Tectonic evolution of Sundaland

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Abstract: Sundaland, the continental core of SE Asia, is a heterogeneous collage of continental blocks and volcanic arcs bounded by narrow suture zones that represent the remnants of ancient ocean basins. All the continental blocks of Sundaland were derived directly or indirectly from the Arabia-India–Australia margin of eastern Gondwana by the opening and closure of three successive ocean basins, the Palaeo-Tethys (Devonian-Triassic), Meso-Tethys (Permian-Cretaceous) and Ceno-Tethys (Jurassic-Cretaceous), and assembled by the closure of these ocean basins. Core Sundaland comprises a western Sibumasu block and an eastern Indochina–East Malaya block with an island arc terrane, the Sukhothai Island Arc, sandwiched between. The Palaeo-Tethys is represented by the Changning–Menglian, Chiang Mai-Chiang Rai, Chanthaburi and Bentong–Raub Suture Zones that form the boundary between Sibumasu and the Sukhothai Arc. The Indochina block was derived from Gondwana in the Devonian when the Palaeo-Tethys opened. The Sukhothai Arc formed on the margin of Indochina in the Carboniferous, and then separated by back-arc spreading in the Permian. The Jinghong, Nan–Uttaradit and Sra Kaeo Sutures represent this closed back-arc basin. The Sibumasu Terrane separated from Gondwana in the late Early Permian when the Meso-Tethys opened and collided with the Sukhothai Arc and Indochina in the Middle-Late Triassic. The Cathaysian West Sumatra block possibly represents a part of the Sukhothai Arc and was emplaced by strike-slip tectonics outboard of Sibumasu in the Triassic. The West Burma Block was already attached to Sundaland before the Late Triassic and is likely a disrupted part of Sibumasu. East Java-West Sulawesi and South West Borneo are tentatively identified as the missing "Argoland" and "Banda" blocks which must have separated from NW Australia in the Jurassic and subsequently accreted to SE Sundaland in the Cretaceous.

Keywords: Sundaland, SE Asia, tectonics, Gondwana, Tethys, palaeogeography

INTRODUCTION

Sundaland (Molengraaff, 1921) is a biogeographic region that comprises the Malay Peninsula, Sumatra, Java, Borneo and Palawan together with areas of shallow-water on the Sunda Shelf that were exposed as land during low sea level stands in the Pleistocene (Bird *et al*., 2005). The region is a globally significant biodiversity hotspot (Myers *et al.*, 2000; de Bruyn *et al.*, 2014) that occurs northwest of the Wallace Line biogeographic boundary and adjacent to the zone of collision between Australia and Asia (Metcalfe *et al*., 2001). In modern geological plate tectonic terms, Sundaland (the Sundaland Block) forms the SE promontory of the Eurasian Plate and includes Myanmar, Thailand, Indochina (Laos, Cambodia, Vietnam), Peninsular Malaysia, Sumatra, Java, Borneo and the Sunda Shelf, and is located at the zone of convergence between the Indian–Australian, Philippine and Eurasian Plates (Simons *et al*., 2007; Figure 1). East and SE Asia (including Sundaland) comprises a heterogeneous collage of continental crustal blocks, volcanic arcs, and suture zones that represent the closed remnants of ocean basins and back-arc basins (Figure 2). The continental blocks of the region were derived, at different times, from the Indo-Australian margin of eastern Gondwana and assembled during the Late Palaeozoic to Cenozoic (Metcalfe, 2011a, 2011b, 2013a). This paper focuses on the Sundaland core of SE Asia which is bounded to the west, south and east by subduction and collision zones and to the north by major shear zones along the Red River and Song Ma suture zone (Figures 1 and 2).

Sundaland was constructed essentially in its present configuration in the Triassic by amalgamation of continental blocks during the Indosinian Orogeny with additional material being accreted during the later Mesozoic (Metcalfe, 1988, 1990, 1996a, 1996b, 1998, 1999, 2000, 2006, 2011a, 2011b, 2013a; Hall, 1996, 2002, 2012, 2013; Wakita & Metcalfe, 2005; Sone & Metcalfe, 2008) and has been largely emergent or only submerged to very shallow depths since the early Mesozoic. Sundaland and the surrounding region includes many economically important hydrocarbon-bearing Cenozoic basins developed by varied tectonic processes including subduction-related deformation, arc–continent and continent–continent collision, and intra-continental strike-slip deformation (Hall & Morley, 2004; Morley, 2012; Pubellier & Morley, 2014).

This paper presents the Phanerozoic tectonic framework, and tectonic and palaeogeographic evolution of Sundaland within the wider framework and geological evolution of East and SE Asia.

TECTONIC FRAMEWORK OF SUNDALAND

The continental core of Sundaland comprises the Sibumasu Terrane, the Sukhothai Arc, the Indochina Block, the West Sumatra Block, the West Burma Block, the SW Borneo Block and the Semitau Block (Figures 2 and 3). The South China Block is located to the northeast of Sundaland, and India to the northwest. A major Late Palaeozoic palaeobiogeographic divide is recognised between the Sibumasu Terrane, derived from the Australian

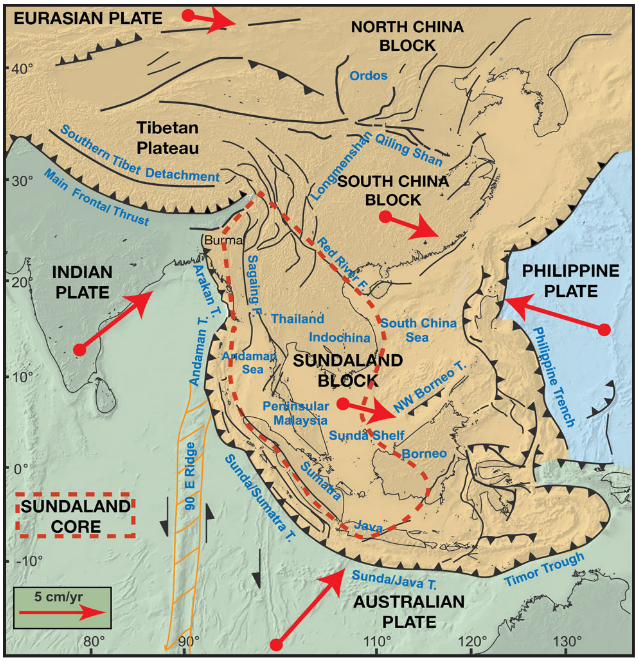

Figure 1: Topography and main active faults in East Asia and location of the Sundaland Block and Sundaland Core in SE Asia at the zone of convergence of the Eurasian (pale orange), Philippine (pale blue) and Indian–Australian plates (pale green). Large arrows represent absolute motions of plates (after Simons *et al.*, 2007; Metcalfe, 2011a, 2013a).

margin of eastern Gondwana in the late early Permian, and the Sukhothai Arc and Indochina Block that were located in the northern hemisphere Cathaysian biogeographic province in the late Palaeozoic. This palaeobiogeographic divide is marked in Sundaland by the Changning-Menglian, Chiang Mai-Chiang Rai, Chanthaburi, and Bentong-Raub suture zones that represent the remnants of the ancient Palaeo-Tethys ocean basin that existed from the Devonian to the Triassic (Metcalfe, 2013a; Figure 3).

Other continental fragments, including the Gondwana-derived East Java-West Sulawesi Terrane, were added to the Sundaland core during the Late Cretaceous-Cenozoic.

Continental blocks of Sundaland and their origins

The various continental blocks and fragments that comprise Sundaland, and suture zones that represent the remnants of former ocean basins that separated them are shown in Figure 3. Only the continental blocks comprising Sundaland will be discussed here in detail. For descriptions of other continental blocks of East and SE Asia see Metcalfe (2013a).

Sibumasu Terrane

The Sibumasu terrane was defined by Metcalfe (1984) as including the "Shan States of Burma, Northwest Thailand, Peninsular Burma and Thailand, western Malaya and

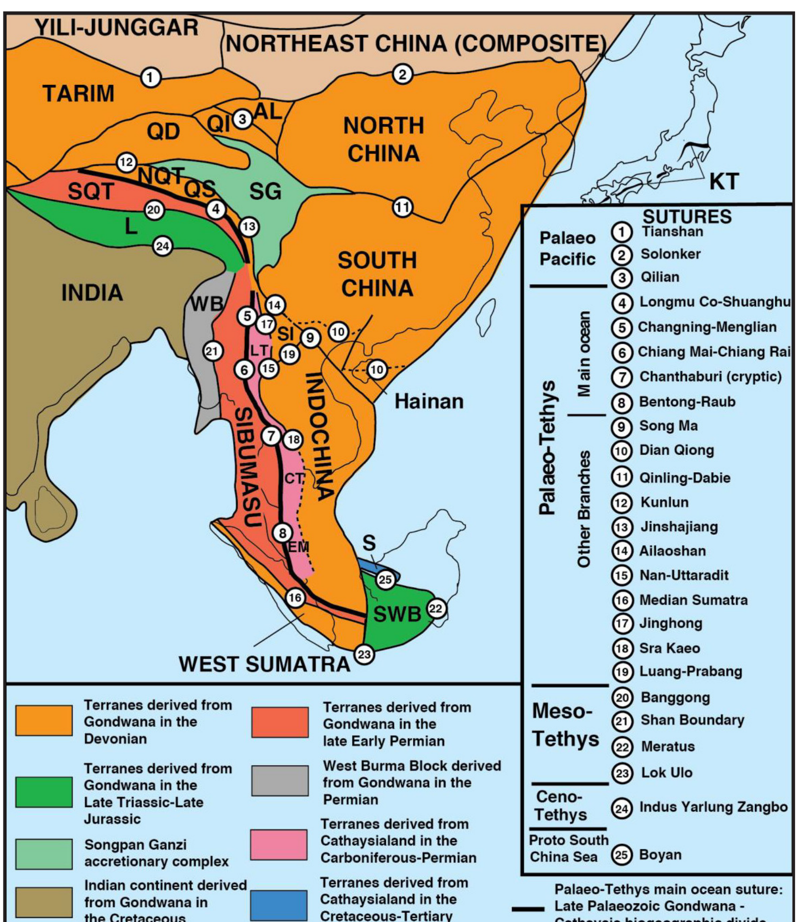

Figure 2: Distribution of principal continental blocks, arc terranes and sutures of eastern Asia. WB = West Burma, SWB = South West Borneo, S = Semitau, L = Lhasa, SQT = South Qiangtang, NQT = North Qiangtang, QS = Qamdo–Simao, SI = Simao, SG = Songpan Ganzi accretionary complex, QD = Qaidam, QI = Qilian, AL = Ala Shan, KT = Kurosegawa Terrane, LT = Lincang arc Terrane, CT = Chanthaburi arc Terrane, EM = East Malaya. After Metcalfe (2011a, 2011b, 2013a).

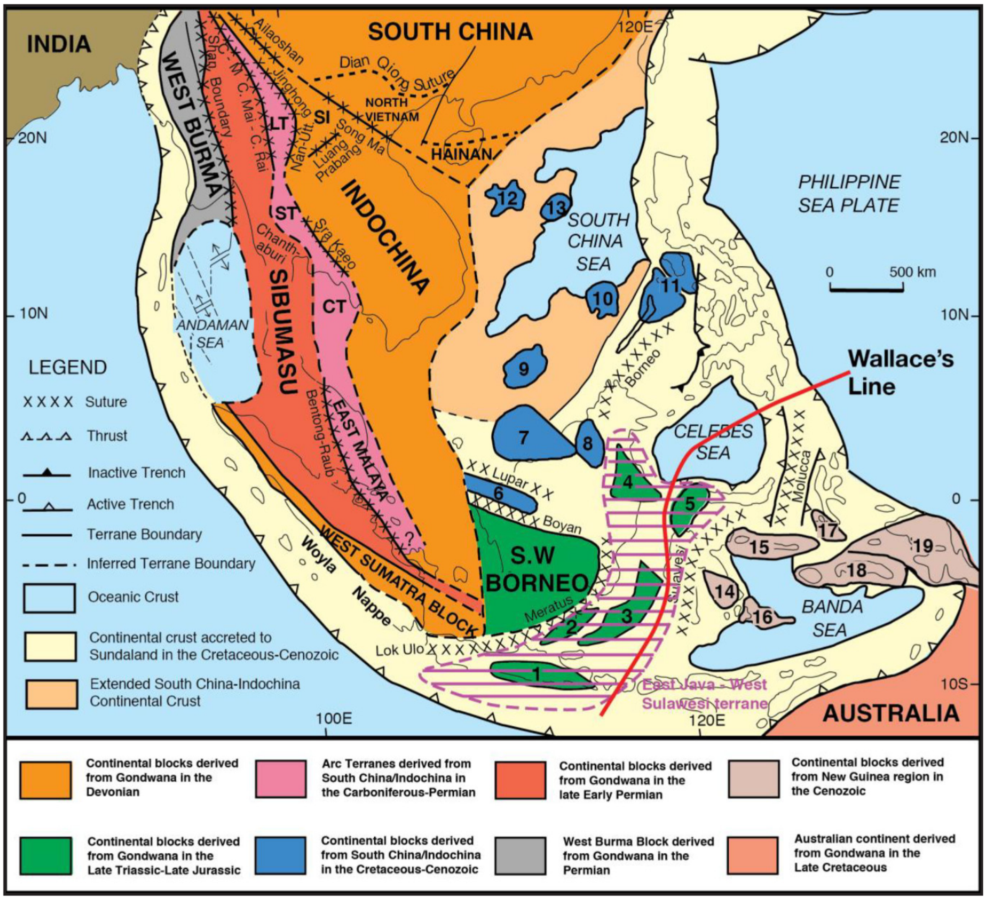

Figure 3: Distribution of continental blocks, fragments and terranes, and principal sutures of Sundaland and Southeast Asia. Numbered micro-continental blocks, 1. East Java 2. Bawean 3. Paternoster 4. Mangkalihat 5. West Sulawesi 6. Semitau 7. Luconia 8. Kelabit–Longbowan 9. Spratly Islands–Dangerous Ground 10. Reed Bank 11. North Palawan 12. Paracel Islands 13. Macclesfield Bank 14. East Sulawesi 15. Banggai–Sula 16. Buton 17. Obi–Bacan 18. Buru–Seram 19. West Irian Jaya. LT = Lincang Terrane, ST = Sukhothai Terrane and CT = Chanthaburi Terrane. C–M = Changning–Menglian Suture, C.-Mai-C. Rai = Chiang Mai-Chiang Rai Suture, and Nan–Utt. = Nan–Uttaradit Suture.

Sumatra'' and possibly extending northwards into western China and Tibet. The name SIBUMASU was an acronym derived by combining SI (Sino, Siam), BU (Burma), MA (Malaya) and SU (Sumatra). The recent suggestion by Ridd (2016) that Sibumasu (as defined by Metcalfe, 1984) comprises a western "Irrawaddy Block" and an eastern "Sibuma" block bounded by a cryptic Cretaceous suture zone is not accepted here. Ridd (2016) proposed the re-naming of Sibumasu as "Sibuma" but this is not a mere semantic change but one based on excluding Ridd's proposed "Irrawaddy Block" from Sibumasu. Interpretation of differences in the thickness and nature of glacial-marine deposits of Sibumasu to justify a separate "Irrawadi Block" by Ridd (2016) is poorly founded, and in fact was regarded as "tentative" by Ridd himself. The "Irrawadi Block" of Ridd (2016) is essentially the same as the "Karen–Tenasserim block" of Bender (1983) and Mitchell *et al*. (2004), the "Mergui Group Nappe" of Mitchell (1992), the "Phuket Terrane" of Ridd (2009) and the "Phuket-Slate Belt terrane" of Ridd & Watkins (2013). I regard Ridd's own interpretation (Ridd, 2009) of the deposition of varied thickness and nature of Upper Carboniferous-Lower Permian glacial-marine deposits on Sibumasu as the most plausible. There is no substantive evidence for a Cretaceous suture zone between the "Irrawaddy Block" and the "Sibuma Block" of Ridd (2016) or evidence of a Cretaceous collision between these. In this paper, the Sibumasu Terrane of Metcalfe (1984) is retained and used.

The west and south-western boundary of the Sibumasu Terrane is formed by the Mogok Metamorphic Belt, the Andaman Sea, and the Medial Sumatra Tectonic zone (Barber & Crow, 2009). The eastern and north-eastern boundary of Sibumasu is formed by sutures that represent the main Palaeo-Tethys ocean. These Palaeo-Tethyan sutures are, from north to south, the Changning– Menglian suture in SW China, the Chiang Mai–Chiang Rai (re-named in Metcalfe *et al*., 2017) and Chanthaburi sutures in Thailand and the Bentong–Raub Suture in the Malay Peninsula (Figures 2 and 3). The Sibumasu Terrane is the eastern part of the Cimmerian continent of Sengör (1984) and is here regarded as including the Baoshan and Tengchong blocks of western China and extending to the South Qiangtang Block of Tibet.

The Sibumasu Terrane has a Proterozoic (with possible minor Neoarchaean) basement. This is indicated by Nd–Sr and U–Pb zircon dating of Permian–Triassic granitoids in the Malay Peninsula (Liew & McCulloch, 1985) suggesting that the crust beneath the Sibumasu Block is 1500–1700 Ma old. More recent detrital zircon studies in the Malay Peninsula (Sevastjanova *et al*., 2011; Hall & Sevastjanova, 2012) indicate that the basement of the Sibumasu Block can be dated as primarily Palaeoproterozoic, around 1.9–2.0 Ga. There are also probable minor Mesoproterozoic (1.6 Ga) and Neoarchaean (3.0–2.8 Ga) components.

