Palaeozoic−Mesozoic history of SE Asia

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Abstract: SE Asia comprises a collage of Gondwana-derived continental blocks assembled by the closure of multiple Tethyan and back-arc ocean basins now represented by suture zones. Two major biogeographical boundaries, the Late Palaeozoic Gondwana–Cathaysia divide and the Cenozoic-Recent Australia–Asia divide (Wallace Line) are present. Palaeozoic and Mesozoic evolution involved the rifting and separation of three collages of continental terranes from eastern Gondwana and the opening and closure of three successive ocean basins, the Palaeo-Tethys (Devonian–Triassic), Meso-Tethys (Permian–Cretaceous) and Ceno-Tethys (Late Triassic–Cenozoic). This led to the opening and closing of ocean gateways and provision of shallow-marine and terrestrial land bridges and stepping-stones for biotic migration. The SE Asia core (Sundaland) comprises a western Sibumasu block, an eastern Indochina–East Malaya block, and the Sukhothai Island Arc terrane between. The Jinghong, Nan-Uttaradit and Sra Kaeo sutures represent the Sukhothai closed back-arc basin. The Palaeo-Tethys is represented by the Changning-Menglian, Chiang Mai/Inthanon and Bentong-Raub suture zones. The West Sumatra and West Burma blocks were accreted to the Sundaland core in the Late Permian–Early Triassic. SW Borneo and/or East Java–West Sulawesi are now identified as the missing 'Argoland' that separated from NW Australia in the Jurassic and accreted to SE Sundaland in the Cretaceous.

SE Asia is located at the zone of convergence between the ESE moving Eurasia Plate, the NE moving Indian and Australian Plates and the ENE moving Philippine Plate (Fig. 1). SE Asia and adjoining regions comprise a complex collage of continental blocks, volcanic arcs, and suture zones that represent the closed remnants of ocean basins (including back-arc basins). The continental blocks of the region were derived from the margin of eastern Gondwana as three successive continental strips or collages of continental blocks that separated in the Devonian, Early Permian and Triassic–Jurassic and which then assembled during the Late Palaeozoic to Cenozoic to form present day East and SE Asia (Metcalfe 2005).

Global, regional and local Palaeozoic–Mesozoic tectonic evolution resulted in changes to continent–ocean configurations, dramatic changes in relief both on land and in the seas, and changes in palaeo-ocean currents, including the opening and closing of oceanic gateways. The significant effect on ocean circulation caused by ocean gateway closure/opening is well documented (e.g. Von der Heydt & Dijkstra 2006, 2008). The changes in continent–ocean, land–sea, relief, and ocean current patterns are fundamental factors leading to both global and regional climate-change and to important changes in biogeographical patterns. Changes in biogeographical barriers and bridges caused by geological evolution and consequent climate-change have also influenced the course of migration, dispersal, isolation and evolution of biota, both globally and in SE Asia.

This paper provides an overview of the tectonic framework, and Palaeozoic and Mesozoic geological evolution and palaeogeography of SE Asia and adjacent regions as a background to and to underpin studies of the Indonesian Throughflow Gateway and the distribution and evolution of biota in the region.

Geological and tectonic framework of SE Asia and adjacent regions

Mainland East and SE Asia comprises a giant 'jigsaw puzzle' of continental blocks, volcanic arc terranes, suture zones (remnants/sites of destroyed ocean basins) and accreted continental crust (Figs 2 & 3).
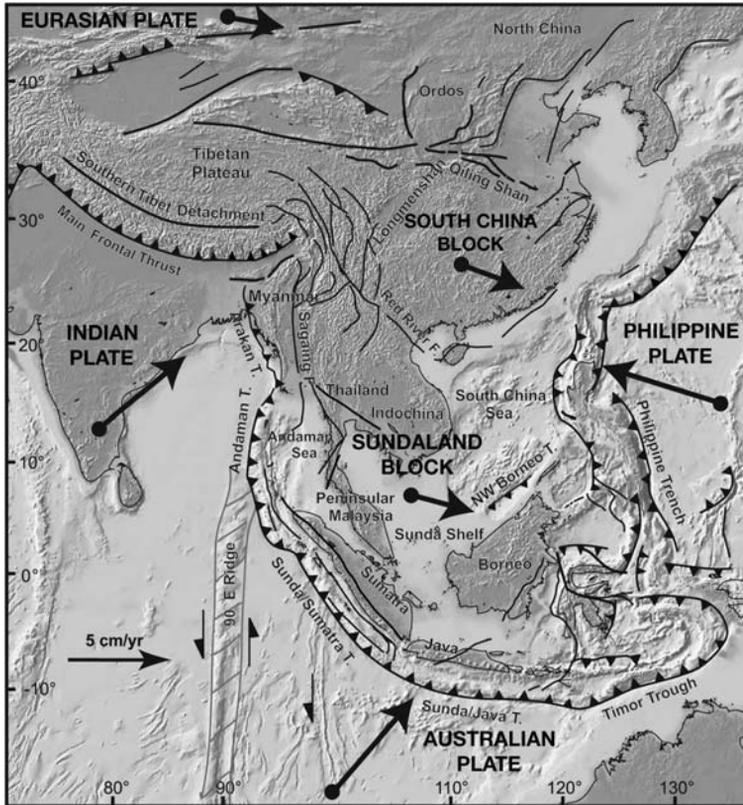
Fig. 1. Topography and main active faults in East Asia and location of SE Asia at the zone of convergence of the Eurasian, Philippine and Indian–Australian plates. Large arrows represent absolute (International Terrestrial Reference Frame 2000, Altamimi *et al*. 2000) motions of plates (After Simons *et al.* 2007).

Continental blocks of SE Asia

The principal continental blocks located in mainland SE Asia (Fig. 2) have been identified and established over the last two decades (e.g. Metcalfe 1984, 1986, 1988, 1990, 1996*a*, 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 & Crow 2003, 2009; Barber *et al.* 2005) and a volcanic arc terrane is now identified, sandwiched between Sibumasu and Indochina–East Malaya (Sone & Metcalfe 2008). A series of smaller continental blocks are identified in eastern (maritime) SE Asia and these were accreted to the mainland core of SE Asia in the Mesozoic–Cenozoic.

The continental terranes of SE Asia and adjacent regions are here categorized into six types based on their specific origins, times of rifting and

separation from Gondwana, and amalgamation/accretion to form SE Asia. These are discussed below and the suture zones between them are described separately.

Continental blocks derived from Gondwana in the Devonian

The South China, Indochina and East Malaya blocks (Figs 2 & 3) 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, 1996*a*, *b*, 1998, 2002, 2005, 2006). The West Sumatra block (originally proposed by Hutchison 1994; Barber & 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
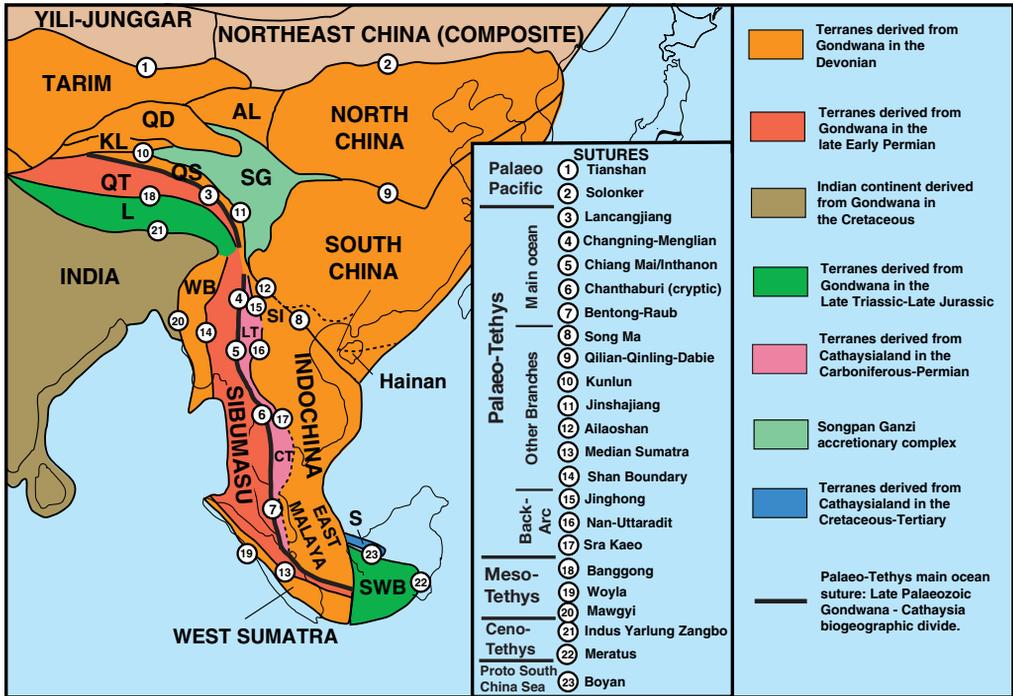
Fig. 2. Distribution of principal continental blocks, arc terranes and sutures of eastern Asia. WB, West Burma; SWB, SW Borneo block; S, Semitau block; L, Lhasa block; QT, Qiangtang block; QS, Qamdo-Simao block; SI, Simao block; SG, Songpan Ganzi accretionary complex; KL, Kunlun block; QD, Qaidam block; AL, Ala Shan block; LT, Linchang arc terrane; CT, Chanthaburi arc terrane.

(which also included North China and Tarim) that separated from Gondwana in the Devonian (Barber *et al.* 2005; Metcalfe 2005, 2009*a*; Barber & Crow 2009). For more detailed description of these blocks and assessment of the evidence for Gondwana origin see Metcalfe (1988, 1996*a*, 2006).

The Late Palaeozoic faunas and floras of these continental blocks are warm-water, equatorial Tethyan/Cathaysian Province biotas that contrast starkly with temporally 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 & Powell 2001; Li *et al.* 2004; see Fig. 4). A newly described Early Permian flora (*Comia* flora) from the West Sumatra block (Booi *et al.* 2009) indicates relationships with North China and possibly Angara in the Early Permian suggesting a continental migration zone running from the North China Block (via South China and Indochina/East Malaya to the West Sumatra–West Myamar terrane.

