Tectonic framework and Phanerozoic evolution of Sundaland

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A B S T R A C T

Sundaland comprises a heterogeneous collage of continental blocks derived from the India–Australian margin of eastern Gondwana and assembled by the closure of multiple Tethyan and back-arc ocean basins now represented by suture zones. The continental core of Sundaland comprises a western Sibumasu block and an eastern Indochina–East Malaya block with an island arc terrane, the Sukhothai Island Arc System, comprising the Linchang, Sukhothai and Chanthaburi blocks sandwiched between. This island arc formed on the margin of Indochina–East Malaya, and then separated by back-arc spreading in the Permian. The Jinghong, Nan–Uttaradit and Sra Kao Sutures represent this closed back-arc basin. The Palaeo-Tethys is represented to the west by the Changning–Menglian, Chiang Mai/Inthanon and Bentong–Raub Suture Zones. The West Sumatra block, and possibly the West Burma block, rifted and separated from Gondwana, along with Indochina and East Malaya in the Devonian and were accreted to the Sundaland core in the Triassic. West Burma is now considered to be probably Cathaysian in nature and similar to West Sumatra, from which it was separated by opening of the Andaman Sea basin. South West Borneo and/or East Java–West Sulawesi are now tentatively identified as the missing “Argoland” which must have separated from NW Australia in the Jurassic and these were accreted to SE Sundaland in the Cretaceous. Revised palaeogeographic reconstructions illustrating the tectonic and palaeogeographic evolution of Sundaland and adjacent regions are presented.

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1. Introduction

Geographically, Sundaland comprises the Malay Peninsula, Sumatra, Java, Borneo and Palawan which are all located on the shallow-water Sunda Shelf that was exposed as land during low sea level stands in the Pleistocene (Bird et al., 2005). Biogeographically, Sundaland is a globally important hot spot of biodiversity (Sodhi and Randhawa, 2004). Sundaland is a globally important hot spot of biodiversity (Sodhi and Randhawa, 2004).

Mainland eastern Asia (with Sundaland at its core) comprises a complex assembly of continental blocks, arc terranes, suture zones and accreted continental crust (Figs. 2 and 3).

2. Tectonic framework of Sundaland and adjacent regions

2.1. Continental blocks of Sundaland

The principal continental blocks that form the core of Sundaland have been identified and established over the last two decades (e.g. Metcalfe, 1984, 1986, 1988, 1990, 1996a, 1998, 2002, 2006) and include the South China block, the Indochina–East Malaya block(s), the Sibumasu block, West Burma block and SW Borneo block (Fig. 3). More recently, the West Sumatra block has been established outboard of Sibumasu in SW Sumatra (Barber and Crow 2003, Barber and Crow in press: Barber et al., 2005) and a volcanic arc terrane is now identified, sandwiched between Sibumasu and Indochina–East Malaya (Sone and Metcalfe, 2008).

The continental terranes of Sundaland and adjacent regions can be categorised into six types based on their specific origins and timing of rifting and separation from Gondwana and amalgamation/accretion.
to form SE Asia. These are discussed below under those six categories and the suture zones of the region are briefly described separately.

2.1.1. Continental blocks derived from Gondwana in the Devonian

The South China, Indochina and East Malaya blocks are interpreted to have formed part of the India–Australian margin of Gondwana in the Early Palaeozoic and to have rifted and separated from Gondwana by the opening of the Palaeo-Tethys ocean in the Early Devonian (Metcalfe, 1984, 1988, 1990, 1996a, b, 1998, 2002, 2005, 2006). The West Sumatra block (originally proposed by Hutchison, 1984 and Barber and Crow, 2003) and possibly the West Burma block (originally called the “Mount Victoria Land Block” by Mitchell, 1986, 1989) are now also interpreted to have originally formed part of this collage of terranes (which also included North China and Tarim) that separated from Gondwana in the Devonian (Barber et al., 2005; Metcalfe, 2005; Barber and Crow, in press; Metcalfe, 2009a). For more detailed description of these blocks and assessment of the evidence for Gondwana origin see Metcalfe (1988, 1996a, 2006).

The Late Palaeozoic faunas and floras of these continental blocks are warm-water, equatorial Tethyan/Cathaysian Province biotas that contrast starkly with coeval cold-water and cold-climate Gondwana biotas (Metcalfe, 2005). This indicates that these terranes had already separated from Gondwana by Carboniferous times and migrated northwards to more equatorial palaeolatitudes. This is supported by palaeomagnetic data (Zhao et al., 1996; Li and Powell, 2001; Li et al., 2004; see Fig. 4).

