Palaeozoic and Mesozoic geological evolution of the SE Asian region: multidisciplinary constraints and implications for biogeography

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Key words: SE Asia, geological evolution, terranes, Gondwanaland, Palaeo-Tethys, Meso-Tethys, Ceno-Tethys, biogeography, palaeogeography

Abstract

East and SE Asia is a giant 'jigsaw puzzle' of continental blocks (terranes) which are bounded by faults, narrow mobile belts or sutures that represent the sites of former ocean basins. Comparative studies of the tectono-stratigraphy, palaeontology, and palaeomagnetism of the various terranes suggests that they were all derived directly or indirectly from Gondwanaland and that they formed part of a 'Greater Gondwanaland'. Rifting and separation of three continental slivers occurred on the northern margin of Gondwanaland, in the Devonian, Early-Middle Permian, and Late Triassic to Late Jurassic. The northwards drift of these terranes was accompanied by the opening and closing of three successive oceans, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys. Amalgamation and accretion of Asian terranes occurred progressively between the Late Devonian and the Cretaceous, beginning with the intra-Tethyan amalgamation of South China and Indochina to form Cathaysialand in the Late Devonian-Early Carboniferous, followed by the accretion of the Tarim terrane to Kazakhstan/Siberia in the Permian. Suturing of Sibumasu and Qiangtang to Cathaysialand and amalgamation of this super-terrane with North China occurred in the Permian-Triassic, and accretion to Laurasia was completed by Late Triassic-Early Jurassic times. The highly disrupted Kurosegawa terrane of Japan, possibly derived from Australian Gondwana, accreted to Japanese Eurasia in the Late Jurassic. The Lhasa, West Burma and Woyla terranes, which rifted from NW Australian Gondwana in the Late Triassic to Late Jurassic were accreted to proto-SE Asia in the Cretaceous. The SW Borneo and Semitau terranes were derived from the South China/Indochina margin by the opening of a marginal basin in the Cretaceous which was subsequently destroyed by southwards subduction during the rifting of the Reed Bank-Dangerous Grounds terrane from South China when the South China Sea opened. Following the final breakup of Gondwanaland, India travelled rapidly northwards to make its initial contact with Eurasia at the end of the Cretaceous. Reconstructions showing the postulated positions of the various terranes and the distribution of land and sea in the Palaeozoic and Mesozoic are presented.

Biogeography and Geological Evolution of SE Asia, pp. 25-41
Edited by Robert Hall and Jeremy D. Holloway

Introduction

Geographic distributions of plants and animals in East and SE Asia show complex and evolving patterns that are the result of plate movements, shifting land/sea and continent/ocean configurations, shifting coastlines, and changing palaeoclimates and environments. Movements of continents and continental fragments and the development and destruction of oceanic basins during the evolution of the SE Asian region have resulted in the creation and destruction of biogeographic barriers at various times and the development, and disappearance of faunal and floral provinces. The dispersal and evolution of faunas and floras of SE Asia are intimately linked with the geological evolution of the region. Biogeographic data alone can help to constrain palaeogeographic reconstructions, but reconstructions based on other types of data can also elucidate observed biogeographic data which are difficult to understand in terms of present-day geography.

Mainland East and SE Asia is like a giant 'jigsaw puzzle' of continental fragments bounded by major geological discontinuities that represent the sites of former ocean basins (Fig.1). Some of these major discontinuities are now huge strike-slip faults, whereas others are actual suture zones that include remnants of oceanic crust (ophiolites), oceanic and continental-margin sedimentary rocks, accretionary complexes, melange, and sometimes volcanic arcs. Eastern SE Asia comprises a series of small continental fragments set in a 'matrix' of stretched continen-