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

The Nan-Uttaradit suture, formerly considered to represent the main Palaeo-Tethys ocean, and to mark the boundary between the Sibumasu and Indochina blocks in Thailand, is now regarded as representing a closed back-arc basin (Wu *et al.* 1995; Ueno 1999; Ueno & Hisada 1999, 2001; Wang *et al.* 2000). This recognition, and correlation of this suture with the Sra Kaeo suture in southern Thailand and the Jinghong Suture in southern China led Sone & Metcalfe (2008) to propose the Sukhothai Arc System derived from the margin of South China–Indochina–East Malaya by back-arc spreading in the Late Carboniferous–Early Permian. The Sukhothai Arc System 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 western boundary of the arc is delineated by the Inthanon (Chiang Mai) Suture in NW Thailand, the cryptic Chanthaburi Suture in southern Thailand and the Bentong-Raub Suture in Peninsular Malaysia (Fig. 3; Sone & Metcalfe 2008). The arc is here interpreted to have
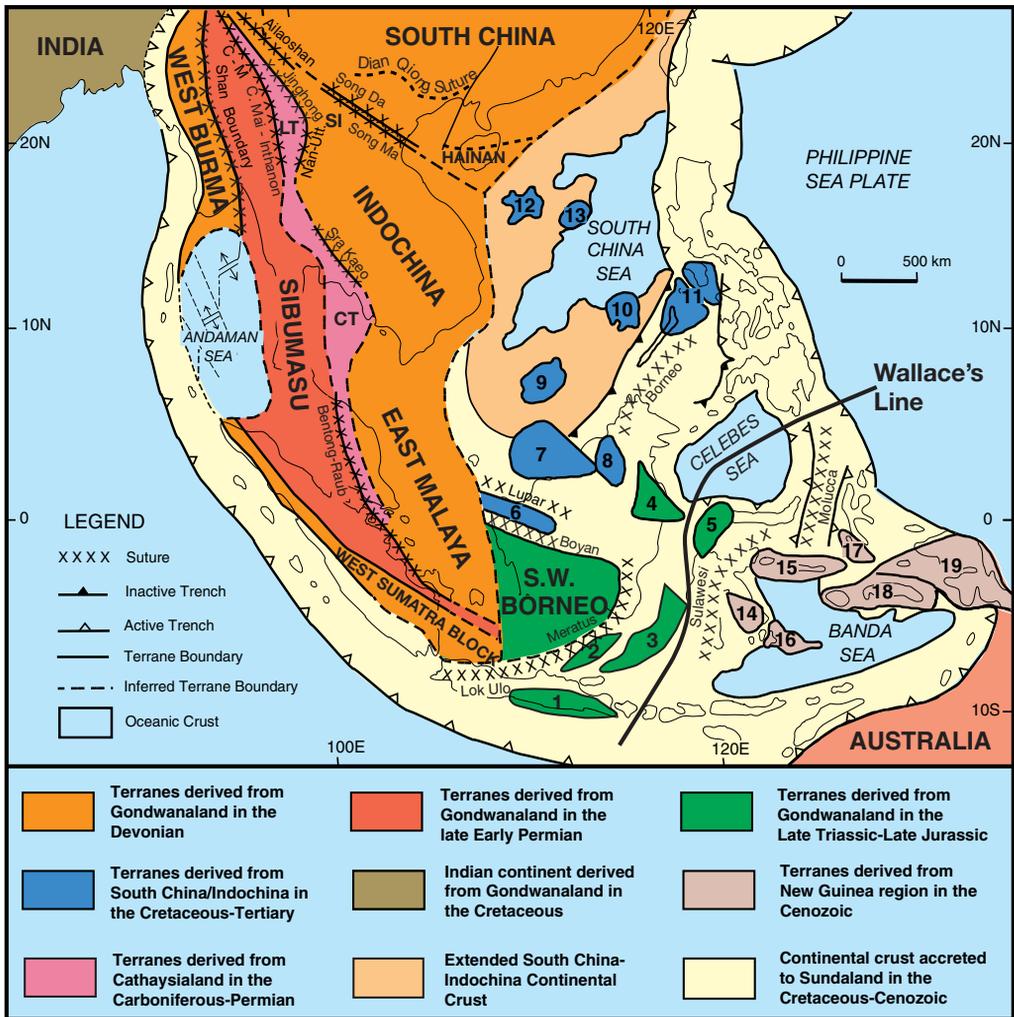
Fig. 3. Distribution of continental blocks, fragments and terranes, and principal sutures of SE Asia. Numbered microcontinental blocks: 1, East Java; 2, Bawean; 3, Paternoster; 4, Mangkalihat; 5, West Sulawesi; 6, Semitau; 7, Luconia; 8, Kelabit-Longbowan; 9, Spratly Islands-Dangerous Ground; 10, Reed Bank; 11, North Palawan; 12, Paracel Islands; 13, Macclesfield Bank; 14, East Sulawesi; 15, Bangai-Sula; 16, Buton; 17, Obi-Bacan; 18, Buru-Seram; 19, West Irian Jaya. LT, Lincang Terrane; CT, Chanthaburi Terrane; C-M, Changning-Menglian Suture; C.-Mai – Inthanon, Chiang Mai – Inthanon Suture; Nan-Utt., Nan-Uttaradit Suture.

a thin continental basement that formed the margin of the South China–Indochina–East Malaya super-terrane. It 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 recognized 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).

Continental blocks derived from Gondwana in the Early Permian

Palaeozoic faunas and floras and the presence of Late Palaeozoic cool/cold water shallow-marine environments, coupled with the presence of Upper Carboniferous–Lower Permian glacial-marine diamictites and palaeomagnetic data suggests that the Sibumasu block, together with the Baoshan, Tengchong, Qiangtang and Lhasa blocks of western China and Tibet remained attached to NE
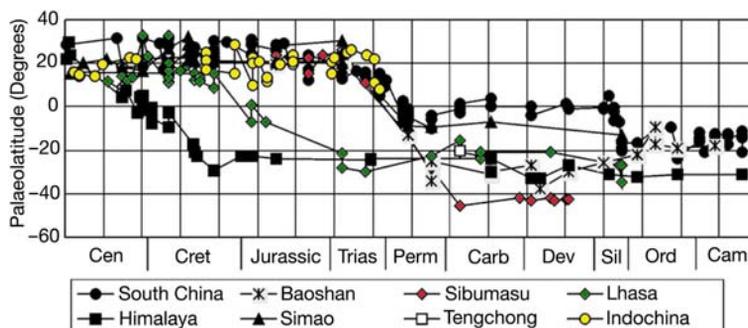
Fig. 4. Palaeolatitude v. Time for some principal SE Asian continental blocks (After Li *et al.* 2004). Note northwards migration of South China, Sibumasu and Lhasa from southern to northern latitudes in the Late Silurian–Early Devonian, Permian, and Jurassic–Cretaceous respectively.

Gondwana until Early Permian times. 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 characterized by Late Palaeozoic Gondwana faunas and floras and by Late Carboniferous–Early Permian glacial-marine diamictites that are interbedded with other marine clastics and turbidites that fill rift grabens (Jin 1994; Wopfner 1996; Wang *et al.* 2001; Ridd 2009). Metcalfe (1988, 1990) included the Qiang-tang and Lhasa blocks as part of the separating eastern Cimmerian continent, but recognized the later docking of the Lhasa block to Eurasia in the Late Jurassic–Early Cretaceous. Metcalfe (1999 & 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 (1996*a*).

By the end of the Sakmarian, however, the Sibu-masu, Baoshan and Tengchong blocks were separating from Gondwana as the eastern part of the Cimmerian continental strip of Sengör (1979, 1984). Post Sakmarian strata of these blocks no longer contain any Gondwana biota but instead show progressive changes in biotic provinces from peri-Gondwana (Indoralian) to Cimmerian to Cathaysian provinces as this continental strip migrated northwards into lower latitudes and warmer climates during the Permian.

Recent confusing usage of the term 'Shan–Thai' and incorrect correlation with Sibumasu requires some clarification here. The term Sibumasu (Metcalfe 1984) replaced previous terms used for the elongate Gondwana-derived block in SE Asia characterized by Late Palaeozoic Gondwana biotas and Late Carboniferous–Early Permian glacial-marine diamictites. The acronym SIBUMASU explicitly included 'SI' for Sino and Siam, 'BU' for Burma, 'MA' for Malaya and 'SU' for Sumatra where unequivocal Early Permian glacial-marine diamictites are known. 'Shan–Thai', 'Sinoburma-laya' and 'West Malaya' were considered unusable, principally because they did not include the Suma-tran 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. Sibu-masu and 'Shan–Thai' have unfortunately been used interchangeably by many recent authors. In addition, recent interpretations of the Late Palaeozoic Gondwana–Cathaysian biogeographical 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 (2009*a*, *b*) and will not be repeated here. The tectonic framework for the Sundaland region recently proposed by Ferrari *et al.* (2008) is not supported here. 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 Figure 6, is here rejected (see Metcalfe 2009*b* for details).

Continental blocks derived from Gondwana in the Jurassic

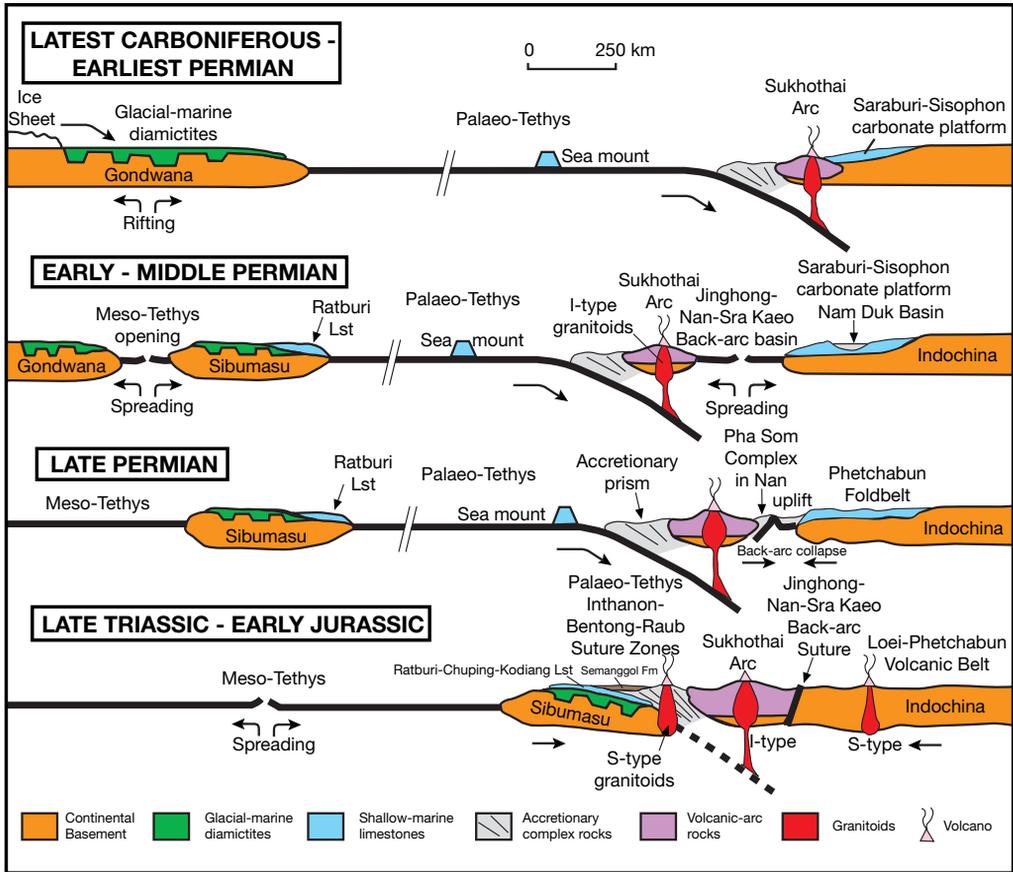Rift-related basin formation and development of unconformities on the NW Australian margin,

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 & Hisada 1999; Metcalfe 2002; Sone & Metcalfe 2008).