2.1.2. Arc terranes derived from South China/Indochina in the Carboniferous–Permian

Re-interpretation of the Nan–Uttaradit Suture as a probable back-arc suture which does not represent the main Palaeo-Tethys ocean (Wu et al., 1995; Ueno, 1999; Ueno and Hisada, 1999, 2001; Wang et al., 2000) and correlation of this suture with the Sra Kaeo Suture in southern Thailand and the Jinghong Suture in southern China led Sone and Metcalfe (2008) to propose the Sukhothai Arc System which was interpreted as being derived from the margin of South China–Indochina–East Malaya by back-arc spreading in the Late Carboniferous–Early Permian following the previous suggestion of Ueno and Hisada (1999). This arc terrane is represented by the Lincang block in SW China, the Sukhothai block in Central Thailand and the Chanthaburi block in SE Thailand–Cambodia (Fig. 3). The Sukhothai Arc terrane is here interpreted to have a thin continental basement that formed the margin of the South China–Indochina–East Malaya super-terrane. The arc separated from Indochina by back-arc spreading in the Early–Middle Permian and was then accreted to Indochina by back-arc collapse in the Late Permian (Fig. 5). Extension of this arc terrane into the Malay Peninsula is equivocal and the previously recognised East Malaya block may form this continuation,
but a more likely extension is beneath the Central Belt of the Malay Peninsula (Fig. 3) that forms a gravity high (Ryall, 1982).

2.1.3. Continental blocks derived from Gondwana in the Early Permian

At the end of the Sakmarian stage of the Early Permian the elongate Cimmerian continental strip (Sengör, 1984) separated from eastern Gondwana. The eastern portion of this Cimmerian continent includes the Baoshan and possibly the Tengchong blocks of Yunnan, China (Jin, 1994; Wopfner, 1996), and the Sibumasu block (Metcalfe, 1984). These eastern Cimmerian blocks are characterised by Late Palaeozoic Gondwana faunas and floras and by Late Carboniferous–Early Permian glacial-marine diamictites which are interbedded with other marine clastics and turbidites that fill rift grabens (Jin, 1994; Wopfner, 1996; Wang et al., 2001). Metcalfe (1996a) included the Qiangtang and Lhasa blocks as part of the separating eastern Cimmerian continent, but recognised the later docking of the Lhasa block to Eurasia in the Late Jurassic/Early Cretaceous. Metcalfe (1988) included the Qiangtang and Lhasa blocks as part of the separating eastern Cimmerian continent, but recognised the later docking of the Lhasa block to Eurasia in the Late Jurassic/Early Cretaceous. Metcalfe (1988 and subsequent papers) retained the Lhasa block on the margin of Gondwana until the Late Triassic, a scenario supported by Golonka et al. (2006). Other authors (e.g. Baud et al., 1993; Dercourt et al., 1993) have maintained an Early Permian separation of Lhasa as part of the "Mega-Lhasa" Block. A Triassic–Jurassic separation is still advocated here as proposed and discussed by Metcalfe (1996a).

The term Sibumasu block, was proposed by Metcalfe (1984) to replace previous terms used for the elongate Gondwana-derived block in SE Asia characterised by Late Palaeozoic Gondwana faunas and Late Carboniferous–Early Permian glacial-marine diamictites. The term was coined so as to explicitly include the elements of SW China "Si" for Sino, "BU" for Burma, "MA" for Malaya and "SU" for Sumatra where unequivocal Early Permian glacial-marine diamictites are known. Previous terms such as "Shan–Thai", "Sinoburmalaya" “West Malaya” were found wanting, principally because they did not include the Sumatran element of the block. Recent usage of the term "Shan–Thai" has become so diverse as to become confusing at best and meaningless at worst. Many authors have in recent times wrongly used Sibumasu and "Shan–Thai" interchangeably. In addition, recent interpretations of the Late Palaeozoic Gondwana–Cathaysian biogeographic divide in mainland SE Asia have led to erroneous placements of the eastern margin of Sibumasu and misidentification of the location of the Palaeo–Tethyan Suture Zone by some authors. A
discussion of these issues is contained in Metcalfe (2009a,b) and will not be repeated here. The tectonic framework for the Sundaland region recently proposed by Ferrari et al. (2008) is here challenged and regarded as both inappropriate and confusing. The use of the term "Shan–Thai" by Ferrari et al. (2008) for a Cathaysian continental block, which in fact includes both continental crustal and suture zone elements, and which bears very little resemblance or relationship to the Gondwanan Shan–Thai block of Bunopas (1982) — see Fig. 6 above, is here rejected (see Metcalfe, 2009b for details).