The basement of Sibumasu is overlain by middle Cambrian to Early Ordovician clastic sedimentary rocks of

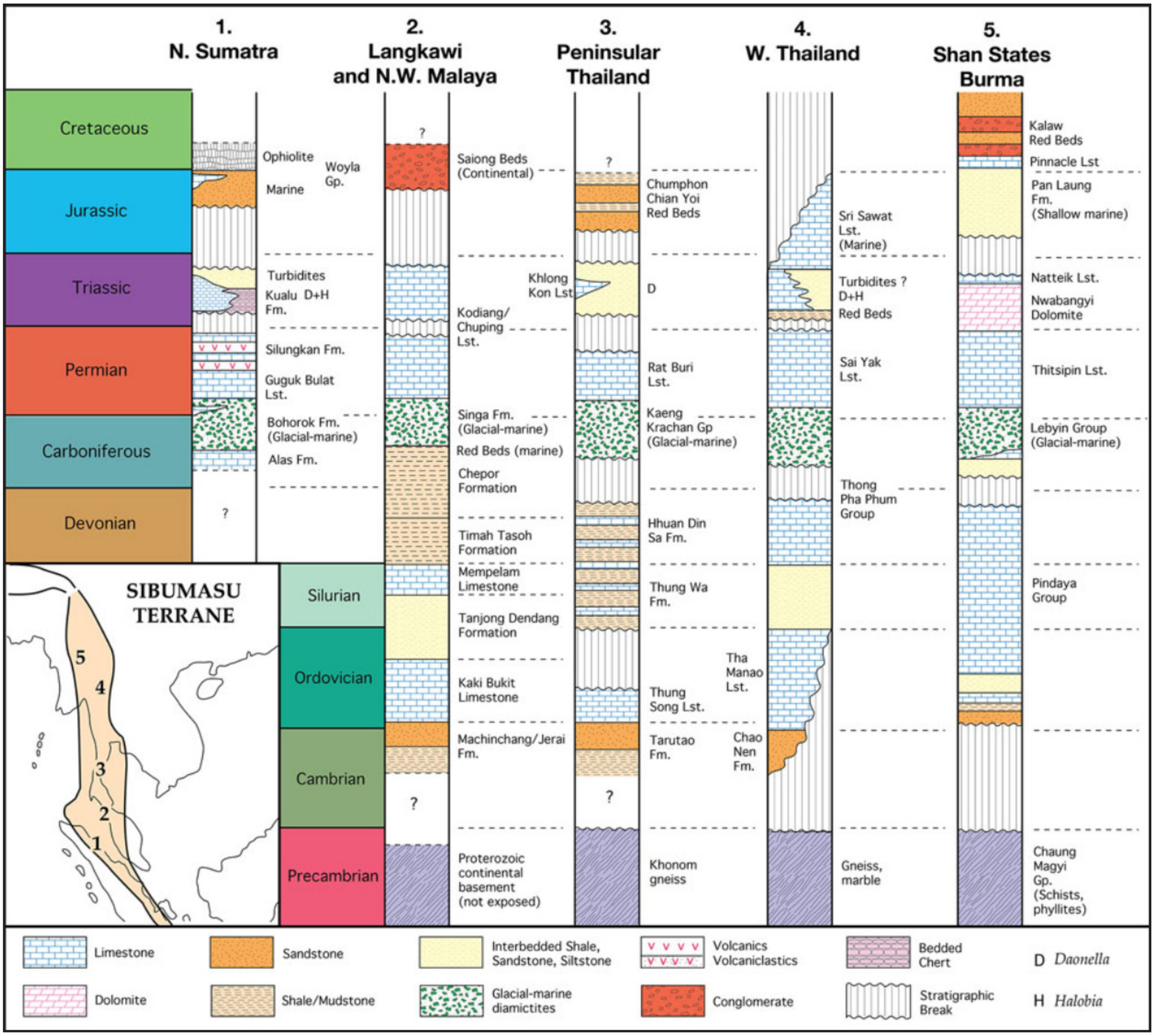

Figure 4: Stratigraphy of the Sibumasu Terrane. Mainly after Metcalfe (2005). Langkawi and NW Malaya Palaeozoic stratigraphy from Lee (2009).

the Machinchang and Jerai formations in NW Peninsular Malaysia (Lee, 2009), the Turatao Formation in southern Thailand, and the Chao Nen Formation in western Thailand (Figure 4). These are in turn overlain by middle and upper Palaeozoic and Triassic shallow-marine continental margin sediments in western Sibumasu and hemi-pelagic continental margin/slope deposits in eastern Sibumasu. Cambrian to Lower Permian faunas and floras of Sibumasu are distinctively Gondwanan with NW Australian affinities (Archbold *et al*., 1982; Burrett & Stait, 1985; Metcalfe, 1988, 1990, 1991, 1994, 2002a; Burrett *et al*., 1990; Shi & Waterhouse, 1991). This suggests a NW Australian origin for the Sibumasu terrane.

The presence of Upper Carboniferous–Lower Permian glacial-marine diamictites (Stauffer & Mantajit, 1981; Metcalfe, 1988; Stauffer & Lee, 1989; Ampaiwan *et al*., 2009; Meor *et al*., 2014), Lower Permian cool-water fauna and $\delta^{18}O$ cool-water indicators (Waterhouse, 1982; Ingavat & Douglass, 1981; Rao, 1988; Fang & Yang, 1991) indicate proximity of Sibumasu to the Upper Palaeozoic Gondwana glaciated region (see Figures 4 and 5). Upper Carboniferous and Lower Permian plant fossils are extremely rare on Sibumasu but a *Glossopteris* flora has been reported south of Baoshan in western Yunnan (Wang & Tan, 1994).

Gross stratigraphical comparisons between Sibumasu and NW Australia (Figure 5) also show similarities consistent with Sibumasu having been positioned outboard of NW Australian Gondwanaland in the Paleozoic. Paleozoic paleomagnetic data indicates southern paleolatitudes (Figure 6) consistent with a position off NW Australian Gondwana in the Devonian, Carboniferous and Early Permian (Fang *et al*., 1989; Bunopas, 1982; Bunopas *et al*., 1989; Metcalfe, 1990; Huang & Opdyke, 1991). Recent detrital zircon provenance studies in SE Asia have provided exciting new data and valuable constraints on the origin and evolution of the continental blocks of the region. New data for the

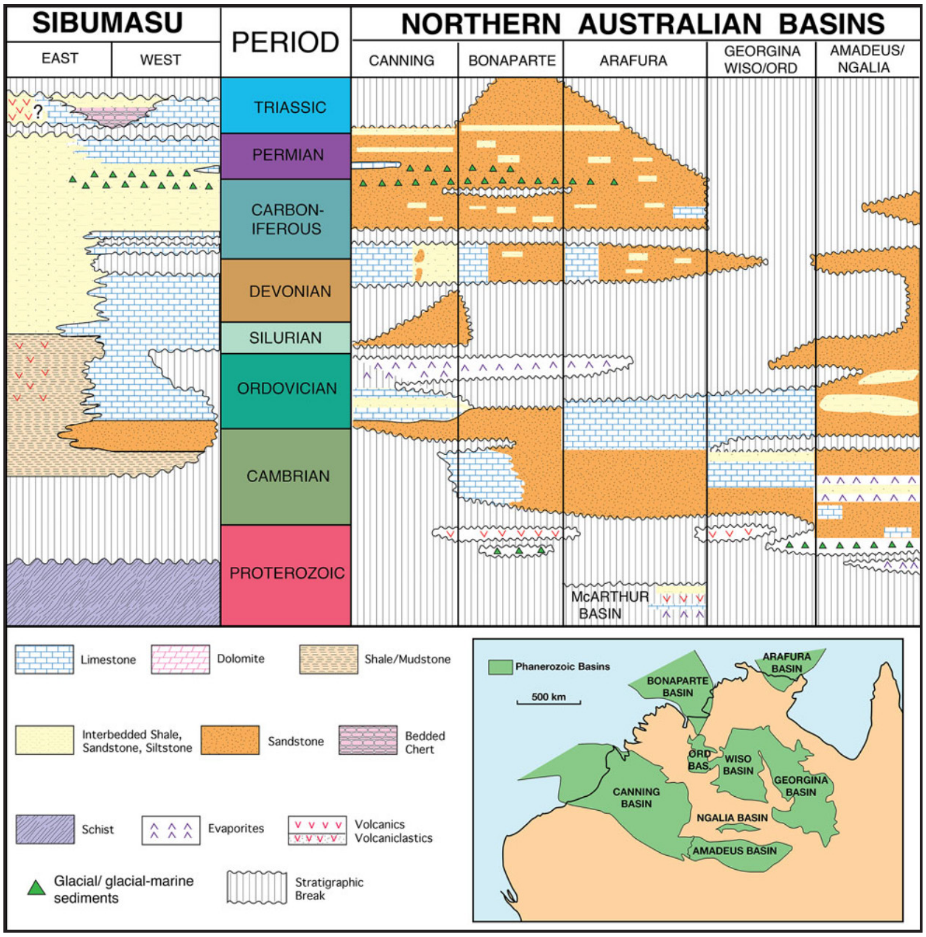

Figure 5: Comparison of gross stratigraphies and facies of Sibumasu with northern Australia Basins. After Metcalfe (1994, 2013a).

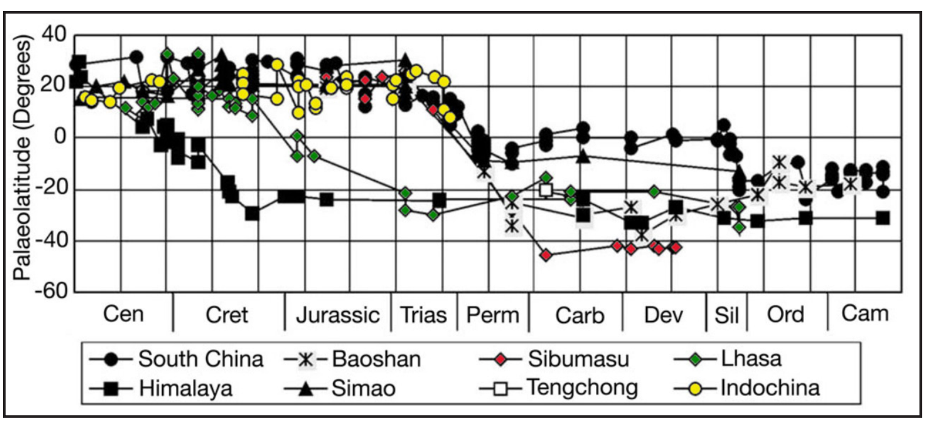

Figure 6: Palaeolatitude vs. time for some principal east and southeast Asian continental blocks (after Van Der Voo, 1993; Li *et al*., 2004). See text for explanation.

Sibumasu Terrane (Burrett *et al*., 2014; Cai *et al*., 2017) based on detrital zircon age spectra for samples ranging in age from Late Cambrian to Triassic (Figure 7) support the interpretation that Sibumasu had its origin on the NW Australian margin of Gondwana.

The western Australian Gondwana margin origin for Sibumasu now seems to be generally accepted, however the size, orientation and specific sites of attachment of Sibumasu on the Gondwana margin varies according to different authors depending on emphasis of constraining data. A selection of recent palaeogeographic reconstructions indicating interpreted positions of Sibumasu and other Asian blocks at various times from Cambrian to Permian is given in Figure 8. Torsvik & Cocks (2009), Guynn *et al*. (2012), Metcalfe (2013a), Ali *et al*. (2013), Burrett *et al*. (2014), and Cai *et al*. (2017) agree on the Palaeozoic placement of Sibumasu adjacent to NW Australia outboard of the Canning and Bonaparte Gulf Basins (Figure 8) and this position is here favoured. See Metcalfe and Aung (2014) for detailed discussion of alternative models.

Indochina Terrane

The western boundary of the Indochina Terrane is marked by the back-arc basin Nan-Uttaradit and Sra Kaeo suture zones and a cryptic suture offshore eastern Malay Peninsula (Figures 2, 3 and 9).

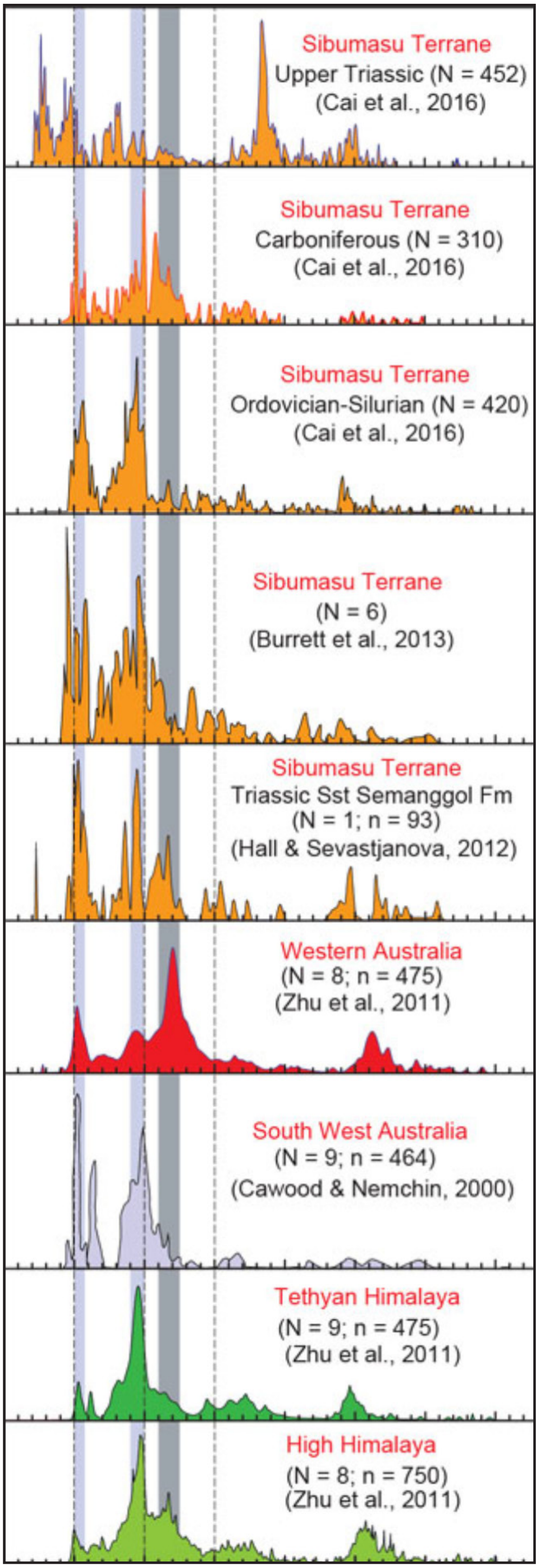

Figure 7: Detrital zircon age distributions for sedimentary rocks of the Sibumasu Terrane (Hall &Sevastjanova, 2012; Burrett *et al*., 2014; Cai *et al*., 2017) compared to zircon age distributions for North West Australia (Zhu *et al*., 2011), SouthWest Australia (Cawood &Nemchin, 2000) and the Himalayas (Zhu *et al*., 2011). N = number of samples; n = number of analyses.

The northern boundary of the Indochina Block is delineated by the complex North Vietnam Orogenic Belt that includes the Song Ma suture zone, the Trung Son Belt and the Tamky Phuok Son suture zone and the recently established Luang Prabang Suture Zone in Laos (Figure 9). The eastern boundary is poorly defined but broadly corresponds to the eastern margin of Sundaland in the South China Sea region and to a cryptic Cretaceous suture offshore SW Borneo.

The Indochina Block has a metamorphic core (Kontum massif) of granulite facies rocks exposed in Vietnam, and it has been suggested that this may have originally formed part of the Gondwana granulite belt (Katz, 1993), and hence represents the Indochina basement. Crustal formation of the Indochina basement in the Palaeoproterozoic and Mesoproterozoic is indicated by Nd depleted mantle model ages of 1.2– 2.4 Ga (Lan *et al*., 2003). U–Pb (monazite and zircon) and Ar–Ar (mica) ages in the granulites of the Kontum Massif indicate two thermotectonic events, one in the Middle Ordovician (470–465 Ma) and the other in the Early Triassic (250–245 Ma) (Roger *et al*., 2007). Upper intercept ages for monazites of 635 ± 160 Ma, 1 ± 0.3 Ga and 1421 ± 120 Ma are interpreted by Roger *et al*. (2007) as minimum ages of an inherited component related to the sedimentary protolith age or to the age of a previous metamorphic event. Ordovician ages in the Kontum Massif are similar to U–Pb ages in the Song Chay (northern Vietnam) for a magmatic event dated at 428 ± 3 Ma (Roger *et al*., 2000) and at 418–407 Ma in the Dailoc Massif of the Central Truong Son Belt (Carter *et al*., 2001). Superimposed Triassic Indosinian granulite facies metamorphism is indicated by U–Pb SHRIMP zircon and Ar–Ar mica dates of 250–245 Ma (Nam *et al*., 2001; Maluski *et al*., 2005; Roger *et al*., 2007).

