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Tectonic evolution of Southeast Asia

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Abstract: The prominent N–S Palaeo-Tethys Bentong-Raub suture divides Peninsular Malaysia into a Sibumasu block on the west and an Indochina block on the east, known locally as East Malaya. The suture zone is characterized by an imbricated complex resembling an accretionary prism, of carbonaceous pelitic schist, serpentinite, amphibole schist, mélange-olistostrome and chert, as well as undated post-suture redbeds. Oceanic cherts record a Palaeo-Tethys history from Late Devonian to at least Late Permian. Extrapolation southwards is towards the Indonesian islands of Bangka and Billiton, and northwards along the Gulf of Thailand to the Sa Kaeo suture that has been strongly offset left-laterally by the Chao Phraya and Mae Ping faults to the Nan Uttaradit Suture, associated with less prominent island arcs of the Sukhothai zone, that correlates with the western part of East Malaya. Sa Kaeo and Nan-Uttaradit are now interpreted as closed back-arc basins. The suture zone accretionary prism and associated island arc rocks are known in northern Thailand as the Inthanon zone associated with the Chiang Mai suture, equivalent to the Bentong-Raub suture zone of Peninsular Malaysia, but problems of polarity remain.

Sibumasu is characterized by Carboniferous–Permian glacial pebbly mudstones, whereas the East Malaya and Indochina Block are characterized by fusulinid limestones and Cathaysian equatorial *Gigantopteris* flora. Sumatra has a Cathaysian affinity terrain west of the Sibumasu Block, formerly referred to as the "Jambi Nappe". Characteristic Lower Palaeozoic fossils allow the Sibumasu localities of Langkawi, Tarutau and Phuket to have been positioned near the Canning Basin of Australia before its Lower Permian rifting from Gondwanaland. The Indochina and South China terranes had rifted from Gondwanaland in the Early Devonian and were spared the Upper Palaeozoic glaciation and instead developed equatorial *Gigantopteris* flora.

Sibumasu collided with East Malaya and Indochina in the Late Triassic (the Indosinian Orogeny), causing crustal thickening resulting in important tin-bearing S-type granites, characterised by the Main Range of the Peninsula, the 'tin islands' of Indonesia and parts of central Thailand. Late Cretaceous granites, commonly associated with high grade metamorphic core complexes, have not yet been successfully integrated into the regional tectonic analyses.

Eocene collision of India, with maximum impact at the Assam–Yunnan syntaxis, caused escape tectonics, resulting in oroclinal clockwise rotation of northern Sundaland brought about by a large number of right-lateral wrench faults and regional oroclines. The faults are associated with transtensional Tertiary basins and tanspressional transverse ranges of Jurassic–Cretaceous formations. Oroclinal bending of southern Sundaland resulted in anticlockwise rotations, forming a great arcuate structure known as the Anambas Zone. The right-lateral faulting of Sumatra is attributed to ongoing oblique subduction at the active trench.

Keywords: tectonics, Southeast Asia, Bentong-Raub suture, Sibumasu block, Indochina block

INTRODUCTION

The great Dutch geologists, notably Umbgrove (1947) and Van Bemmelen (1949) who worked in Indonesia, recognised and described large arcuate structures of regional dimension and gave names such as Anambas Zone. Later Carey (1958) used the term orocline for such structures and defined them as orogenic belts with an imposed curvature as a result of horizontal bending of the crust.

Much later Tapponnier *et al.* (1982, 1986) described a new mechanism, known as escape or extrusion tectonics, which could be applicable to Southeast Asia. They emphasised the major faults that seemed to radiate from the Assam-Yunnan syntaxis (Figure 1), and paid no attention to the oroclines. Hutchison (1994) proposed a modification of escape tectonics that could explain both the faults and oroclines of Southeast Asia. The indentation of Asia by India is held responsible for the oroclines and the mechanism requires regional right-lateral wrench faulting or clockwise rotation, and this was a major goal of palaeomagnetic research. The proof was excellent for the Khorat Basin of the Indochina Block. The opposite curvature of the Anambas Zone orocline, extending from Borneo through Billiton and Bangka, results from anticlockwise rotation for Borneo and southern Peninsular Malaysia, confirmed by palaeomagnetic research.

Recognition and naming of ophiolitic sutures (Hutchison, 1975) and dating by radiolaria contained in the cherts (Metcalfe, 2000) resulted in the deduced duration of the Palaeo-Tethys Ocean, from the Early Devonian to its elimination at the Indosinian Orogeny in the Late Triassic. The main Palaeo-Tethys suture is interpreted as the Bentong-Raub and Chiang Mai sutures. Subdivision of Southeast Asia into blocks of different Carboniferous–Permian stratigraphy allowed Wakita and Metcalfe (2005) to give a chronology for the separation of the Sibumasu and Indochina blocks from Gondwanaland to their collision at the Indosinian Orogeny.

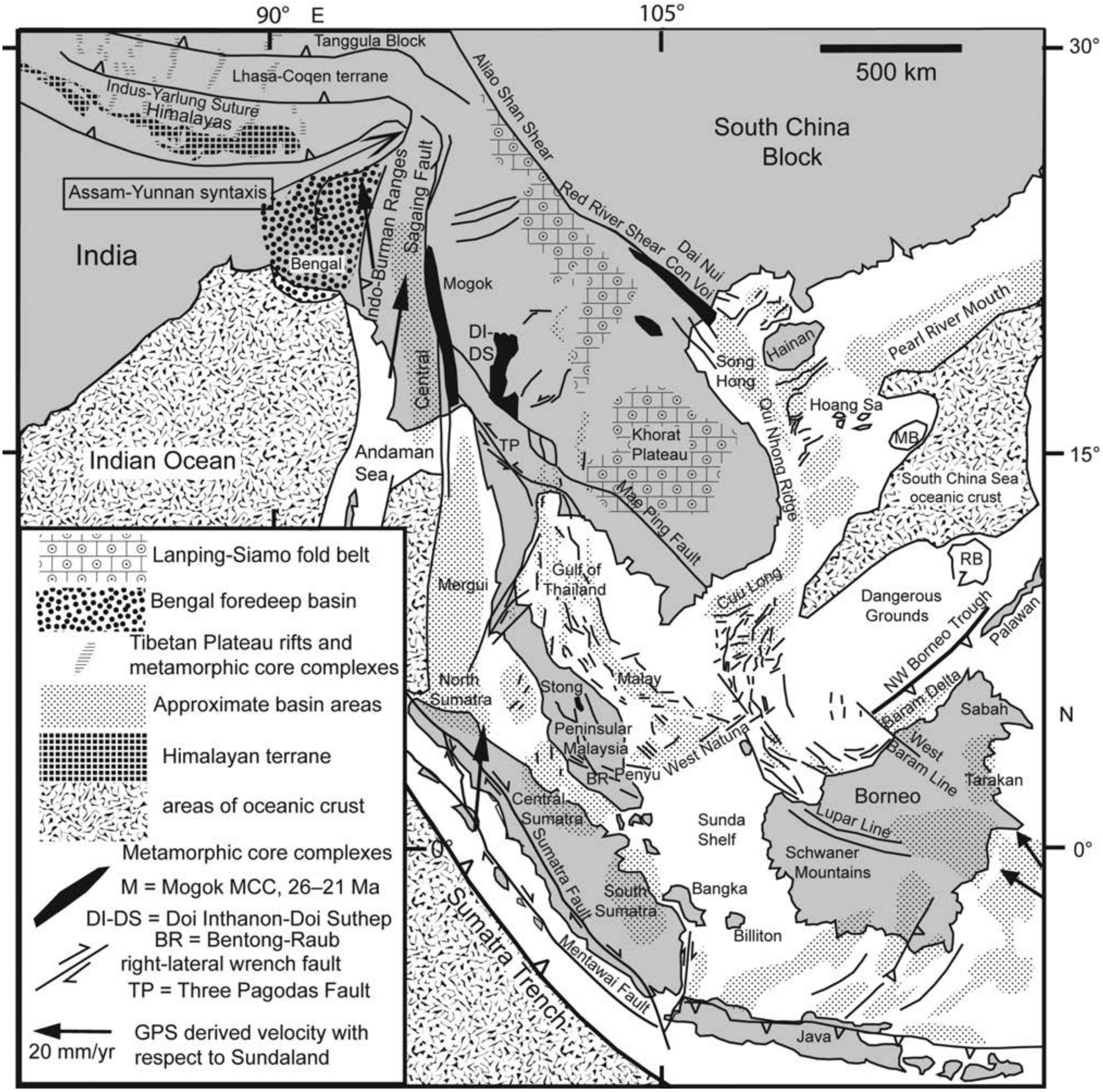

Figure 1: Regional location map illustrating the Cenozoic structural setting of Southeast Asia. Modified after Searle and Morley (2011).

PALAEO-TETHYS SUTURE

Peninsular Malaysia

The Palaeo-Tethys suture occupies the eastern foothills of the Main Range. Alexander (1968) used the term "Bentong Group" for the rocks of the suture, but Haile and Stauffer (1972) pointed out, rather amusingly, that this name should be abandoned because it contains both radiolarian chert (oceanic) and redbeds (continental).

The most accessible part of the suture extends southwards from Cheroh (Figure 2), through the Raub and Bentong areas and southwards towards Kuala Pilah. The largest bodies of serpentinite and amphibole schist occur to the west and north-west of Cheroh (Richardson,1939), and this is where the Bentong–Raub Line was first defined (Hutchison, 1975).

Thailand

In early models (Barr and MacDonald, 1987), Sibumasu was thought to extend as far as the Nan-Uttaradit Suture, as defined by Hutchison (1975), and to have represented the main collision zone between Sibumasu and the Indochina Block (Bunopas, 1982). Subsequently, intervening areas, named the Inthanon and Sukhothai zones (Figure 3), were identified by Barr and MacDonald (1991). More recent studies have recognised that the Nan-Uttaradit and Sa Kaeo sutures represent closed back-arc basins and that

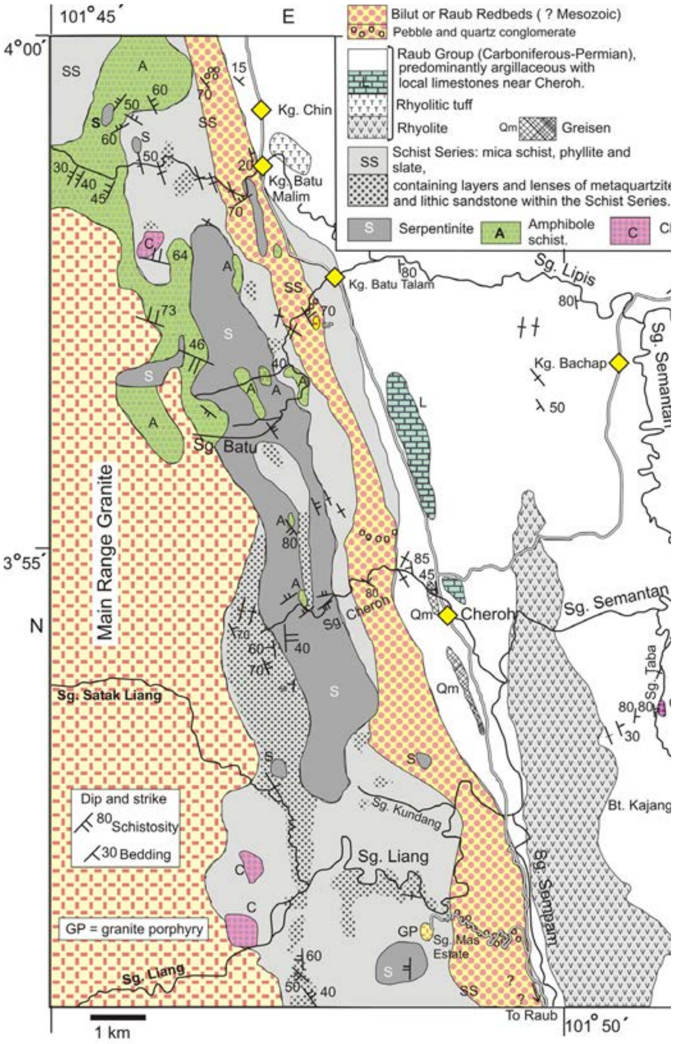

Figure 2: The Bentong-Raub suture zone in the Cheroh district north of Raub. Based on Richardson (1939), whose terminology is not now relevant. Modifications after Haile *et al.* (1977) have been added. The undated Bilut Redbeds form a band of discontinuous erosional outliers although shown here as continuous.

the Inthanon and Sukhothai zones are composed of a number of small intermediate terranes (accretionary prism, seamounts and island arcs) that lie between the Indochina Terrane and Sibumasu (Hirsch *et al.* 2006, Sone and Metcalfe, 2008a).