2.1.4. Continental blocks derived from Gondwana in the Jurassic

Magnetic anomaly data, evidence of rifting, basin formation, and development of unconformities on the NW Australian margin, and sediment source and palaeocurrent data from Timor, suggest that a


Fig. 4. Palaeolatitude vs. Time for some principal SE Asian continental blocks (After Li et al., 2004). Note northwards migration of South China, Sibumasu and Lhasa from southern to northern latitudes in the Late Silurian–Early Devonian, Permian, and Jurassic–Cretaceous respectively.
piece or pieces of continental crust rifted and separated from Australian Gondwana in the Jurassic. The continental pieces were identified as South Tibet, Burma, Malaya, SW Borneo and Sumatra by Audley-Charles (1988) who proposed their separation from Australian Gondwana in the Jurassic. Veevers et al. (1991) did not identify the continental block that separated from the Argo abyssal plain region in the Jurassic but named this “Argo Land” (subsequently “Argoland”). Metcalfe (1990) suggested that the continental block that must have separated from the Argo abyssal plain in the Jurassic might be the “Mount Victoria Land” block of Mitchell (1989) located in western Burma. Little evidence supporting this could be presented at that time as the age and nature of the schist basement of this terrane was not known and no rocks older than Triassic were known. The block was re-named the “West Burma block” by Metcalfe (1996a,b). Mitchell (1993) re-interpreted the block as part of an island arc formed by SW directed subduction that was then accreted on to mainland Asia. This interpretation is recently re-proposed by Hall et al. (in press). Other authors have continued to identify “Argoland” as West Burma (e.g. Jablonski and Saitta, 2004; Heine and Müller, 2005).

The West Burma block is bounded to the west by a belt of ophiolites that includes the Mount Victoria metamorphics and to the east by the Mogok Metamorphic Belt that has recently been correlated with the Medial Sumatra Tectonic Zone (Barber and Crow, in press). The recent report of Middle Permian rocks from the West Burma block near Karmine with Cathaysian fusulinids similar to those of the West Sumatra block (Oo et al. 2002) suggest that the West Burma block may well have a Palaeozoic or older continental basement, and may have, together with the West Sumatra block, formed part of a Cathaysian terrane derived from the South China–Indochina–East Malaya composite terrane and later disrupted by the opening of the Andaman Sea (Barber and Crow, in press). This leaves the identity of “Argoland” yet to be established. Hall et al. (2008), Hall (2009) and Hall et al. (in press) have identified “Argo” and “Banda” blocks that separated from the Argo abyssal plain and Banda embayment, NW Australia respectively in the Jurassic. They identify the Argo block as comprising the East Java and West Sulawesi blocks and the Banda block as SW Borneo. A Jurassic Gondwana origin for SW Borneo was previously ruled out on the basis that Cathaysian faunas were known from the Carboniferous–Lower Permian Terbat Limestone on the Sarawak–Kalimantan border (Sanderson, 1966; Metcalfe, 1985) which were considered part of the SW Borneo basement (Metcalfe, 1988). The recognition of a small continental block, the Semitau block, sandwiched between the Lepar and Boyan melanges in West Sarawak (Metcalfe, 1990) de-coupled the Terbat limestones from the core of the SW Borneo block which then allows SW Borneo to become a candidate for the Australian Gondwana-derived “Argoland” or “Banda” blocks. This would be supported by the occurrence of diamonds in headless placers (placer diamond deposits without any obvious local or regional diamond source) in Kalimantan (Bergman et al., 1988), SW Borneo (Fig. 7). Nitrogen-defect aggregation studies of these diamonds suggest a Gondwana mantle source (Taylor et al., 1990) consistent with SW Borneo having been derived from NW Australia in the Jurassic.

Fig. 5. 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 and Hisada, 1999; Sone and Metcalfe, 2008).
Recent provenance studies (Smyth et al., 2007) have identified an Australian Gondwana-derived East Java terrane. The previously recognised Bawean Arch and Paternoster Platform pre-Cenozoic continental blocks (Manur and Barraclough, 1994) are also possibly of Australian Gondwana origin but hard data supporting this is at present lacking. Other small continental blocks postulated to have had their origin on the Mesozoic margin of Australian Gondwana include the West Sulawesi block (which has been linked with the East Java block) and the Mangkalihat block in northeast Borneo. It is possible that these micro-continental blocks (numbered 1–5 on Fig. 3) may in fact represent two disrupted terranes derived from NW Australia (Hall et al., in press).