The metamorphic basement of the Indochina Block is overlain by Palaeozoic to Triassic marine strata (Figure 10) which are in turn covered by Jurassic-Cretaceous continental red bed successions regarded by many as molasse deposits following the Triassic Indosinian Orogeny. These Jurassic-Cretaceous continental successions are known as the Gres Superieurs in west Kampuchea and southern Laos, the Khorat Group in Thailand, and the Terrain Rouge in eastern and central Laos. U–Pb ages and Hf isotopes of detrital zircons from the Trung Son Belt of northern Indochina suggest that the Indochina Block was located outboard of Qiangtang and in close proximity to South China on the Indian-Australian margin of Gondwana during the Early Palaeozoic (Usuki *et al*., 2013). Other recent U–Pb age spectra data for Indochina (Burrett *et al*., 2014) has been interpreted to place Indochina on the Indian-Arabian Peninsula margin of Gondwana in the early Palaeozoic. There are no reliable Palaeozoic palaeomagnetic data to provide constraints on the Palaeozoic palaeolatitude of Indochina (Figure 6) or to test proposed models for the position of Indochina in Palaeozoic palaeogeographical reconstructions of eastern Gondwana. Changes in the biogeographic affinities of Indochina biota indicate a change from Gondwana biota in the Middle Palaeozoic to Cathaysian biota in the Late Palaeozoic and

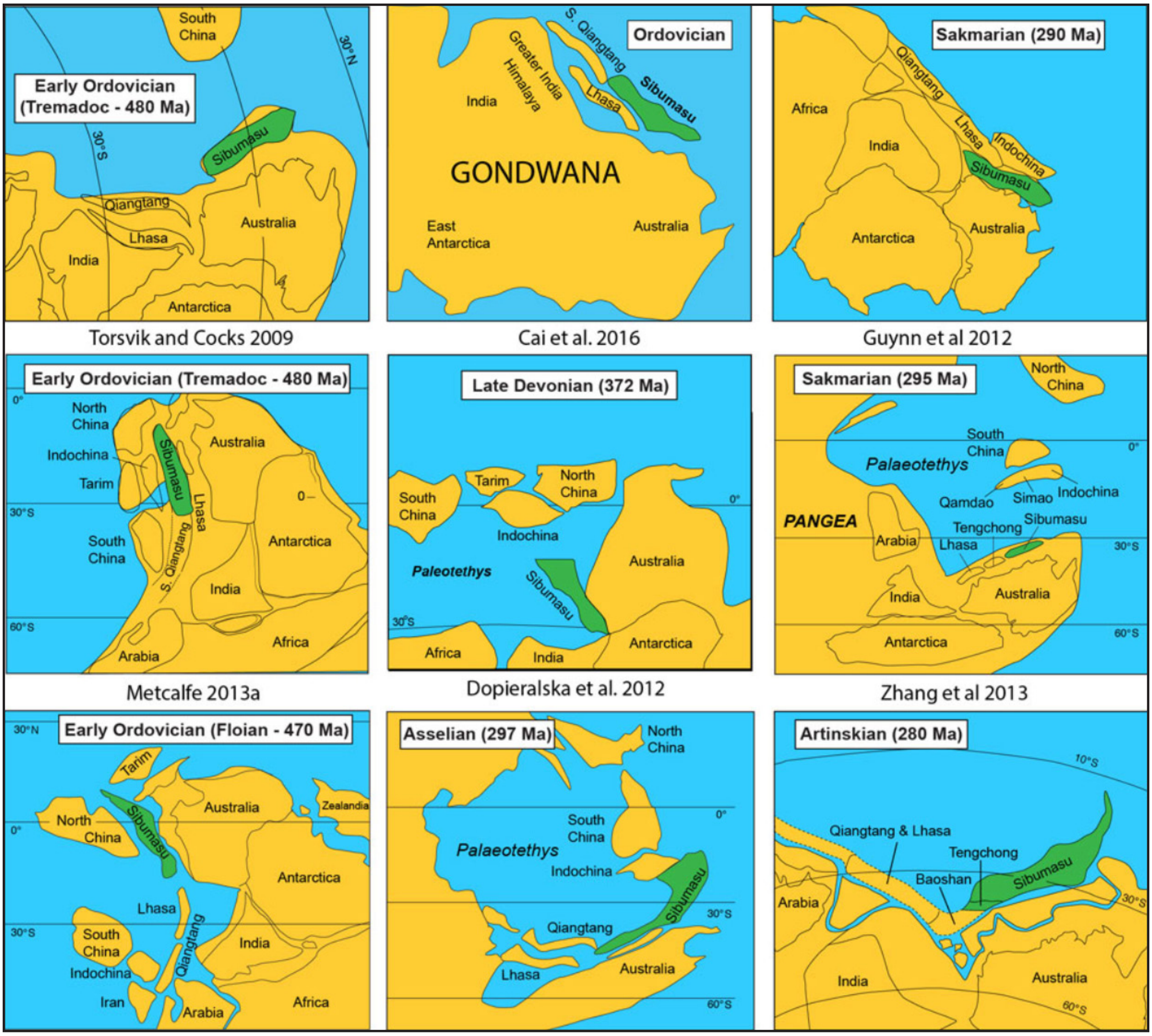

Figure 8: A selection of recent palaeogeographic reconstructions for the Early Ordovician (Torsvik & Cocks, 2009; Burrett *et al*., 2014; Metcalfe, 2013a; Cai *et al*., 2017), Late Devonian (Dopieralska *et al*., 2012), Asselian (Shen *et al*., 2013), Sakmarian (Guynn *et al*., 2012; Zhang *et al*., 2013), and Artinskian (Ali *et al*., 2013) showing interpreted origins and palaeo-positions for the Sibumasu Terrane. Modified after Metcalfe & Aung (2014).

hence separation and northwards drift from Gondwana in the Devonian (Metcalfe, 2011a, 2013a; Figure 11).

Simao Block

The concept of a Simao Block (Figures 2, 3 and 8) was introduced by Wu *et al*. (1995) for the region bounded by the Palaeo-Tethys Changning–Menglian–Chiang Mai sutures to the west, the Ailaoshan suture to the northeast and the Uttaradit–Nan Suture and Luang Prabang-Dien Bien Phu sutures to the southeast. Metcalfe (2002b) accepted this interpretation and correlated the Simao Block with the Qamdo-Simao block to the north in Tibet, regarding them as a single disrupted terrane derived from South China–Indochina by back-arc spreading. More recent interpretations of suture zones in this region and re-interpretation of part of the Simao Block as the Sukhothai Arc with its eastern boundary marked by the Uttaradit–Nan and Jinghong suture zones (Sone & Metcalfe, 2008; Metcalfe, 2011a,b) leaves only a remnant part of the original Simao Block, between the western Jinghong and eastern Ailaoshan suture zones and the Luang Prabang suture to the south. Metcalfe (2013a) considered the Simao block a likely north-west sub-terrane extension of the Indochina Block. However, Roger *et al*. (2014) proposed that the Luang Prabang and Dien Bien Phu sutures form the SE boundary of a separate Simao block and suggested Triassic subduction of a branch of the Palaeo-Tethys beneath Indochina. This is supported by recent new data suggesting a Triassic magmatic arc along the Luang Prabang zone (Rossignol *et al*., 2016). The Simao Block (re-defined) is here regarded as a separate block from Indochina. It seems likely that it had a similar origin to Indochina and South China on the margin of Gondwana

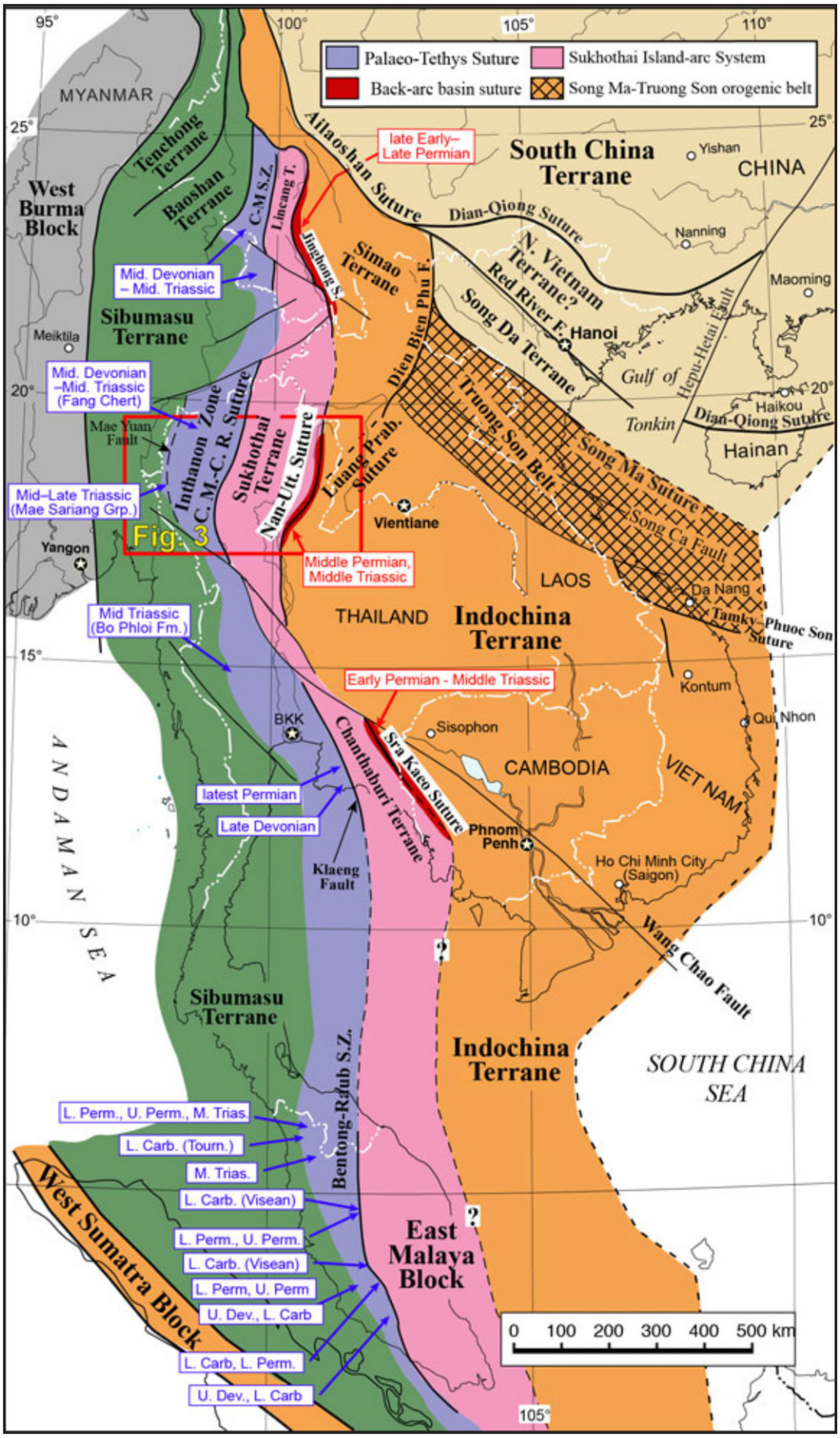

Figure 9: Tectonic subdivision of mainland SE Asia Sundaland showing the Sukhothai Arc terranes and bounding Palaeo-Tethys and back-arc suture zones. The Palaeo-Tethys Suture Zone as depicted includes suture zone rocks thrust westwards over the leading edge of Sibumasu (e.g. in the Inthanon Zone). Ages of deep marine radiolarian cherts are shown in boxes. C–M S.Z. = Changning–Menglian Suture Zone; C.M.-C.R. Suture = Chiang Mai-Chiang Rai Suture Zone. Modified after Sone & Metcalfe (2008) and Metcalfe (2011a, 2011b, 2013a).

and separated with those blocks in the Devonian as the Palaeo-Tethys opened.

Sukhothai Arc

The Sukhothai Arc comprises, from north to south, the Linchang, Sukhothai, and Chanthaburi terranes and the Central plus Eastern Belts of the Malay Peninsula (Ueno, 1999; Ueno & Hisada, 1999, 2001; Sone & Metcalfe, 2008; Sone *et al*., 2012; Metcalfe, 2013a). The arc has a continental basement that originally formed the margin of the Indochina Block and is bounded to the west by the Changning–Menglian, Chiang Mai-Chiang Rai, and Bentong–Raub Palaeo-Tethyan suture zones (Figure 8). The eastern boundary of the arc is marked by the Jinghong, Nan–Uttaradit and Sra Kaeo suture zones and a cryptic suture offshore eastern Malay Peninsula that represent a closed back-arc basin (Figure 8). The arc was constructed in the Early Carboniferous– Early Permian on the margin

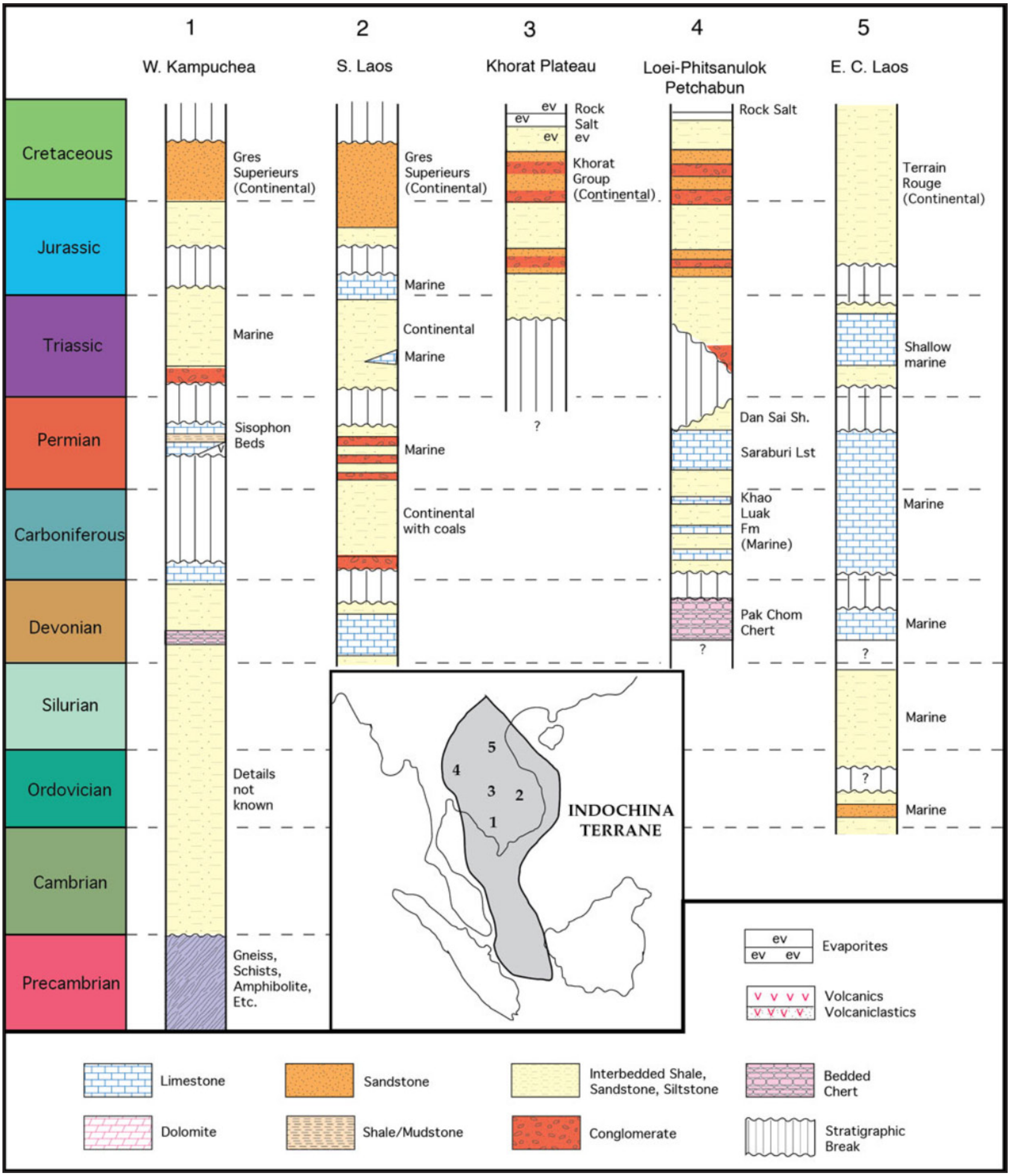

Figure 10: Stratigraphy of the Indochina Block. Mainly after Metcalfe (2005).

of the South China–Indochina superterrane by northwards subduction of the Palaeo-Tethys. Recent evidence from SW Yunnan suggests that the arc may well have already been in existence in the Late Devonian (Nie *et al.*, 2016). The arc was detached from Indochina by back-arc spreading in the Early–Middle Permian and was then accreted back onto South China–Indochina by back-arc collapse in the Triassic (Figure 12). Continuation of this arc terrane southwards into the Malay Peninsula is equivocal and Metcalfe (2011b) suggested continuation to the central Belt of the Malay Peninsula that forms a gravity high (Ryall, 1982). Metcalfe (2013a, 2013b), however, based mainly on the distribution of I-Type granitoids, has subsequently interpreted that both the Central and Eastern Belts of the Malay Peninsula (East Malaya Block) to represent the southern continuation of the Sukhathai Arc (Figure 8). In this case, the Central Belt would

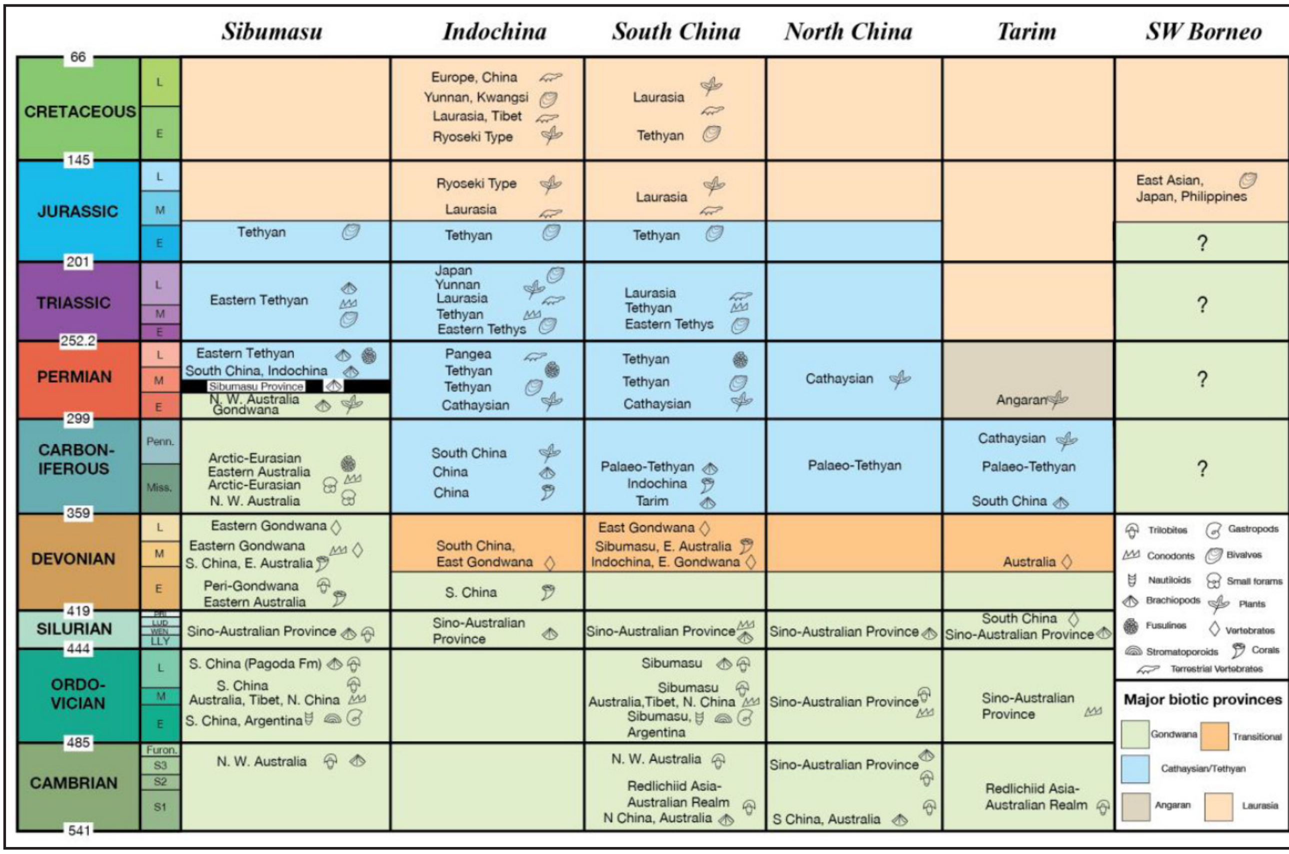

Figure 11. Palaeozoic and Mesozoic faunal and floral provinces and affinities vs. time for the principal East Asian continental blocks (after Metcalfe, 2001, 2011a, 2013a).

represent the fore-arc basin and the Eastern Belt the Arc and its continental basement derived from Indochina. Highly deformed Carboniferous continental margin sequences along the eastern part of East Malaya (e.g. Tjia, 1978; Chakraborty & Metcalfe, 1984; Mustaffa, 2009) may be the expression of orogenic deformation related to the closure of the back arc basin, which must then be located offshore eastern Malay Peninsula (Metcalfe, 2013a, 2013b).

