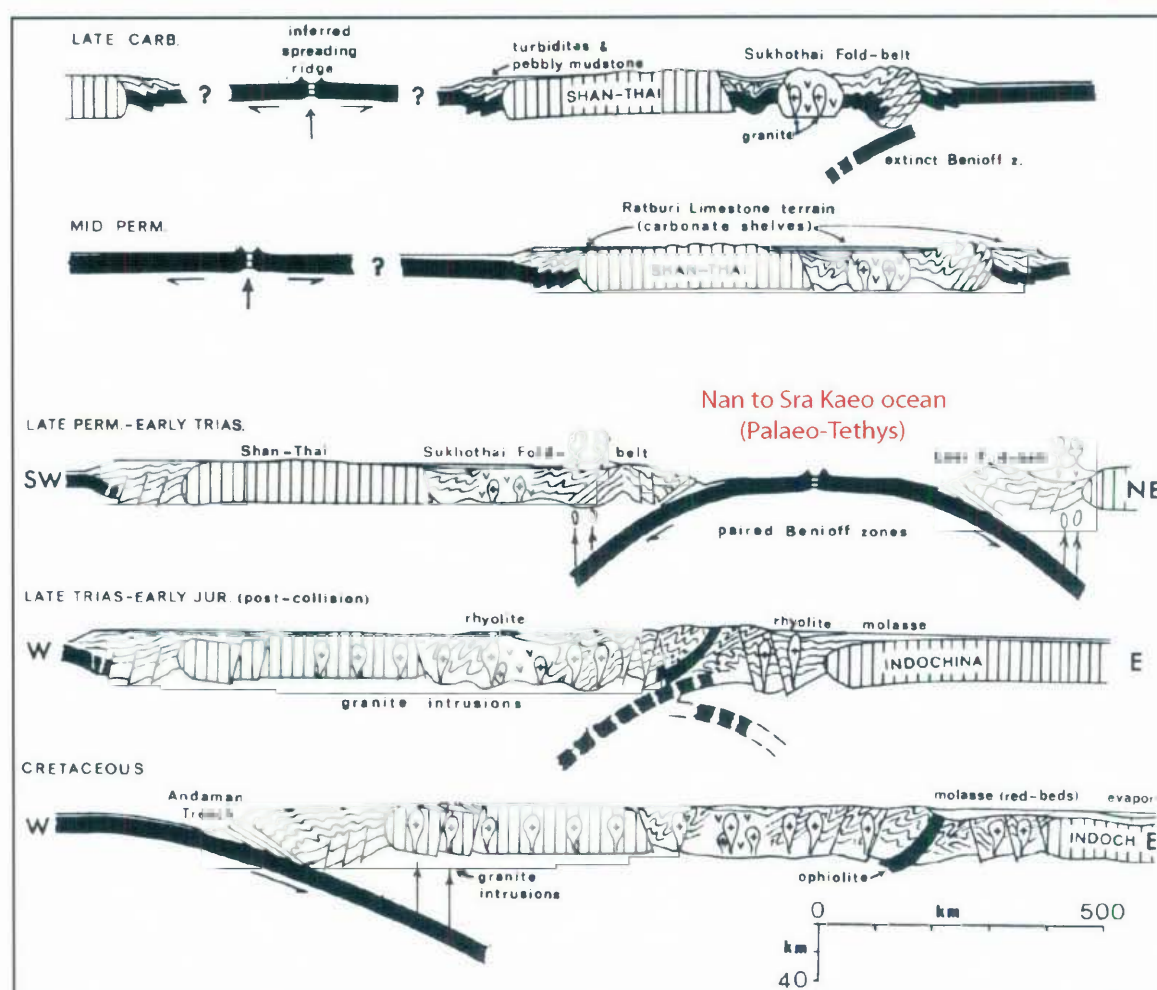


Figure 7.12 Tectonic evolution of Thailand from the Late Carboniferous to the Cretaceous proposed by Bunopas (1981, fig. 164). Note that he did not recognise his Inthanon Zone as a tectonic suture, and interpreted the Nan to Sra Kaeo seaway as the major ocean between the Indochina and Shan-Thai terranes.

However, many igneous rocks of the Loei–Phetchabun Volcanic Belt, previously considered Permo-Triassic in age, are now confirmed to be much older (Devonian) or younger (Cenozoic). The rhyolite and basalt near Loei show Sr/Nd isotopic ages of 374 ± 33 Ma (Middle Devonian) and 361 ± 11 Ma (Late Devonian), respectively (Intasopa and Dunn, 1994). Thus, these volcanics are too old to attribute to the Palaeo-Tethyan subduction. They are more likely related to older events such as the Palaeo-Tethys opening or the break-up of Indochina from Gondwana and/or South China, as considered by Intasopa and Dunn (1994). Another volcanic site near Lopburi, south of Phetchabun, has rhyolites, andesites, and basalts of Tertiary age, indicated by $^{40}\text{Ar}/^{39}\text{Ar}$ dating (Intasopa et al., 1995).