2.1.5. Continental blocks derived from South China/Indochina in the Cretaceous–Cenozoic

A number of small micro-continental blocks, the Semitau, Luconia, Kelabit–Longbawan, Spratley Islands–Dangerous Ground, Reed Bank, North Palawan, Paracel Islands and Macclesfield Bank (numbered 6–13 on Fig. 3) are interpreted to have originated on the South China–Indochina margin and been translated southwards during NW–SE extension of eastern Sundaland and opening and spreading of the South China Sea. This collage of small blocks may be the disrupted parts of one or two larger terranes. Hall et al. (in press) have suggested that these small blocks represent a single large "Dangerous Grounds" terrane that was accreted to Sundaland in the Early Cretaceous and then disrupted by rifting and spreading of the South China Sea.

3. 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 Figs. 2 and 3 and comprise the Inthanon, Chanthaburi (cryptic) and Bentong–Raub Sutures that represent the destroyed Palaeo-Tethys ocean, the Jinghong, Nan–Uttaradit and Sra Kaeo Sutures that represent the Sukhothai back-arc basin, the Shan Boundary and Medial Sumatra Palaeo-Tethyan Sutures, the Meratus–Luk–Ulo Meso-Tethys Suture and the Boyan Proto-South China Sea Suture. These are briefly discussed below.

3.1. Inthanon, Chanthaburi and Bentong–Raub (Palaeo-Tethys) Sutures

The Inthanon and Bentong–Raub Sutures in Thailand and Peninsular Malaysia are here interpreted to represent the main Palaeo-Tethys Ocean. The Chanthaburi Cryptic Suture is inferred in southern Thailand but details of this hidden suture are poorly known due to younger cover strata. The northern extension of the suture zone is the Changning–Menglian Suture of Yunnan Province, SW China.

In Thailand, the Inthanon Suture corresponds broadly to the Inthanon Zone of Ueno and Hisada (1999) and Ueno (2003) and to the Chiang Mai Suture of Metcalfe (2005) and Wakita and Metcalfe (2005). Deep oceanic sediments in the suture zone include radiolarian cherts that range in age from Middle Devonian to Middle Triassic. In addition, conodont faunas of Upper Devonian and Lower Carboniferous age are reported from oceanic cherts (Radon et al., 2006). Late Devonian, Late Permian and Middle Triassic radiolarian cherts are...
known from the cryptic Chanthaburi Suture in south Thailand (see Sone and Metcalfe, 2008 for details; and Fig. 8). The Inthanon Suture also contains Carboniferous–Permian shallow-marine limestones with Cathaysian faunas deposited on intra-oceanic volcanic edifices. These are here interpreted as Palaeo-Tethyan sea mounts now incorporated into the Palaeo-Tethyan Suture Zone following Metcalfe (2005), Wakita and Metcalfe (2005), Feng et al. (2008) and Ueno et al. (2008). Complete Ocean Plate Stratigraphy (OPS) can be seen in some single outcrop exposures or can be reconstructed from dating of clasts in melange (Wakita and Metcalfe, 2005). One such example of OPS with a sequence ranging from pillow basalt up through radiolarian chert, interbedded radiolarian chert and pelagic limestones to deep sea argillites exposed in a single road cutting south of Chiang Mai, Thailand is shown in Fig. 9. Melange kinematics within the Inthanon Suture, northern Thailand confirm original northward (present-day eastwards) subduction of the Palaeo-Tethys during the Permian–Triassic (Hara et al., 2009) which is of the same polarity as that seen in the Bentong–Raub Suture of the Malay Peninsula.

The Bentong–Raub Suture Zone of the Malay Peninsula includes oceanic radiolarian cherts that range in age from Devonian to Upper Permian (Fig. 10). Triassic cherts of the Semanggol Formation have been interpreted as forming in a foredeep successor basin developed on top of the accretionary complex (see Metcalfe, 2000 for discussion). A slightly earlier (Early Triassic) closure of Palaeo-Tethys in the Malay Peninsula compared to a Late Triassic closure in Thailand is indicated.