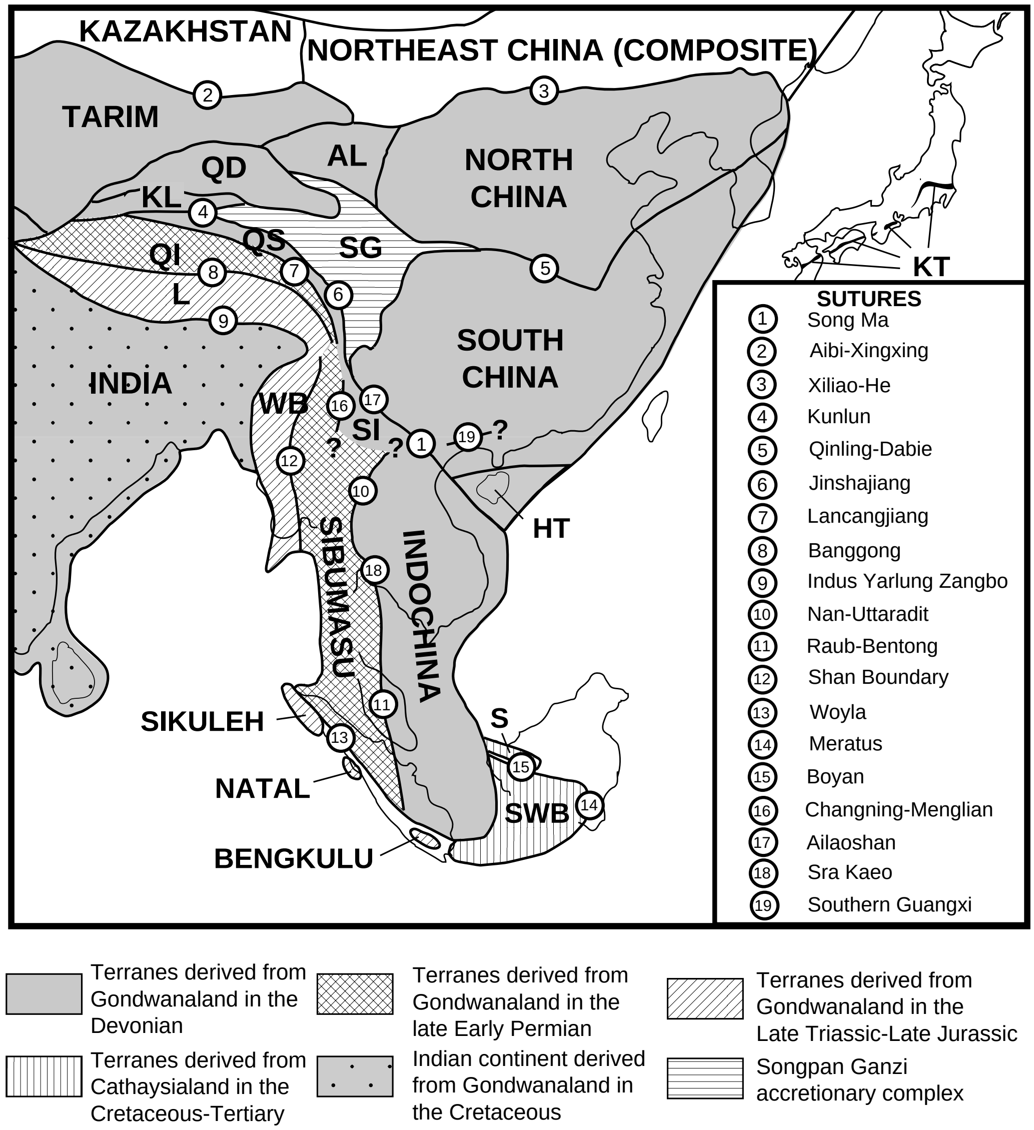


Fig.1. Distribution of principal continental terranes and sutures of East and SE Asia. WB = West Burma, SWB = South West Borneo, S = Semitau Terrane, HT = Hainan Island terranes, L = Lhasa Terrane, QI = Qiangtang Terrane, QS = Qamdo-Simao Terrane, SI= Simao Terrane, SG = Songpan Ganzi accretionary complex, KL = Kunlun Terrane, QD = Qaidam Terrane, AL = Ala Shan Terrane, KT = Kurosegawa Terrane.

tal crust or oceanic crust (marginal basins), accretionary complexes, ophiolites and volcanic arcs (Fig.2). The various continental fragments (terranes) have progressively assembled over the last 400 million years. In this paper, I shall discuss the origins and the Palaeozoic and Mesozoic evolution (540-65 million years ago) of these various continental terranes from a multidisciplinary viewpoint and emphasise the importance of, and implications for biogeographical data. The Cenozoic (65 million years ago to present) evolution of the region is discussed by Hall (1998 this volume).