The presence of some Permo-Triassic volcanics in the western Indochina Terrane can be known from some available studies, although they may mostly be Triassic. Cobbing et al. (1986) illustrated another plutonic body of unknown age near Phetchabun (between Loei and Saraburi). Intasopa et al. (1995, p. 393) also noted the presence of Permo-Triassic volcanic rocks dated 225–275 Ma in the Phetchabun area, cited from a result of Intasopa's 1993 PhD thesis; her result, however, has never been published. The presence of such a granitic unit is not recognised in the Phetchabun area in the official geological map of Thailand. Nevertheless, it is evident that the Middle Permian Saraburi Limestone around Phetchabun is often intruded by postdating andesitic dykes (pers. observation, Nov. 2002). Hence, it is quite plausible that there is some unearthed pluton of post-Middle Permian age (most likely Triassic) in the Phetchabun area. Nevertheless, this requires to be verified.

A relatively large plutonic body is known in the Saraburi area, south of Phetchabun (see Fig. 7.6). No geochemical data is available for this intrusive, and its exact age is unknown. Nevertheless, the surrounding Saraburi Limestone sequence of Early to Middle Permian ages are known to have been contact-metamorphosed by this pluton, and the excavation of marble is a major local business. Therefore, the intrusion must be post-Middle Permian. It may be Triassic in age (Pol Chaodumrong, pers. commun., Jun. 2005); this seems most likely, considering the most common occurrence of Triassic granites in the western Indochina Terrane, reviewed below.

The Loei–Phetchabun Volcanic Belt (also Foldbelt) can be extended to the Paklay Foldbelt of northern Laos. K/Ar dates of Permian ages (255 and 264 Ma) were reported by Lasserre et al. (1972) for granodiorites of the Paklay Foldbelt. However, the necessary correction for atmospheric argon of those rocks results in a Triassic age (von Braun et al., 1976, p. 176). Those Laotian granodiorites were believed by Fontaine and Workman (1978) to be most likely Early Triassic in age. Yet, Late Triassic and Cretaceous granites were dated by Stokes

(1996) from the Paklay Foldbelt, implying the likeliness of a Late Triassic age for the granodiorites of Lasserre et al. (1972).

A large granitic unit, the Tasal Pluton, is known in the south of Tonle Sap Lake, central-western Cambodia (see Brookfield, 1996, p. 239; Jacobson et al., 1969) (see Fig. 7.6). This unit is here regarded as a peri-Indochina granitoid. It is a two-mica granite body, which gave a Rb/Sr isochron of 195 ± 12 Ma, with an initial Sr ratio of 0.710 ± 0.004 (Lasserre et al., 1970), that is, Late Triassic S-type granite. It is associated with volcanic rocks, such as dacites, rhyolites, and rhyolitic tuffs, and is overlain by Early Cretaceous redbeds (Lasserre et al., 1970).

Except for the Tasal Pluton, no other initial Sr ratios are available for granites of the western Indochina Terrane. Note that Lasserre et al. (1968) reported other Late Triassic granites with S-type indicative initial Sr ratios from Bo Kham, NE Cambodia (see Fig. 7.6). Considering its location, it may be related to another Mesozoic orogeny within the Truong Son Foldbelt in central Vietnam. It may be alternatively a product of intra-cratonic crustal thickening within the Indochina Terrane.

In addition, an andesitic tuffaceous sequence is known to underlie a Middle Permian carbonate sequence in western Cambodia, and it was defined as Member A of the Sisophon Limestone (Ishii et al., 1969). It is recorded to be about 5 m thick. One may take this as evidence of Permian magmatism in the western Indochina Terrane. However, no Middle Permian volcanic site is known around Cambodia or even over the western Indochina Terrane. The source of the tuffaceous material may be the Sukhothai-Eastmal island arc (i.e. Eastern Granitoid Province), which would not have been so distant from the Indochina Terrane beyond its marginal sea (i.e. the Jinghong to Sra Kao Back-arc Basin). It seems unlikely that the Sisophon volcanics are indicative of Permian *in-situ* magmatism of the western Indochina Terrane. Most granite intrusions in Cambodia are believed to be Triassic (Hutchison, 1989, p. 301–303).

In conclusion, it seems probable that there is no Permian plutonic activity in the western Indochina Terrane. Most of the so-called Permo-Triassic granitic rocks in this region, which are here called the peri-Indochina granitoids, are probably Mesozoic, most commonly Triassic. They do not seem to include subduction-induced arc granites, although this was previously believed. The tectonic cause for Mesozoic peri-Indochina plutonism can be referred to post-collisional crustal thickening within the western Indochina Terrane after the suturing of the Jinghong to Sra Kao Back-arc Basin and then the suturing of the Palaeo-Tethys. This may be intimately related to the Indosinian Orogeny. Arc magmatism for the Loei–Phetchabun

Volcanic Belt is considered implausible, and the Permo-Triassic (eastward) subduction of the Nan to Sra Kao basin beneath the Indochina Terrane is not supported in this study; the conclusion differing from that of Bunopas (1981). The peri-Indochina granitoids possibly constitute a new granitoid province; nevertheless, geochemical data from each pluton of the western Indochina Terrane is not sufficient to define this.