3.2. Jinghong, Nan–Uttaradit and Sra Kaeo (Sukhothai back-arc) Sutures

The Jinghong, Nan–Uttaradit and Sra Kaeo Sutures represent the closed back-arc basin that opened in the Permian when the Sukhothai volcanic arc separated from the margin of South China–Indochina–East Malaya. Radiolarian cherts in these sutures are restricted in age from Lower to Upper Permian compared to the age-range for the main Palaeo-Tethys ocean of Devonian to Triassic (see Fig. 2 and discussion in Sone and Metcalfe, 2008).

3.3. Shan Boundary and Medial Sumatra Tectonic Zones (Palaeo-Tethyan “Sutures”)

The Cathaysian West Sumatra and West Burma blocks, now positioned outboard of the Gondwanan Sibumasu block must have arrived in their present relative locations to other continental blocks of the region by strike-slip tectonics (Barber and Crow, 2003; Wakita and Metcalfe, 2005; Metcalfe 2009a; Barber and Crow, in press). The boundary between the Sibumasu block and the SW Sumatra block in Sumatra is the Medial Sumatra Tectonic Zone (Barber and Crow, 2003) that represents a major transcurrent shear zone. There is no evidence to date of the remnants (ocean floor stratigraphy, melange, ophiolites) of the intervening branch of Palaeo-Tethys that must have existed. This zone appears to correlate with the Mogok Metamorphic Belt in Burma that forms the boundary between Sibumasu and West
Burma and which is also interpreted as a major transcurrent shear zone (Barber and Crow, in press).

3.4. Meratus–Luk–Ulo Meso-Tethys Suture

The Jurassic–Cretaceous SW Borneo Meratus and central Java Luk–Ulo Sutures represent the destroyed Meso-Tethys ocean that separated the East Java, Bawean and Paternoster blocks from SW Borneo/Sundaland. The Meratus Suture complex comprises melange, siliceous shale, limestone, basalt, ultramafic rocks and schist. Radiolarian cherts range in age from Middle Jurassic to Early Cretaceous (Wakita et al., 1997, 1998). The Luk–Ulo Suture complex comprises similar lithologies (Wakita et al., 1994; Wakita, 2000). Reconstructed ocean plate stratigraphies represent the entire Cretaceous and include sea mount rock associations (Wakita and Metcalfe, 2005).

3.5. Boyan Proto-South China Sea Suture

The Boyan Suture is located between the small Semitau block and SW Borneo. Melange in the suture extends for over 200 km in a belt 5–20 km width. It comprises polymict tectonic breccia with fragments and blocks of a wide variety of sedimentary and igneous rocks in a pervasively sheared pelitic matrix. The clasts in the melange include limestone blocks of Cenomanian age and Cretaceous radiolarian cherts (Williams et al., 1988). The suture is interpreted to be of Late Cretaceous age and formed by destruction of the Proto-South China Sea (Metcalfe, 1999).

4. Phanerozoic evolution and palaeogeography of Sundaland

Research over the last two decades has established the Gondwana origins of all the Sundaland (and adjacent East and SE Asia region, e.g., Villeneuve et al., 2010) component continental blocks. These continental blocks rifted and separated from the NE Gondwana margin as three continental slivers or collages of terranes in the Early–Middle Devonian, Early Permian, and Late Triassic–Jurassic. The separation of these three continental strips successively opened the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys ocean basins between them and Gondwana. The separated continental blocks migrated successively northwards to in some cases amalgamate, and then accrete to form the

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Fig. 10. Map showing the distribution of the Palaeo-Tethys Bentong–Raub Suture Zone and Semanggol Formation rocks of the Malay Peninsula, ages of radiolarian cherts, and postulated possible extension of the Sukhothai Arc beneath the Central Belt. After Metcalfe (2000).
Sundaland core of East and SE Eurasia. Fig. 11 shows the timings of rifting and separation of these continental blocks and ages of amalgamation and accretion in relation to the three successive Tethyan ocean basins.

4.1. Early-middle Palaeozoic evolution and palaeogeography

Tectonostratigraphic, biogeographic,geochemical, provenance study, and palaeomagnetic data suggest that all the principal continental blocks of East and SE Asia were located on a greater Indian–Australian Gondwana margin in the Early Palaeozoic (Fig. 12). Detailed summaries of the evidence for such placement and for specific sites of attachment to Gondwana have been presented in previous papers (e.g. Metcalfe, 1988, 1990, 1996a, 1999, 2006) and will not be repeated here. The positions for the North China, South China, Tarim, Indochina, Sibumasu, Qiangtang, and Lhasa blocks are based on multidisciplinary data and Cambro–Ordovician faunas on these blocks define an Asia–Australia province at this time. Other workers have invoked a similar reconstruction scenario (e.g. Fortey and Cocks, 1998; Golonka, 2000; Golonka et al., 2006; Hendricks et al., 2008). By Mid–Late Silurian times, Gondwana had rotated clockwise significantly but northeast Gondwana remained in low northern palaeolatitudes (Fig. 12). The Sundaland/Asian terranes remained in their previous relative positions, continuing to form a greater Gondwana margin. Again, biogeographic data indicates an Asia–Australian province particularly well illustrated by the distribution of the Retziella brachiopod fauna (Fig. 12).