Nd–Sr and U–Pb zircon dating of Permian–Triassic granitoids in the Malay Peninsula (Liew & McCulloch, 1985) indicated a Proterozoic basement age of 1100–1400 Ma for the East Malaya segment of the Sukhothai Arc. Detrital zircon U–Pb and Hf-isotope data for Peninsular Malaysia (Sevastjanova *et al*., 2011; Hall & Sevastjanova, 2012) also supports a Proterozoic basement age but suggests older ages of 1.7–2.0 Ga with some older (2.7 Ga) age components. The oldest unequivocal exposed rocks of the Sukhothai Arc (Figure 13) are Lower Carboniferous marine siliciclastics, volcaniclastics and carbonates of the Chanthaburi Terrane and the East Malaya segment of the Sukhothai Arc (East Malaya Block: east of the Bentong–Raub suture zone). Limestones dated as Visean (late Mississippian) occur in the central part of the Chanthaburi Terrane (Sone *et al*., 2012). Sandstones and shales in Pahang and Trengganu, East Malaya contain Cathaysian Mississippian plants (Asama, 1973; Jennings & Lee, 1985; Ohana *et al*., 1991). Shallow-marine basal Pennsylvanian reefal carbonates (Panching Limestone) in Pahang contain a rich warm-water Tethyan fauna (Metcalfe, 1980; Metcalfe *et al*., 1980). Possible pre-Carboniferous (Devonian?) deformed metasedimentary rocks were reported in the East Malaya Block by Chakraborty & Metcalfe (1995), based on structural geology, and suggest the presence of older Palaeozoic strata in the basement of the Sukhothai Arc. The recent discovery of Upper Devonian arc-related tuffs and volcaniclastics in the southern Lancangjiang zone in western Yunnan suggest that the Sukhothai Arc may have been initiated in the Late Devonian (Nie *et al*., 2016).

The Carboniferous and older continental basement of the Sukhothai Arc is covered by Permian and Triassic shallow-marine carbonates, siliciclastics, volcaniclastics and arc-related volcanics (Figure 13). These late Palaeozoic and Triassic sequences contain warm-water Tethyan faunas and Cathaysian floras (Metcalfe, 2013a) and are overlain by post-Indosinian Orogeny continental molasse deposits.

West Sumatra Block

The West Sumatra Block (Figures 2 and 3) is an elongate continental sliver in Sumatra bounded to the SW by the Woyla suture and terranes and to the NE by the Medial Sumatra Tectonic Line (Hutchison, 1994; Barber & Crow, 2003, 2009). The oldest dated sedimentary rocks in this micro-terrane are the Carboniferous Kluet and Kuantan formations that have yielded Visean conodonts including *Gnathodus girtyi rhodesi* Higgins (Metcalfe, 1983, 1986). Substantial Permian volcanics are known on

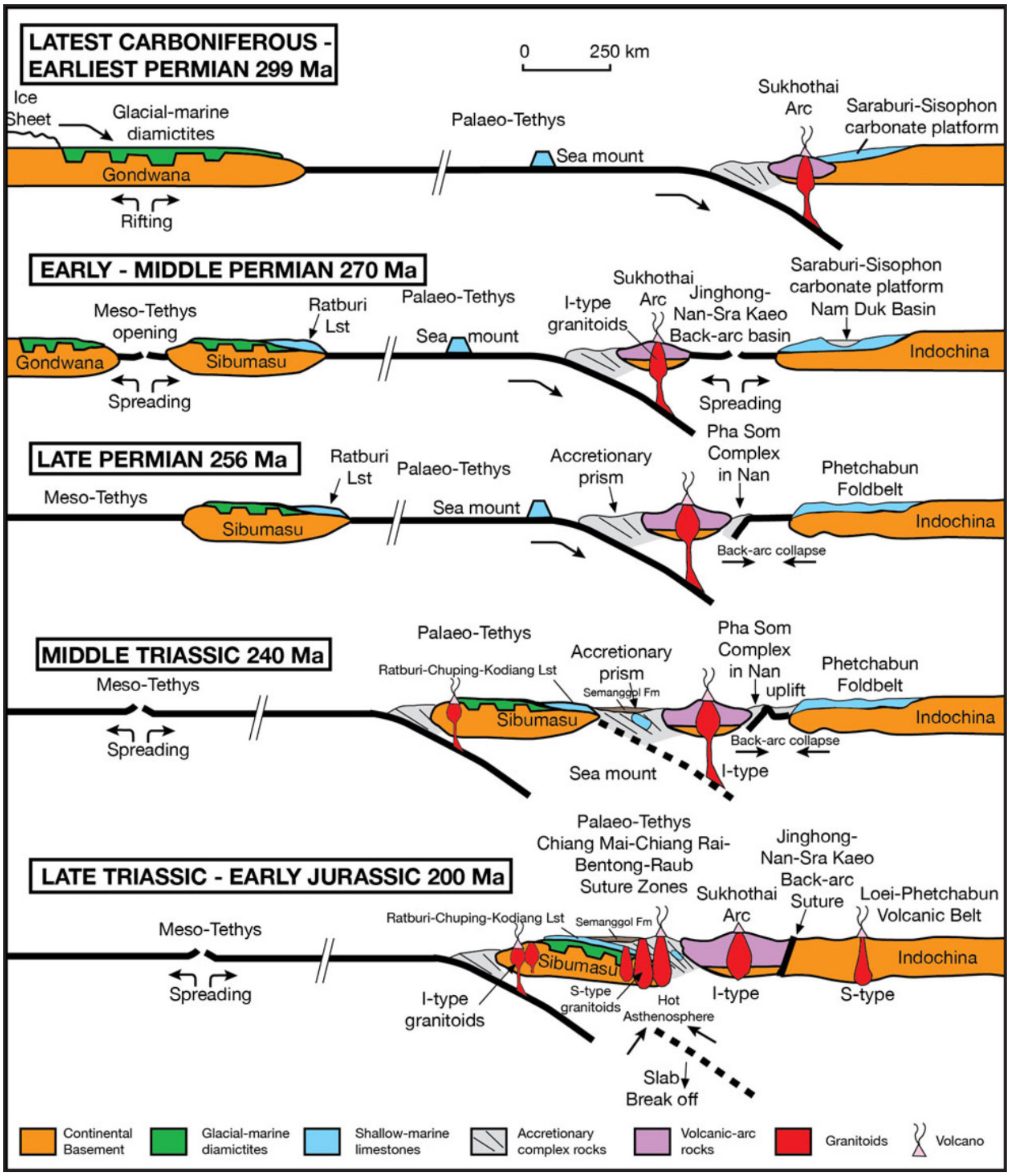

Figure 12: Cartoon showing the tectonic evolution of Sundaland (Thailand–Malay Peninsula) and evolution of the Sukhothai Arc System during Late Carboniferous–Early Jurassic times (after Ueno & Hisada, 1999; Metcalfe, 2002a; Sone & Metcalfe, 2008; Metcalfe, 2011a,b; Searle *et al*., 2012; Metcalfe 2013a; Ng *et al*., 2015a, 2015b).

this terrane and constitute a Permian West Sumatra volcanic arc. Geochemical studies of the Permian volcanics suggest a continental margin arc underlain by continental crust (Gasperon & Varne, 1995, 1998). Lower Permian (Asselian-Sakmarian) strata associated with Permian volcanics on the West Sumatra Block contain floras that belong to the warm-climate equatorial *Gigantopteris* Cathaysian floral province and include the famous Djambi flora of the Mengkarang Formation (Jongmans & Gothan, 1925, 1935; Vozenin-Serra, 1989; Van Waveren *et al*., 2005, 2007). Recent studies of palynomorphs from the Mengkarang Formation confirms the Cathaysian affinity of the floras (Crippa *et al*., 2014). Lower Permian shallow-marine faunas of the West Sumatra Block, especially brachiopods, fusulinids and corals, belong to the Tethyan equatorial faunal province (Thompson, 1936; Fontaine & Gafoer, 1989; Metcalfe, 2005, 2006; Crippa *et al*., 2014). The Cathaysian West Sumatra Block (with its warm climate low-latitude floras and faunas) is located outboard of the Sibumasu terrane (with high southern latitude cold climate Gondwanan faunas and floras and glacial deposits in the early Permian). This unusual location in Sumatra led to the interpretation that it was derived from the Indochina terrane and emplaced by strike-slip tectonics in the Permo-Triassic (Metcalfe, 2006, 2011a,b; Barber & Crow, 2009). It is here considered that the West Sumatra Block with its continental margin arc may well be a displaced segment of the Sukhothai Arc system translated outboard of Sibumasu by strike-slip tectonics in the Triassic (Barber & Crow, 2009; Metcalfe, 2013a).

West Burma Block

The West Burma Block is bounded to the east by the Sagaing Fault zone and to the west by the Ceno-Tethys Naga-Kalaymyo-Chin Hills ophiolite belt (Figure 14). Recent geochronological data from the Kalaymyo ophiolites suggets correlation with the Yarlung-Tsangpo suture of Tibet (Liu *et al*., 2016). The Myitkyina Ophiolite belt in NE Myanmar has recently been dated as Middle Jurassic and

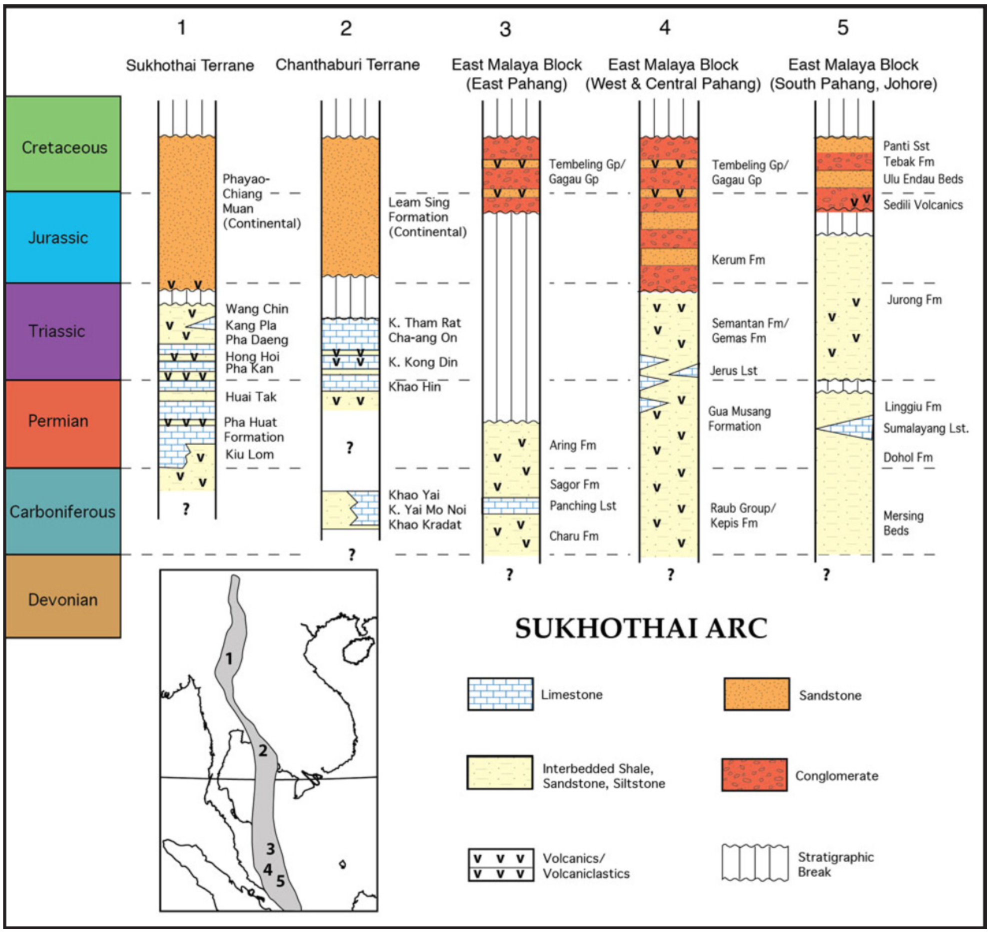

Figure 13: Stratigraphy of Sukhothai Arc terranes. Partly after Sone & Metcalfe (2008), Sone *et al.* (2012) and Metcalfe (2013b).

correlated with the Meso-Tethys Bangong-Nujiang suture in the Tibetan Plateau (Liu *et al.*, 2016) suggesting that the Tagaung-Myitkyina Belt between this ophiolite belt and the Mogok Metamorphic belt (Figure 14) is not a part of the West Burma Block as previously suggested. The West Burma Block has a continental basement (Mitchell, 1989) but the block's origin has been, and still is, equivocal. Mitchell (1989) proposed that the West Burma Block represents an extension of the Gondwana-derived Lhasa Block of Tibet. Metcalfe (1990) suggested that the "Mount Victoria Land" (West Burma) Block may represent the continental block referred to as "Argo Land" that must have rifted from NW Australia in the Jurassic (Veevers *et al.*, 1991). Subsequently, Metcalfe (1996a, 1996b) positioned the West Burma Block on the NW Australian Gondwana margin in the Triassic on the basis that Triassic quartz-rich turbidites and a pre-Mesozoic schist basement could have provided a source for quartz-rich sediments on Timor. It was, however, pointed out that there was no unequivocal direct evidence for the origin of the West Burma block.

The interpretation of West Burma as the missing "Argo Land" block (Metcalfe, 1996a, 1996b) was accepted by many authors (e.g. Longley *et al*., 2002; Heine *et al*., 2004; Heine & Muller, 2005; Hoernle *et al*., 2011). However, following a report of Cathaysian Middle Permian fusulinids from Karmine on this block (Oo *et al*., 2002), and interpreted as similar to the Middle Permian faunas of the West Sumatra Block (Barber & Crow, 2009), West Burma was interpreted as a disrupted northwards extension of West Sumatra and that both these blocks were derived from the Indochina–South China superterrane (Barber & Crow, 2009). There is, however, some confusion regarding the reported Permian fusulinids from the West Burma Block. The only locality that could be accepted as possibly being on the West Burma Block is the Karmine locality. The precise age, taxonomy and affinities of the Permian fusulinids reported from Karmine, and other localities along the Sagaing Fault zone by Oo *et al*. (2002) are still equivocal. Oo *et al*. (2002) referred to massive to poorly bedded, creamy-white and grey limestones in the vicinity of Karmine and at several other localities "within the Sagaing Fault zone". The limestones were said to contain the fusulinids *Schwagerina* sp., *Parafusulina* sp., *Rugososchwagerina* sp. and *Cribrogerinerina* sp. characteristic of the Middle Permian (Murghabian) *Neoschwagerina*-*Verbeekina* zone citing Thein *et al*. (1982) and Nyunt (1993). No specific information on fusulinids from individual localities nor any systematic descriptions of fusulinid species were given. Specimens illustrated and assigned to *Schwagerina* by Thein *et al*. (1982) were subsequently re-assigned to *Pseudofusulina* by Thein (2012) and more recently to *Pseudofusulina postkraffti* by Shi & Jin (2015) who also suggested that the fusulinids from limestones in the Sagaing Fault zone were of Peri-Gondwana affinity. Samples of

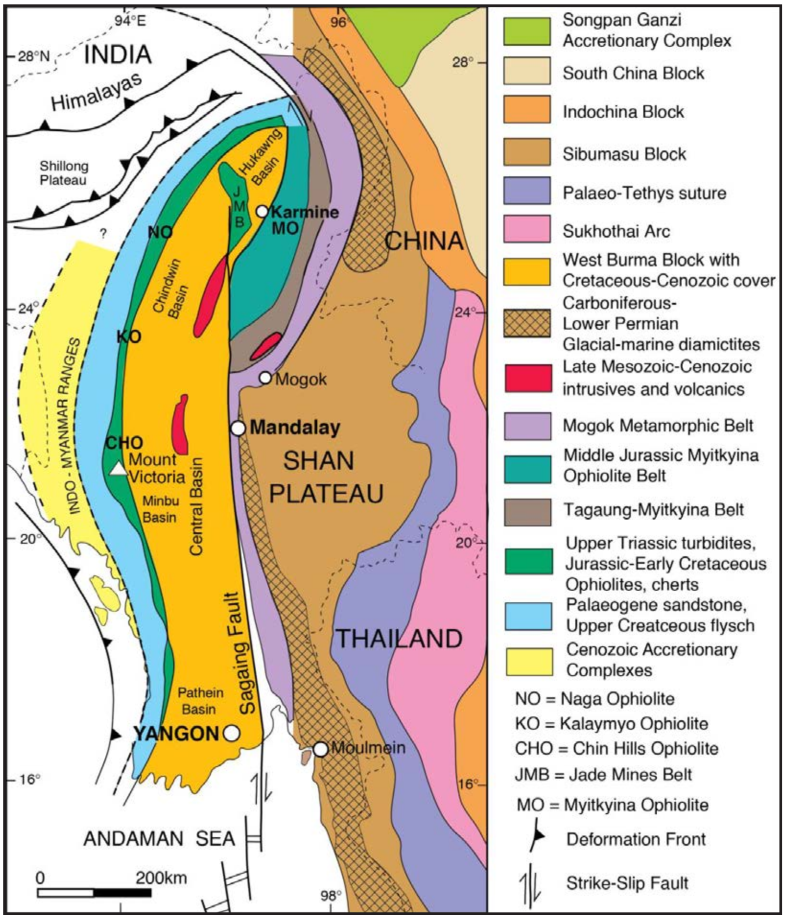

Figure 14: Key geological and tectonic elements of Myanmar and adjacent region. Partly after Mitchell (1993); Mitchell *et al*. (2004, 2007, 2012); Sone & Metcalfe (2008); Barber & Crow (2009); Morley (2012).

fusulinid limestone purportedly from Karmine were sent to Katsumi Ueno (Fukuoka University) for assessment. The samples of limestone sent to Katsumi Ueno were not from the Karmine locality but from near Tigyaing north of Mandalay (Locality 3 of Oo *et al*., 2002). The Peri-Gondwana affinity of the Tigyaing fusulinids is challenged by Katsumi Ueno who has re-evaluated the taxonomy of the fusulinids and based on identification of *Psedofusulina kraffti,* interprets them as upper Lower Permian (Yakhtashian = Artinskian) in age and of Tethyan affinity based on the overall faunal composition (Ueno *et al*., 2016). The small tectonic slices of shallow-marine Lower Carboniferous and Lower Permian limestone lenses occurring within the highly sheared Sagaing Fault zone near Mandalay (Thein, 2015) are here interpreted as disrupted slices of Sibumasu Shan Scarps platform limestones. These do not have any bearing on the origin of the west Burma Block. It is not clear if any of the fusulinid species reported by Thein *et al*. (1982) and Oo *et al*. (2002) are in fact from near Karmine and further investigations are required to assess that reported occurrence and its nature.