sediment source and palaeocurrent data from Timor, and offshore ocean floor magnetic anomaly data suggest that a piece or pieces of continental crust rifted and separated from Australian Gondwana in the Jurassic. The rifting microcontinents were identified as South Tibet, Burma, Malaya, SW Borneo and Sumatra by Audley-Charles (1988). 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) identified the continental block that must have separated from the Argo abyssal plain as the 'Mount Victoria Land' block of Mitchell (1989) located in western Burma. Hard evidence supporting this was lacking because the age and nature of the schist basement of this terrane was not known and no rocks older than Triassic were known. Metcalfe (1996*a*, *b*) re-named the block 'West Burma Block' to avoid confusion with Mount Victoria

Land in Antarctica. 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.* (2009). Other authors have continued to identify 'Argoland' as West Burma (e.g. Jablonski & Saitta 2004; Heine & Müller 2005). The West Burma block is bounded to the east by the Mogok Metamorphic Belt that has recently been correlated with the Medial Sumatra Tectonic Zone (Barber & Crow 2009). Its western boundary is formed by a belt of ophiolites that includes the Mount Victoria metamorphics. The 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) suggests that the West Burma block has 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
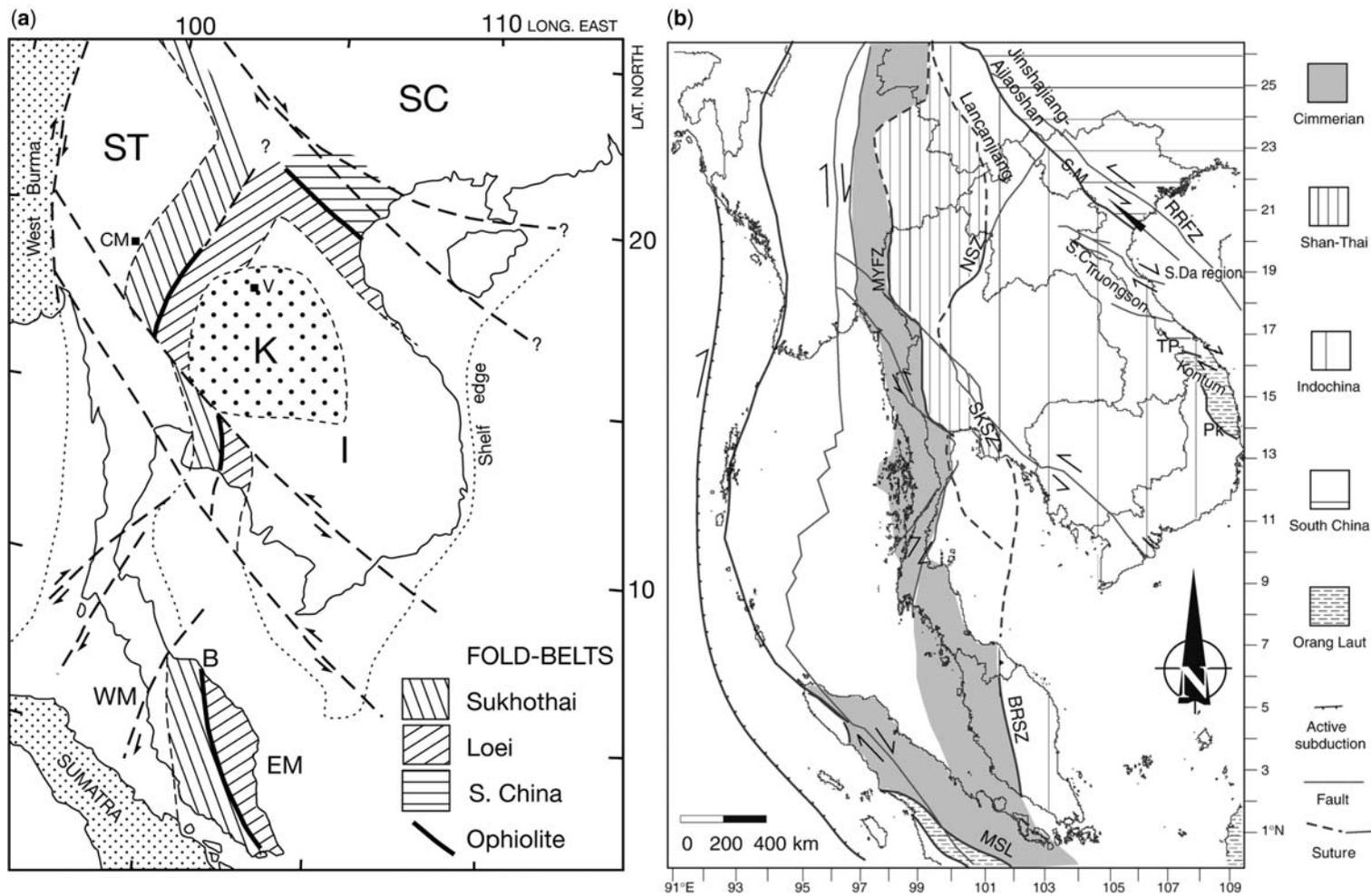
Fig. 6. Comparison of the (**a**) Gondwanan Shan–Thai (ST) block of Bunopas (1982) and (**b**) Cathaysian 'Shan–Thai' block of Ferrari *et al.* (2008).

China–Indochina–East Malaya composite terrane and later disrupted by the opening of the Andaman Sea (Barber & Crow 2009). If this interpretation is correct, then the identity of 'Argoland' is yet to be established. Hall *et al.* (2008), Hall (2009) and Hall *et al.* (2009) 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 Lupar and Boyan melanges in west Sarawak (Metcalfe 1990) de-coupled the Cathaysian fusuline-bearing Terbat limestones from the core of the SW Borneo block which then allows SW Borneo to becomes 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.

Recent provenance studies (Smyth *et al.* 2007) have identified an Australian Gondwana-derived East Java terrane. The previously recognized Bawean Arch and Paternoster Platform pre-Cenozoic continental blocks (Manur & 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 NE 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.* 2009).

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

A number of small micro-continental blocks, the Semitau, Luconia, Kelabit-Longbawen, Spratley Islands-Dangerous Ground, Reed Bank, North Palawan, Paracel Islands and Macclesfield Bank
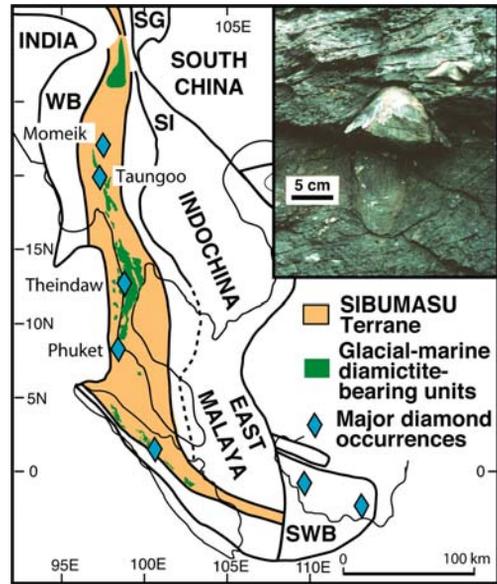
Fig. 7. Map of mainland SE Asia, showing the distribution of Late Carboniferous–Early Permian glacial-marine sedimentary rocks and major alluvial diamond deposits. Inset photo: Dropstone in glacial marine diamictite oriented vertical to bedding, Singa Formation, Langkawi Islands, Peninsular Malaysia.

(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. Clift *et al.* (2008) and Hall *et al.* (2009) 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. Yan *et al.* (2010) identify 'Nasha' (=Spratley-Dangerous Ground) and 'Reed-Northeastern Palawan' blocks in the southern South China Sea region and data from dredged Mesozoic tonalites indicate a probable Precambrian continental basement. The Spratley Islands comprise Cenozoic carbonate reefs constructed on Triassic–Cretaceous sedimentary cuesta basement (Hutchison & Vijayan 2010). Hutchison & Vijayan (2010) do not regard the Spratley-Dangerous Ground region as allochthonous.

Palaeozoic and Mesozoic suture zones of SE Asia

The suture zones of SE Asia represent the sites of closed oceanic or back-arc basins and form the

boundaries of the continental and arc terranes of the region. The Palaeozoic and Mesozoic suture zones (Figs 2, 3 & 8) comprise the Changning-Menglian, Inthanon, Chanthaburi (cryptic) and Bentong-Raub sutures that represent the destroyed Main Palaeo-Tethys ocean, the Ailaoshan, Song Ma, Shan
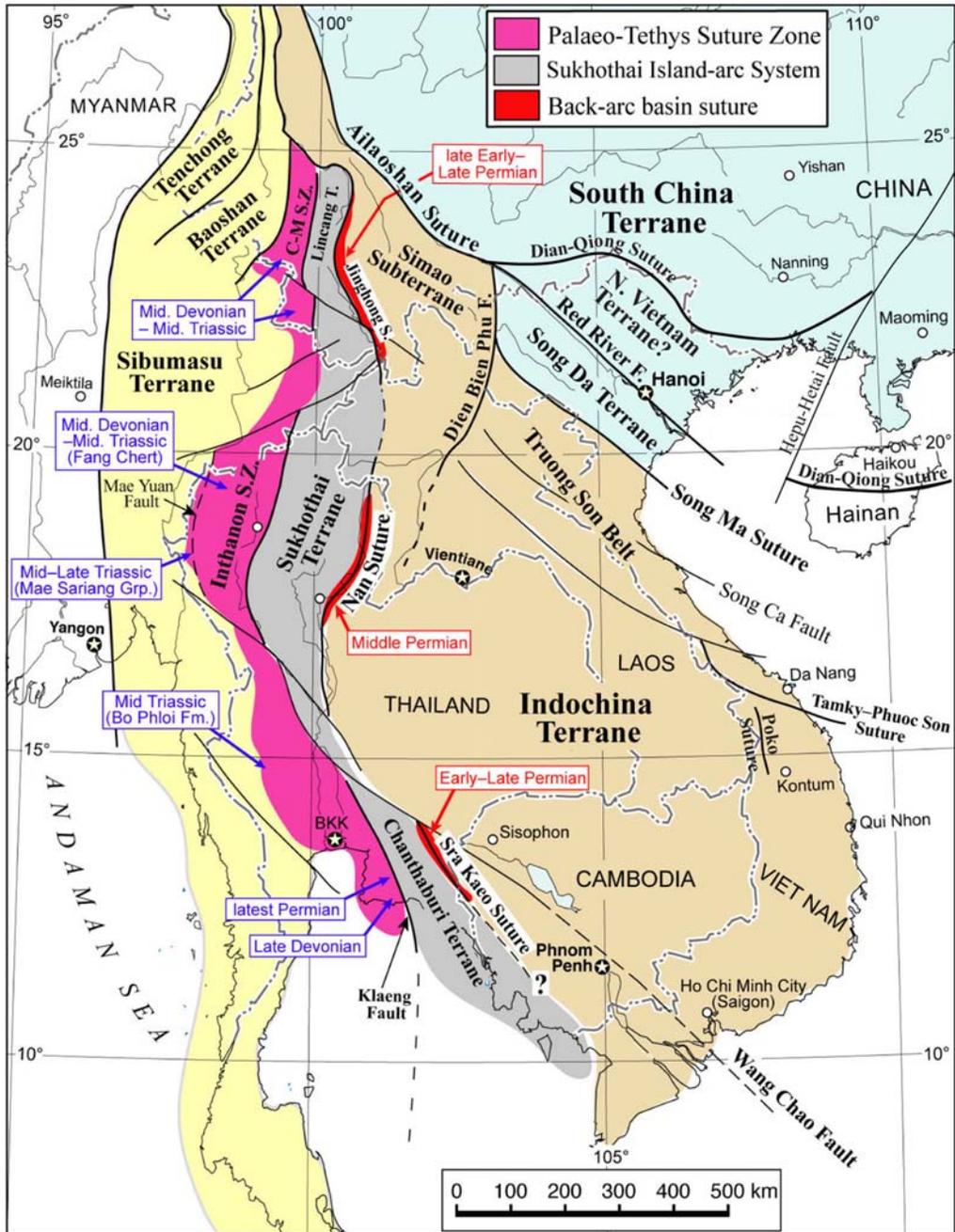

Fig. 8. Tectonic subdivision of Thailand and adjacent regions of Sundaland showing the principal suture zones. Ages of deep marine radiolarian cherts are shown in boxes. C-M S.Z., Changning-Menglian Suture Zone. Modified after Sone & Metcalfe (2008).