The Sukhothai zone appears to be a Permo-Triassic magmatic arc developed on rifted fragments of the Indochina terrane that developed by eastwards subduction (using present-day orientation) of the Palaeo-Tethys Ocean under Indochina (Sone and Metcalfe, 2008a). This is comparable to Peninsular Malaysia and Kampong Awah and Jengka Triangle andesitic arcs may be equated with the Sukhothai zone (Figure 3).

The Sibumasu terrane is present only in westernmost Thailand. The location of the contact with the Inthanon zone (the Palaeo-Tethys suture zone) is best defined around Mae Sariang in the vicinity of the Mae Yuan Fault (Kamata *et al.*, 2002). The Inthanon zone is interpreted as overthrust slices of Palaeo-Tethyan pelagic cherts and basaltic seamounts with carbonate caps, representing the accretionary complex of the Sukhothai arc emplaced along a major low-angled thrust onto folded and thrust marginal sedimentary rocks of Sibumasu (Sone and Metcalfe, 2008a). The Inthanon zone may be extrapolated into Peninsular Malaysia as the Bentong-Raub zone complex, interpreted also as the Palaeo-Tethyan accretionary prism.

Sumatra

The Bentong-Raub suture (Hutchison, 1975), was shown trending SE from the vicinity of Gunung Ledang (Mount Ophir), to transect the gabbroic outcrops of south Johor and Singapore, extending SE through the Riau Archipelago ('1' on Figure 4). This extrapolation was based on the distribution of granite types (Hutchison, 1977), and the initial misinterpretation of the gabbros as ophiolite. The Main Range biotite granite west of

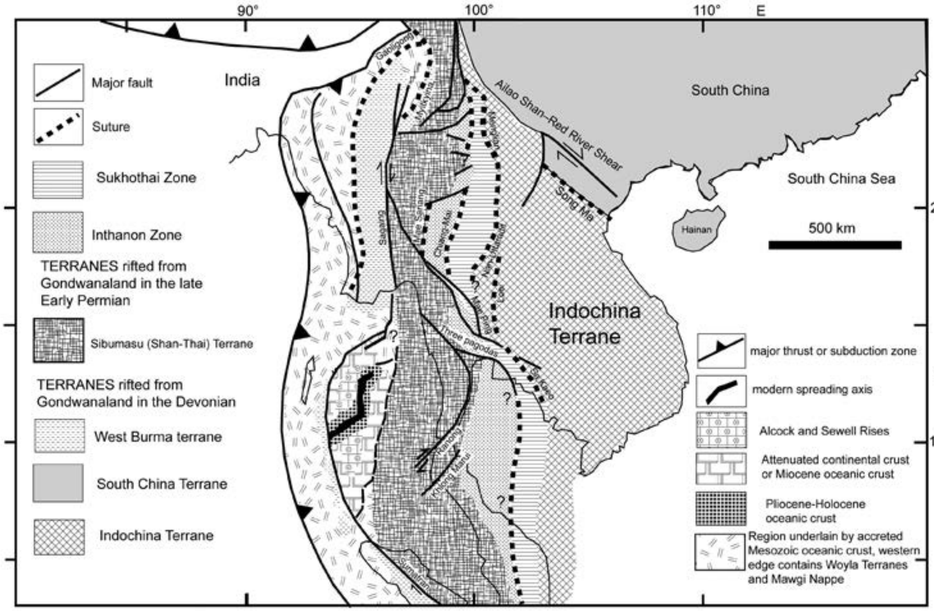

Figure 3: Geological terrane map of northern Southeast Asia showing the sutures and major faults, modified from Searle and Morley (2011). The Palaeo-Tethys and island arc terrane is that proposed by Sone and Metcalfe (2008a). The Sukhothai Zone is one of island arcs on the western margin of the Indochina block. The Inthanon Zone includes a record of the Palaeo-Tethys Ocean, mainly accretionary prism.

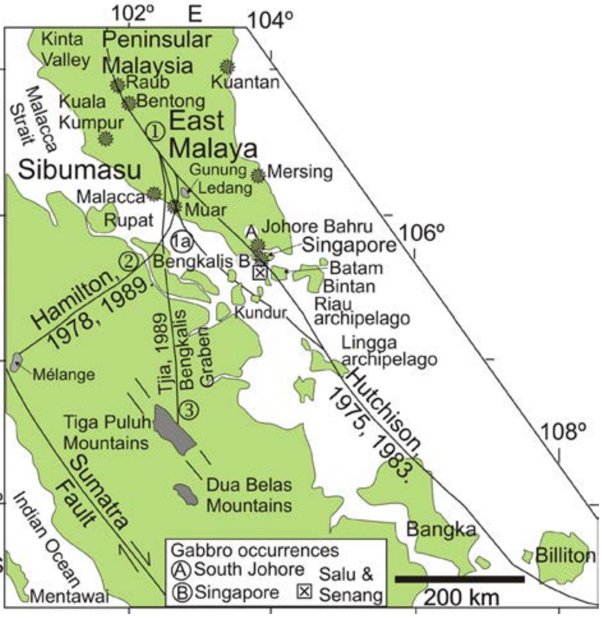

Figure 4: Positions of the Bentong-Raub suture as proposed by various workers. It was also called the Medial Malaya Zone by Şengör (1984). None of these can separate all Gondwana from Cathaysia terrains, from Hutchison (1994).

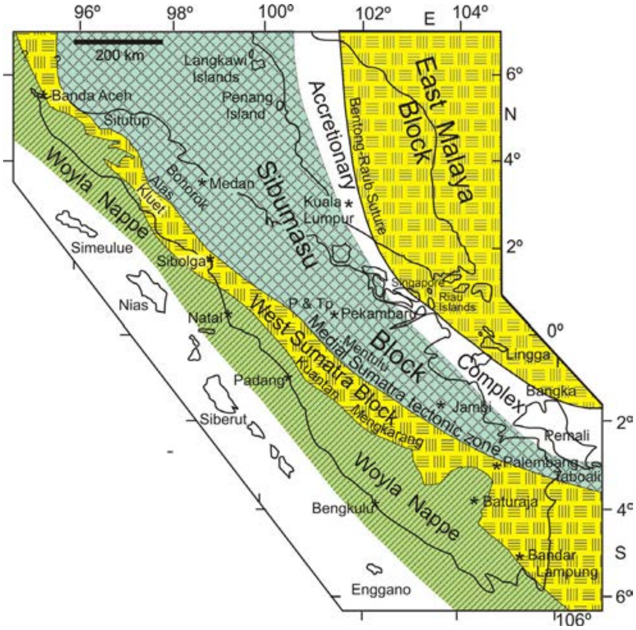

Figure 5: Pre-Tertiary tectonic blocks of Sumatra and Peninsular Malaysia, according to Barber *et al.* (2005).

the suture is distinctly megacrystic and of ilmenite series, whereas the granitoids of East Malaya are more equigranular, contain both biotite and hornblende, and many are of magnetite series (Hutchison, 1989a,b; Ishihara *et al.*, 1979). Hutchison (1983) later concluded that the gabbros belong to the eastern volcano-plutonic belt, and that the suture extends into the Straits of Malacca ('1a' in Figure 4) between Malacca and Muar, where serpentinite and amphibolite, reported 11 km SE of Malacca (Hutchison, 1973), have been mapped.

Extrapolation through the Riau Archipelago towards Bangka and Billiton has never been satisfactorily located in the field. However, the islands to the SW of Singapore, Salu and Senang (Figure 4) contain chert and spilite (Singapore, 1976). A case can be made for extending the suture between Kundur, where the granitoids are of ilmenite-series, and Batam where they are of magnetite series (Wikarno *et al.*,1988). Barber *et al.* (2005) and Ko (1986) described pebbly mudstone in Bangka Island, allowing Barber *et al.* (2005) to extend the suture north of the island (Figure 5). Cobbing *et al.* (1992) were unable to discover any granitoid petrological difference between Bangka and Billiton.

Hamilton (1979, 1989) showed the suture swinging west from Malacca (Figure 4) through a rock assemblage near 0° 10´ S. and 100° 10´ E., interpreted as mélange. His extrapolation has to be rejected because it cuts across the stratigraphic distribution and structural geology.

Tjia (1989) linked the Triassic Palaeo-Tethys Bentong-Raub suture with the Palaeogene Bengkalis graben of Sumatra because of their approximate alignment. He coined the term 'Bentong-Bengkalis Suture'. This hypothesis was temporarily followed by Metcalfe (1991). The Bengkalis Graben is entirely of Tertiary age; it transects the regional structure (Figure 4), and terminates abruptly at the Tiga Puluh Mountains. The graben nowhere separates Gondwana from Cathaysia terrains in the same way that the Bentong-Raub suture does. Therefore, the Bengkalis Graben does not represent the suture position.

The Bentong-Raub suture defines the western margin of the Central Basin of Peninsular Malaysia, dominated by folded predominantly Carnian-Norian (Semantan Formation) strata (Hutchison, 1989a). This Triassic belt continues through the Riau and Lingga archipelagoes to Bangka and Billiton (Figure 5). The suture should therefore logically be expected to continue parallel to the 'tin islands', to be buried beneath Cenozoic formations and sea, but geophysical evidence has not yet been presented to define its location.

CONTRASTING TERRANES

The major contrasts are in the Carboniferous and Permian rock formations and fossils, resulting from contrasting palaeo-latitude positions. The main terranes of Southeast Asia are shown in Figure 6, excluding the complexities of the Sukhothai and Inthanon zones.