In discussing the geological evolution of the region, a variety of multidisciplinary data (Table 1) is used here to constrain the origins of terranes; the timing of rifting and separation from their parent cratons; timing, directions and amount of drift; and timing of suturing (collision and welding) of terranes to each other. Some terranes sutured to each other (amalgamated) within a major ocean before they, as an amalgamated com-

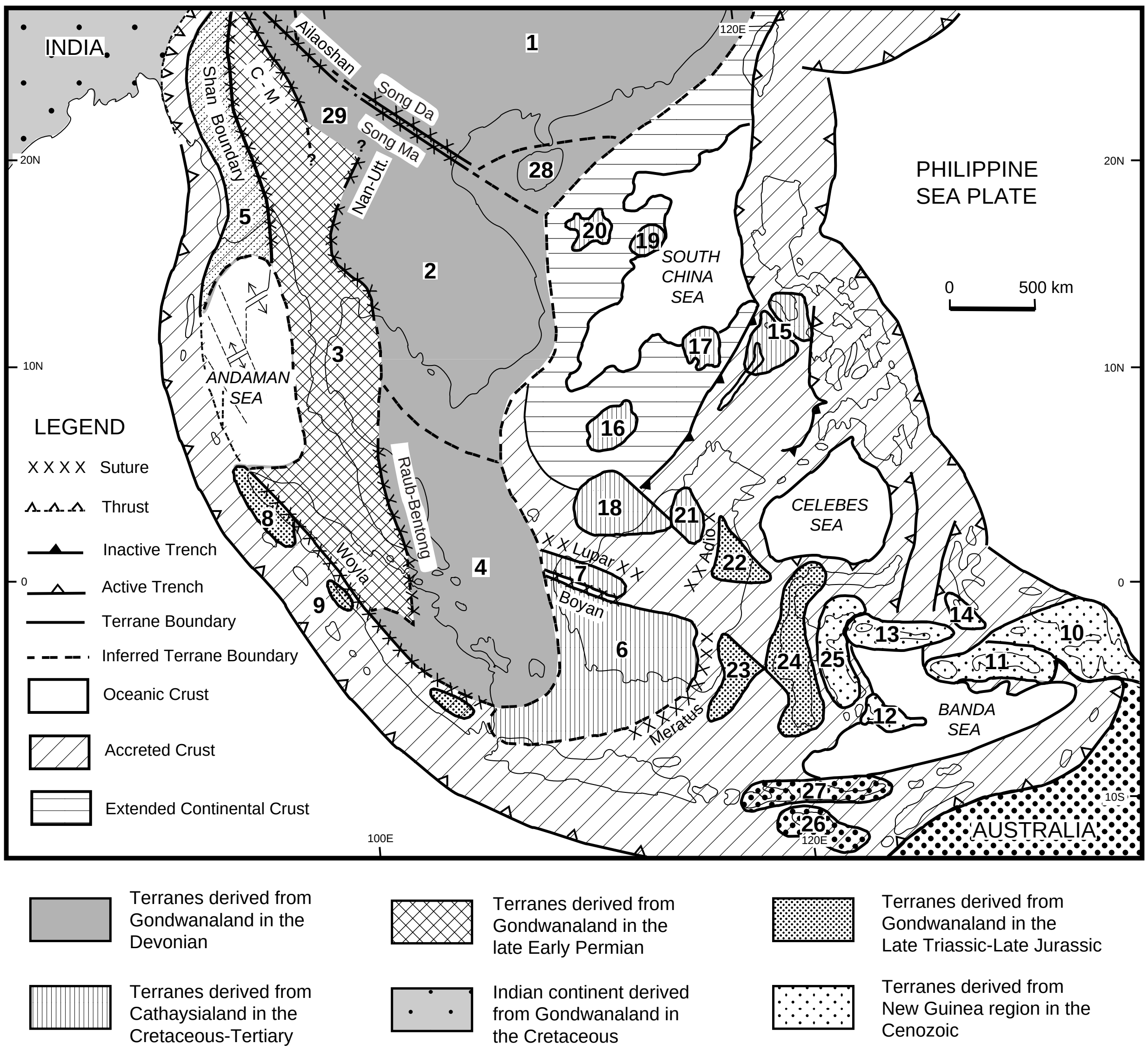


Fig.2. Distribution of continental blocks and fragments (terranes) and principal sutures of SE Asia (modified after Metcalfe, 1990). 1. South China 2. Indochina 3. Sibumasu 4. East Malaya 5. West Burma 6. SW Borneo 7. Semitau 8. Sikuleh 9. Natal 10. West Irian Jaya 11. Buru-Seram 12. Buton 13. Banggai-Sula 14. Obi-Bacan 15. North Palawan 16. Spratley Islands-Dangerous Ground 17. Reed Bank 18. Luconia 19. Macclesfield Bank 20. Paracel Islands 21. Kelabit-Longbowan 22. Mangkalihat 23. Paternoster 24. West Sulawesi 25. East Sulawesi 26. Sumba 27. Banda Allochthon 28. Hainan Island terranes. 29. Simao terrane.

posite terrane, sutured (accreted) to proto-Asia.