Sevastjanova *et al*. (2016) presented vital new provenance data from Myanmar that provide important constraints on competing models for the tectonic evolution of Myanmar and the origin of the West Burma block. Heavy mineral and detrital zircon U-Pb age data from Triassic turbidite sandstones in the Chin Hills suggest that West Burma, until the Devonian, was located close to Sibumasu on the western Australian Gondwana margin and an abundance of Permian and Triassic zircons, occurrences of Cr spinel in the Chin Hills turbiditic sandstones suggest that West Burma was part of SE Asia before the Upper Triassic (Sevastjanova *et al*., 2016). The question still remains: Was West Burma originally part of Sibumasu or possibly originally part of the Lhasa Block? The new detrital zircon and provenance data of Sevastjanova *et al*. (2016) precludes the West Burma Block being originally part of the Lhasa Block because the Lhasa Block only separated from Gondwana in the Late Triassic and collided with Asia in the Cretaceous. Gardiner *et al*. (2016) in their model for the evolution of Myanmar regard the continental crust beneath western Myanmar as forming part of the Sibumasu Terrane and pending further investigations this interpretation is here favoured.

SW Borneo Block

The SW Borneo Block is bounded to the southeast by the Meratus and Luk Ulo sutures (Wakita, 2000) and to the north by the Lupar and Boyan zones, with the small Semitau Block between (Williams *et al*., 1988; Hutchison, 1989, 2005; Metcalfe, 1990, 1996a; Figure 3). The western margin of the block with the West Sumatra, Sibumasu and East Malaya blocks is cryptic. The nature of the basement of SW Borneo is poorly known. Pelitic schists, slates, phyllites, and hornfelses of the Pinoh Metamorphic Group have previously been assumed to be Carboniferous-Permian or older. These are intruded by Jurassic-Cretaceous granitoids of the Schwaner batholith. Devonian limestones reported from the ''Old Slates Formation'' of Borneo (Rutten, 1940) are now known to form part of a melange unit accreted to the NE margin of SW Borneo (Sugiaman & Andria, 1999) and not therefore part of the core SW Borneo Block. Carboniferous-Permian fusulinid and conodont-bearing Cathaysian limestones (Terbat Limestone) in Sarawak (Cummings, 1962; Metcalfe, 1985) were also previously considered part of the SW Borneo Block but are now regarded as forming part of the accreted material on the northern margin of the block rather than representing part of its core basement. Separation of these Palaeozoic Cathaysian elements from core SW Borneo led Hall *et al*. (2008, 2009), Hall (2009a, 2009b, 2012) and Metcalfe (2011a, 2011b) to propose that SW Borneo was derived from NW Australia in the Jurassic. Diamonds occurring in SW Borneo placer deposits without any apparent local source, have geochemical and isotope signatures similar to Australian diamonds (Taylor *et al*., 1990; Smith *et al*., 2009; Nico Kueter *et al*., 2016; White *et al*., 2016) which would support such a proposition. Van Leeuwen (2014) reviews diamond occurrences in Sundaland and suggests various possible models for the origin of Kalimantan diamonds, including fluvial derivation from mainland Sundaland during the Mesozoic. Recent U-Pb SHRIMP dating of zircons in the Pinoh Metamorphic Group (Davies *et al*., 2012) indicates a mid-Cretaceous (volcaniclastic) protolith. In addition, zircons from granitoids that intrude the metamorphic rocks exhibit middle Cretaceous age populations at c. 112, 98, and 84 Ma and a single granite body is dated as Lower Jurassic (186 ± 2.3 Ma). Davies *et al*. (2012) suggest that fine-grained volcanogenic sediments were deposited on, or are reworked, older crust during the Early Cretaceous. These sediments were subjected to low-pressure 'Buchan-type' metamorphism soon after deposition. This further suggests that the Pinoh metamorphic rocks of SW Borneo are not an ancient core to the island as previously assumed. The nature of any hidden continental core of SW Borneo thus remains enigmatic. The recent report of adakitic metatonalite in western Kalimantan dated at 233 ± 3 Ma (early Late Triassic) and interpreted as the result of northwards subduction of the Meso-Tethys ocean (Setiawan *et al*., 2013) might suggest that SW Borneo was already accreted to Sundaland before the Late Triassic. However, a more likely scenario is that the SW Borneo Block is smaller than previously interpreted and that the Triassic adakitic metatonalite and other Triassic rocks in western Kalimantan may form part of mainland Sundaland and a Jurassic derivation of SW Borneo from Australian Gondwana is still tenable.

Suture zones of Sundaland

The continental and arc terranes of Sundaland are bounded by suture zones that represent the sites of closed oceanic or back-arc basins. The principal suture zones are shown in Figures 2 and 3 and comprise the Chiang Mai-Chiang Rai, Chanthaburi and Bentong–Raub Sutures that represent remnants of the now destroyed main Palaeo-Tethys ocean; the Jinghong, Nan–Uttaradit and Sra Kaeo Sutures that represent remnants of the Sukhothai back-arc basin; the Luang Prabang suture that represents a branch of the Palaeo-Tethys between the Simao and Indochina blocks; the Song Ma suture zone that forms the boundary between Indochina and South China; the Shan Boundary and Medial Sumatra "sutures"; the Meratus and Luk–Ulo Meso-Tethys sutures; and the Boyan "Paleo-South China Sea" Suture. These are briefly described below:

Palaeo-Tethys suture zones

Chiang Mai-Chiang Rai Suture Zone

Baum *et al*. (1970) mapped a north–south ophiolite belt between Chiang Mai and Chiang Rai. This ophiolitic zone is now regarded as a segment of the main Palaeo-Tethys suture zone and is located between the Inthanon Zone, a fold and thrust belt located to the west, and the Sukhothai Arc to the east. The suture has been variously referred to as a "cryptic" suture (e.g. Barr & MacDonald, 1991), the Chiang Mai Tectonic Line (Hara *et al*., 2009), the Chiang Rai Line (e.g. Barber *et al*., 2011; Gardiner *et al*., 2016), the Chiang Mai suture (Metcalfe, 2002) and the Chiang Mai-Inthanon Suture Zone (Metcalfe, 2013a). Because of the historically varied names applied to this suture zone, and to avoid confusion with the Inthanon fold and thrust belt zone, Metcalfe *et al*. (2017) propose that this suture be named the Chiang Mai-Chiang Rai Suture Zone and this name is adopted here. Suture zone rocks, including elements of the suture thrust westwards and located in the Inthanon Zone, include Mid Ocean Ridge Basalts (MORB), pelagic radiolarian cherts, pelagic limestones, and pelagic mudstones and turbidites that range in age from Middle Devonian to Middle Triassic (Metcalfe, 2013a, Metcalfe *et al*., 2017; see Figure 15).

Chanthaburi Suture Zone

This largely cryptic suture zone, previously referred to as the "Klaeng tectonic line" (Sone *et al*., 2012) and " Klaeng fault" (Sone & Metcalfe, 2008) forms the boundary between the Sibumasu Terrane and the Chanthaburi terrane of the Sukhothai Arc in southern Thailand. Late Devonian, Late Permian and Middle Triassic radiolarian cherts are known in the suture zone (Sone & Metcalfe, 2008; Sone *et al*., 2012; Metcalfe, 2013a), consistent with the age-range known from other Palaeo-Tethys main ocean suture zones (Figure 13). The suture was reactivated as a sinistral strike-slip fault zone in the Cenozoic (Morley, 2002; Morley *et al*., 2011).

Bentong-Raub Suture Zone

The Bentong–Raub Suture Zone of the Malay Peninsula represents the main Palaeo-Tethys ocean basin and forms the boundary between the Sibumasu terrane in the west and the Sukhothai Arc in the east (Figures 2, 3 and 8) and was discussed in detail by Metcalfe (2000, 2013b). The suture includes oceanic radiolarian cherts ranging in age

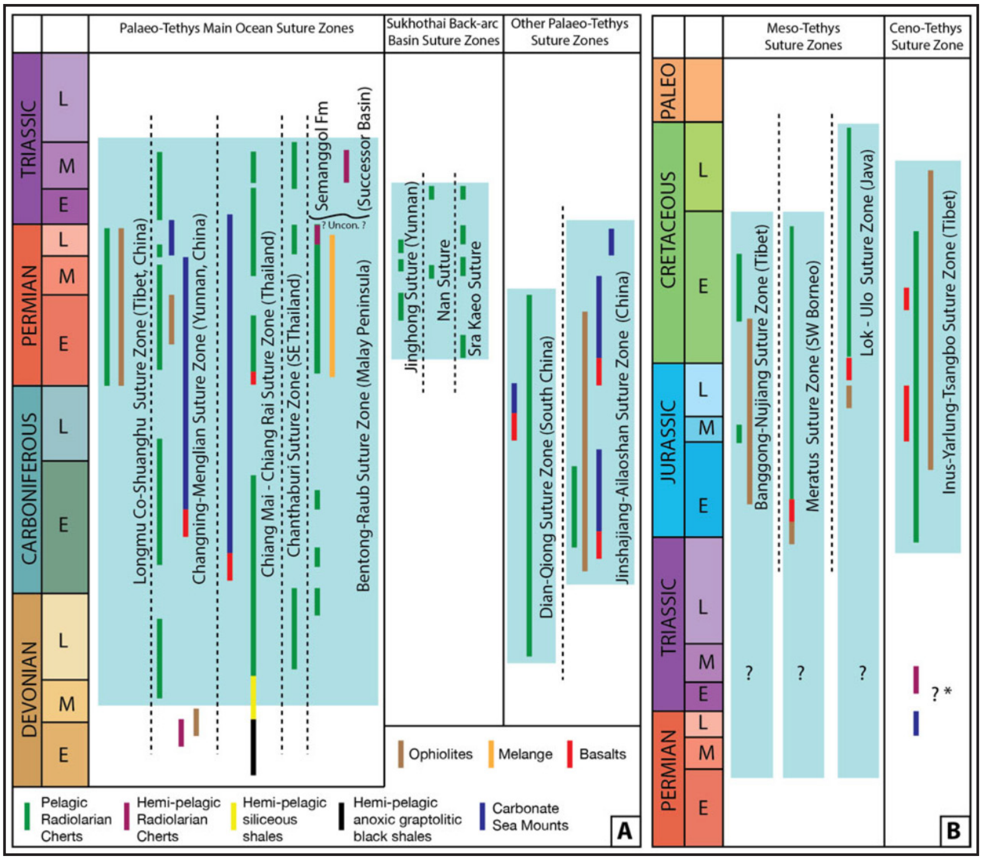

Figure 15: Ages of cherts, siliceous shales, graptolitic black shales, carbonates, ophiolites, melange and basalts that constrain the age-duration of: A. Eastern Palaeo-Tethys suture zones, and; B. Meso- and Ceno-Tethys suture zones. Compiled from multiple sources discussed in the text. *Changhsingian sea mount limestones, and hemipelagic Triassic sediments may represent elements of Meso-Tethys incorporated along the Indus-Yalung-Tsangbo suture by strike-slip tectonics. After Metcalfe (2013a); Metcalfe *et al.* (2017).

from Devonian to Upper Permian (Figure 13), melanges with clasts of ribbon-bedded chert, limestone, sandstone, conglomerate, blocks of turbiditic rhythmites, volcanic and volcaniclastic rocks ranging in size from a few millimetres to several metres and exceptionally, up to several hundred metres, and serpentinite bodies up to 20 km in length interpreted as representing mafic–ultramafic igneous rocks and oceanic peridotites (Metcalfe, 2000). Chert and limestone clasts in melange are dated by radiolarians, conodonts and foraminifera as Carboniferous and Permian (Metcalfe, 2000). Triassic hemipelagic cherts, turbidites and conglomerates of the Semanggol ''Formation'' have been interpreted as forming in a successor or foredeep basin developed on top of the accretionary complex (Metcalfe, 2000) or in submarine grabens alongside coeval carbonates deposited on horsts following collision of Sibumasu and east Malaya in the Late Permian–Early Triassic (Barber & Crow, 2009). Alternatively, the Semanggol cherts can be regarded as part of the Bentong–Raub Suture Zone thrust westwards over Sibumasu in a similar situation to the Inthanon Zone in Thailand to the north. For more detailed discussion see Metcalfe (2000, 2013a, 2013b).

Song Ma Suture Zone

The Song Ma Suture Zone, located in north Vietnam, forms the north-eastern boundary of the Indochina Block (Figures 2, 3 and 8). The suture forms the northern part of the complex North Vietnam Orogenic Belt that also includes the Trung Son Belt and the Tamky Phuok Son suture zone (Figure 8). The nature and age of the Song Ma suture zone, generally regarded as representing a branch of the Palaeo-Tethys and forming the boundary between the Indochina and South China Blocks, remains controversial. Belts of Palaeo-Tethyan ophiolitic rocks NE of the Red River Fault, recognised as the Dian Qiong Suture Zone (Zhang *et al.*, 2006; Zhang & Cai, 2009; Cai & Zhang, 2009), the Song Chay Suture Zone (Faure *et al.*, 2014) and the Song Hien Tectonic Zone (Halpin *et al.*, 2016) has led some authors to propose these sutures as the southern boundary of the South China Block and the continental crust between these and the Song Ma sutures as a disrupted fragment of Indochina which Metcalfe (2013a) named the North Vietnam Terrane. The Dian Qiong and Song Chay suture zones and possibly the Song Hien Tectonic Zone are here regarded as segments of the Song Ma Suture Zone disrupted by significant left-lateral movement on the Cenozoic Red River Fault. Various ages for collision along the Song Ma suture zone have been proposed, including Devonian (Janvier *et al.*, 1996; Thanh *et al.*, 1996), Carboniferous (Tri, 1979; Metcalfe, 1999), Late Permian–Early Triassic (Lepvrier *et al.*, 1997; Cai & Zhang, 2009), Late Middle Permian (Halpin *et al.*, 2016), Early Triassic (Carter *et al.*, 2001; Lepvrier *et al.*, 2004, 2008; Faure *et al.*, 2014) and Middle Triassic (Zhang *et al.*, 2013). The polarity of Palaeo-Tethyan subduction along the Song Ma Suture has also been debated with competing models for both north-directed subduction beneath South China (Lepvrier *et al.*, 2004, 2008; Zhang *et al.*, 2013), and south-directed subduction beneath Indochina (Hoa *et* *al*., 2008a, 2008b; Lepvrier *et al*., 2011; Liu *et al*., 2012; Faure *et al*., 2014; Lai *et al*., 2014a,b). Serpentinites in the suture zone are interpreted as representing original peridotite (lherzolitic harzburgite), comparable to Tethyan lherzolitic ophiolites (Trung *et al*., 2006) and Sm/Nd isochron dating of titanites from these indicate Middle Devonian–Upper Carboniferous (387–313 Ma) crystallisation ages (Nguyen Van Vuonga *et al*., 2013). Eclogites and granulites of the suture zone (Osanai *et al*., 2008; Nakano *et al*., 2010; Zhang *et al*., 2013) are variably interpreted as subduction-related (Nakano *et al*., 2010; Zhang *et al*., 2013), or related to plume activity that produced rifting in the Permian and the Emeishan basalt LIP (Chen *et al*., 2014; Shellnutt *et al*., 2015). The presence of Permian-Triassic rift-related magmatism and sedimentation in the Song Da rift and Song Hien Tectonic Zone needs to be incorporated into models for the Permian-Triassic evolution of the North Vietnam Orogenic Belt. Middle Permian–Early Triassic granitoids along the Trung Song belt are interpreted to record subduction (Liu *et al*., 2012). Metamorphic ages along the Song Ma zone are generally Permian–Triassic. Pelitic gneiss associated with granulites along the suture have provided an early Late Triassic U–Th–Pb age of 233 ± 5 Ma and the associated granulites have been interpreted as having formed in a crustal subduction environment (Nakano et al., 2008). 40Ar–39Ar dating of biotite and muscovite along the Trung Song belt yield Early to early Middle Triassic ages of 250–240 Ma (Maluski *et al*., 2005) indicating an Early Triassic thermo-tectonic event. Zhang *et al*. (2013) report a U–Pb SHRIMP zircon age of 230 ± 8.2 Ma (early Late Triassic) for the Song Ma eclogites and interpret this age to represent the closure age of the Palaeo-Tethys along the Song Ma suture. Detailed comparison of competing models for the evolution of northern Vietnam are beyond the scope of this paper. However, the growing body of geochronological and geochemical data in the region seem to support an Indochina-South China collision along the Song Ma Suture Zone in the Triassic following southwards subduction of the Palaeo-Tethys beneath Indochina. Permian rifting along the Song Da and Song Hien zones cannot therefore be back-arc related as this would require northwards subduction. Interestingly, Halpin *et al*. (2016) illustrate this rifting but do not indicate any genetic mechanism in the overall convergent setting they propose. The model here favoured is that of Faure *et al*. (2014) who advocate southwards subduction of Palaeo-Tethys beneath Indochina and concurrent plume generated rifting that was also responsible for the late Middle Permian Emeishan Large Igneous Province of South China (Figure 16). A land bridge connection between Indochina and South China is required in the Late Permian as indicated by the presence of the tetrapod *Dicynodon* in Laos (Battail, 2009).

Luang Prabang Suture Zone

There has long been debate regarding the relationship between the Simao Block of SW China and the Indochina block of Sundaland. It has been regarded as a northwards extension of the Indochina Block or as a separate block depending on acceptance of a suture or sutures (and hence an intervening ocean) between the blocks. In addition, some authors have identified the entire or part of the Simao Block as part of the Sukhothai Arc depending on varied correlations of suture zones in Thailand, Laos and SW China. Recent studies have provided vital new data on the SW-NE oriented Luang Prabang tectonic zone in Laos and the Dien Bien Phu fault zone in Vietnam that suggests that these zones do in fact represent a Palaeo-Tethyan suture zone, the Luang Prabang Suture, that separates the Simao Block from the Indochina Block. Qian *et al.* (2016) presented new geochronological and geochemical data from the Luang Prabang zone that indicates that the mafic rocks in this zone are Carboniferous in age (335.5 ± 3.3 Ma for a diabase dyke and 304.9 ± 3.9 Ma for basalt) and that the mafic rocks represent a continental back-arc basin which they correlate with the Nan-Uttaradit suture to the SW and the Jinshajiang–Ailaoshan suture zone to the north. Blanchard *et al*. (2013) and Rossignol *et al*. (2016) present evidence from the Luang Prabang Basin in Laos for a Triassic magmatic arc and they correlate the Luang Prabang Suture with the Nan-Uttaradit Suture. Rossignol *et al*. (2016) also indicate that the Luang Prabang Suture is contiguous with the Ailaoshan Suture in Yunnan and considered the Sukhothai Arc of Sone & Metcalfe (2008) to be part of the Simao Block. They did not however discuss the broader implications of this and they did not illustrate the Sukhothai Arc on their palaeogeographic reconstruction. In this paper, I follow the correlation of the Nan-Uttaradit suture with the Jinghong Suture as proposed by Sone & Metcalfe (2008) and treat the Simao block as a separate block but acknowledge a possible alternative model in which all or part of the Simao block may be part of the Sukhothai Arc.