Boundary and Medial Sumatra sutures that represent other branches of the Palaeo-Tethys, the Jinghong, Nan-Uttaradit and Sra Kaeo sutures that represent the Sukhothai back-arc basin, the Meratus-Lok-Ulo Meso-Tethys suture and the Boyan Proto-South China Sea suture. Other postulated Palaeo-Tethys sutures include the 'Song Da' suture (zone) and the 'Da Nang-Zeijiang' suture (central Vietnam–South China), Tamky-Phuoc Son suture (South Vietnam), Poko suture (South Vietnam), and Dian-Qiong suture (Yunnan–Hainan). These are briefly discussed below.

Changning-Menglian, Inthanon, Chanthaburi and Bentong-Raub (Main Palaeo-Tethys Ocean) sutures

The Changning-Menglian suture zone of Yunnan Province, SW China and 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 and details of this hidden suture are poorly known due to younger cover strata.

The Inthanon Suture in Thailand (Figs 2, 3 & 8) corresponds broadly to the Inthanon Zone of Ueno & Hisada (1999) and Ueno (2003) and to the Chiang Mai Suture of Metcalfe (2005) and Wakita & Metcalfe (2005). The suture zone includes radiolarian cherts and deep oceanic sediments that range in age from Middle Devonian to Middle Triassic (Fig. 9). Despite being largely cryptic, Late Devonian, Late Permian and Middle Triassic radiolarian cherts are known from the Chanthaburi Suture in south Thailand (see Sone & Metcalfe 2008 for details; and Fig. 8). Carboniferous–Permian shallow-marine limestones with Cathaysian faunas constructed on intra-oceanic volcanic edifices within the Inthanon Suture are interpreted as Palaeo-Tethyan sea mounts following Metcalfe (2005), Wakita & Metcalfe (2005), Feng et al. (2008) and Ueno et al. (2008). Ocean Plate Stratigraphy (OPS) can be observed in some single outcrop exposures or can be reconstructed from dating of clasts in melange (Wakita & 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 Figure 10. Recent studies of melange kinematics within the Inthanon Suture, northern Thailand confirm original northwards (present day eastwards) subduction of the Palaeo-Tethys during the Permian–Triassic (Hara et al. 2009).
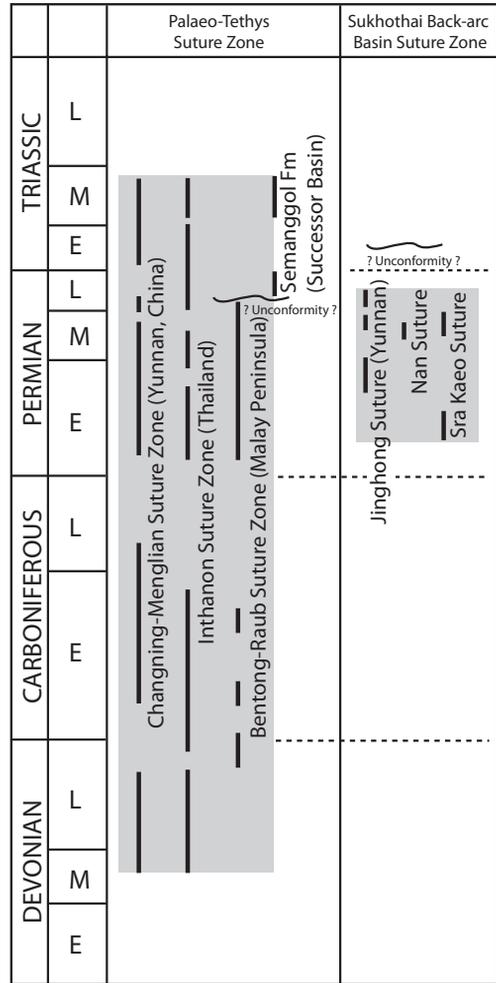
Fig. 9. Ages of oceanic sediments (mainly radiolarian cherts) reported from the main Palaeo-Tethys suture zone segments and from sutures that represent the closed Sukhothai back-arc basin. Grey shaded areas show maximum age ranges for the Palaeo-Tethys ocean and Sukhothai back-arc ocean. E, Early; M, Middle; L, Late. Modified after Sone & Metcalfe (2008).

The Bentong-Raub Suture Zone of the Malay Peninsula includes oceanic radiolarian cherts that range in age from Devonian to Upper Permian (Figs 9 & 11). Triassic cherts of the Semanggol Formation have been interpreted as forming in a 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.
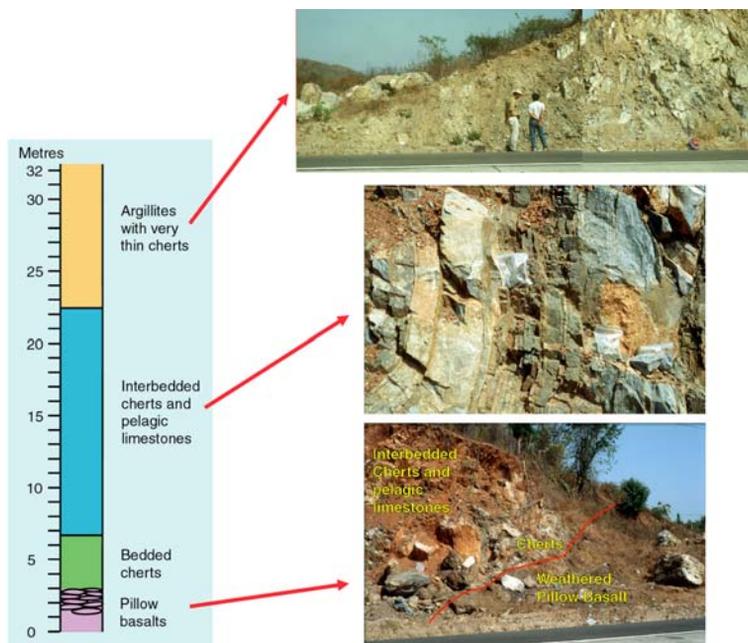
Fig. 10. Ocean Plate Stratigraphy (OPS) of the Inthanon Suture Zone exposed in a road cutting south of Chiang Mai, northern Thailand.

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. 9 and discussion in Sone & Metcalfe 2008).

Ailaoshan, Song Ma and Dian-Qiong (Palaeo-Tethys Branch) sutures

A broad NW–SE mobile belt forms the complex boundary zone between the South China and Indochina blocks in north Vietnam and southern China. This complex zone probably also includes micro-continental blocks and accreted volcanic arcs, has been difficult to interpret, and has led to a range of models for the timing and nature of collision between South China and Indochina. The Red River Fault, a major Cenozoic strike-slip fault has often been portrayed as the boundary between South China and Indochina but this is not regarded here as a suture zone (Fig. 8). The amount of displacement along the Red River Fault and fault

reversal history is debated and linked to the India–Asia collision driven Cenozoic extrusion model for the region (e.g. Tapponnier *et al.* 1982, 1990). A number of narrow belts that contain oceanic rock assemblages ('ophiolites', ultramafics, ocean–floor basalts, deep-marine radiolarian cherts) are recognized in north Vietnam–SE China and interpreted as suture zones.

The Ailaoshan suture zone has been interpreted as probably representing a back-arc basin between the Simao block and South China (Wang *et al.* 2000) or an Atlantic type ocean basin (Jian *et al.* 2009), see Figure 8. Ophiolitic assemblages of the suture include meta-peridotite, gabbro, diabase and basalt capped by radiolarian-bearing siliceous rocks. Plagiogranite (Shuanggou ophiolite) has been dated as early Carboniferous (Jian *et al.* 1998*a*, *b*) and the radiolarian siliceous rocks are Lower Carboniferous in age (Wang *et al.* 2000; Yumul *et al.* 2008). The suture was correlated with the Jinshajiang suture to the north and the Nan-Uttaradit suture to the south by Wang *et al.* (2000). Sone & Metcalfe (2008) however, correlate the Nan-Uttaradit back-arc suture with the Jinghong suture (Fig. 8).

The Song Ma Suture zone includes massive serpentinite, altered gabbro and chromitite. The gabbros have a MORB-like affinity and chromian-spinels suggest serpentinites represent remnants of the Palaeo-Tethys oceanic lithosphere (Trung

Fig. 11. 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).

et al. 2006). Large scale folding, thrust and nappe formation in the Early–Mid Carboniferous, blanketing Middle Carboniferous strata and plant biogeography suggests that the suture is of Early Carboniferous age (Metcalfe 1998). However, geochronological data suggests an Early Triassic event (Lepvrier *et al.* 2008). It seems unlikely that this event is a collisional one in view of evidence of rifting in Vietnam and South China in the Permo-Triassic. Carter *et al.* (2001) and Carter & Clift (2008) suggest that there is little evidence to support Indosinian Triassic collision and mountain building in Indochina–South China and that the Early Triassic thermochronology event relates to the accretion of Sibumasu to Indochina. Other authors maintain that the Song Ma Suture provides evidence of continental collision such as granulite-facies metamorphism (Nakano *et al.* 2008). However, the studied granulites are an allochthonous boulder with no proven source.

Deep-marine radiolarian-bearing sediments of Devonian to Triassic age along the southern border of the Nanpanjian Basin in South China have been known for some time and these were regarded as failed-rift sediments related to the Devonian

rifting and separation of South China from Gondwana (Zhao *et al.* 1996; Metcalfe 1998). Discovery of associated mid-ocean ridge basalts and identification of a central Hainan late Palaeozoic suture zone (Zhou *et al.* 1999) led Zhang *et al.* (2006), Zhang & Cai (2009) and Cai & Zhang (2009) to propose the Dian-Qiong suture in South China extending to Hainan Island (Figs 2, 3 & 8). This suture is interpreted to correlate with and be originally contiguous with the Song Ma suture now disrupted by Cenozoic strike-slip telescoping. This suture is interpreted to be of Triassic age and indicates separation of Indochina and South China in the Permian–Early Triassic. This seems to be at variance with biogeographical data and other evidence for an earlier suturing between Indochina and South China along the Song Ma suture zone (see above) and evidence of Permian–Triassic plume-related rifting in the region.