In the Late Silurian, a rifting event occurred on the margin of Gondwana and an elongate continental sliver comprising the South China, Tarim, Indochina and North China blocks began to separate from Gondwana in the Early Devonian (Metcalfe, 1996a,b). By late Early to Middle Devonian times, oceanic spreading between this continental sliver and Gondwana opened the Palaeo-Tethys ocean basin as evidenced by oceanic deep sea radiolarian cherts in the suture zone. By latest Devonian–earliest Carboniferous times the separating sliver had almost broken away from Gondwana but retained continental connection in the east explaining continued Devonian fish faunal connections (Metcalfe, 2001). Clockwise rotation of the sliver away from Gondwana corresponds to documented anti-clockwise rotation of Gondwana in the Late Devonian (Metcalfe, 2001). Interestingly, the distribution of the Chuiella brachiopod fauna (Chen and Shi, 1999) in the shallow seas of South China and Tarim on the western extremity of the continental sliver is consistent with this scenario (Fig. 13).

4.2. Late Palaeozoic evolution and palaeogeography

By Late Early Carboniferous (Visean) times, South China and Indochina had amalgamated along the Song Ma Suture Zone. The faunas and floras of North China, South China and Indochina–East Malaya no longer show any Gondwana affinities and these blocks were located in equatorial to low northern palaeolatitudes (Fig. 14). Late Early Carboniferous floras of South China and Indochina–East Malaya are very similar suggesting continental connection between these blocks at this time (Laveine et al., 1999). The Visean biogeographic distribution of the shallow-marine conodont genus Mestognathus indicates that Laurentia and Gondwana were connected but isolated from other continental terranes and the distinctive shallow-marine conodont genus Montognathus links the Sibumasu block with eastern Australia at this time (Fig. 14). The Sibumasu block and the Argo/SW Borneo blocks remained on the NW Australian margin of Gondwana.

Following its separation from Gondwana in the Devonian, the Tarim block collided with Siberia in the Late Carboniferous to Early Permian and was welded to Proto-Asia by the Middle Permian (Carroll et al., 1995).
In the Latest Carboniferous–Earliest Permian Gondwanan glaciation was at its maximum development and ice sheets covered large parts of the super continent, including Australia. Ice rafted onto the shallow-marine continental shelf of Australian Gondwana and dumped glacial debris into marine sediments resulting in the glacial-marine diamictite-bearing deposits on the Sibumasu block (Fig. 7). The Sibumasu block was already at this time in the process of rifting from Gondwana and as a result, glacial-marine strata filled rift grabens both on the western Australian margin of Gondwana and on Sibumasu (Eyles et al., 2003; Fig. 5). The Early Permian was also a time of high provinciality of global floras and faunas and the Sibumasu block floras were typical Gondwanan Glossopteris floras at this time. Floras developed on the North China, South China and Indochina–East Malaya blocks (located in isolated intra-Tethyan positions) developed the typical Cathaysian warm-climate Gigantopteris floras (Fig. 15). Conodont faunal provinciality was also marked with a distinct southern hemisphere high-latitude peri-Gondwana cool-water province characterised by the genus Vjalovognathus, an equatorial warm-water Sweetognathus-dominated province and a northern hemisphere high-latitude cool-water Neostreptognathodus-dominated province (Fig. 16). Continental connection or close proximity of South China and Indochina in the Kungurian is indicated by the endemic
occurrence of Pseudosweetognathus on these two blocks (Sone and Metcalfe, 2008; Fig. 16).