Origins of the East and SE Asian terranes

Using multidisciplinary data (Table 1), all the East and SE Asian continental terranes are interpreted to have had their origin on the margin of Gondwanaland, and probably on the India-N/NW Australian margin. Cambrian and Ordovician shallow-marine faunas of the North China, South China, and Sibumasu terranes have close affinities with those of eastern Gondwanaland, and especially Australian Gondwanaland (Burrett, 1973; Burrett and Stait, 1985; Metcalfe, 1988, Burrett *et al.*, 1990). This is observed in trilobites (Shergold *et al.*, 1988), brachiopods (Laurie and Burrett, 1992), corals and stromatoporoids (Webby et al., 1985; Lin and Webby, 1989), nautiloids (Stait and Burrett, 1982, 1984; Stait *et al.*, 1987), gastropods (Jell *et al.*, 1984), and conodonts (Burrett *et al.*, 1990; Nicoll and

Table 1. Multidisciplinary constraining data for the origins and the rift/drift/suturing of terranes.

Origin of Terranes	**Age of Rifting and Separation**	**Drifting (Palaeo-positions of terranes)**	**Age of Suturing (Amalgamation/Accretion)**
INDICATED BY	INDICATED BY	INDICATED BY	INDICATED BY
Palaeobiogeographic constraints (fossil affinities with proposed parent craton)	Ocean floor ages and magnetic stripe data	Palaeomagnetism (palaeolatitude, orientation)	Ages of ophiolite and ophiolite obduction ages (pre-suturing)
Tectonostratigraphic constraints (similarity of gross stratigraphy with parent craton, presence of distinctive lithologies characteristic of parent craton, *e.g.* glacial lithologies)	Divergence of Apparent Polar Wander Paths (APWPs) indicates separation	Palaeobiogeography (shifting from one biogeographic province to another due to drift)	Melange ages (pre-suturing)
Palaeolatitude and orientation from palaeomagnetism consistent with proposed origin	Divergence of palaeolatitudes (indicates separation)	Palaeoclimatology (indicates palaeolatitudinal zone)	Age of 'stitching' plutons (post-suturing)
	Age of associated rift volcanism and intrusive rocks		Age of collisional or post-collisional plutons (syn- to post-suturing)
	Regional unconformities (formed during pre-rift uplift and during block-faulting)		Age of volcanic arc (pre-suturing)
	Major block-faulting episodes and slumping		Major changes in arc chemistry (syn-collisional)
	Palaeobiogeography (development of separate biogeographic provinces after separation)		Convergence of Apparent Polar Wander Paths (APWPs)
	Stratigraphy-rift sequences in graben/half graben		Loops or disruptions in APWPs (indicates rapid rotations during collisions)
			Convergence of palaeo-latitudes (may indicate suturing but no control on longitudinal separation)
			Age of blanketing strata (post-suturing)
			Palaeobiogeography (migration of continental animals/plants from one terrane to another indicates terranes have sutured)
			Stratigraphy/sedimentology (*e.g.* provenance of sedimentary detritus from one terrane onto another)
			Structural geology (age of deformation associated with collision)

Totterdell, 1990; Nicoll and Metcalfe, 1994). More recently, the Gondwanaland acritarch *Dicrodiacroium ancoriforme* Burmann has been reported from the Lower Ordovician of South China (Servais *et al*., 1996). Little is known of Cambrian-Ordovician faunas of Indochina, but Silurian brachiopods, along with those of South China, North China, Eastern Australia and the Tarim terrane belong to the Sino-Australian province characterised by the *Retziella* fauna (Rong *et al*., 1995). Lower Palaeozoic sequences and faunas of the Qaidam, Kunlun, and Ala Shan blocks are similar to those of the Tarim block and also to South and North China (Chen and Rong, 1992), and these blocks are regarded as disrupted fragments of a larger Tarim terrane by Ge *et al*. (1991). These biogeographic data suggest that North China, South China, Tarim (here taken to include the Qaidam, Kunlun and Ala Shan blocks), Sibumasu (with the contiguous Lhasa and Qiangtang blocks), and Indochina formed the outer margin of northern Gondwanaland in the Early Palaeozoic. The close faunal affinities, at both lower and higher taxonomic levels, suggest continental contiguity of these blocks with each other and with Gondwanaland at this time rather than mere close proximity.