Other possible suture zones recognized in the Indochina region include the 'Song Da suture' (N. Vietnam) and the 'Da Nang-Zeijiang' suture (central Vietnam–South China), Tamky-Phuoc Son suture (South Vietnam), Poko suture (South Vietnam). The Song Da 'suture' or zone is here regarded as a Permian–Triassic continental rift zone. The Song Da Rift includes Middle–Late Permian rift related basic volcanic rocks, including komatiite rocks, equivalent to those known in South China (Emenshian volcanic province) and related to mantle–plume activity, and Lower Triassic terrigenous facies sedimentary rocks (see Lepvrier *et al.* 2008 for discussion). The Da Nang-Zeijiang suture, equivalent to the South Trung Song ophiolite Belt of Hutchison (1989) was proposed by Hoe & Rangin (1999). The nature and age of this 'suture' is unclear. Ultramafic and mafic rocks are associated with Cambrian–Silurian rocks and Precambrian blocks but evidence for these representing a subduction zone is unconvincing (Hoe & Rangin 1999). Tamky-Phuoc Son 'suture' (Tran 1979; Sengör *et al.* 1988) includes serpentinized ultramafic rocks in association with mafic and felsic volcanic rocks mixed with continental formations to form a mélange zone. The zone was regarded as a rift zone by Gatinsky & Hutchison (1987). The Poko 'suture' is a major shear zone that incorporates some peridotite, pyroxenite and layered gabbro associated with rhyolitic and andesitic rocks. This suture was regarded as a continental rift by Ferrari *et al.* (2008) relating to their 'Orang Laut terranes'.

Shan Boundary and Medial Sumatra Tectonic Zones (Palaeo-Tethyan 'sutures')

The Cathaysian West Sumatra and West Burma blocks are now positioned outboard (current west)

of the Gondwanan Sibumasu block. The mechanism of emplacement to their present relative locations to other continental blocks of the region is interpreted as strike-slip tectonics (Barber & Crow 2003; Wakita & Metcalfe 2005, 2009a; Barber & Crow 2009). The boundary between the Sibumasu block and the SW Sumatra block is the Medial Sumatra Tectonic Zone (Barber & 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 & Crow 2009).

Meratus-Lok-Ulo Meso-Tethys suture

The Jurassic–Cretaceous SW Borneo Meratus and central Java Lok-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. Reconstructed ocean plate stratigraphies represent the entire Cretaceous and include sea mount rock associations (Wakita & Metcalfe 2005).

Boyan Proto-South China Sea suture

The Boyan suture is located between the small Semitau block and SW Borneo. Melange in the suture is of Late Cretaceous age formed by destruction of the Proto-South China Sea (Metcalfe 1999).

Palaeozoic–Mesozoic evolution and palaeogeography of SE Asia

The Gondwana origins of all component continental blocks of SE Asia is now widely accepted. These continental blocks rifted and separated from NE Gondwana as three continental slivers or collages of terranes in the Early–Middle Devonian, Early Permian, and Late Triassic–Jurassic. Successive Tethyan ocean basins, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys opened between each separating sliver and Gondwana. The separated continental blocks migrated successively northwards to in some cases amalgamate, and then accrete to form the core of East and SE Eurasia. 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 are shown in Figure 12.

Early–Middle Palaeozoic evolution and palaeogeography

Tectonostratigraphical, biogeographical, geochemical, provenance study, and palaeomagnetic data indicate that all the principal continental blocks of East and SE Asia formed a greater Indian–Australian Gondwana margin in the Early Palaeozoic (Fig. 13a). Metcalfe (1988, 1990, 1996a, 1999, 2006) has presented the evidence for such placement and this will not be repeated here. Cambro-Ordovician faunas on the North China, South China, Tarim, Indochina, Sibumasu, Qiangtang, and Lhasa blocks define an Asia–Australia province at this time (Fig. 14) and palaeomagnetic data is consistent with their placement on the India–Australian Gondwana margin. Other workers have invoked a similar reconstruction scenario (e.g. Fortey & Cocks 1998; Golonka 2000, Golonka et al. 2006; Hendricks et al. 2008). By Mid–Late Silurian times, Gondwana had rotated clockwise significantly but NE Gondwana remained in low northern palaeolatitudes (Fig. 13b). The Sundaland/Asian terranes remained in their previous relative positions, continuing to form a greater Gondwana margin. Again, biogeographical data indicates an Asia–Australian province particularly well illustrated by the distribution of the Retziella brachiopod fauna (Fig. 13b).

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 & 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. 15).
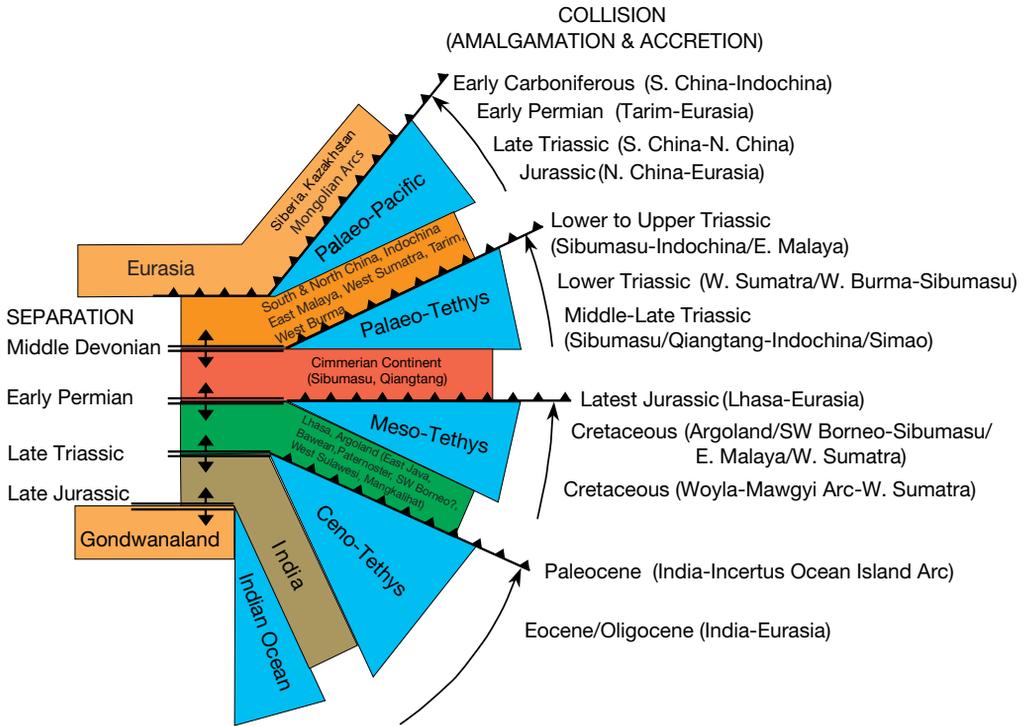
Fig. 12. Schematic diagram showing times of separation and subsequent collision of the three continental slivers/ collages of terranes that rifted from Gondwana and translated northwards by the opening and closing of three successive oceans, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys.

## Late Palaeozoic evolution and palaeogeography

In Late–Early Carboniferous (Visean) times the faunas and floras of North China, South China and Indochina–East Malaya no longer exhibited any Gondwana affinities and these blocks were located in equatorial to low northern palaeolatitudes (Fig. 16). South China and Indochina had probably amalgamated along the Song Ma suture zone. 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 biogeographical 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. 16). The Sibumasu block and the Argo/SW Borneo blocks remained on the NW Australian margin of Gondwana.

The Tarim block, following its separation from Gondwana in the Devonian, collided with Siberia in the Late Carboniferous to Early Permian and was welded to proto-Asia by the Middle Permian (Carroll *et al.* 1995).