In the Asselian–Sakmarian, Sibumasu block faunas were peri-Gondwanan Indoralian Province faunas, but as Sibumasu separated and moved northwards during the Permian its faunal characteristics changed, first to endemic Sibumasu province faunas in the Middle Permian and then to Cathaysian Province faunas in the Late Permian (Shi and Archbold, 1998; Ueno, 2003). As Sibumasu was translated northwards during the Permian, the Palaeo−Tethys was subducted beneath northern Pangea, North China and the amalgamated South China−Indochina−East Malaya terrane (Cathaysialand). Subduction beneath Cathaysialand resulted in the Sukhothai Arc on its margin which was then separated from Cathaysialand by back-arc spreading to become an island arc in the Late Permian (Fig. 16). The resulting narrow back-arc basin collapsed at the end of the Permian to form the Jinghong, Nan−Uttaradit and Sra Kaeo Sutures (Sone and Metcalfe 2008). Collision of the Sibumasu block with the Sukhothai Island Arc terranes and Cathaysialand closed the southeastern Palaeo−Tethys in the Late Permian−Early Triassic producing the Changning−Menglian, Inthanon and Bentong−Raub Suture Zones. A later timing (Late Triassic or even Jurassic) for this collision has been suggested by some authors based on interpretation of the Semanggol cherts and equivalents as Palaeo−Tethyan deposits (e.g. Sashida et al., 1995, 2000a, 2000b; Kamata et al., 2002; Ueno et al., 2006; Ishida et al., 2006; Hirsch et al., 2006). The earlier timing is here supported following Metcalfe (2000) and Barber and Crow (in press). A younger (late Triassic) collision and suturing to the north along the Changning−Menglian Suture in SW China is however considered possible (Liu et al., 1996).

It is postulated here that during the collision of Sibumasu and Cathaysialand, which occurred at the zone of convergence between the north moving Meso−Tethys and west moving Palaeo-Pacific plates, that the West Burma and West Sumatra blocks (initially as a single block) were translated westwards by transcurrent tectonics to their current positions outboard of the Sibumasu terrane.

The South and North China blocks were in close proximity during the Permian. The timing of their collision and welding is an ongoing controversy with mid-Palaeozoic, Late Palaeozoic and Late Triassic−Jurassic timings being proposed. Studies of low grade metamorphics in the Sulu belt (Zhou et al., 2008) and geochronological and structural data (e.g. Faure et al., 2003) indicate Permian subduction of South China beneath North China. Identification of a Devonian−Triassic accretionary wedge that includes eclogites, and which formed a coeval volcano−plutonic arc that stretches from the Longmen Shan to Korea supports subduction beneath the Qinling−Sino−Korean plate and a Permian−Triassic collision (Hacker et al., 2004).

A land connection between Indochina and Pangea in the Late Permian is indicated by the confirmed presence of the Late Permian tetrapod vertebrate Dicynodon in Laos (Battail, 2009). The most likely land connection was via South and North China rather than via the western Cimmerian continental strip that was largely submerged below sea level in the Permian (Fig. 16).

4.3. Mesozoic—Cenozoic evolution and palaeogeography

Collision and welding of the Sibumasu block to Indochina−East Malaya, begun in the latest Permian, continued in the Early−Middle Triassic. By Late Triassic times this collision and welding was complete (Fig. 17). Collision between South and North China, begun in the Permian, continued in the Triassic, and comparisons of Apparent Polar Wander Paths of these blocks indicates that collision between these blocks also continued into the Jurassic but was complete by the Late Jurassic. The time of rapid (1°/Ma) relative angular velocity between the two plates (225 to 190 Ma) coincides with a peak in U−Pb and Ar−Ar dates obtained from metamorphic rocks in the
Qingling—Dabie—Sulu Suture (Gilder and Courtillot, 1997). Thus, the initial consolidation of what is now Sundaland and mainland East and Southeast Asia took place in Late Triassic—Jurassic times. The Songpan Ganzi Giant Suture knot represents Palaeo-Tethyan ocean crust trapped between the western Cimmerian continent, Cathaysialand, North China and Siberian Pangea and covered by thick Triassic deposits eroded from adjacent collisional orogens (Fig. 17).

Further rifting of the Indian—Australian margin of Gondwana was initiated in the Triassic and continued into the Jurassic (Fig. 18). The Lhasa block is here interpreted to have separated from Indian Gondwana in the Late Triassic (following Metcalfe, 2002; Golonka et al., 2006; Golonka, 2007) but other authors have advocated an earlier separation as part of the Cimmerian continent (e.g. Allègre et al., 1984; Dercourt et al., 1993, 2000). A Permian separation of Lhasa may be supported by Permian limestone blocks interpreted as possible seamount caps in the Indus—Yarlung Suture Zone (Shen et al., 2003) but this would require the unlikely longitudinal splitting of the Cimmerian continent during its northwards movement and the opening of a new ocean basin between Lhasa and Qiangtang. A possible slab pull mechanism has been advocated by Stampfl and Borel