Plants

East Malaya (Indochina Block)

East Malaya has two described fossil plant localities that confirm a Carboniferous-Permian equatorial climate (Figure 7). The Linggiu Formation of SE Johor contains nineteen plant species of definite Cathaysian *Gigantopteris* type (Kon'no *et al.*, 1971). At the Jengka Pass, on the road between Kuala Lumpur and Kuantan, the Cathaysian flora contain *Bicoemplectopteris hallei* that is one of the most important Upper Permian members of the Cathaysian

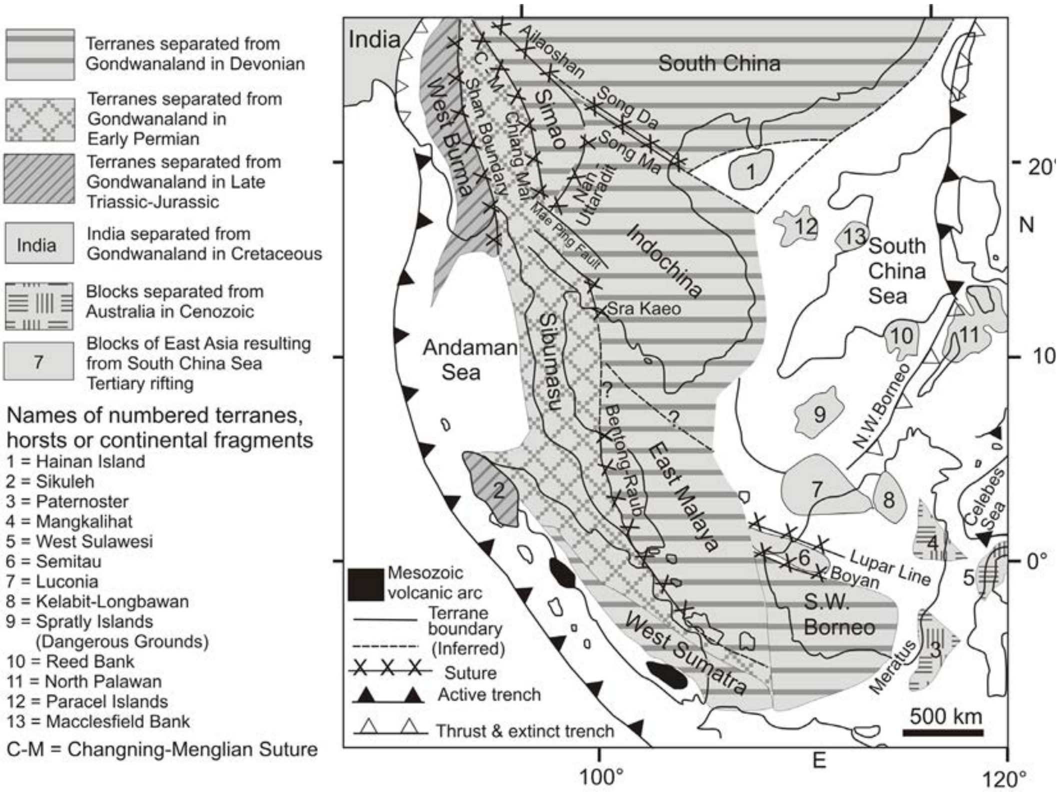

Figure 6: Distribution of continental blocks, fragments, terranes and principal sutures of South-East Asia redrawn from Wakita and Metcalfe (2005), without showing the the Sukhothai and Inthanon zones.

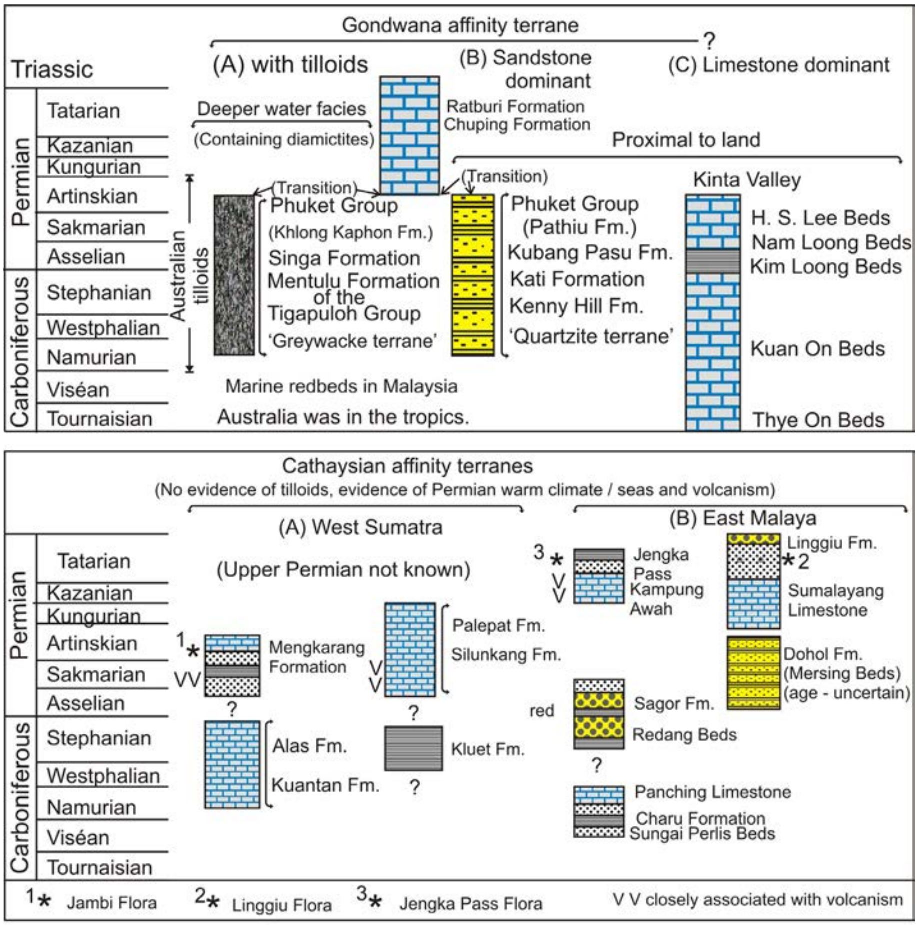

Figure 7: Summary of Carboniferous and Permian stratigraphy of the Gondwana and Cathaysia affinity blocks of Southeast Asia, from Hutchison (1994).

Gigantopteris flora of South China (Kon'no & Asama, 1970). The Indochina Block is probably continuous beneath the Gulf of Thailand with East Malaya. Throughout Indochina, Permian shale-coal sequences contain good Cathaysian *Gigantopteris* flora (Fontaine & Workman, 1978). An Upper Permian locality near Loei in Thailand contains only Cathaysian flora characterised by *Gigantopteris* species such as *Bicoemplectopteris hallei* that characterise the type localities of the Yangzi Platform (Asama, 1976). Good floral localities occur 100 km NE of Loei, to the NW of Vientiane, and in the Phong Saly district of Laos. The type locality of Cathaysian *Gigantopteris* flora is in the continental sequences of the Yangzi Platform of South China (Yang *et al.*, 1986).

Sumatra

The Mengkarang Formation of SW Sumatra contains the Jambi Flora (Figure 7), first collected by Zwierzijcki (1935). Asama *et al.* (1975) concluded that the flora are composed entirely of Cathaysian species, but are older than the typical *Gigantopteris* of South China and may represent an earlier stage in development. Vozenin-Serra (1989) reported *Cordaites* and coniferous wood fragments that show no annual growth rings and represent the southernmost record of equatorial Cathaysian flora.

There are no Carboniferous and Permian glacial deposits in Cathaysia, West Sumatra, Indochina and East Malaya and the Permian plants indicate widespread emergence of land in an equatorial climate.

Sibumasu

No *Glossopteris* plants of Gondwanaland affinity have been found in the southern parts of Sibumasu. The reason is that nowhere was there emergent land and the whole of Sibumasu was covered by Permian shallow seas. This does not preclude the possibility of finding *Glossopteris*-type palynomorphs.

Glossopteris flora have been reported from south of Baoshan in western Yunnan (Wang & Tan, 1994), and typical Lower Permian Gondwanaland spores, including *Primuspollenites levius* and *Schauringipollenites maximus*, have been recovered from near Tenchong, western Yunnan (Yang, 1994). This Tenchong flora of Sibumasu are remarkably similar to palynoflora from the Collie Basin of Western Australia.

Limestone and volcanic rocks

Sibumasu

The Gondwana-affinity Sibumasu terrane has no Carboniferous and Permian volcanic rocks, and limestone is notably absent (see the Kinta Valley exception below) from the Carboniferous and begins to appear only in the Artinskian (Figure 7). This limestone is conformable upon the pebbly-mudstone-bearing facies and upon the sandy facies of the Phuket Group, Singa Formation and Kubang Pasu Formation. It is known as the Ratburi Limestone in southern Thailand, and the Chuping Formation in northern Peninsular Malaysia. It is poorly fossiliferous, possibly because it was deposited in cold water (Figure 7). The solitary rugose coral *Iranophyllum* has been recorded by Fontaine (1989) from Phanggna, near Phuket. Its colonialisation of Sibumasu may indicate a warming of the sea as Sibumasu drifted northwards into warmer parts of the Palaeo-Tethys away from Gondwanaland.

The Kinta Valley sequence (Ipoh, Kinta in Figure 7), lying on strike between the Kubang Pasu, Kati and Kenny Hill Formations, represents a unique exception. There are 700 m of Carboniferous through Lower Permian limestone with 100 m of shale and argillaceous sandstone (Suntharalingam, 1968). The Nam Loong Beds contain Lower Permian (Sakmarian) brachiopods that share a cold temperate provinciality with southern Thailand and eastern Australia. Shi and Waterhouse (1991) interpreted this to mean that in Asselian to Sakmarian times Sibumasu was attached to eastern Gondwanaland. By sharp contrast, the overlying H.S. Lee beds contain fusulinids, amminoids and abundant gastropods of Late Lower Permian (Sakmarian to Artinskian) age, interpreted as a warm water fauna. The abrupt change in provinciality within some 5 m.y. caused Shi and Waterhouse (1991) to infer a rapid northwards migration of Sibumasu, causing a reorganisation of sea currents that brought in the warm water fauna. Climatic belts also were reorganised following the end of the Gondwanaland Ice Age.

Indochina terrane

By contrast with Sibumasu, there are Carboniferous limestones throughout Cathaysian-affinity terranes and the Permian limestones are rich in fauna, especially fusulinids. There is a close relationship with andesitic volcanism, as at Kampong Awah. The richly fossiliferous limestone is known in Thailand as the Saraburi Limestone (Dawson, 1978). The rich fauna of the Kuantan Formation limestone of southern Sumatra represents deposition in a tropical warm water environment (Fontaine & Gafoer, 1989).