Medial Sumatra Tectonic Zone
(Palaeo–Tethyan "Suture")

The Median Sumatra Tectonic Zone forms the boundary between the Cathaysian West Sumatra Block to the SW and the Gondwanan Sibumasu Terrane to the NE (Barber *et al*., 2005; Barber & Crow, 2009). This major fault zone, running NW–SE through Sumatra (Figures 2 and 3) comprises highly deformed rocks including lenses of massive marble, phlogopite, graphitic marble, scapolite–calc-silicate schist, garnetiferous augen gneiss, slate, phyllite, biotite–garnet–sillimanite schist, biotite–andalusite hornfels with cordierite, and chiastolite, quartzite, quartz–feldspar augen gneiss, migmatite, mylonite, and cataclasite (Barber & Crow, 2009). No ophiolites or components or remnants of rocks that would represent a former ocean basin are found within the zone and it therefore does not represent a true suture. It is interpreted as a major crustal shear zone or transcurrent fault along which the West Sumatra Block was translated westwards from the Sukhothai Arc/Indochina/ South China and emplaced outboard of the Gondwanan Sibumasu Terrane.

Sukhothai Back-Arc Suture Zones

Jinghong Suture Zone

The Jinghong Suture (Figures 2, 3, 9) includes melange, serpentinites tholeiitic basalts and cherts (Sone & Metcalfe, 2008). The suture zone hosts MORB-like basaltic andesites and gabbros (Nanlianshan volcano–plutonic complex). Fine-grained gabbro with a U–Pb zircon age of 292±1 Ma and εNd(t) of 5.3 is indicative of early Permian sea-floor spreading and a short-lived Permian ocean basin is indicated (Hennig *et al*., 2009). Deep-marine radiolarian cherts are of late Early, Middle and Late Permian age (Feng & Liu, 1993; Feng & Ye, 1996). The suture is equivalent to what has been previously referred to as the Lancangjiang Belt or the southern Lancangjiang Suture by some authors (Liu *et al*., 1991, 1996; Fang *et al*., 1994, 1996) and is here regarded as a segment of the Sukhothai back arc basin.

Nan–Uttaradit Suture

The Nan-Uttaradit Suture includes ophiolitic rocks of Late Carboniferous-Middle Triassic age including mélange composed of gabbro, tholeiitic metabasalt, andesite and radiolarian chert. Samples of gabbro and meta-basalt in the Nan-Uttaradit suture yield zircon U-Pb ages of 311±10 and 316±3 Ma, respectively, interpreted as the crystallization ages of the rocks, suggesting the Nan-Uttaradit Ocean already existed in the Late Carboniferous (Yang *et al*., 2016). Middle Triassic (Anisian) bedded radiolarian cherts are described from the suture zone by Saesaengseerung *et al*. (2008) and suture zone rocks are overlain by Jurassic–Cretaceous continental sediments. The Pha Som Metamorphic Complex within the suture includes blueschists, bedded cherts and basic/ultrabasic igneous rocks. Actinolite in mafic schist yields an early Middle Permian K–Ar age of 269 ± 12 Ma providing a minimum metamorphic age (Barr & Macdonald, 1987). The Nan–Uttaradit suture is now interpreted as representing a segment of the Sukhothai back-arc basin which opened in the Carboniferous and closed by the Late Triassic (Ueno & Hisada, 1999; Wang *et al*., 2000; Metcalfe, 2002b; Sone & Metcalfe, 2008).

Sra Kaeo Suture

The Sra Kaeo Suture (Figures 2, 3, 9 and 15) is a segment of the Sukhothai back arc basin in southern Thailand. It forms the boundary between the Chanthaburi terrane of the Sukhothai Arc in the west and the Indochina Block in the east (Sone *et al*., 2012). Ophiolitic rocks in the suture are represented by the Thung Kabin melange with clasts of bedded chert, limestone, serpentinite, gabbro, and basaltic pillow lavas. Bedded radiolarian cherts associated with pillow basalts in the Thung Kabin melange have been dated as Early Permian and late Middle to early Late Permian by radiolarians and conodonts (Hada *et al*., 1999; Saesaengseerung *et al*., 2009). In addition, cherts from the ‘‘Chert-Clastic Sequence’’ (Hada *et al*., 1999) have been dated as Middle Triassic (Sashida *et al*., 1997).

Meso -Tethys Sutures

The Meratus and Luk-Ulo suture zones form the boundary between the East Java–West Sulawesi Terrane and SW Borneo (Figures 2, 3, 15) and represent remnants of the destroyed Meso-Tethys Ocean.

Meratus Suture

The Meratus suture zone comprises an ophiolitic tectonic assemblage of slabs and blocks of high-pressure metamorphic rocks, ultramafic rocks and polymict melange with clasts of chert, limestone and basalt within a sheared shale matrix (Sikumbang, 1986; Sikumbang & Heryanto, 1994; Heryanto *et al*., 1994; Wakita *et al*., 1998; Wakita 2000; Wakita & Metcalfe, 2005). The ages of suture zone rocks range from Jurassic to early Late Cretaceous (Figure 15) and these are unconformably overlain by Late Cretaceous volcanic rocks and turbidites, such as the Pitap (Alino) and Haruyan (Pudak) Formations. All these Mesozoic rocks are then in turn unconformably covered by Eocene and younger formations.

Luk–Ulo Suture

The Luk-Ulo Suture Zone rocks include Meso-Tethys ophiolitic rocks comprising pillow basalt, dolerite, gabbro, serpentinized peridotite and lherzolite that have suffered zeolite to greenschist facies metamorphism (Suparka, 1988; Suparka & Soeria-Atmadja, 1991). Pillow basalts, pelagic chert, pelagic limestone, and hemipelagic shale, tuffaceous shale and sandstone are now incorporated as clasts in a melange complex. Pillow basalts are dated as Lower Cretaceous and pelagic limestone and chert clasts are dated as Lower to Upper Cretaceous in age (Wakita *et al*., 1994; Wakita, 2000; Figure15) and represent Cretaceous Ocean Plate Stratigraphy disrupted by subduction-accretion processes during the Late Cretaaceous. The Cretaceous suture zone rocks are unconformably overlain by the Eocene Karangsambung Formation.

Shan Boundary tectonic zone/suture

The Shan Boundary tectonic zone is marked by the Cenozoic Sagaing Fault and the Mogok Metamorphic Belt (MMB) in Myanmar and forms the boundary between the West Burma Block and the Sibumasu Terrane. The MMB includes a variety of paragneisses, orthogneisses and migmatites with multiple generations of leucogranites. Geochronological data suggest that the MMB may link north to the unexposed middle or lower crust rocks of the Lhasa terrane, south Tibet (Searle *et al*., 2007). There is no unequivocal evidence that the MMB represents a true suture zone representing a destroyed ocean basin. There are reports of Cretaceous carbonates with foraminifera, Jurassic-Cretaceous cherts with radiolaria, pelites and greenschists in the highly sheared narrow zone immediately west of the Sagaing Fault in the Mandalay region (Thein, 2015) suggesting possible remnants of the Meso-Tethys

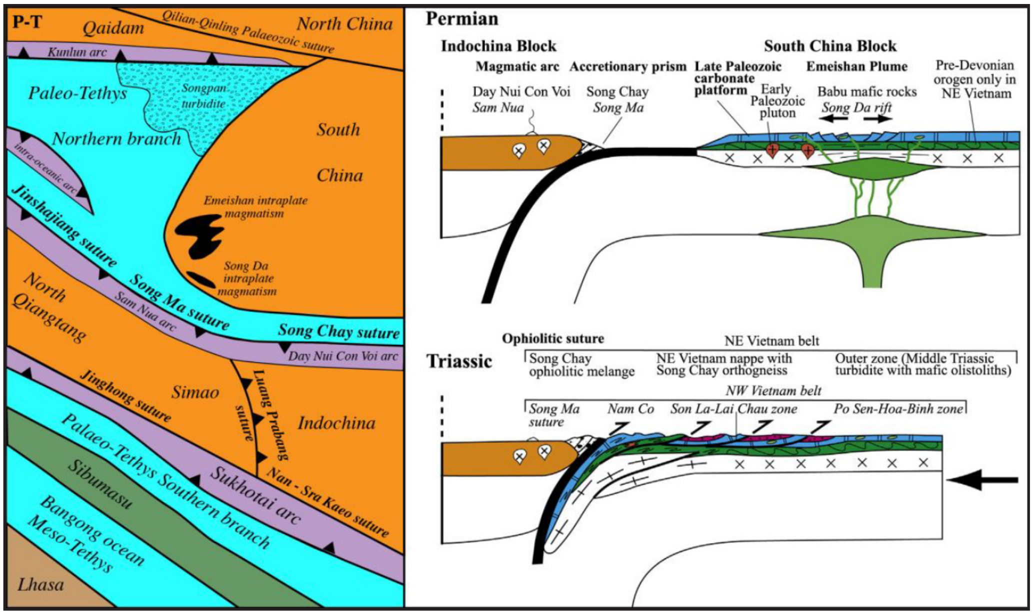

Figure 16: Conceptual Late Permian-Early Triassic paleogeodynamic reconstruction of the Indochina- South China-East Tibet area (left) and geodynamic evolution model of the NE and NW Vietnam belts (right). Note southwards subduction of Palaeo-Tethys beneath Indochina and concurrent plume-driven rifting and volcanism in South China. Modified after Faure *et al.* (2014).

ocean along what Hutchison (1975, 1989) referred to as the "Mandalay ophiolite belt" and which he linked with the Jade Mines Belt. However, Thein (2015) refers to these as occurring "N of the metamorphic bend" and these rocks appear to be the Tagaung-Myitkyina ophiolite belt recently dated as Middle Jurassic and correlated with the Meso-Tethys Bangong-Nujian suture of Tibet by Liu *et al*. (2016). Gardiner *et al*. (2016) regard both west and east Burma to be underlain by Sibumasu continental crust.

Boyan "Paleo-South China Sea" Suture

In the SW Sarawak - NW Kalimantan region of Borneo, a broad WNW-ESE oriented tectonic zone termed the Kuching Zone includes Cretaceous ophiolitic rocks and melanges. The zone is bounded to the NE by the Lupar Line which separates the Kuching Zone from the Sibu Zone (deep-water Rajang Group) and to the SE by the Schwaner Mountains. Most previous interpretations of the Kuching Zone have regarded the ophiolites and melanges as the result of southwards subduction of either the Proto-South China Sea, Paleo-South China Sea or an embayment of the Palaeo-Pacific ocean beneath SW Borneo, the Rajang Group as a subduction-related accretionary complex, and the Schwaner Mountains as the root of the subduction related Cretaceous Arc (Hamilton, 1979; Taylor & Hayes,1980; Holloway, 1981, 1982; Hinz *et al*.,1991; Hutchison, 1989, 1996, 2010; Moss, 1998; Clift *et al*., 2008). Middle Carboniferous-Lower Permian fusulinid limestones (Terbat Formation) within the Kuching Zone and exposed close to the Sarawak-Kalimantan border south of Kuching near Terbat Village contain a Cathaysian foraminiferal-conodont fauna (Cummings, 1962; Sanderson, 1966; Vachard, 1990; Fontaine, 2002) and were regarded as forming part of the continental core of the SW Borneo Block. Identification of Cretaceous ophiolitic rocks to the south of the Terbat Limestone in NW Kalimantan (Williams *et al*., 1988) led Metcalfe (1990) to interpret these as a suture which was named the Boyan Suture. Melange in the suture extends for over 200 km in a belt 5– 20 km width and includes fragments and blocks of a wide variety of sedimentary and igneous rocks in a pervasively sheared pelitic matrix, including limestone blocks of Cenomanian age and Cretaceous radiolarian cherts. Metcalfe (1990) also proposed an allochthonous continental fragment, the Semitau Block, sandwiched between the Lupar Line and the Boyan Suture. This interpretation is followed here and this deconstructs the Terbat Formation from core SW Borneo as interpreted by Metcalfe (2011b, 2013a). There is now mounting evidence that suggests no subduction occurred beneath Sarawak, SW of the West Baram Line, between the Eocene and Early Miocene and that the oceanic lithosphere subducted beneath Sarawak in the Cretaceous should not be referred to as the "Proto-South China Sea" and this term should be restricted to the oceanic lithosphere subducted beneath northern Borneo and Cagayan in the Eocene to Early Miocene (Hall & Breitfeld, this volume). The term "Paleo-South China Sea" (Gatinsky & Hutchison, 1986) may be appropriate for the Mesozoic oceanic crust subducted beneath Sarawak in the Cretaceous. For a comprehensive discussion of the terms and usage of "Proto-South China Sea" and "Paleo-South China Sea" please see Hall & Breitfeld (this volume).

TECTONIC AND PALAEOGEOGRAPHIC EVOLUTION OF SUNDALAND

Multi-disciplinary studies, including tectonostratigraphy, biogeography, palaeoclimatology, geochemistry, geochronology, palaeomagnetism and provenance studies (especially detrital zircon age spectra) have established that all the continental blocks of Sundaland together with other continental blocks of East and SE Asia had their origins, either directly or indirectly, in the southern hemisphere on the Arabia-Himalaya-NW Australia margin of eastern Gondwana (e.g. Stauffer, 1974, 1983; Ridd, 1980; Audley-Charles, 1983, 1984, 1988; Sengör, 1984, 1987; Metcalfe,

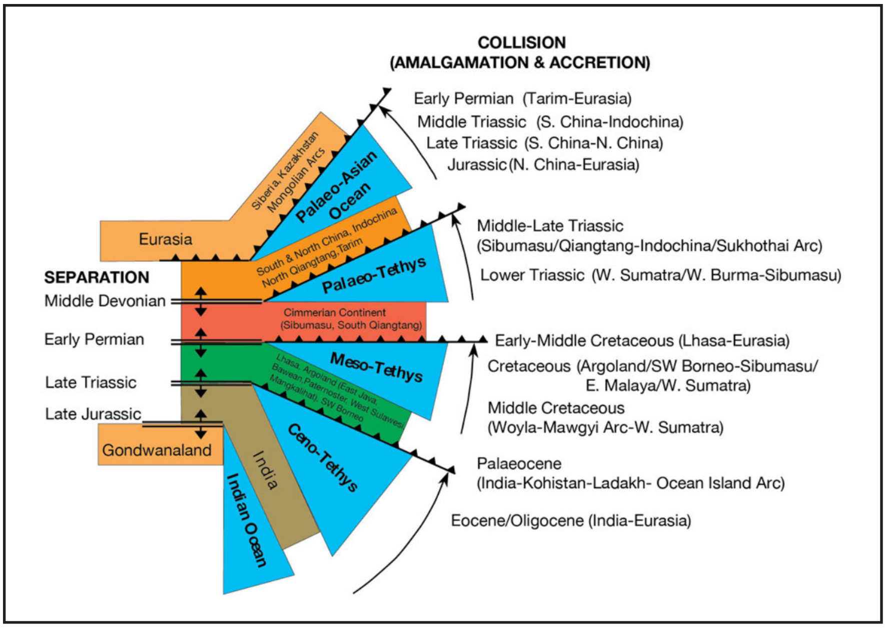

Figure 17: Schematic diagram showing times of separation and subsequent collision of the three continental slivers/collages of terranes that rifted from Gondwana by the opening and closure of three successive oceans, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys. Modified after Metcalfe (2011b, 2013a).

1984, 1988, 1990, 1991, 1994, 1996a, 1996b, 1998, 1999, 2001, 2005, 2006, 2011a, 2011b, 2013a; Burrett & Stait, 1985; Burrett *et al*., 1990, 2014; Smyth *et al*., 2007; Villeneuve *et al*., 2010; Metcalfe & Aung, 2014). The Phanerozoic evolution of Sundaland (and East and SE Asia) is characterised by the successive rifting and separation of three continental slivers (or collages of continental blocks) from the Gondwana margin, their northwards translation, and subsequent collision to form Sundaland and East and SE Asia. This Gondwana dispersion and Asian accretion process took place in three phases in the Early Devonian, late Early Permian and Late Triassic-Jurassic with the opening of successive Palaeo-Tethys, Meso-Tethys and Ceno-Tethys ocean basins between the separating continental strips and Gondwana (Figure 17).

Cambrian-Ordovician-Silurian evolution and palaeogeography

Whilst there is general agreement that East and SE Asian continental blocks were located on the margin of eastern Gondwana in the early Palaeozoic, there continues to be debate relating to the specific sites of origin for specific blocks. Recent new data from detrital zircon age spectra and heavy mineral studies have provided valuable new constraints on the palaeo-positions of Asian blocks along the Gondwana margin (Leier *et al*., 2007; Sevastjanova *et al*., 2011; Hall & Sevastjanova, 2012; Zhu *et al*., 2013; Burrett *et al*., 2014; Cai *et al*., 2017). In addition, there has been new data, mainly geochronological and geochemical, suggesting that a narrow "Proto-Tethys ocean" (or oceans) may have existed between some Asian blocks and eastern Gondwana in the Ordovician (Li *et al*., 2008; Wang *et al*., 2008, 2015; Li *et al*., 2010; Zhai *et al*., 2010; Mao *et al*., 2012; Wu, 2013; Deng *et al*., 2014; Nie *et al*., 2015) and that the "Proto-Tethys" was destroyed by eastwards subduction and collision of Asian blocks with Gondwana in the Silurian (Zhang *et al*., 2014) prior to the opening of the Palaeo-Tethys in the Devonian. Other models favour Cambrian collision of North China and Tarim with Gondwana and their subsequent separation from Gondwana in the Devonian (Han *et al*., 2016) and do not recognise a "Proto-Tethys" ocean. Detailed discussion of current debates relating to the "Proto-Tethys" ocean are beyond the scope of this paper and will not be considered further here. Figure 18 shows palaeogeographic reconstructions for the Early Ordovician and Late Silurian showing interpreted locations of Sundaland and other Asian blocks on the Arabia-Himalaya-NW Australia margin of eastern Gondwana.