Lower Palaeozoic palaeomagnetic data for the

Table 2. Suggested origins for the East and SE Asian continental terranes.

Terrane	Origin
North China	N Australia
South China	Himalaya-Iran Region
Indochina-East	
Malaya	E Gondwana
Sibumasu	NW Australia
West Burma	NW Australia
Lhasa	Himalayan Gondwana
Qiangtang	Himalayan Gondwana
Qamdo-Simao	E Gondwana? Extension of Indochina
Kunlun	NE Gondwana? Originally part of Tarim?
Qaidam	NE Gondwana? Originally part of Tarim?
Ala Shan	NE Gondwana? Originally part of Tarim?
Tarim	Australian Gondwana?
SW Borneo	Cathaysialand (S China/Indochina margin)
Hainan	NE Gondwana?
Kurosegawa	Australian Gondwana?

various East and SE Asian terranes are variable in both quantity and quality and often equivocal. This makes reconstructions based purely on palaeomagnetic data both difficult and suspect. However, sufficient data exist to be able in some cases to reasonably constrain palaeolatitudes (but not always the hemisphere) and in some cases the actual position of attachment to Gondwanaland. North China data (Zhao *et al.*, 1996) provide a Cambrian to Late Devonian pole path segment, which, when rotated about a Euler pole to a position of fit with the Australian Cambrian to Late Devonian pole path, produces a good fit with North China positioned adjacent to North Australia (Klootwijk, 1996). This position is consistent with that proposed in reconstructions by Metcalfe (1993, 1996a, 1996b) and in this paper. Comparisons of the gross stratigraphies of North China and the Arafura basin (Fig.5 in Metcalfe, 1996b) show a remarkable similarity in the early Palaeozoic, also supporting the proposed position for North China. Positions for South China, Tarim, and Indochina are more equivocal, but latitudes of between 1 and 15 degrees are indicated for the Late Cambrian-Early Ordovician for the South China Block (Zhao *et al.*, 1996). Palaeolatitudes of between 6 and 20 degrees south are indicated for the Tarim block for the same time period, which is broadly consistent with a position on the Gondwanaland margin between the North and South China blocks. Comparisons of the Precambrian sequence on the northeast margin of the Tarim block with Australia led Li *et al.* (1996) to propose that this block had its origin outboard of the Kimberley region of Australia. Similar comparisons of the Precambrian of South China however led Li *et al.* (1995, 1996) to propose that South China was positioned between eastern Australia and Laurentia in the Late Proterozoic. This is rather different to the Early Palaeozoic position suggested here. Cambrian to Early Permian faunas of the Sibumasu terrane have strong Gondwanaland affinities, and in particular show close relationships with western Australian faunas (Metcalfe, 1988, 1996a,b; Burrett *et al.*, 1990). In addition, Gondwanaland plants and spores are also reported from this terrane (Wang and Tan, 1994; Yang and Liu, 1996). Glacial-marine diamictites, with associated cold-water faunas and sediments, of Late Carboniferous to Early Permian age, are also found distributed along the entire length of Sibumasu and indicate attachment to the margin of Gondwanaland where substantial ice reached the sea. The most likely region for attachment of this terrane is NW Australia. Palaeomagnetic data for the Late Carboniferous suggest a palaeolatitude of 42 degrees south (Huang and Opdyke, 1991), which is consistent with such a placement. Comparison of the gross stratigraphy of Sibumasu with the Canning basin of NW Australia also reveals striking similarities in the Cambrian to Early Permian, and Sibumasu could easily have been positioned outboard of the Canning basin of western Australia during this time. Both the Qiangtang and Lhasa blocks of Tibet exhibit Gondwanaland faunas and floras up to the Early Permian, and also have glacial-marine diamictites, till, and associated cold-water faunas and sediments in the Late Carboniferous to Early Permian. Thus, all the East and SE Asian continental terranes appear to have had their origins on the margin of Gondwanaland (Table 2).