Gondwanan glaciation was at its maximum development in the Latest Carboniferous–Earliest Permian 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 (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. Early Permian floras of the North China, South China and Indochina–East Malaya blocks (located in isolated intra-Tethyan positions) are typical Cathaysian warm-climate *Gigantopteris* floras (Fig. 17). Conodont faunal provinciality was also marked in the early Permian with a distinct southern hemisphere high-latitude peri-Gondwana cool-water province characterized by
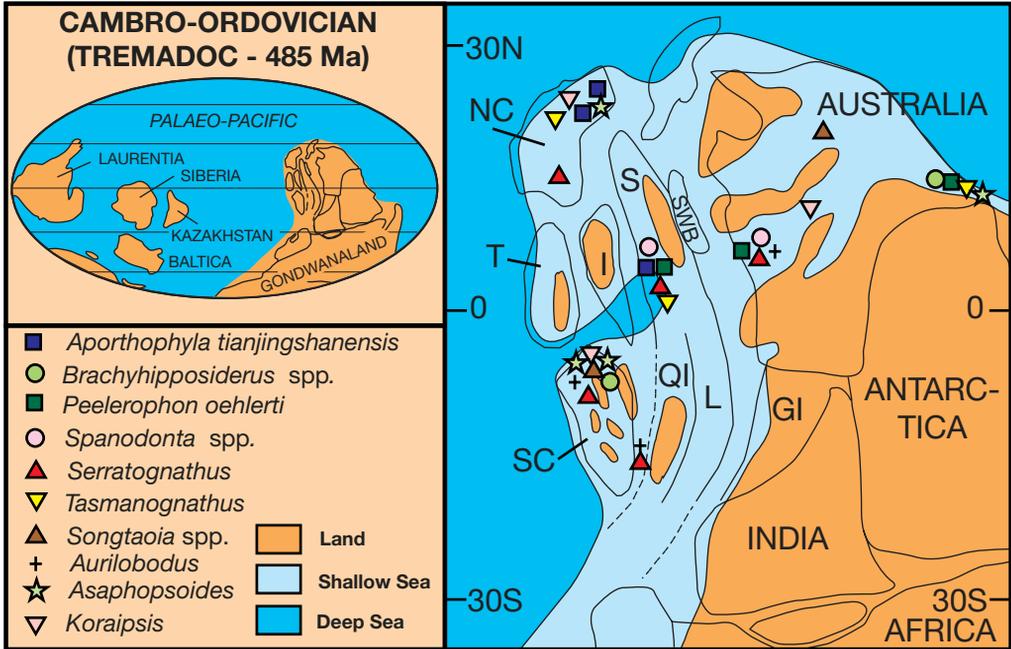
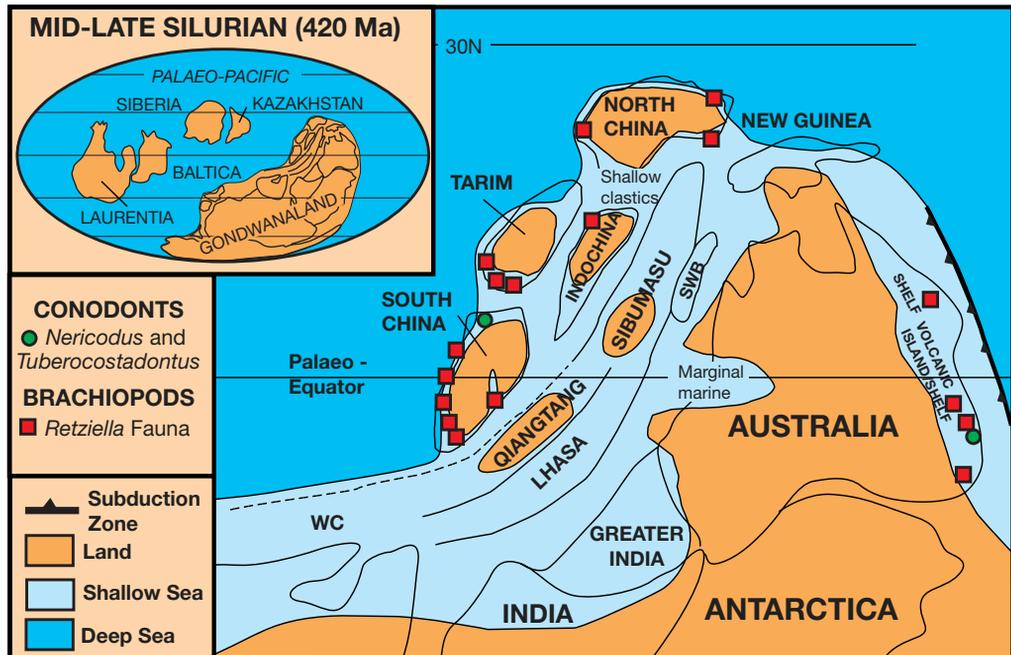**Fig. 13.** Reconstructions of eastern Gondwanaland for (**a**) Cambro–Ordovician (Tremadoc) and (**b**) Mid - Late Silurian showing the postulated positions of the East and SE Asian terranes, distribution of land and sea, and shallow-marine fossils that illustrate Asia–Australia connections at these times. NC, North China; SC, South China; T, Tarim; I, Indochina/East Malaya/West Sumatra; QI, Qiangtang; L, Lhasa; S, Sibumasu; WC, Western Cimmerian Continent; GI, Greater India; SWB, Argoland/SW Borneo.
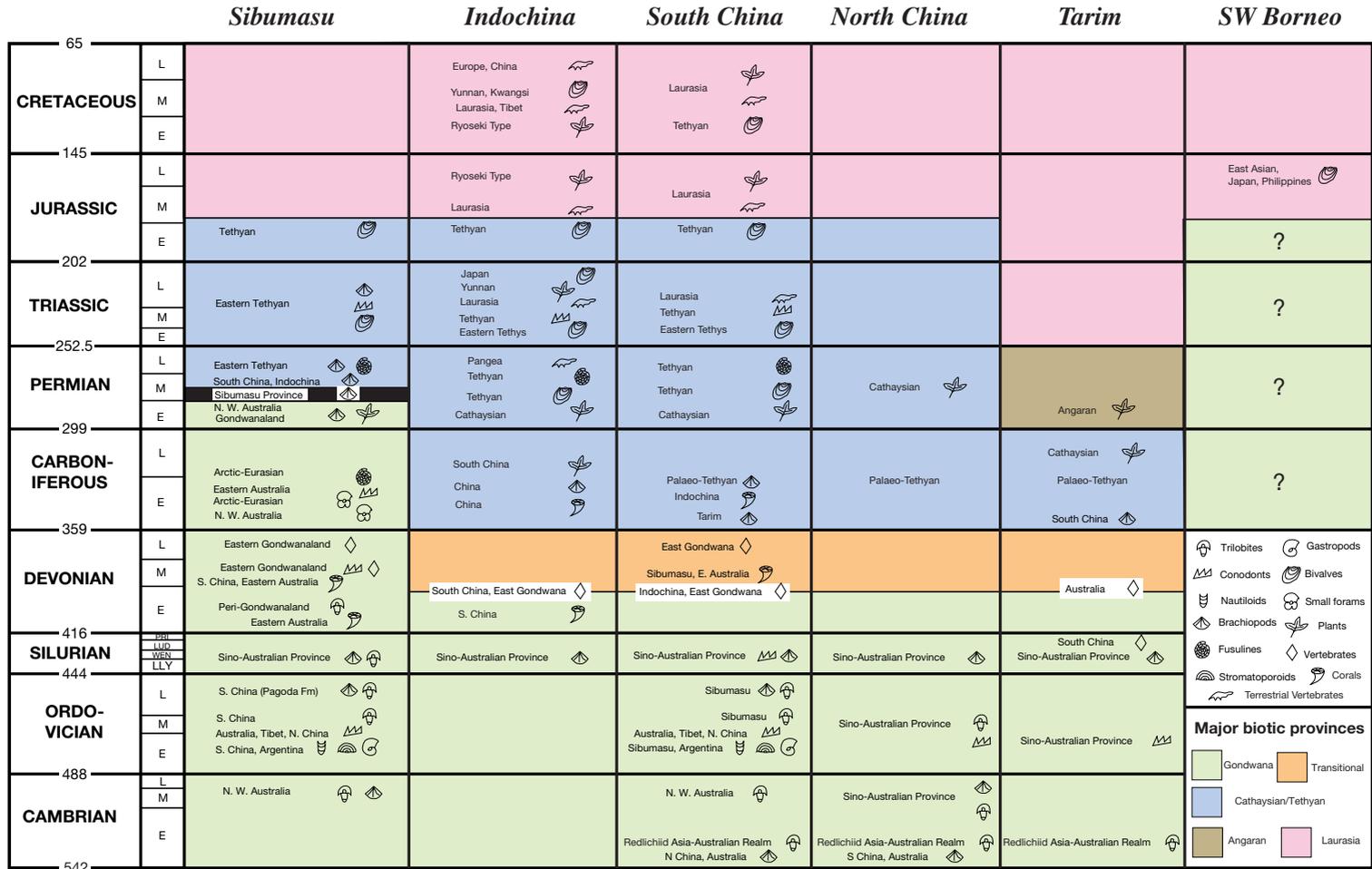
		Sibumasu	Indochina	South China	North China	Tarim	SW Borneo
CRETACEOUS (65)	L		Europe, China				
	M		Yunnan, Kwangsi / Laurasia, Tibet	Laurasia			
	E		Ryoseki Type	Tethyan			
JURASSIC (145)	L		Ryoseki Type	Laurasia			East Asian, Japan, Philippines
	M		Laurasia				
	E	Tethyan	Tethyan	Tethyan			?
TRIASSIC (202)	L	Eastern Tethyan	Japan / Yunnan / Laurasia	Laurasia			?
	M		Tethyan	Tethyan			
	E		Eastern Tethys	Eastern Tethys			
PERMIAN (252.5)	L	Eastern Tethyan	Pangea	Tethyan			?
	M	South China, Indochina / Sibumasu Province	Tethyan	Tethyan	Cathaysian		
	E	N. W. Australia Gondwanaland	Tethyan / Cathaysian	Cathaysian		Angaran	
CARBON-IFEROUS (299)	L	Arctic-Eurasian	South China			Cathaysian	?
	E	Eastern Australia / Arctic-Eurasian / N. W. Australia	China / China	Palaeo-Tethyan / Indochina / Tarim	Palaeo-Tethyan	Palaeo-Tethyan / South China	
DEVONIAN (359)	L	Eastern Gondwanaland		East Gondwana			
	M	Eastern Gondwanaland / S. China, Eastern Australia	South China, East Gondwana	Sibumasu, E. Australia		Australia	
	E	Peri-Gondwanaland / Eastern Australia	S. China	Indochina, East Gondwana			
SILURIAN (416)	PRI/LUD/WEN/LLY	Sino-Australian Province	Sino-Australian Province	Sino-Australian Province	Sino-Australian Province	South China / Sino-Australian Province	
ORDO-VICIAN (444)	L	S. China (Pagoda Fm)		Sibumasu			
	M	S. China / Australia, Tibet, N. China		Sibumasu / Australia, Tibet, N. China	Sino-Australian Province	Sino-Australian Province	
	E	S. China, Argentina		Sibumasu, Argentina			
CAMBRIAN (488)	L	N. W. Australia		N. W. Australia	Sino-Australian Province		
	M						
	E			Redlichiid Asia-Australian Realm / N China, Australia	Redlichiid Asia-Australian Realm / S China, Australia	Redlichiid Asia-Australian Realm	
(542)							

Legend: Trilobites, Gastropods, Conodonts, Bivalves, Nautiloids, Small forams, Brachiopods, Plants, Fusulines, Vertebrates, Stromatoporoids, Corals, Terrestrial Vertebrates

Major biotic provinces: Gondwana, Transitional, Cathaysian/Tethyan, Angaran, Laurasia

Fig. 14. Palaeozoic and Mesozoic faunal and floral provinces and affinities v. time for the principal East Asian continental blocks (After Metcalfe 2001).

Fig. 15. Reconstruction of eastern Gondwana in Late Devonian to Lower Carboniferous (Tournaisian) times showing the postulated positions of the East and SE Asian terranes. Also shown is the distribution of the endemic Tournaisian brachiopod genus *Chuiella*. NC, North China; SC, South China; T, Tarim; I, Indochina/East Malaya/West Sumatra/West Burma; QI, Qiangtang; L, Lhasa; S, Sibumasu; SWB, Argoland/SW Borneo; WC, Western Cimmerian Continent.

the genus *Vjalovognathus*, an equatorial warm-water *Sweetognathus*-dominated province and a northern hemisphere high-latitude cool-water *Neo-streptognathodus*-dominated province (Fig. 18). Continental connection or close proximity of South China and Indochina in the Kungurian is indicated by the endemic occurrence of *Pseudo-sweetognathus* on these two blocks (Metcalfe & Sone 2008; Fig. 18).