7.2.2 Subduction for the arc magmatism of the Sukhothai Volcanic Belt

In addition, Bunopas (1981) interpreted that there was another Permo-Triassic (westward) subduction zone in the Nan Basin (= Palaeo-Tethys in his concept) beneath the Sukhothai Terrane, concurrent to the eastward subduction zone within the same basin (see Fig. 7.12). Thus, he proposed the occurrence of double subduction zones in the Nan Basin. Eastward subduction is considered unlikely with respect to the peri-Indochina granitoids of the western Indochina Terrane, as discussed earlier. The presence of westward subduction is also arguable, as discussed below.

Westward subduction was interpreted by Bunopas (1981) to explain the cause of Permo-Triassic arc magmatism in the Sukhothai Volcanic Belt (i.e. Eastern Province revised). Late Permian blueschists and greenschists are recognised in the Pha Som Metamorphic Complex of the Nan Suture. This suggests the occurrence of Late Permian high-pressure compressional movement within the Nan Basin, that is, the closing of the back-arc basin. The deformational structure of the Pha Som greenschists indicates a west-dipping thrust. Thus, the Pha Som Complex has been interpreted as an accretionary prism of the subduction zone beneath the Sukhothai Terrane by some authors (Bunopas, 1981; 1992; Singharajwarapan and Berry, 1993; Singharajwarapan and Berry, 2000).

However, as mentioned earlier, the cause of the Sukhothai arc magmatism can now be better explained by eastward subduction at the Palaeo-Tethyan Inthanon Suture Zone from the present west (e.g. Ueno and Hisada, 1999). In addition, it is unlikely that a major Permo-Triassic subduction zone existed for the Nan Basin as this existed only in the Permian, as indicated by the deep-water records (see earlier discussion). It is reiterated that the Nan Basin was not the Palaeo-Tethys Ocean, but was a back-arc basin. Furthermore, the Pha Som Complex *mélange* is restricted to the Late Permian (see Singharajwarapan and Berry, 2000), and no evidence of ongoing Triassic subduction is present in the Nan Suture.

It is here interpreted that the west-dipping structure of the Pha Som Complex probably represents underthrusting of the Nan sea floor during the closure of the Nan Back-arc Basin in the Late Permian. It is also believed that the underthrust crust beneath the Sukhothai Terrane has never reached the Benioff zone to induce the arc magmatism. The occurrence of a true prolonged subduction zone in the Nan Back-arc Basin is unlikely.

7.2.3 Uncertainty of Carboniferous plutonism

In both Main-Range and Eastern granitoid provinces, it is traditionally believed that magmatism started from the Carboniferous (e.g. Altermann, 1991; Bunopas, 1981; Mitchell, 1977). However, von Braun et al. (1976, p. 195) concluded that there is no radiometric evidence of Carboniferous granite in northern Thailand. Beckinsale et al. (1979) showed that most granitic rocks in Thailand are Mesozoic in age. Bunopas (1981, p. 403) reviewed previous geochemical reports of so-called Carboniferous granites from NW Thailand (both the Inthanon Suture Zone and the Sukhothai Terrane in current recognition), and questioned the reliability of those results in terms of age. He did not recognise definite Carboniferous granite in the region after all.

In the Main-Range Province, the only Carboniferous granite known so far is that of a Late Carboniferous Rb/Sr age (307 Ma) reported by Krähenbuhl (1991) and then Kwan et al. (1992) from Penang Island (western Peninsular Malaysia, Sibumasu Terrane). It is the peculiar occurrence, surrounded by much younger Mesozoic batholiths within the same province. Krähenbuhl (1991) interpreted it an anorogenic origin, separate from the younger granites of post-collisional/orogenic origin. Because of its old age, it must be attributable to peri-Gondwanan magmatism while Sibumasu was still part of Gondwana.

As for the Eastern Granitoid Province, some authors (e.g. Altermann, 1991; Mitchell, 1977) considered that arc magmatism started in the Carboniferous. However, no Carboniferous plutonic rock has been confirmed in this province. Once, Late Carboniferous to Early Permian K/Ar ages were calculated for granites from the Eastern Coast of Peninsular Malaysia (East Malaya Terrane) by Snelling et al. (1968). However, those geochemical results were later acknowledge by Bignell and Snelling (1977, p. 18) to contain some error, as the ages should have been much younger. Those authors were convinced that a Late Carboniferous–Early Permian intrusive event in the area would be inconclusive. The presence of Carboniferous granitic rocks has never been confirmed in the current Sukhothai-Eastmal arc terranes or in the western Indochina Terrane by subsequent investigations.