Carboniferous and younger faunas and floras of the North China, South China, Tarim, and Indochina terranes are typically Cathaysian in nature and they show no relationship with those of Gondwanaland (Metcalfe, 1988). These terranes were also situated at palaeolatitudes that indicate they were no longer attached to the margin of Gondwanaland from the Carboniferous onwards (Zhao *et al.*, 1996) and that they separated from Gondwanaland in the Devonian

Table 3. Major Palaeozoic and Mesozoic tectonic events on the Australian NW Shelf (Colwell *et al.*, 1994).

Age	Event
Early Ordovician	Major intracontinental extension
Late Devonian-Early Carboniferous	Major upper crustal extension
Early Carboniferous-Early Permian	Extension: initiation of Westralian Superbasin
Late Permian	Uplift, extension, igneous activity
Middle Triassic	Structuring in parts of NW Shelf
Late Triassic-Early Jurassic	Regional structuring, compression, transpression, extension: Fitzroy Movement
Middle-Late Jurassic	Breakup in Argo Abyssal Plain

as previously suggested by Metcalfe (1994, 1996a, 1996b). Sibumasu, Qiangtang, and the Lhasa terrane continued to remain on the margin of Gondwanaland until the Permian, with the Lhasa terrane remaining attached to Gondwanaland possibly until the Late Triassic but with Sibumasu and Qiangtang separating in the late Early Permian.

The continental sliver which was located immediately outboard of NW Australia in the Triassic, and which must have rifted and separated in the Jurassic, is here considered to have comprised West Burma, the small Sikuleh, Natal and possibly Bengkulu terranes now located in SW Sumatra, and perhaps small continental fragments (West Sulawesi, Mangkalihat and the Banda allochthon) that now form parts of Borneo and eastern Indonesia. There is however little direct evidence to support this, apart from stratigraphic similarities between the Sikuleh block and the NW Australian shelf, and sparse palaeomagnetic data showing this block to be derived from the south in the Mesozoic (Haile, 1979; Görür and Sengör, 1992). The small Hainan Island terranes had their origin on the Early Palaeozoic margin of Gondwanaland but had probably separated by the Late Palaeozoic (Metcalfe, 1996b). The disrupted composite Kurosegawa terrane of Japan is believed to have been derived from Gondwanaland, and a position adjacent to eastern South China in the Silurian/Devonian has been suggested (Saito, 1992, Hisada *et al.*, 1994).

Carboniferous and Permian faunas of the South West Borneo and Semitau blocks do not appear to have any affinities with those of Sibumasu, but are very similar to those of South and North China (Vachard, 1990). Triassic and Jurassic floras and faunas have affinities with South China, Indochina and Japan and a South China/Indochina origin seems likely.

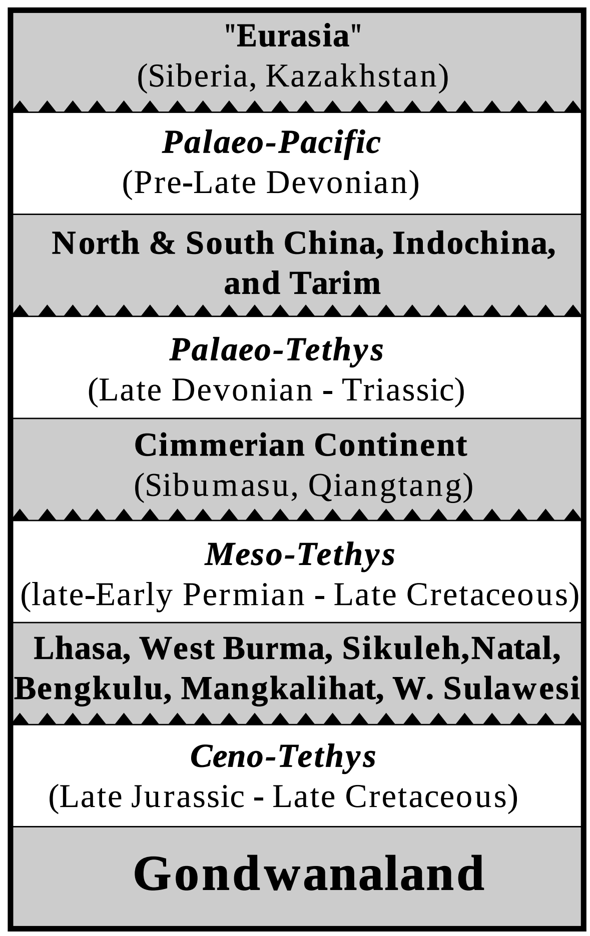


Fig.3. Schematic diagram showing the three continental slivers/collages of terranes, rifted from Gondwanaland and translated northwards by the opening and closing of three successive oceans, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys.