Glacial diamictites

Sibumasu

Upper Carboniferous to Lower Permian glacial-marine diamictites (pebbly mudstones) occur widely throughout Sibumasu (Figure 7). In the north, there are excellent outcrops in the Tengchong–Baoshan terrain of SW Yunnan (Jin, 1994; Wopfner, 1994). The best outcrops of pebbly mudstones in the Malay Peninsula are in the Phuket Group (Ridd, 2009) at Phanggna, and in the Langkawi Islands within the Singa Formation (Stauffer & Mantajit, 1981; Stauffer & Lee, 1989). Typical outcrops are shown in Figure 8. The farthest south occurrences of pebbly mudstone tilloids are in Sumatra within the Bohorok Formation and Mentulu Formation (Barber & Crow, 2005).

The most widely accepted theory for the origin of the diamictites is that the unsorted clasts, ranging up to 20 cm size in Malaysia but up to 80 cm in east Aceh, represent drop-stones from melting icebergs offshore a glaciated continent (Gondwanaland). The clast lithologies are predominantly of local origin, mainly Lower Palaeozoic limestones and siltstones, but boulders of exotic coarse muscovite pegmatite and trondhjemite granitoid have been found in Langkawi. The latter gave a K:Ar date of 1029 Ma (Stauffer and Snelling, 1977). A granite clast in the Cucut #1 well of Central Sumatra gave a K:Ar age of 348 Ma (Koning & Darmono, 1984).

Sibumasu Formations devoid of diamictites

The diamictite-bearing belt is flanked on the east by a sandstone-dominant facies (Figures 7 & 9). It is also characteristically impoverished in fossils. The sandstone-dominant formations represent a lateral facies transition from the diamictite-bearing formations. Both are underlain by Devonian–Lower Carboniferous marine redbeds. Both demonstrate an upwards conformable transition in NW Peninsular Malaysia to the Chuping Limestone (Figure 7). The sandstone-dominant facies (Kubang Pasu, Kati, Kenny Hill and 'Quartzite'; Figure 7) is interpreted as nearshore fluvio-glacial, whereas the diamictite-bearing facies lay farther from the coast to be reached by drifting and melting icebergs over deeper water. This interpretation follows a similar deduction for the Grant Group of the Canning Basin of Australia by Mory *et al.* (2008). Pebbly mudstones have also been described from Oman, which in the Late Palaeozoic was also an integral part of Gondwanaland (Martin *et al.*, 2008). Therefore, it seems that the eastern margin of Sibumasu was formerly attached to and also rifted from Gondwanaland.

EARLY PERMIAN GONDWANALAND ASSEMBLY

The Phuket and Langkawi regions of Sibumasu may be positioned in proximity to the Canning Basin of Australia (Figure 10). This was demonstrated by Burrett and Stait (1985, 1986) who showed that the Cambrian–Ordovician faunas of Thailand and Malaysia have a very close relationship to those of Australia. The Upper Cambrian trilobite and brachiopod fauna of Tarutau Island are closely similar to those of the Bonaparte Gulf Basin of northwest Australia and the sediments are also amazingly similar. Nautiloid fauna from the dominantly peritidal carbonates of Langkawi are closely similar to those of the Canning, Amadeus and Georgina Basins, suggesting contiguity of these terrains before the supposed Carboniferous rifting of Sibumasu from Australia. Limited conodont and microfossil data suggest that no sedimentation occurred during much of the late Middle and Late Ordovician over most of Sibumasu. This hiatus is evident over the northern half of Australia (Burrett & Stait, 1985). Palaeocurrent data from the limestone sequence in southern Thailand and northern Peninsular Malaysia suggest a source area to the present E and NE.

The elongated Gondwana aulacogens of Peninsular India began their sedimentary history with latest Carboniferous glacial Talchir Boulder Beds (Veevers & Tewari, 1995). The diamictites are predominantly continental, with occasional marine influences in the Som Valley. Diamictites in the Canning Basin of Australia are assigned to the Upper Carboniferous to Lower Permian Grant Group (Towner, 1981). The diamictites overlie glacial striated pavement. Both the Canning and Carnarvon Basins contain a complete range from continental to marine diamictites (van de Graaff, 1981). The distribution of continental and marine tillites, known as Blaini deposits in Pakistan, allows an understanding of why all the pebbly mudstones of Sibumasu are marine (Figure 10).

The Cathaysian affinity continental blocks of North and South China, Tarim, Indochina (including East Malaya) and Qaidam are postulated to have rifted from Gondwanaland in the early Palaeozoic but it is not possible to be specific about their attachment.

PALAEOGEOGRAPHIC RECONSTRUCTIONS OF THE DRIFT PATTERN

Metcalfe (1996) compiled the published palaeo-latitudes of Southeast Asian terranes, based on which Wakita and Metcalfe (2005) constructed realistic palaeogeographic sketches for the drifting of rifted continental terrains across the Tethys (Figure 11). Of course, there is no control on the palaeo-longitudinal terrane positions. The Cathaysian terrains of South China, Simao, Indochina, East Malaya and West Sumatra are shown drifted across the Palaeo-Tethys Ocean far north of Gondwanaland by Early Carboniferous

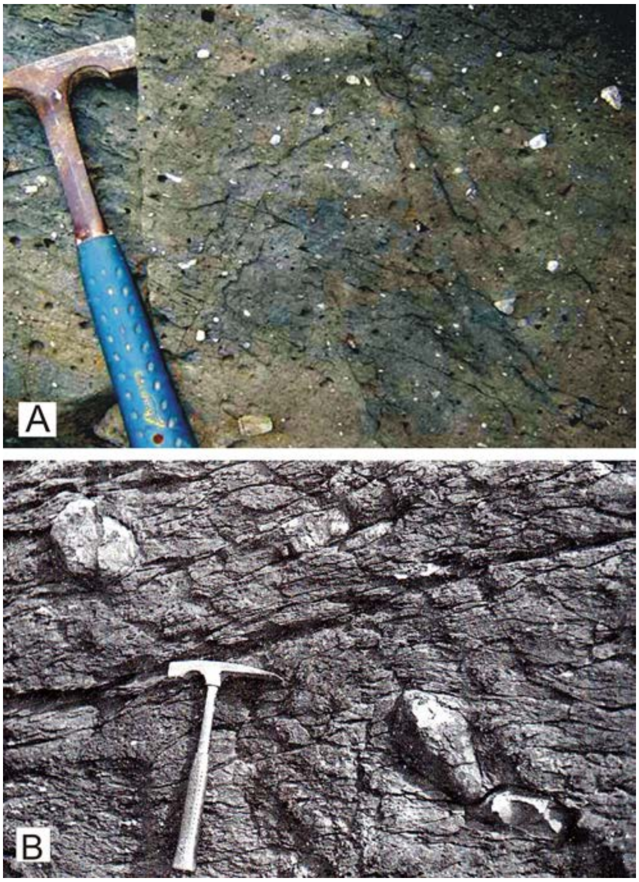

Figure 8: Outcrops of Singa Formation and Phuket Group marine glacial diamictites (pebbly mudstones). A: east coast of Phuket Island (photo M.F. Ridd). B: Pulau Ular, Langkawi (photo C.P. Lee).

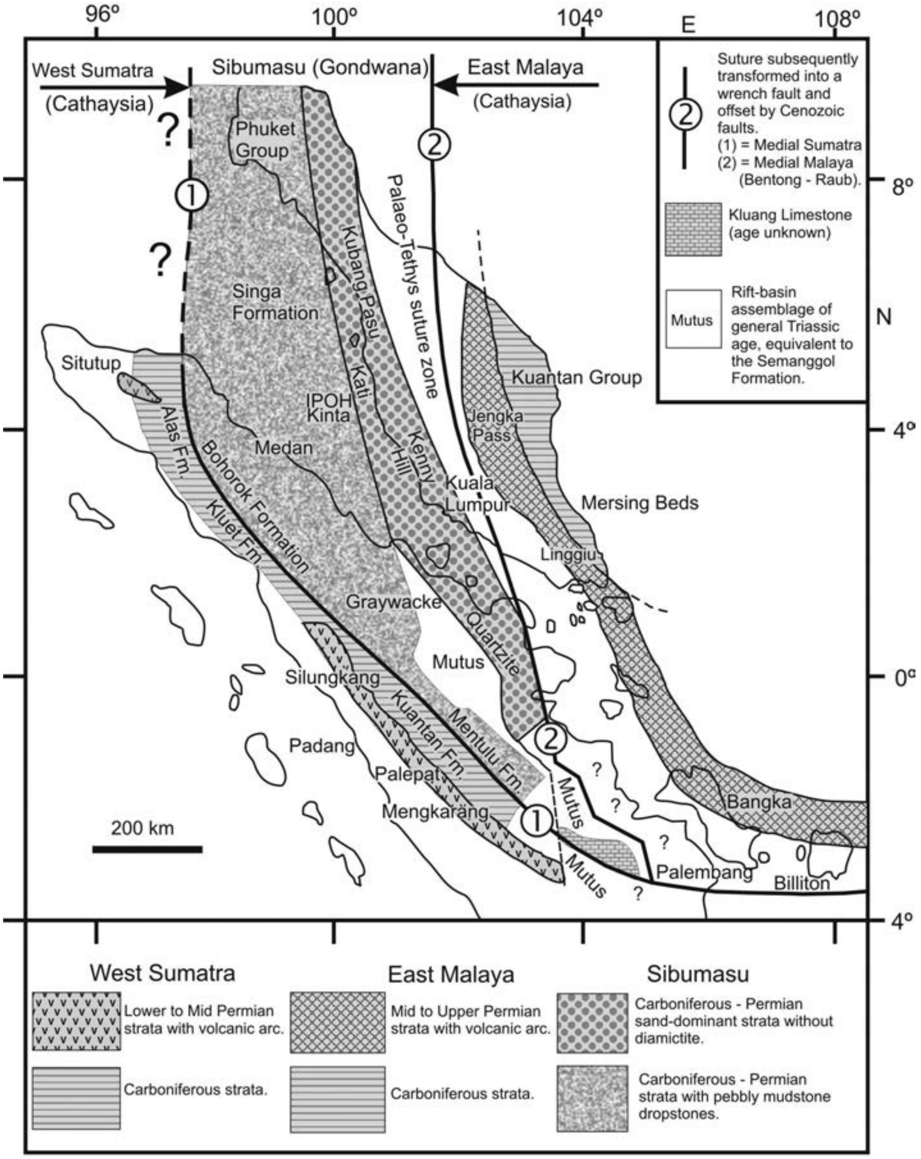

Figure 9: Proposed subdivisions of Peninsular Malaysia and Sumatra into Gondwana and Cathaysia Carboniferous–Permian entities, after Hutchison (1994). The major formations of Sumatra are named 'Greywacke', 'Quartzite', 'Mutus' and Kluang Limestone and are confined to the pre-Cenozoic basement, accessed only by drilling.