Fig. 14. Early Carboniferous (Visean) reconstruction showing postulated positions of Sundaland and SE Asian blocks. The biogeographic distributions of the conodont genera Mestognathus (Illustrated specimen is Mestognathus beckmanni from the Kanthan Limestone, Peninsular Malaysia) and Montognathus (Montognathus carinatus from Peninsular Malaysia illustrated) are also shown.
but is here considered unlikely. A Late Triassic separation advocated here is supported by information on oceanic cherts from the Yarlung–Zangbo Suture (Matsuoka et al., 2002) and recent palaeomagnetic data (Otofuji et al., 2007).

A collage of small continental blocks rifted and separated progressively westwards from the NW Australian margin in the Late Jurassic—Early Cretaceous (Fig. 18). These included the Argoland block that separated by opening of the Argo abyssal plain and SW Borneo (referred to as the “Banda” block by Hall et al., in press) from the Banda embayment region. These were previously identified as West Burma, and other small continental blocks in the Sumatra and Borneo region (Metcalfe, 1990; Jablonski and Saitta, 2004; Heine and Müller, 2005). Argoland is now tentatively identified as the East Java, Bawean, Paternoster, Mangkalihat, and West Sulawesi blocks (numbered 2–5 on Fig. 3) and the Banda block as SW Borneo, following Hall et al. (in press).

SW Borneo and Argoland were translated northwards during the Cretaceous and by Late Cretaceous times had accreted to SE

Fig. 15. Distribution of Lower Permian floral provinces plotted on (A) present-day geographic map, and (B) Early Permian palaeogeographic map. KT = Kurosegawa Terrane. Other abbreviations as for Figs. 2 and 3.

Fig. 16. 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 Dicynodont 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; QI = Qiangtang; L = Lhasa; SWB = South West Borneo; and WC = Western Cimmerian Continent.
Sundaland. The Incertus Island Arc developed within the Ceno-Tethys during the Cretaceous (Aitchison et al., 2007; Ali and Aitchison, 2008; Hall et al., in press) and collided with northwards moving India at c. 55 Ma. By Middle Eocene times (45 Ma), India (with accreted Incertus Arc segment) was probably in its initial collision with Eurasia (Fig. 18). The 45 Ma timing is temporally coincident with large-scale regional and global plate reorganisations at this time (Hall et al., in press). A younger “hard” collision between India and Eurasia at c. 35 Ma has however been recently proposed by Aitchison et al. (2007) and Ali and Aitchison (2008).

5. Conclusions

The Phanerozoic evolution of Sundaland and adjacent regions of SE Asia involved the rifting and separation of three collages of continental terranes (probably as elongate slivers) from eastern Gondwana and the successive opening and closure of three oceanic micro-blocks. A younger collision between India and Eurasia at c. 35 Ma has however been recently proposed by Aitchison et al. (2007) and Ali and Aitchison (2008).

The Palaeo-Tethys is represented in Sundaland by the Inthanon–Chiang Mai, Chanthaburi (cryptic) and Bentong basins, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys. Gondwana and the successive opening and closure of three continental terranes (probably as elongate slivers) from eastern Asia involved the rifting and separation of three collages of continental terranes (probably as elongate slivers) from eastern Gondwana and the successive opening and closure of three oceanic micro-blocks.

Fig. 17. Palaeogeographic reconstructions 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; QI = Qiangtang block; I = Indochina block; S = Sibumasu block; EM = East Malaya block; WS = West Sumatra block; WB = West Burma block; L = Lhasa block; SWB = Argoland/South West Borneo.

Fig. 18. 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–Australia and land and sea. SC = Songpan Ganzi accretionary complex; SC = South China; QS = Qando–Simao; SI = Simao; QI = Qiangtang; S = Sibumasu; SA = Sukhothai Arc; I = Indochina; EM = East Malaya; WSJ = West Sumatra; L = Lhasa; WB = West Burma; SWB = South West Borneo; NP = North Palawan and other small continental fragments now forming part of the Philippines basement M = Mangkalihat; WS = West Sulawesi; P = Paternoster; B = Bawean; PA = Incipient East Philippine arc; PS = Proto-South China Sea; Z = Zambales Ophiolite; ES = East Sulawesi; O = Obi–Bacan; Ba–Su = Bangai–Sula; Bu = Buton; and WJ = West Irian Jaya. M numbers represent Indian Ocean magnetic anomalies.