Devonian-Carboniferous-Permian evolution and palaeogeography

Zircon Hf and geological data indicate that in the Early Devonian there was a major shift in accretionary orogens along the northern margins of Tarim and North China from advancing to retreating mode, possibly caused by slab rollback of the subducting Palaeo–Asian Ocean plate (Han *et al*., 2016). This coincides with the separation of South China, Tarim, Indochina, North Qiangtang, Simao, and North China from Gondwana and the opening of the Palaeo-Tethys ocean (Figure 19). The northwards movement of these blocks is recorded in their palaeomagnetic data (Figure 6) and biogeographic affinities of biota on these blocks also changes from southern hemisphere Gondwanan to palaeoequatorial Cathaysian/Tethyan at this time (Figure 11).

In Early Permian (late Sakmarian) times, the Cimmerian continental strip (Sengör, 1984) including the South Qiangtang, Baoshan and Tengchong blocks of Tibet and Yunnan, and the Sibumasu Terrane of Sundaland separated from eastern Gondwana and the Meso-Tethys ocean basin opened between these separating blocks and Gondwana (Figure 17). In the early Permian, prior to and during rifting of Sibumasu, icebergs originating on the glaciated Gondwana continent deposited distinctive glacial-marine deposits (with dropstones) on Sibumasu (Figure 20). These glacial-marine

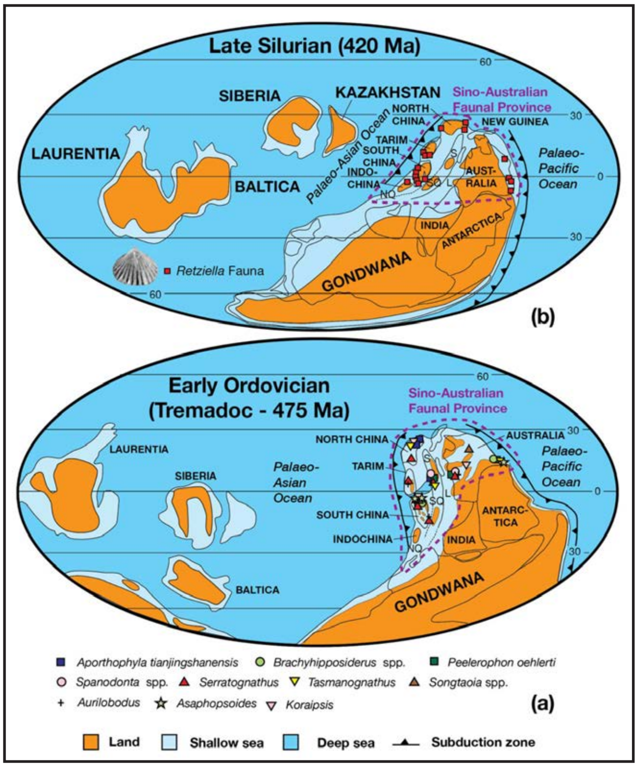

Figure 18: Palaeogeographic reconstructions for (A) Early Ordovician and (B) Late Silurian showing the postulated positions of Sundaland and other Asian continental blocks on the Arabia-Himalaya–Australia margin of Gondwana and Sino-Australian province faunas linking the Asian blocks with Australia. I = Indochina/East Malaya/West Sumatra/West Burma; SQ = South Qiangtang; L = Lhasa; S = Sibumasu. Modified after Metcalfe (2011b, 2013a).

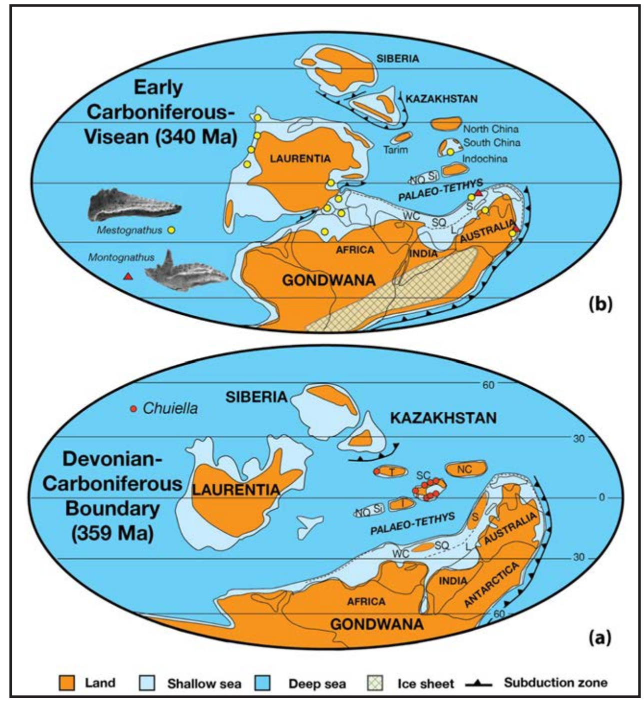

Figure 19: Palaeogeographic reconstructions of eastern Gondwana at (a) Devonian–Carboniferous boundary and (b) Early Carboniferous (Visean) times showing interpreted positions of the Sundaland and East and Southeast Asian terranes. Also shown is the distribution of the endemic Tournaisian brachiopod genus *Chuiella* and the biogeographic distributions of the conodont genera *Mestognathus* (Illustrated specimen from the Kanthan Limestone, Peninsular Malaysia) and *Montognathus* (*Montognathus carinatus* from Peninsular Malaysia illustrated). NC = North China; SC = South China; T = Tarim; I = Indochina/East Malaya/West Sumatra/West Burma; SQ = South Qiangtang; NQ–QS = North Qiangtang–Qamdo–Simao; L = Lhasa; S = Sibumasu; and WC = Western Cimmerian Continent. Modified after Metcalfe (2011b, 2013a).

deposits include diamictites, shallow-marine clastics on horsts, and deeper-water turbiditic deposts in rift-related graben structures (Stauffer & Mantajit, 1981; Metcalfe, 1988, 2013a; Stauffer & Lee, 1989; Ampaiwan *et al*., 2009; Ridd, 2009; Meor *et al*., 2014). Early Permian faunas and floras of the region also show marked provinciality and the Gondwana-Cathaysia biogeographic divide in Sundaland and east Asia, which corresponds to the trace of the main Palaeo-Tethys suture zones (Figure 2) is a prominent feature of the region (Figure 20). As the Sibumasu Terrane moved northwards, faunal affinities changed from peri-Gondwanan Westralian Province to an endemic Sibumasu province and then to Cathaysian Province (Figures 20, 21).

During the Permian the North China, South China, Indochina, North Qiangtang and Simao blocks were located in equatorial to low latitude northern hemisphere positions within the Palaeo-Tethys ocean (Figure 21). In Early Permian times, Sibumasu was still attached to the India-Australian margin of Gondwana and deposition of ice-rafted glacial-marine deposits occurred on this terrane (Figure 21a). The Palaeo-Tethys was subducted northwards beneath Indochina and NE Pangea. The Sukhothai Arc was developed on the margin of Indochina and was separated from Indochina by back-arc extension, and a narrow back-arc basin now represented by the Jinghong, Nan-Uttaradit and Sra Kaeo suture zones was opened. Branches of the Palaeo-Tethys between South China and Indochina (Song Ma Suture Zone) and between North Qiangtang-Simao and Indochina (Luang Prabang Suture Zone) were subducted southwards and eastwards respectively. By late Early Permian times Sibumasu was rifting and separating from Gondwana (Figure 21b) and marine faunas of the region exhibited markedly different warm equatorial and cool peri-Gondwana southern and northern provinces. By Late Permian times (Figure 21c) Sibumasu (as part of the Cimmerian continent) had drifted northwards towards its collision with the Sukhothai Arc and Indochina and the Meso-Tethys was by this time a wide ocean to the south. The Meso-Tethys had also began to subduct southwards beneath the India-Australia margin of Gondwana (Metcalfe, 2013a). A land connection between Indochina and Pangea via South and North China is indicated by the occurrence of the tetrapod *Dicynodon* in Laos (see Figure 21c).

During the Middle Permian to early Late Triassic, subduction-related I-type granites intruded the Sukhothai Arc and Indochina margin. New geochemical and U-Pb zircon geochronology from the Malay Peninsula clearly

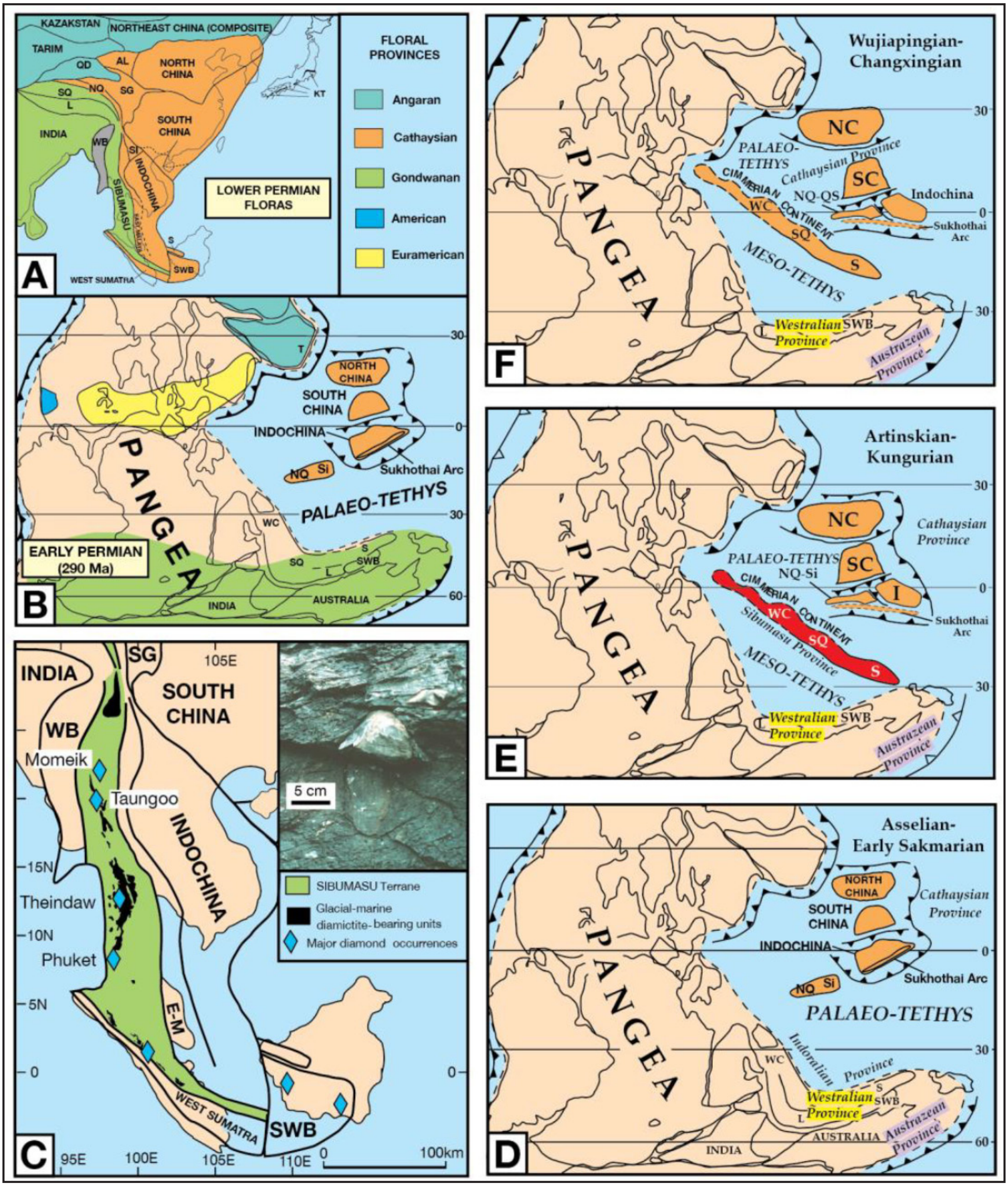

Figure 20: Distribution of Early Permian floral provinces in extant east Asia (A) and on an Early Permian palaeogeographic reconstruction (B); Distribution of Early Permian glacial-marine diamictites (glacial dropstone shown in inset) and western Australian-derived diamonds in SE Asia (C); and palaeogeographic reconstructions (D, E, F) showing the changing biotic provinces on the Sibumasu Terrane as it moved northwards from high southern to equatorial latitudes during the Permian (Shi & Archbold, 1998). After Metcalfe (2002, 2011a,b, 2013a). WS = West Sumatra; SWB = South West Borneo; S = Semitau; L = Lhasa; SQT = South Qiangtang; NQ = North Qiangtang; SI = Simao; SG = Songpan Ganzi accretionary complex; QD = Qaidam; AL = Ala Shan; KT = Kurosegawa Terrane; NC = North China; SC = South China; T = Tarim; I = Indochina; SQ = South Qiangtang; NQ–QS = North Qiangtang–Qamdo–Simao; S = Sibumasu; WB = West Burma; and WC = Western Cimmerian Continent.

demonstrate this (Ng *et al*., 2015a, 2015b) and the ages of granites in the east Malaya block of the Sukhothai Arc trend from older to younger from east to west consistent with eastwards (originally northwards) subduction polarity (Figure 22).

Triassic-Jurassic-Cretaceous evolution and palaeogeography

Triassic evolution of Sundaland and East and SE Asia saw major collisional events that represent in a broad sense the Indosinian Orogeny. The Sibumasu Terrane collided with the Sukhothai Arc and Indochina in the Middle to Late Triassic and the main Palaeo-Tethys ocean was closed along the Chiang Mai-Chiang Rai, Chanthaburi and Bentong-Raub suture zones and the short-lived Sukhothai back-arc basin collapsed at the same time forming the Jinghong, Nan-Uttaradit and Sra Kaeo suture zones (Figure 6). During the collision between Sibumasu and the Sukhothai Arc and Indochina, Sibumasu continental crust was thickened and melted to produce voluminous S-Type granites of mainly Late Triassic (but also including minor earliest Jurassic) age (Searle *et al*., 2012; Ng *et al*., 2015b; Figure 22). These Late Triassic granites stitched the Bentong-Raub Suture Zone (Figure 23). The Cathaysian West Sumatra block interpreted as possibly originally part of the Sukhothai Arc, now located outboard of Sibumasu, was probably emplaced by strike-slip translation in the Late Triassic (Barber & Crow, 2009; Metcalfe, 2013a). The West Burma Block, also located outboard of Sibumasu in Myanmar, was also interpreted as a Cathaysian block similarly emplaced (Barber & Crow, 2009) but is here regarded as a probable disrupted part of Sibumasu (Gardiner *et al.*, 2016).

By Late Triassic times the principal continental core blocks of Sundaland (Sibumasu, Sukhothai Arc, Simao, Indochina) had amalgamated and collided with South and North China to form proto-East and SE Asia (Figure 24). The Palaeo-Tethys was closed by this time apart from a remnant basin which would become the Songpan Ganzi suture knot (Figure 23). The Meso-Tethys was now a wide ocean basin and the collision between Sibumasu and the Sukhothai Arc and Indochina had initiated northwards subduction of Meso-Tethys beneath Sibumasu (Searle *et al*., 2012; Metcalfe, 2013a; Ng *et al*., 2015b). Southwards subduction of Meso-Tethys beneath SE Pangea initiated rifting of the India-Australia Pangea margin and led to separation of the Lhasa, East Java-West Sulawesi and SW Borneo blocks from Gondwana and opening of the Ceno-Tethys ocean in the Jurassic, and their accretion to Sundaland and mainland Asia by the Late Cretaceous (Figure 25). The Woyla Arc interpreted as a Ceno-Tethys intra-oceanic arc (together with the Kohistan- Ladakh Arc - the ‘‘Incertus’’ arc of Hall, 2011) also accreted to SW Sundaland in the Late Cretaceous (Metcalfe, 2013a). By Late Cretaceous time the continental core of Sundaland had been constructed and it formed a SE promontory of East Asia.

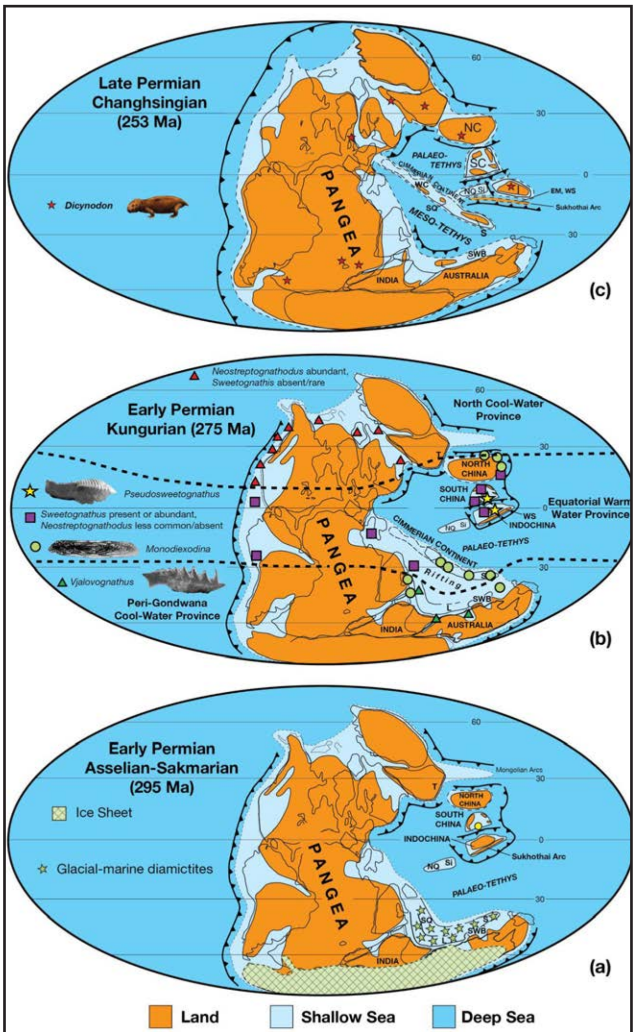

Figure 21: Palaeogeographic reconstructions of the Tethyan region for (A) Early Early Permian (Asselian–Sakmarian), (B) Late Early Permian (Kungurian) and (C) Late Permian (Changhsingian) showing relative positions of the East and Southeast Asian terranes and distribution of land and sea. Also shown is the Late Early Permian distribution of biogeographically important conodonts, and Late Permian tetrapod vertebrate *Dicynodon* localities on Indochina and Pangea in the Late Permian. SC = South China; T = Tarim; I = Indochina; EM = East Malaya; WS = West Sumatra; NC = North China; SI = Simao; S = Sibumasu; WB = West Burma; SQ = South Qiangtang; NQ–QS = North Qiangtang–Qamdao–Simao; L = Lhasa; SWB = South West Borneo; and WC = Western Cimmerian Continent. After Metcalfe (2011b, 2013a).