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 & Archbold 1998; Ueno 2003). As Sibumasu was translated northwards during the Permian, the Palaeo-Tethys was subducted beneath northern Pangaea, 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. 18). The resulting narrow back-arc basin collapsed at the end of the Permian to form the Jinghong, Nan-Uttaradit and Sra Kaeo sutures (Sone & 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, 2000*a*, *b*; 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 & Crow (2009). 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 the West Burma and West Sumatra blocks (initially as a single block) were translated westwards by transcurrent tectonics
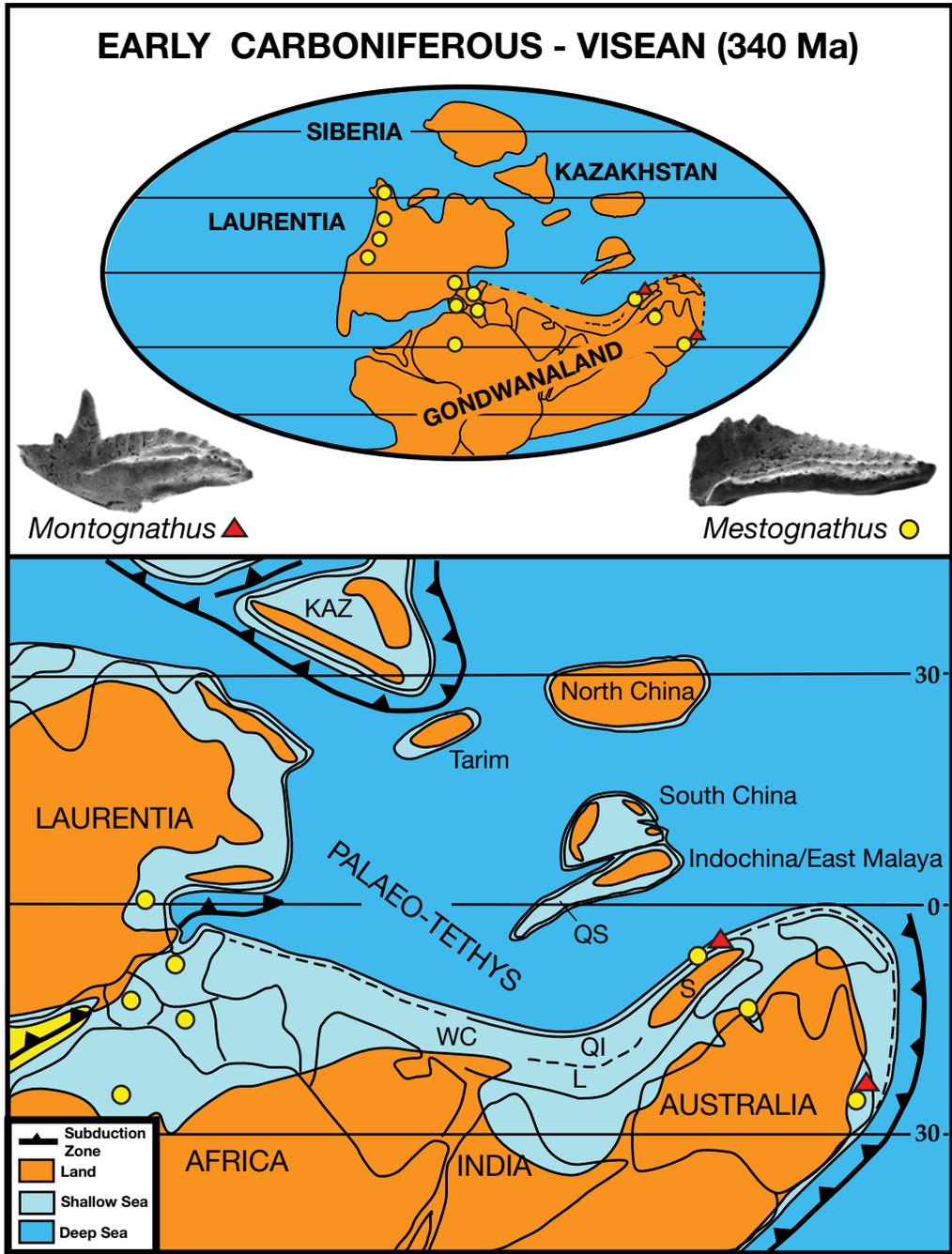
Fig. 16. Early Carboniferous (Visean) reconstruction showing postulated positions of East and SE Asian blocks. The biogeographic distributions of the conodont genera *Mestognathus* (Illustrated specimen is *Mestognathus beckmanni* from the Kanthan Limestone, Peninsular Malaysia) and Montognathus (*Montognathus carinatus* from Peninsular Malaysia illustrated) are also shown.
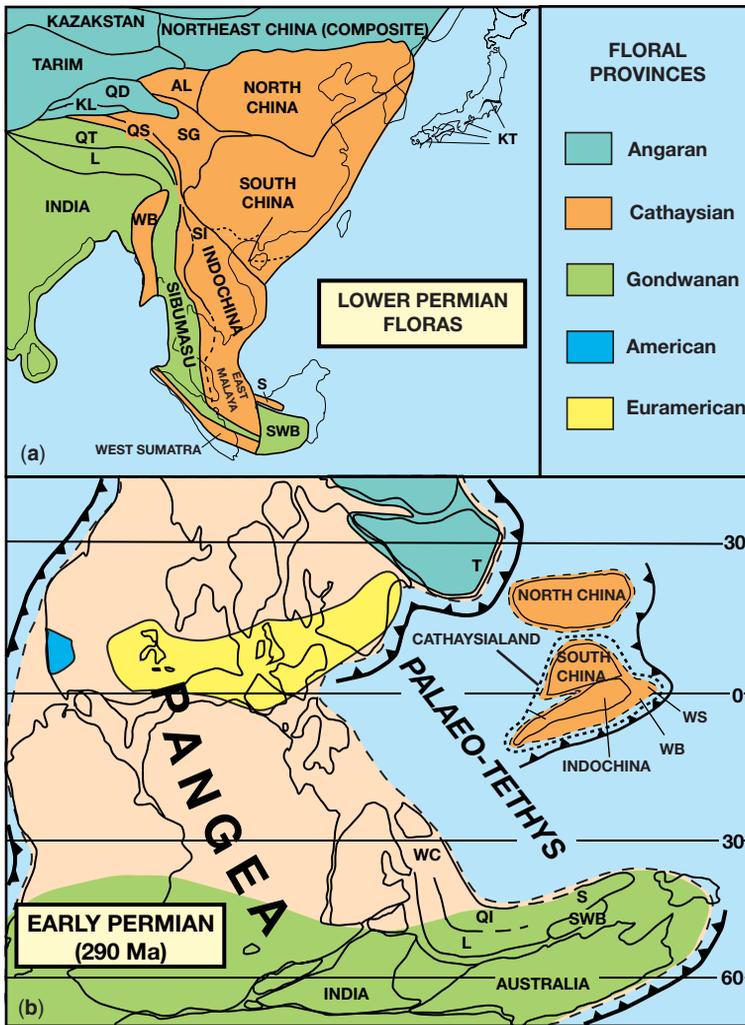
Fig. 17. Distribution of Lower Permian floral provinces plotted on (**a**) present-day geographical map, and (**b**) Early Permian palaeogeographic map. KT, Kurosegawa Terrane. Other abbreviations as for Figures 2 and 3.

to their current positions outboard of the Sibumasu terrane in the Early Triassic. This translation was coeval with and partly the result of 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.

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 Pangaea 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. 18).

(c) Late Permian (Changhsingian)

★ *Dicynodon*

(b) Early Permian (Kungurian)

△ *Neostreptognathodus* abundant, *Sweetognathis* absent/rare

North Cool-Water Province

CATHAYSIALAND

Equatorial Warm Water Province

★ *Pseudosweetognathus*

■ *Sweetognathus* present or abundant, *Neostreptognathodus* less common/absent

● *Monodiexodina*

△ *Vjalovognathus*

Peri-Gondwana Cool-Water Province

(a) Early Permian (Asselian-Sakmarian)

▨ Ice Sheet

☆ Glacial-marine diamictites

● *Comia* Flora

▨ Land   ▨ Shallow Sea   ▨ Deep Sea

Fig. 18.

Fig. 19. Palaeogeographic reconstructions of the Tethyan region for the Late Triassic (Rhaetian) showing relative positions of the East and SE 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/SW Borneo.

Mesozoic 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 and was completed by Late Triassic times (Fig. 19). Collision between South and North China began in the Permian and continued in the Triassic. Comparisons of apparent polar wander paths (APWPs) 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 & Courtillot 1997). Thus, the initial consolidation of what is now Sundaland and mainland East and SE 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 Pangaea and covered by thick Triassic deposits eroded from adjacent collisional orogens.

A third episode of rifting of the Indian–Australian margin of Gondwana was initiated in the Triassic and continued into the Jurassic/Cretaceous (Fig. 20). 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

Fig. 18. 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 SE Asian terranes and distribution of land and sea. Also shown are the Early Permian occurrences of the *Comia* flora linking West Sumatra, North China and Pangaea; Asselian–Sakmarian ice sheet and peri-Gondwana glacial-marine diamictite localities; Late Early Permian biogeographical provinces and distribution of biogeographically important conodonts and the bipolar fusulinid *Monodiexodina*; and Late Permian tetrapod vertebrate *Dicynodon* localities on Indochina and Pangaea 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, SW Borneo; WC, Western Cimmerian Continent.
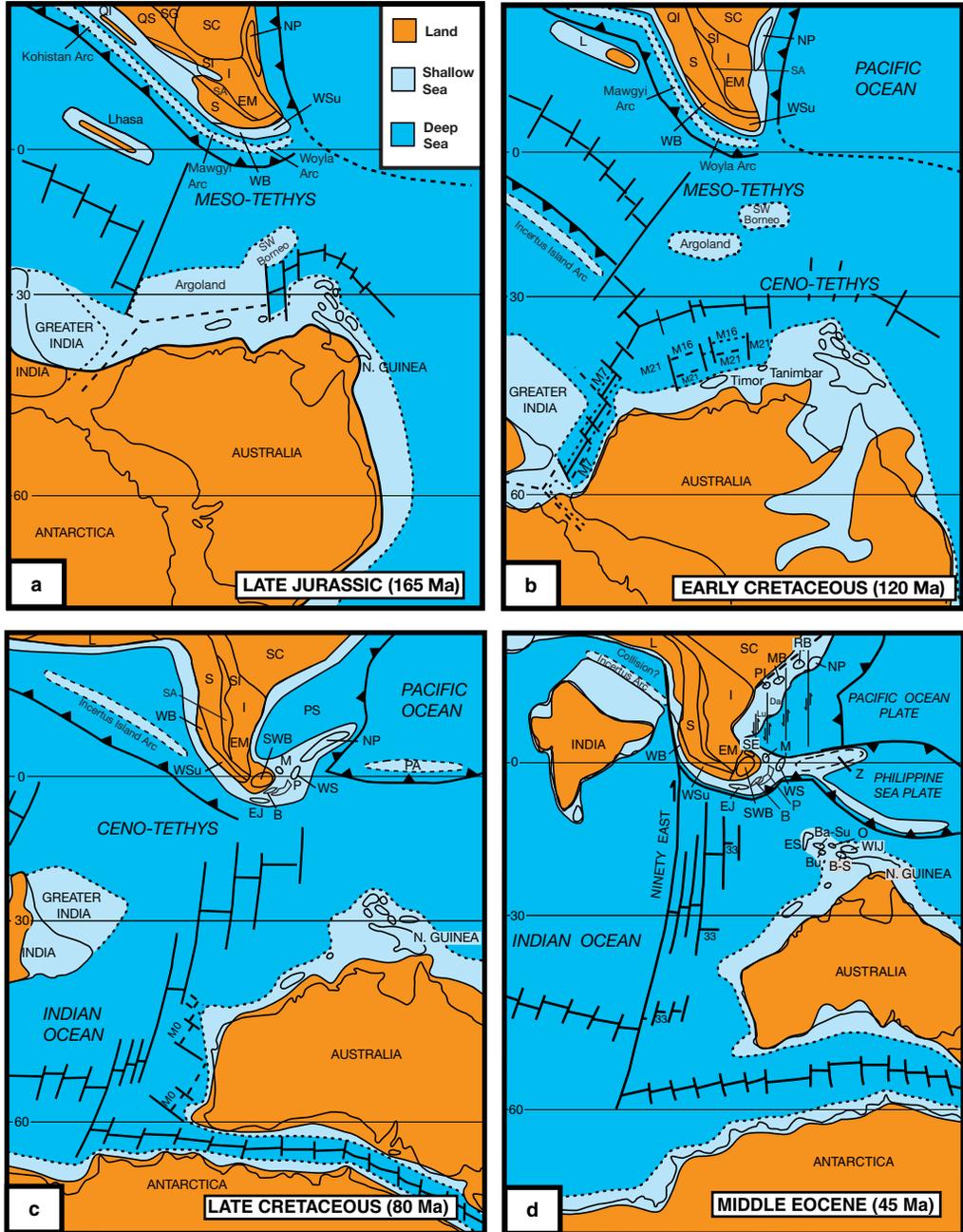
Fig. 20. Palaeogeographic reconstructions for Eastern Tethys in (**a**) Late Jurassic, (**b**) Early Cretaceous (**c**) Late Cretaceous and (**d**) Middle Eocene showing distribution of continental blocks and fragments of SE Asia–Australasia and land and sea. SG, Songpan Ganzi accretionary complex; SC, South China; QS, Qamdo-Simao; SI, Simao; QI, Qiangtang; S, Sibumasu; SA, Sukhothai Arc; I, Indochina; EM, East Malaya; WSu, West Sumatra; L, Lhasa; WB, West Burma; SWB, SW 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, Banggai-Sula; Bu, Buton; WIJ, West Irian Jaya. M numbers represent Indian Ocean magnetic anomalies.