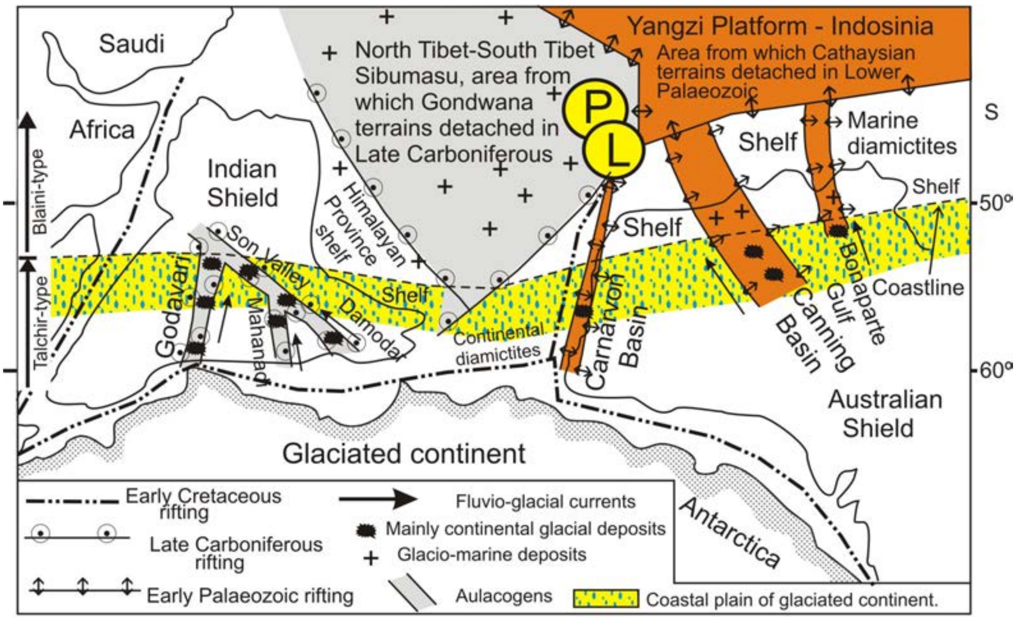

Figure 10: Schematic diagram to illustrate possible northern margin of Gondwanaland in the Late Carboniferous–Early Permian. It shows the distinction between continental fluvio-glacial deposits (Talchir Beds) and marine glacial deposits (Blaini-type) of Tibet and Sibumasu. The aulocogens of India and Australia contain the Talchir Beds. Positions of Phuket (P) and Langkawi (L) are suggested near the Canning Basin because of similar fossils. From Hutchison (1989a).

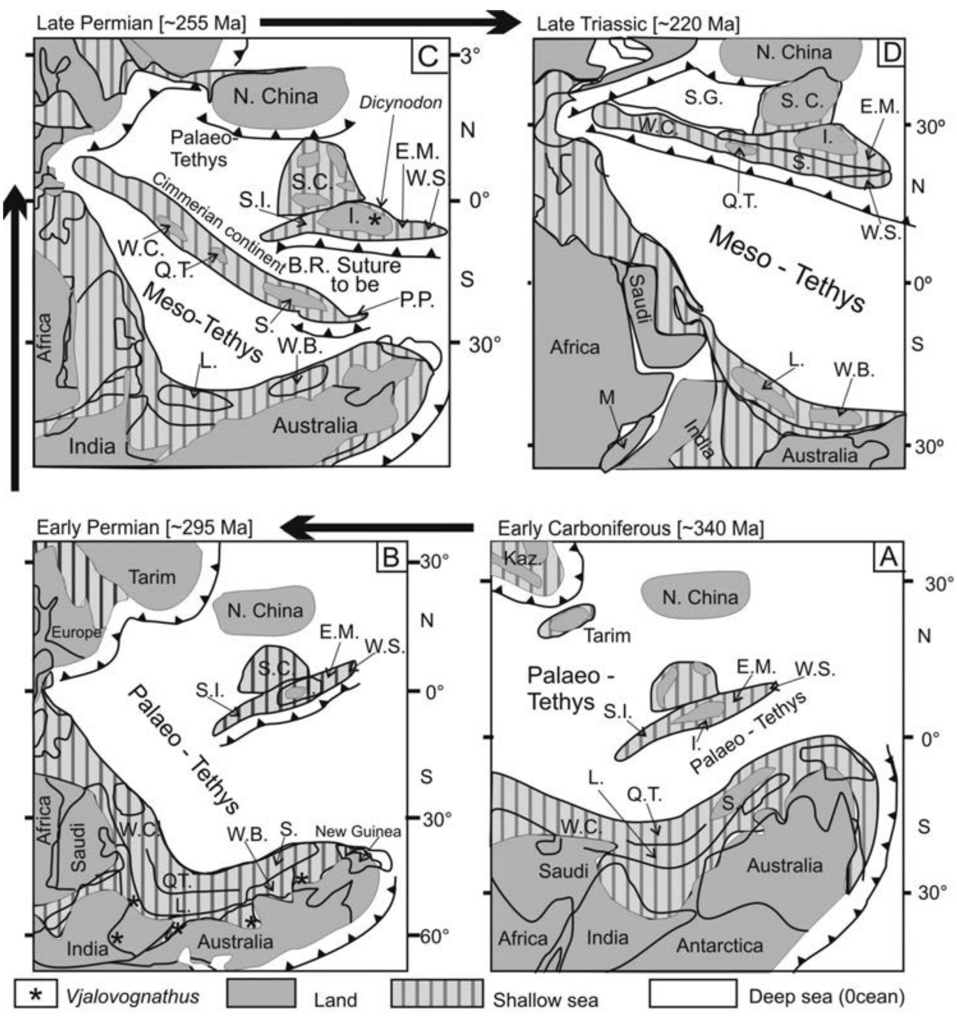

Figure 11: Palaeogeographic reconstructions of the Tethys region showing sketches of the distribution of land and seas for Southeast Asia. The Lower Permian cold-water-tolerant conodont *Vjalovognathus* and the Upper Permian *Dicynodon* localities are shown. B.R. = Bentong–Raub; E.M. = East Malaya; I = Indochina; L = Lhasa; N.C. = North China; P.P. = Peusangan–Pelepat volcanic arc; Q.T. = Qing-Tang; S = Sibumasu; S.C. = South China; S.G. = Song-pan-Ganzi accretionary complex; S.I. = Simao; T = Tarim; W.B. = West Burma; W.C. = West Cimmerian Continent; W.S. = West Sumatra. Diagram based on Wakita and Metcalfe (2005).

time. Indochina and South China had amalgamated along the Song Ma suture. By Early Permian time these amalgamated continental terrains were together known as Cathaysialand upon which the equatorial *Gigantopteris* flora evolved and flourished.

The elongated Cimmerian Continent (Şengör, 1984), consisting of Qiang-Tang and Sibumasu, had rifted from Gondwanaland and began its northwards drift by the Late Permian (Figure 11). By convention, the ocean ahead (north) of it is known as the Palaeo-Tethys, and behind (south) of it is the newly formed Meso-Tethys (Wakita & Metcalfe, 2005). Approach to Cathaysialand was accomplished by northwards subduction, forming the Sukhothai Zone along the margin of the Indochina Block. Sibumasu collided with Cathaysialand in the Triassic to form the Bentong–Raub suture and Cathaysialand amalgamated with North China. The Palaeo-Tethys Ocean was eliminated by formation of the Bentong–Raub suture, resulting in a major mountain-building event, known as the Indosinian Orogeny (Hutchison, 1989), also called the Indochinese Cimmerides by Şengör (1984).

INDOSINIAN OROGENY

A schematic time diagram of the rifting of East Malaya–Indochina and of Sibumasu from Gondwanaland is presented in Figure 12, after Metcalfe (2000). The separation of East Malaya–Indochina from Gondwanaland gave rise to the Palaeo-Tethys Ocean, which was eliminated by Late Triassic time as Sibumasu collided with East Malaya–Indochina, to result in the Bentong–Raub Suture. The Palaeo-Tethys became narrower as it subducted beneath East Malaya–Indochina giving rise to Permo-Triassic volcanic rocks and I-type granites of the Sukhothai Zone (Sone & Metcalfe, 2008b).

The final suturing created crustal thickening resulting in the extensive emplacement of S-type tin-bearing granites, notably as the Main Range, intruding into the suture rocks themselves. The suturing and S-type granite emplacement occurred as an integral part of the mountain building event known as the Indosinian Orogeny.

The polarity for constructing tectonic cross-sections of Peninsular Malaysia is very clearly defined. Permian andesitic volcanic rocks are very abundant on East Malaya. They are interpreted as subduction-related. By contrast they are totally absent from Sibumasu. Therefore the subduction was eastwards beneath East Malaya. The volcanism of East Malaya is characteristically rhyolitic and explosive. The Semantan Basin is characterised by rhyolitic flows and tuffs. The change from Permian andesite to Triassic rhyolite suggests a transition from subduction to collision as the Palaeo-Tethys Ocean was eliminated.

However the polarity in northern Thailand may be the opposite of Peninsular Malaysia, for the main S-type granites all lie west of the Chiang Mai suture. This observation casts doubt on the extrapolation of the Inthanon and Sukhothai zones from Thailand, where they were established, southwards into Peninsular Malaysia. Opposite polarities are perfectly acceptable in plate tectonics by inserting an active transform fault between the terranes of opposite polarity.

The early model of Mitchell (1977), followed by Hutchison (1989a), follows this established polarity of Peninsular Malaysia. The later cross-sections of Metcalfe (2000) were based on these earlier authors, and illustrated here in Figure 13. The Triassic Semantan basin is accordingly interpreted as a fore-arc basin and Barber *et al*. (2005) showed it continuing through Singapore to include the Indonesian islands of Kundur and Lingga (Figure 14).

The Triassic Semanggol rift basin lies on Sibumasu west of the Bentong–Raub Suture (Inthanon Zone) (Figure 14). Barber *et al*. (2005) continued it southwards as the Mutus Basin. During much of its existence it was starved of sediment and is characterised by cherts that have yielded good radiolarian dating extending up to Middle Triassic. Metcalfe (2000) classified the Semanggol-Mutus basin as a foredeep (Figure 13).

LATE CRETACEOUS–PALAEOGENE MIGMATITES AND PLUTONS

Numerous migmatitic complexes occur throughout the region. Some have been appropriately referred to as metamorphic core complexes. Others are simple homogeneous plutons. The metamorphic rocks of the migmatite complexes are of high amphibolites facies. The associated plutonic rocks are both Late Triassic and Late Cretaceous–Palaeocene. The data are often conflicting and their tectonic significance often assigned with insufficient evidence (Searle and Morley, 2011).

Gunung Stong migmatite complex

This migmatite complex forms mountainous country in Kelantan. Excellent outcrops occur in rapids along the Sungai Kenerong and Sungai Semuliang (MacDonald, 1968).

Granitoids

There are three plutonic components (Singh *et al.*, 1984). The earliest two phases (Berangkat Tonalite and Kenerong Leucogranite) are in part highly deformed in a manner similar to that of the marginal country rocks (Figure 15). The third phase, the distinctive pink Noring Granite, is undeformed.