Cenozoic evolution and palaeogeography

Detailed discussion of the Cenozoic evolution of Sundaland and SE Asia is beyond the scope of this paper but some brief observations and references for further reading are here presented. The Cenozoic evolution of Sundaland and the surrounding SE Asia region involved substantial rotations of continental blocks and oceanic plates, disruption by major movements along strike-slip faults, the development and spreading of ‘marginal’ seas, and the formation of important hydrocarbon-bearing sedimentary basins (Hall, 2009c; Hall & Morley, 2004; Pubellier & Morley, 2014). This evolution was driven by convergent interactions of the Eurasian, Pacific, and Indo-Australian plates and the collisions of

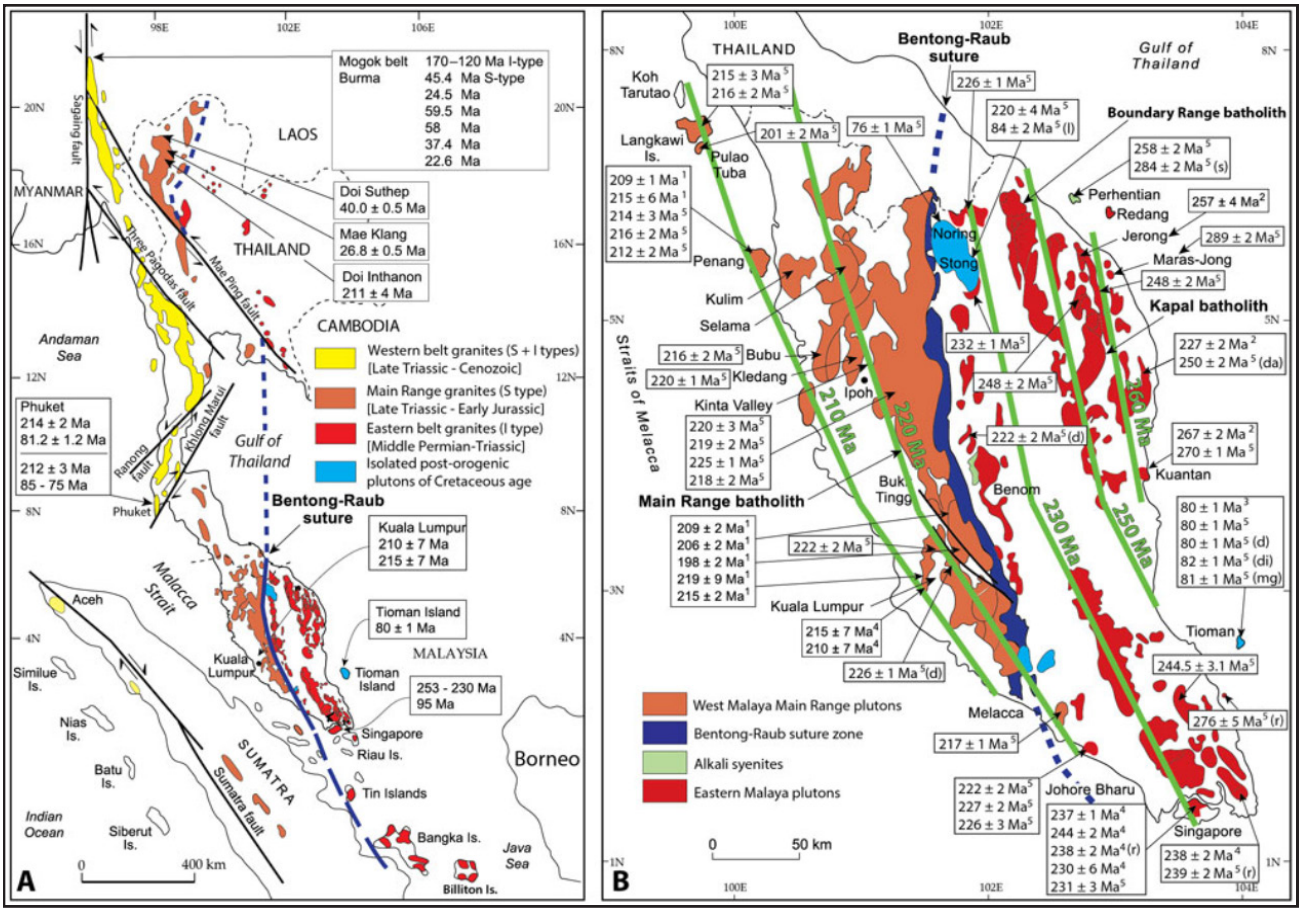

Figure 22: The three main granite provinces of SE Asia (A) and granite plutons of the Malay Peninsula (B), compiled from Cobbing *et al*. (1986), Searle *et al*. (2012) and Ng *et al*. (2015a, 2015b). Ages shown are all U–Pb zircon ages. Ages in (A) from Searle *et al*. (2012); Ages for the Malay Peninsular: 1 Liew (1983) and Liew & Page (1985); 2 Liew (1983) and Liew & McCulloch (1985); 3 Hotson *et al*. (2011), and Oliver *et al*. (2011, 2014); 4 Searle *et al*. (2012) and 5 Ng *et al*. (2015b). Also shown in (B) are U-Pb zircon geochronological isoclines (Ng *et al*., 2015b) illustrating the westwards younging of granitoid plutons. (d) = granitic dyke; (da) = dacite; (di) = diorite; (l) = leucogranite; (mg) = microgranite; (r) = rhyolite; (s) = syenite.

India with Eurasia and of Australia with Southeast Asia (Hall, 1996, 2002, 2013). Different tectonic models for the Cenozoic of the region invoke different mechanisms for the India–Eurasia collision and apply differing interpretations of rotations of continental blocks and oceanic plates. There is continued debate regarding the nature and timing of the collision of India with Eurasia and the effects of this collision on Sundaland and SE Asia. Three principal models have been proposed for the collision of India with Eurasia. The first proposes underthrusting of greater India beneath Eurasia (Powell & Conaghan, 1973; Zhao *et al*., 1993; Zhou & Murphy, 2005), the second involves crustal shortening and thickening (Chang *et al*., 1986; Dewey & Burke, 1973; Dewey *et al*., 1988); and the third involves major eastwards lateral extrusion with large displacements along strike-slip faults and progressive clockwise rotations of China, Indochina, and Sundaland (Tapponnier *et al*., 1982, 1986). The nature and size of “Greater India” proposed in various models has also been subject to significant debate (e.g. Ran *et al*., 2012; van Hinsbergen *et al*., 2011; Ali & Aitchison, 2014). Another on-going debate relates to whether there was a single continent-continent collision (Patriat & Achache, 1984; Lee & Lawver, 1995) or whether India first collided with an intra-oceanic arc (Kohistan–Ladakh-Woyla Arc), and then with Eurasia (Aitchison *et al*., 2007; Hall *et al*., 2008; Zahirovic *et al*., 2012; Bouilhol *et al*., 2013; Metcalfe, 2013a). The timing of collision between India and Eurasia is also still hotly debated and a range of constraining data including sedimentation patterns and in particular beginning of continental molasse deposition (Searle *et al*., 1987; Aitchison *et al*., 2007), changes in arc magmatism and gechemistry (Bouilhol *et al*., 2013; Zhu *et al.*, 2015), oceanic and continental palaeomagnetism (Molnar & Taponnier, 1975; Patriat & Achache, 1984; Klootwijk *et al*., 1992; Lee & Lawver, 1995), ocean floor record and microplate formation (Matthews *et al*., 2016) and mantle tomography (van der Voo *et al*., 1999; Replumaz *et al*., 2004; Hafkenscheid *et al*., 2006) have resulted in a wide range of estimates for the collision that vary between 60 Ma (Yin, 2010) to 35Ma (Aitchison *et al*., 2007; Ali & Aitchison, 2008). It now seems that a complex multi-collision model is most likely with India colliding with the Kohistan-Ladakh Arc around 55-50 Ma and then with Eurasia between 40 and 30 Ma (Figure 25).

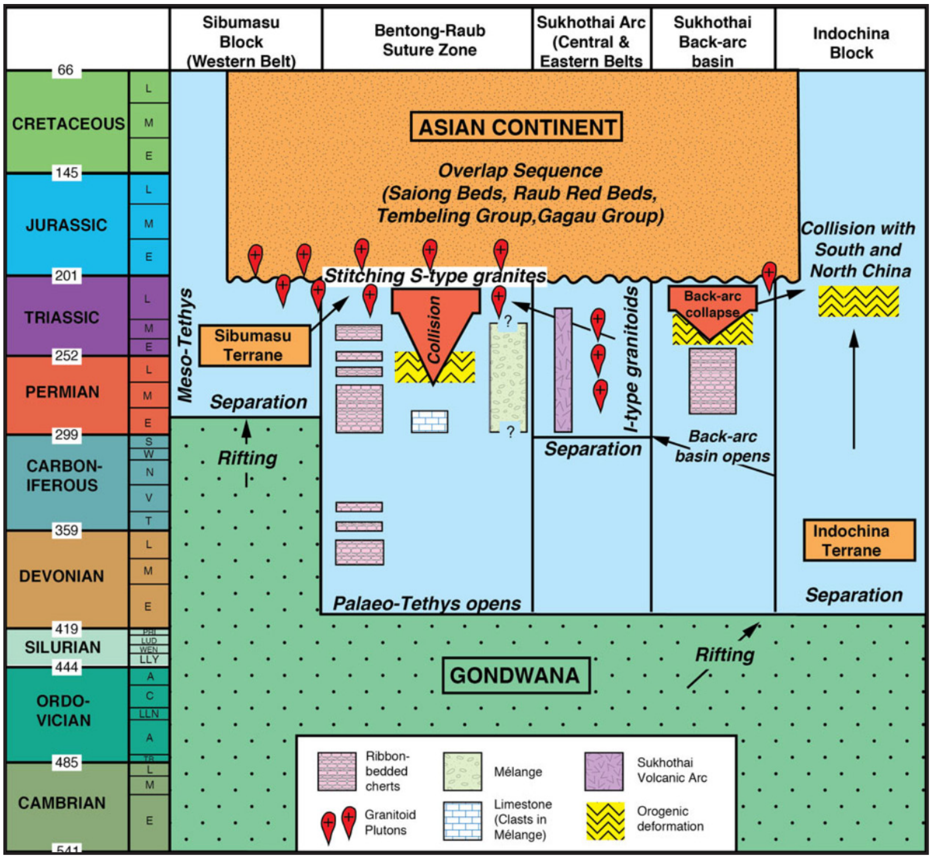

Figure 23: Space–time diagram illustrating the tectonic evolution of the Malay Peninsula. Modified after Metcalfe (2000, 2013b).

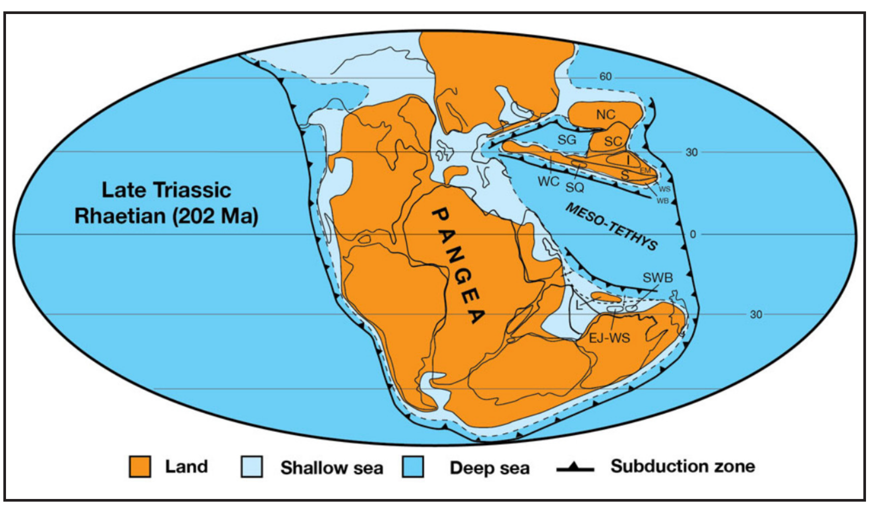

Figure 24: Palaeogeographic reconstruction of the Tethyan region for the Late Triassic (Rhaetian) showing relative positions of the East and Southeast Asian terranes and distribution of land and sea. NC = North China; SG = Songpan Ganzi; SC = South China; WC = Western Cimmerian Continent; SQ = South Qiangtang block; I = Indochina block; S = Sibumasu terrane; EM = East Malaya block; WS = West Sumatra block; WB = West Burma block; L = Lhasa block; EJ-WS = East Java-West Sulawesi terrane; SWB = South West Borneo. After Metcalfe (2013a).

Cenozoic clockwise rotations of crustal blocks are observed in Indochina and western Thailand, but major progressive counter-clockwise rotations are seen in Borneo and the Malay Peninsula. Counter-clockwise rotations observed in Borneo and Malaya, and less than expected displacements along major strike slip faults are at variance with the extrusion model. Most models for the region fail to accommodate the clockwise rotation of the Philippine Sea Plate and/or the counter-clockwise rotation of Borneo. The Cenozoic reconstruction model proposed by Hall (2002, 2012), which takes into account both the clockwise rotation of the Philippine Sea Plate and the counter-clockwise rotation of Borneo and Peninsular Malaysia, is here preferred. However, further detailed palaeomagnetic and structural studies are required to distinguish between competing tectonic models for the Cenozoic evolution of the region.

ACKNOWLEDGEMENTS

I congratulate the Geological Society of Malaysia on its 50th Anniversary and gratefully acknowledge the GSM for providing stimulating opportunities for discussion of the geological evolution and palaeogeography of Sundaland and SE Asia. Many members of the GSM, too many to name here, have and continue to provide valuable discussions on the

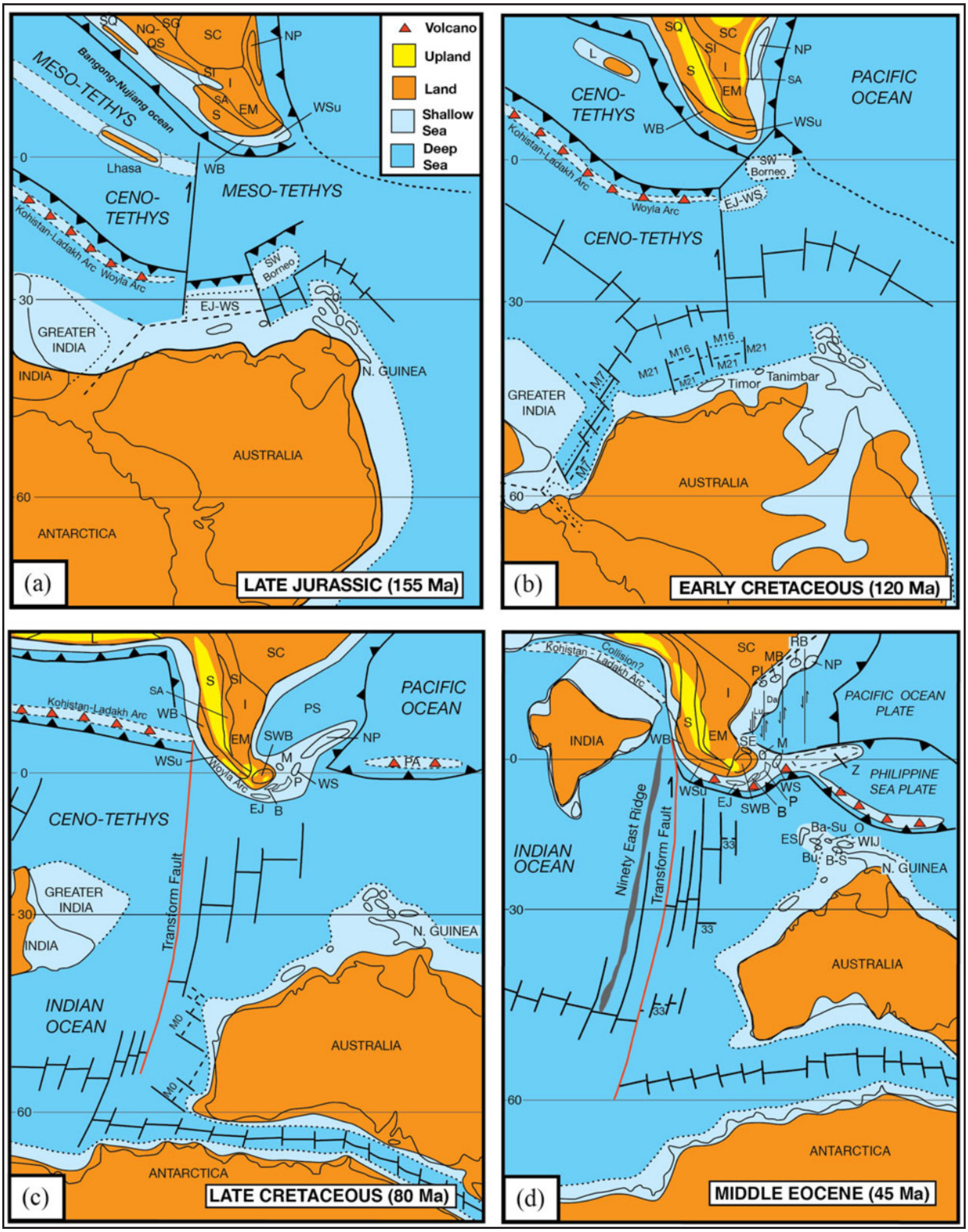

Figure 25: Palaeogeographic reconstructions for Eastern Tethys in (A) Late Jurassic, (B) Early Cretaceous, (C) Late Cretaceous and (D) Middle Eocene showing distribution of continental blocks and fragments of Southeast Asia – Australasia and land and sea. After Metcalfe (2011b). SG = Songpan Ganzi accretionary complex; SC = South China; NQ– QS = North Qiangtang-Qamdo –Simao; SI = Simao; SQ = South Qiangtang; S = Sibumasu; I = Indochina; EM = East Malaya; WSu = West Sumatra; L = Lhasa; WB = West Burma; SWB = Southwest Borneo; SE = Semitau; NP = North Palawan and other small continental fragments now forming part of the Philippines basement; Si = Sikuleh; M = Mangkalihat; WS = West Sulawesi; PB = Philippine Basement; PA = Incipient East Philippine arc; PS = Proto-South China Sea; Z = Zambales Ophiolite; Rb = Reed Bank; MB = Macclesfield Bank; PI = Paracel Islands; Da = Dangerous Ground; Lu = Luconia; Sm = Sumba. M numbers represent Indian Ocean magnetic anomalies.

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