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 Stampfli & Borel (2002) 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 then rifted and separated progressively westwards from the NW Australian margin in the Late Jurassic–Early Cretaceous (Fig. 20). 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.* 2009) 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 & Saitta 2004; Heine & 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.* (2009).
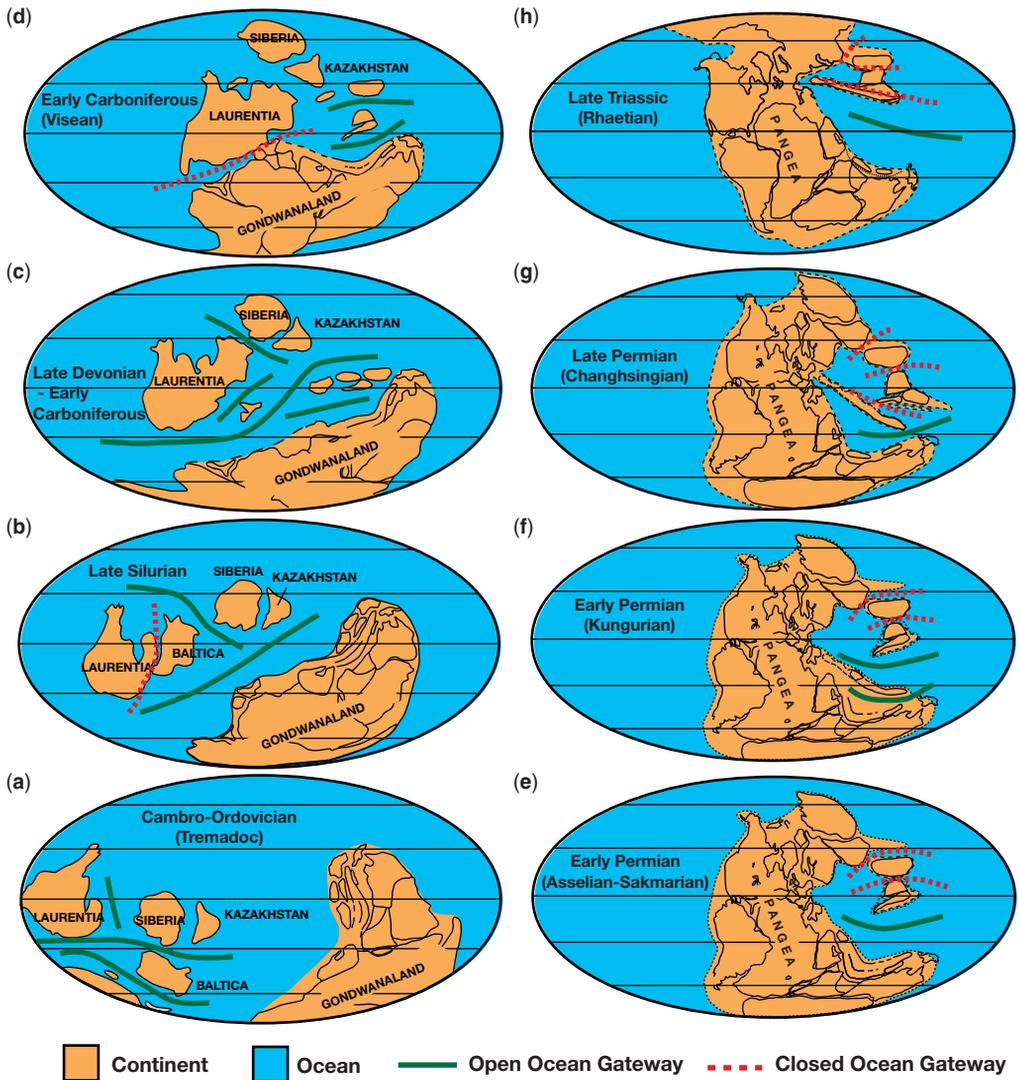
Fig. 21. Changing continent–ocean configurations in the Palaeozoic–Early Mesozoic and evolving ocean gateways.

SW Borneo and Argoland were translated north-wards during the Cretaceous and by Late Cretaceous times had accreted to SE Sundaland. The Incertus Island Arc developed within the Ceno-Tethys during the Cretaceous (Aitchison *et al.* 2007; Hall *et al.* 2009) 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. 20). The 45 Ma timing is temporally coincident with large-scale regional and global plate reorganizations at this time (Hall *et al.* 2009). A younger 'hard' collision between India and Eurasia at *c*. 35 Ma has however been recently proposed by Ali & Aitchison (2007, 2008) but challenged by Yin (2010) who maintains an early *c*. 60 Ma initial collision.

Palaeozoic–Mesozoic ocean gateway evolution

Changes in global continent–ocean configurations during the Palaeozoic–Mesozoic (Fig. 21) have led to both opening and closure of oceanic gateways that undoubtedly had significant effects on both global and SE Asian ocean currents, circulation and upwelling, and climate. This in turn led to

changing biogeographical patterns and biotic provinces. In the early to Middle Palaeozoic, Gondwana was separated from other dispersed major continental blocks with significant ocean gateways between Gondwana and between Laurentia, Baltica, Siberia and Kazakhstan (Fig. 21a–c). Changes in the positions of blocks during the Cambrian and Devonian led to closure of the gateway between Laurentia and Siberia in the Silurian but a major ocean gateway between Gondwana and other blocks was maintained. In the Devonian, North China, South China, Tarim and Indochina/ East Malaya/West Sumatra/West Burma rifted and separated from NE Gondwana opening the Palaeo-Tethys. This eventually led to the opening of a gateway between Gondwana and SE Asian blocks in the Early Carboniferous, and with clock-wise rotation of Gondwana, the closure of the major gateway and separating ocean between Laurentia and north African west Gondwana initiated the final formation of Pangaea.

Northwards migration of SE Asian continental blocks in the Permian–Triassic resulted in the opening and closure of oceanic gateways between the Panthalassa in the east and the largely closed Tethys in the west (Fig. 21e–h). The changing gateways in the Tethyan region during the Permian–Triassic must have resulted in changing ocean
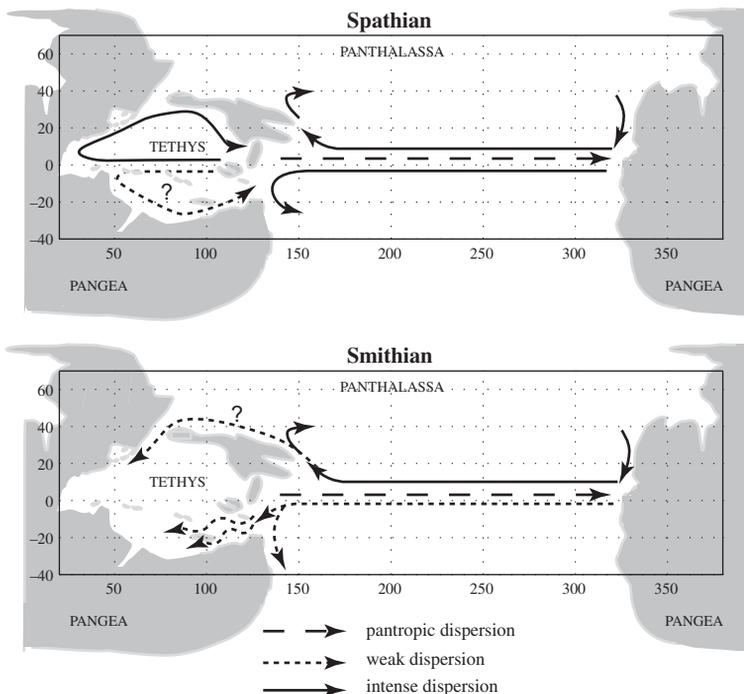

Fig. 22. Ammonoid dispersion for the Olenekian (Smithian and Spathian). After Brayard *et al.* (2009).

currents and regions of deep ocean upwelling affecting climate patterns and dispersal of biota (e.g. ammonite dispersal of Brayard *et al.* 2009; Fig. 22).

Conclusions

The Palaeozoic–Mesozoic evolution of SE Asia involved the rifting and separation of three collages of continental terranes from eastern Gondwana and the successive opening and closure of three ocean basins, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys.

The Palaeo-Tethys is represented in SE Asia by the Inthanon (Chiang Mai), Chanthaburi (cryptic) and Bentong-Raub suture zones.

The Sukhothai Island Arc System, including the Linchang, Sukhothai and Chanthaburi terranes is identified between the Sibumasu and Indochina–East Malaya terranes in mainland SE Asia. It was constructed on the margin of Indochina–East Malaya and separated by back-arc spreading in the Permian. The Jinghong, Nan-Uttaradit and Sra Kaeo sutures represent the closed back-arc ocean basin.

The West Sumatra and West Burma blocks rifted and separated from Gondwana, along with Indochina and East Malaya in the Devonian and formed a composite terrane 'Cathaysialand' with South China in the Permian.

In the Late Permian–Early Triassic, West Sumatra and West Burma were translated westwards to their positions outboard of Sibumasu by strike-slip translation at the zone of convergence between the Meso-Tethys and Palaeo-Pacific plates.

The continental micro-blocks that rifted and separated from Gondwana in the Jurassic are here identified as East Java, Bawean, Paternoster, West Sulawesi, Mangkalihat and SW Borneo. The East Java, Bawean, Paternoster, West Sulawesi and Mangkalihat blocks comprise Argoland, derived from the Exmouth Plateau region of western Australia.

SW Borneo is identified as the 'Banda block' derived from the Banda embayment region of western Australia.

Argoland and SW Borneo were accreted to SE Sundaland in the Late Cretaceous.

Changing continent–ocean configurations during the Palaeozoic and Mesozoic resulted in the closure and opening of ocean gateways that resulted in changes in climatic and ocean current patterns, ocean upwelling and changing patterns of biotic dispersal.

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