The Berangkat Tonalite, at the southern end, is a megacrystic biotite-hornblende tonalite that locally is highly deformed. It may be of Permo-Triassic age (Cobbing *et al.*, 1992), but no dating has been carried out. The tonalite is cut by the Kenerong leuco-microgranite. It forms a complex network of small intrusives and vein systems emplaced into the predominantly pelitic amphibolite-facies metasedimentary envelope (Figure 16). Three samples define an Upper Cretaceous Rb:Sr age of 79 ± 3 Ma, with an initial ratio of 0.70801 (Cobbing *et al.*, 1992). The pink Noring Granite is an undeformed megacrystic biotite-hornblende granite. The Rb:Sr data define an isochron of 90 ± 30 Ma with an initial ratio of 0.70865. The Noring Granite intrudes the earlier Kenerong Leucogranite. Bignell and Snelling (1977) have reported the following K:Ar ages: 65±2 for muscovite and 70±2 Ma for biotite in the Noring Granite at Batu Melintang, and 69±2 Ma for the Kenerong Leucogranite of the Stong Complex. These dates reinforce the interpretation of a Cretaceous age.

The Kenerong Leucogranite at the Sg. Renyok waterfall consists of a sequence of sub-parallel stretched leucogranite veins and metasedimentary enclaves. Ibrahim Abdullah and Jatmika Setiawan (2003) concluded that the rocks had undergone at least four phases of deformation.

Granitoid-metamorphic rock relationships

The appropriate description is that the Stong is an injection migmatite of great complexity and may be appropriately called a metamorphic core complex. The Stong migmatite complex has many analogues within the Inthanon Zone of Central Thailand (Figure 16). The three main types of migmatite are agmatite, venite and nebulite. The granitoid layers have been deformed into boudins (Figure 17) as well as ptygmatic folds. Since two of the granitoids have been dated Cretaceous, it follows that metamorphic folding was also Cretaceous, but some of the metamorphism may have been Triassic, associated with the Indosinian Orogeny, with reactivation in the Late Cretaceous.

Metamorphic paragenesis

The metamorphic rocks of the enclaves within the granitoids comprise meta-pelites, impure meta-arenites, impure to pure marble, and amphibolites in the southern part of the complex (Singh *et al.*, 1984). The common rock types are: finely banded hornblende-quartz schist, staurolite-garnet-biotite schist, fine-grained biotite-muscovite schist, diopside-phlogopite marble and sillimanite-garnet-biotite gneiss. The grade achieved was amphibolite facies, high enough to have caused anatexis (Hutchison, 2009). Radiometric dating has been carried out only of two granitoids, but a comprehensive study needs to be made of the ages of the metamorphic minerals before the metamorphic core complexes can be understood.

Regional distribution

The major occurrence of core-complex migmatites and associated granites is in the Central Belt of Northern Thailand (Figure 17). Cobbing *et al.* (1992) rightly drew attention to the similarity with the Stong Complex of northern Peninsular Malaysia. However, in relation to the sutures, the polarity of Thailand is the opposite of that in Peninsular Malaysia (Figure 17). The migmatite complexes form a belt lying to

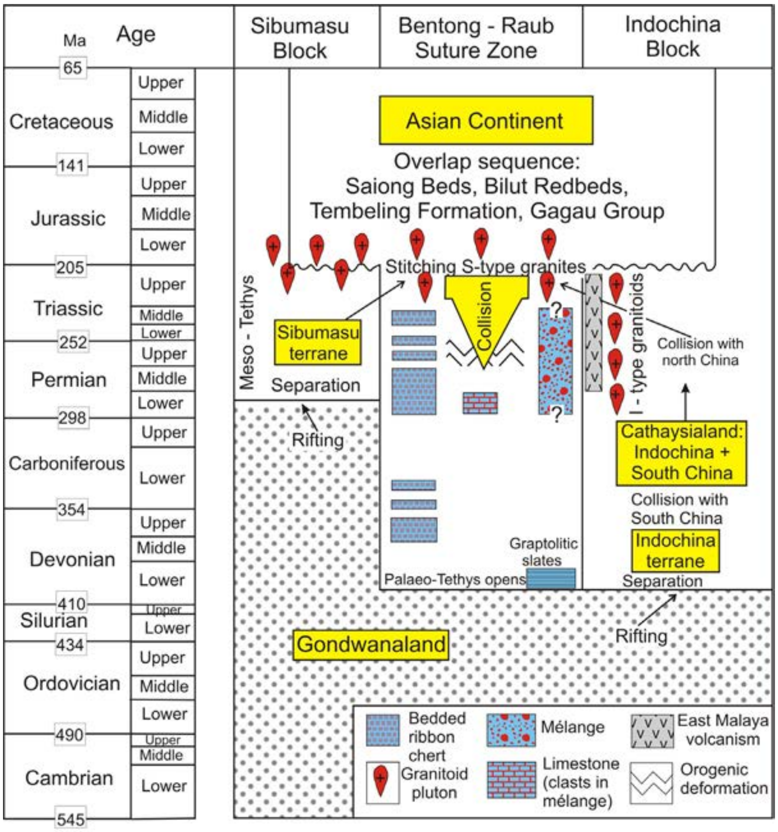

Figure 12: Timing of rifting and collision of the Sibumasu and Indochina teranes and opening and closure of the Palaeo-Tethys Ocean (based on Metcalfe, 2000).

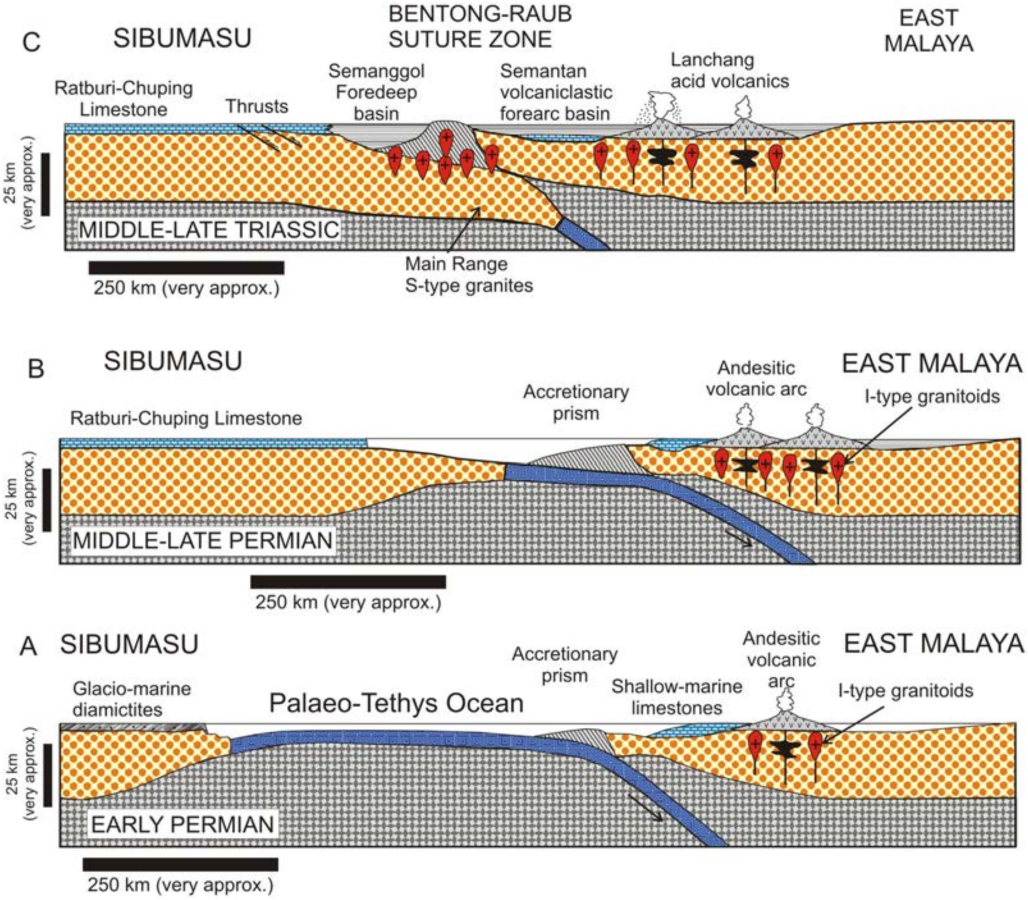

Figure 13: Conceptual cross-sections illustrating formation of the Bentong–Raub Suture by subduction of the Palaeo-Tethys Ocean and collision of Sibumasu with the East Malaya (Indochina) terrane during the Indosinian Orogeny. Modified after Metcalfe (2000).

the west of the Nan-Uttaradit and Chiang Mai sutures, within what is known as the Inthanon zone (Figure 17), whereas the Stong Complex and related Central Belt granitoids lie east of the Bentong-Raub Line. The difference in polarity of the granites with respect to the sutures has already been noted by Hutchison (1977, 1983). The polarity differences have been overlooked by subsequent workers (Figure 3).

The zones of migmatite (Figure 17) are intimately associated with Late Triassic as well as Late Cretaceous granites. The former suggest a genetic relationship to the Indosinian Orogeny; the latter suggest a considerably later reactivation of the migmatite zones. In many cases the Late Cretaceous plutons are of homogeneous pink granite devoid of migmatization, and they are found as far south as Gunong Ledang (Mount Ophir) and Gunung Pulai. Richter *et al.* (1999) concluded that the palaeomagnetism measured in Late Triassic and older Peninsular Malaysian rocks may actually represent a Middle Cretaceous to Paleogene remagnetization caused by an important heat event of that time. This was the important heat event found in the migmatite zone of Figure 17. Could this heat event also have reset radiometric dates, making the Inthanon Zone difficult to analyse?

The Late Cretaceous-Palaeogene S-type granites of the migmatite belt of Thailand had been explained as formed due to collision of the West Burma Block with the Shan Plateau area (Sibumasu) in the Late Cretaceous-Palaeogene (Hutchison 1996; Morley 2004). However U-Pb zircon dating of the Jade Mines Belt of Myanmar gave a radiometric age of Middle Jurassic (Guanghai *et al.*, 2008) and no longer supports an Eocene age for the suture. The West Burma Block has been correlated with the West Sumatran Block of Sumatra, emplaced onto the west side of the Sibumasu during the Triassic (Barber & Crow, 2009). The tectonic cause of the important Late Cretaceous event therefore remains obscure. Apparent understanding of the tectonic evolution often results from poorly supported models that should not have been proposed and later accepted.

OTHER LATE-CRETACEOUS–PALAEOCENE PLUTONIC ARCS

In addition to the association with the magmatic belts, there are two other regionally important occurrences of plutonism of this age (Figure 18). A notable arc extends from western Myanmar through western Thailand as far as Phuket. It appears to extend eastwards as far as Yod Nam, where Ishihara *et al.* (1980) reported a K:Ar age of 67.8±2 Ma for extracted muscovite. The western belt may extend into northern Peninsular Malaysia (Figure 18). The Gunung Raya batholith of Langkawi Island is unlike the Main Range of Peninsular Malaysia. It is an epizonal

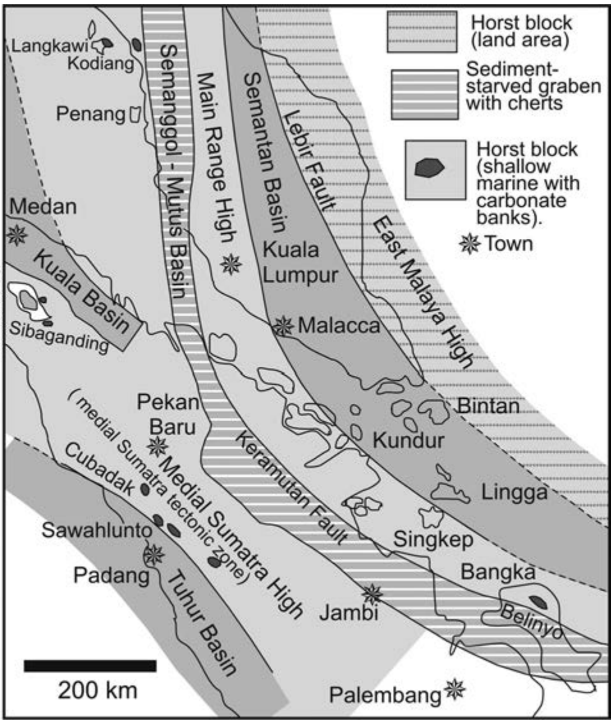

Figure 14: Palaeogeographic map of Sumatra and the Malay Peninsula for the Middle to Late Triassic. Redrawn from Barber *et al.* (2005a).

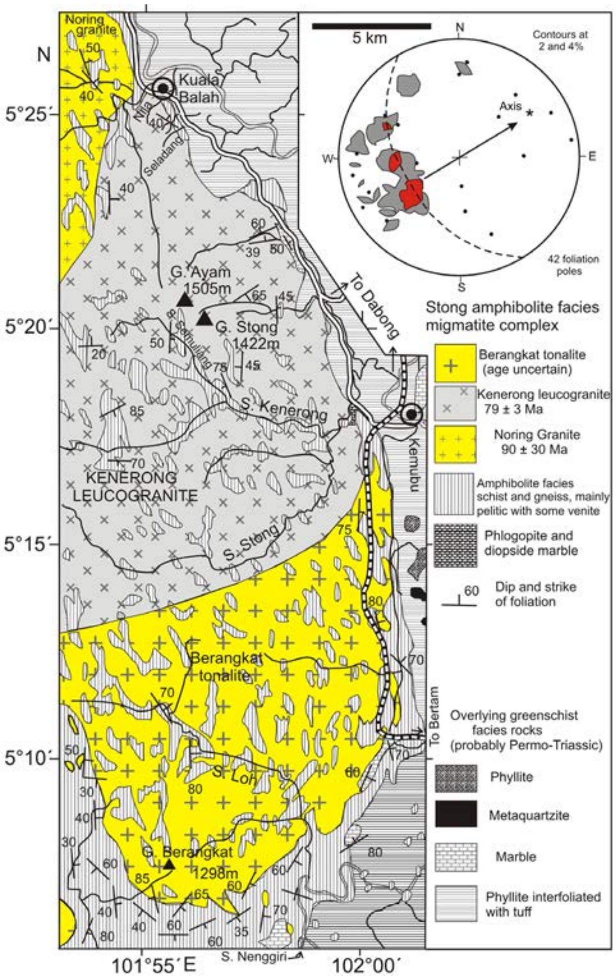

Figure 15: Geological map of the Gunung Stong migmatite complex, Kelantan, after Dawson *et al*. (1968). Lower hemisphere equal-area stereogram of foliations. Granitoids from Singh et al. (1984), radiometric dates from Cobbing *et al*. (1992). Sungai Renyok, where a smaller body of Kenerong Leucogranite borders the Noring Granite along its eastern margin, is ~17 km along the road north of Kuala Balah.

pluton around which the country rocks are domed and contain andalusite in a thermal aureole (Hutchison, 1977). Biotite from the granite has been K:Ar dated 79.1±0.8 Ma and 82±2 Ma (Bignell and Snelling, 1977). Farther south, onland Kedah, the Gunung Jerai granite has similarly domed up and metamorphosed the country rocks and K:Ar ages of 47±2 for biotite and 134±6 Ma for muscovite have been obtained (Bignell and Snelling, 1977). This belt cannot be traced farther southwards, but needs more study and dating.

The great oroclines were important to the early Dutch geologists in their regional synthesis of Southeast Asia and Figure 18 shows the Anambas Zone that Van Bemmelen (1949) emphasised. The oroclinal arcs are prominently seen on SEASAT imagery and are abruptly terminated by the Penyu and West Natuna Basins. An integral component of the oroclines is the Late Triassic granites of Peninsular Malaysia continuing in a curve through Bangka and Billiton with no continuity into Borneo. To the east lie other arcs of Late Cretaceous–Palaeocene granites that continue into Borneo, whose ages have been tabulated by Hutchison (2005). Granite from Tambelan gave a K:Ar biotite date of 84±2 Ma (Bignell, 1972), closely similar to Tioman. The structural oroclines of Figure 5 continue from Sumatra and Peninsular Malaysia into Borneo. They have largely been ignored since the model of escape tectonics emphasised only the major faults of the region. However, Hutchison (1994) gave more attention to the orocline structures in the process of escape tectonics.

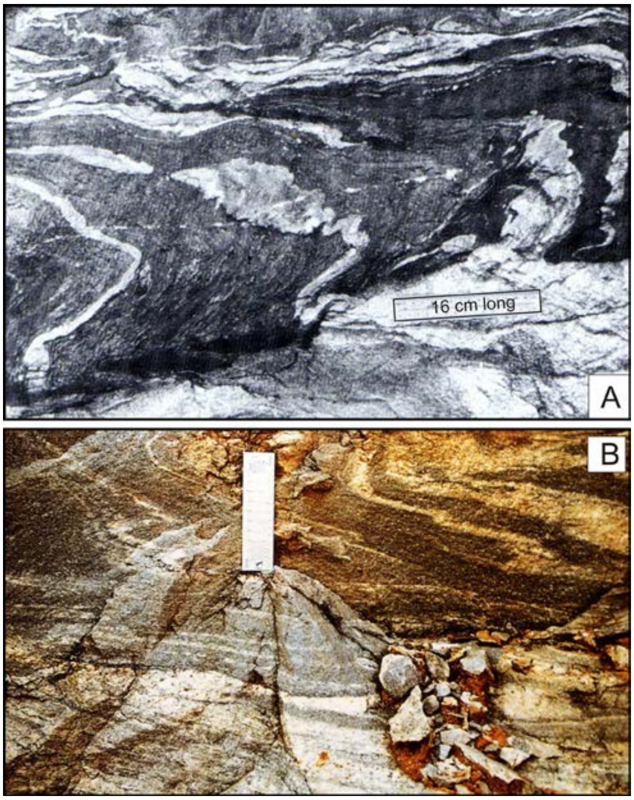

Figure 16: A: Veinlets from the margin of a thick body of Kenerong Leucogranite infolded with the host semi-pelitic schist, Sungai Renyok, Stong migmatite complex, Kelantan (from MacDonald, 1968). B: Folded and banded granite gneiss of the South Samoeng migmatite core complex, north central Thailand (from Cobbing *et al*., 1992).

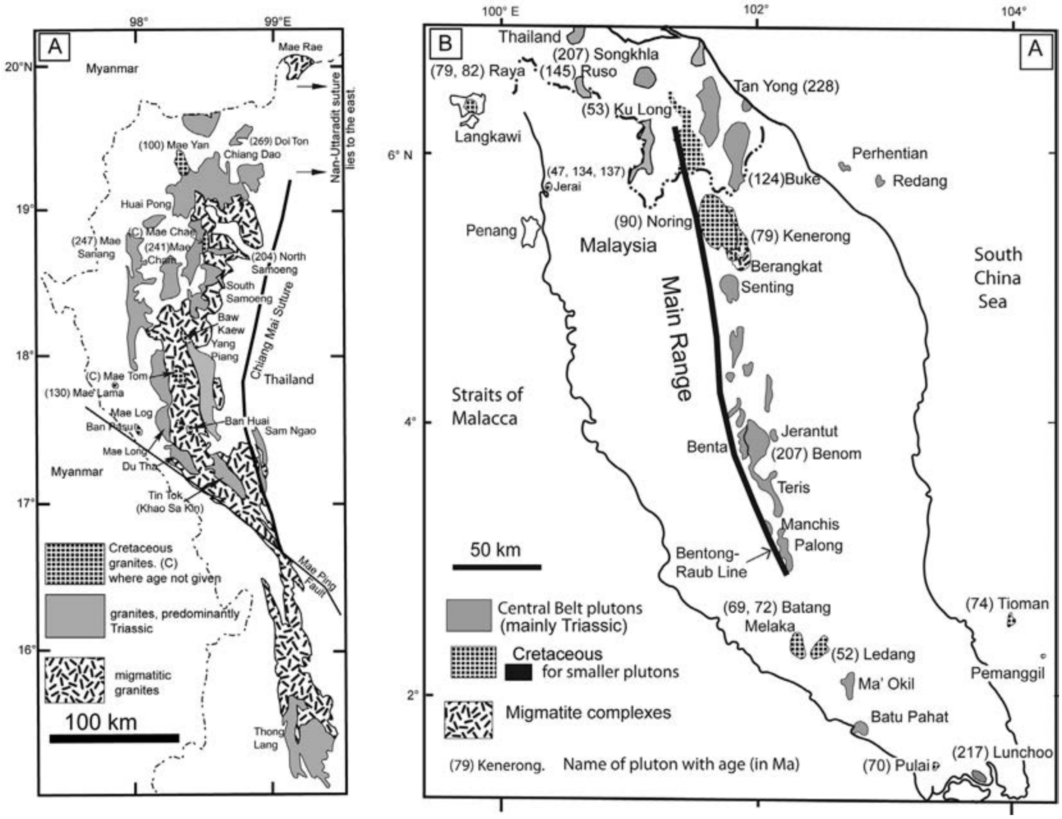

Figure 17: Metamorphic core complexes, associated with both Triassic and Cretaceous granitic plutons. A: North Thailand, Central Belt; B: Central Belt of Peninsular Malaysia. Redrawn and after Cobbing *et al.* (1992). The migmatite belt, or Inthanon Zone, is now regarded as the Chiang Mai suture zone.

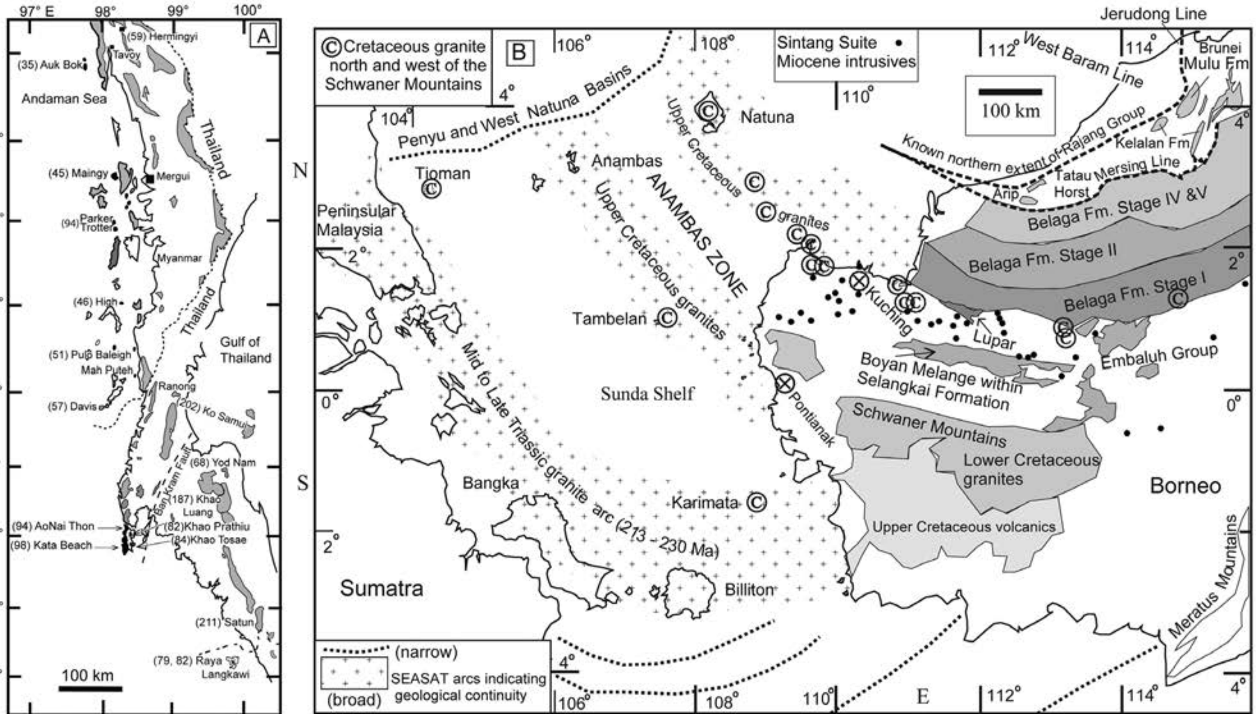

Figure 18: Arcs of Late Cretaceous-Palaeocene granite plutons. A: Western zone of Myanmar and Phuket, Thailand, modified after Cobbing *et al*. (1992). The Anambas Zone and other Late Cretaceous-Palaeocene granite oroclines to which the Peninsular Malaysian island of Tioman may belong. Based on Hutchison (2005).

TERTIARY EXTRUSION TECTONICS AND OROCLINAL BENDING

The prominent node in regional structures at the Assam-Yunnan syntaxis represents the region of maximum indentation of India into Eurasia (Figure 15). The Palaeo-Tethyan formations are bent around the syntaxis from an approximately E–W trend in Tibet to a N–S trend in peninsular Southeast Asia. The region of syntaxis is also unique in its richness in gemstones within the Mogok Gneiss and in the famous jade deposits (Hutchison, 1989a). Mogok metamorphism is now known to be mainly of Early Tertiary age from recent U-Pb dating (Searle *et al*. 2007). Zircon and monazite U-Th-Pb dating has revealed at least two metamorphic events, a Late Cretaceous (?)- Palaeocene event that ended with intrusion of cross-cutting post-kinematic biotite granite dykes at ~59 Ma, and a second event spanning at least from 47 Ma to 29 Ma (Searle *et al*. 2007).

Refined estimates of the relative positions of India and Asia (Aitchison *et al.*, 2007) indicate that they were not close enough to one another to have collided at 55 Ma. On the basis of new field evidence from Tibet and a reassessment of published data, they suggest that continent-continent collision began around the Eocene/Oligocene boundary (34 Ma).

Tapponnier *et al*. (1982) devised an innovative yet deceptively simple laboratory experiment in which a rigid wooden block, representing cratonic India, was slowly driven horizontally into an array of vertically banded plasticene, representing the Eurasian margin (Figure 19). The eastern margin was not fixed to the containing box, because the continental crust towards the east remained free to form active plate margins with the oceanic lithosphere of the Pacific Ocean. The experiment resulted in a newly-coined term ‘extrusion tectonics’ for Southeast Asia. Tapponnier *et al*. (1982) emphasised the major regional faults, such as the Red River Fault, that emanate from the Yunnan syntaxis. Later, Hutchison (1994) proposed that extrusion tectonics not only results in faults, but also in oroclinal bending (Figure 20).

Results of oroclinal Bending

The Sundaland orocline, extending from Tibet (E–W), through the Malay Peninsula (N–S) to Billiton and Borneo (E–W). The whole orocline is Z shaped (Figures 18, 19 & 20). Analysis of the northern part is of necessity different from the southern part.

The bending of northern Sundaland from an E–W fabric in the north to N–S in northern Peninsular Malaysia, resulting from the indentation of India, would result in right-lateral wrench faults, because it assumed its present orientation as a result of a clockwise rotation (Figure 20). This is illustrated and discussed in reference to Figure 20. The dominance of wrench faulting has resulted in a complicated river system characterised by sharp bends in their courses and river capture (Hutchison, 1989a). The clockwise rotation and right-lateral faulting are expected to have resulted in transtensional and transpressional tectonics resulting in, for example, formation of Tembeling Formation transverse ranges (Hutchison, 1994).

By contrast, the oroclinal bending of the ‘tin islands’, Anambas Zone, extending into Borneo (Figure 18) has a different curvature from northern Sundaland. This curvature is required to have resulted from anti-clockwise rotation and any accompanying faults (few are analysed and described) should be left-lateral. The cause of this oroclinal bending cannot be the Indian collision, but rather the ongoing collision of Australia into the Timor region of Indonesia.

SUPPORT FROM PALAEOMAGNETIC RESEARCH

Thailand

Palaeomagnetic research on Southeast Asia has generally supported the extrusion tectonic model. Charusiri *et al.* (2006) have shown, by a programme of palaeomagnetic measurements, that there has been a 20–25° clockwise rotation of the Khorat plateau part of the Indochina block since Late Cretaceous to Early Neogene and they realistically attributed it to the collision of India.

Peninsular Malaysia

The abundant occurrences of Triassic and Late Cretaceous-Palaeocene granites have resulted in remagnetisation of older rocks, making interpretation of palaeomagnetic data unreliable (Richter and Fuller, 1996). Clockwise declinations have been measured in Late Triassic granites, Permian to Triassic volcanics, and remagnetized Paleozoic carbonates. The age of this magnetization is poorly understood and may be as old as Late Triassic, or as young as Middle or Late Cretaceous.

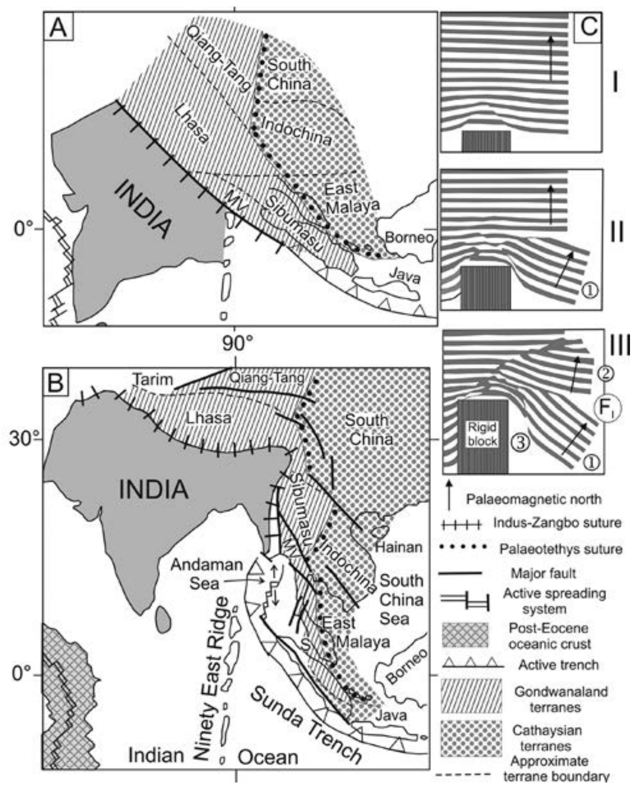

Figure 19: Indentation of India into Southeast Asia. (A) Inferred palaeogeography at 45 Ma (anomaly 20) about 10 Ma after the initial collision, by which time India was rotated into flush orientation with the Eurasian margin. (B) Present-day geography showing maximum indentation into the Yunnan syntaxis and spreading from the Southeast Indian Ocean Ridge (after Hutchison, 1993). MV = Mount Victoria Land. S = Sibumasu. (C) Three successive stages of an indentation experiment on banded plasticene (plan view). 1 is taken as the Indochina-Southeast Asia block, 2 as South China. F1 is taken as the Red River Fault, 3 as the Andaman Sea (after Tapponnier *et al*., 1982).

The Middle Cretaceous to Palaeogene paleomagnetic data for the Peninsula are indistinguishable from the Late Eocene and Oligocene measurements from Borneo and Sulawesi. The similarity in anticlockwise rotations over such a large region suggests that regional block motions have been preserved and show that much of southern Sundaland rotated approximately 30° to 40° anticlockwise relative to the Geocentric Axial Dipole between the Eocene and the Oligocene. These regional anticlockwise rotations are not consistent with simple extrusion based tectonic models. However, they are consistent with anticlockwise oroclinal bending resulting from ongoing collision at the Timor area of Indonesia.

Borneo

Fuller *et al.* (1999) summarised the palaeomagnetic data on Borneo and favoured an essentially rigid plate model with much of Kalimantan, Sarawak and southern Sabah participating in a rotation of about 50° anticlockwise between 30 and 10 Ma, and in an earlier rotation of about 40° sometime between 80 and 30 Ma. The underlying cause of these rotations is convergence between the Australian Plate and Eurasia with collision between the Australian plate and the Indonesian arc at Timor.

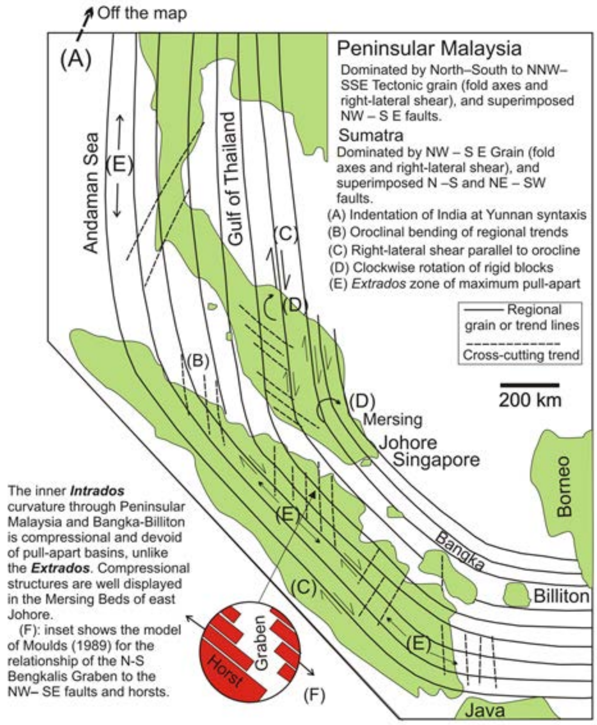

Figure 20: Schematic plan for oroclinal bending resulting from the strong Indian indentation into the Assam-Yunnan syntaxis, from Hutchison (1994). The regional lines are trends of fold axes and strike lines of Triassic strata.

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