Table 4. East and SE Asian sutures and their interpreted ages and age constraints. For location of sutures see Fig.1 and Fig.2.

	Suture Name	Suture Age	Age constraints
1.	Song Ma	Late Devonian-Early Carboniferous	Large-scale folding, thrusting and nappe formation in Early to Middle Carboniferous. Middle Carboniferous shallow marine carbonates reported to blanket Song Ma suture in North Vietnam. Pre-middle Carboniferous faunas on each side of the Song Ma zone are different whilst the middle Carboniferous faunas are essentially similar. Carboniferous floras on the Indochina block in Northeast Thailand indicate continental connection between Indochina and South China in Carboniferous
2.	Aibi-Xingxing	Permian	Lower Carboniferous ophiolites. Major arc magmatism ceased in the Late Carboniferous. Late Permian post-orogenic subsidence and continental sedimentation in Junggar basin. Palaeomagnetic data indicate convergence of Tarim and Kazakhstan by the Permian. Upper Permian continental clastics blanket suture.
3.	Xiliao-He	Jurassic	Late Jurassic-Early Cretaceous deformation and thrust faulting. Widespread Jurassic-Cretaceous granites. Triassic-Middle Jurassic deep-marine cherts and clastics. Upper Jurassic-Lower Cretaceous continental deposits blanket suture.
4.	Kunlun	Permian-Triassic	Permo-Triassic ophiolites and subduction zone melange. Upper Permian calc-alkaline volcanics, strongly deformed Triassic flysch and Late Triassic granites
5.	Qinling-Dabie	Triassic-Jurassic	Late Triassic age of subduction-related granite. Late Triassic U-Pb dates of zircons from ultra-high pressure eclogites. Late Triassic-Early Jurassic convergence of APWPs and palaeolatitudes of South China and North China. Initial contact between South and North China is indicated by isotopic data in Shandong and sedimentological records along the suture. Widespread Triassic to Early Jurassic deformation in the North China block north of the suture.
6.	Jinshajiang	Late Permian-Late Triassic	Ophiolites are regarded as Upper Permian to Lower Triassic in age. Melange comprises Devonian, Carboniferous and Permian exotics in a Triassic matrix. Upper Permian to Jurassic sediments unconformably overlie Lower Permian ophiolites in the Hoh Xil Range.
7.	Lancangjiang	Early Triassic	Suture zone rocks include Devonian and Carboniferous turbiditic 'flysch'. Ocean-floor basalts of Permian age and Carbo-Permian melange. Carboniferous-Permian island arc rocks are developed along the west side of the suture. Upper Triassic collisional granites are associated with the suture. Suture zone rocks are blanketed by Middle Triassic continental clastics.
8.	Banggong	Late Jurassic-Earliest Cretaceous	Suture is blanketed in Tibet by Cretaceous and Paleogene rocks. Structural data indicate collision around Jurassic/Cretaceous boundary.
9.	Indus-Yarlung-Zangbo	Late Cretaceous-Eocene	Jurassic-Cretaceous ophiolites and ophiolitic melange with Jurassic-Lower Cretaceous radiolarian cherts. Eocene collision-related plutons. Palaeomagnetic data indicates initial collision around 60 Ma. Paleogene strata blanket the suture.
10.	Nan-Uttaradit-Sra Kaeo	Late Permian-Early Triassic	Pre-Permian ophiolitic mafic and ultramafic rocks with associated blueschists. Imbricate thrust slices dated as Middle Triassic by radiolarians (Sra Kaeo segment). Mafic and ultramafic blocks in the melange comprise ocean-island basalts, back-arc basin basalts and andesites, island-arc basalts and andesites and supra-subduction cumulates generated in Carboniferous to Pemo-Triassic times. Limestone blocks in melange range from upper Lower Permian to middle Permian. Granitic lens has yielded a zircon U-Pb age of 486 ± 5 Ma. Permo-Triassic dacites and rhyolites associated with relatively unmetamorphosed Lower Triassic sandstone-shale turbidite sequence. Suture zone rocks are overlain unconformably by Jurassic redbeds and post-Triassic intraplate continental basalts.
11.	Raub-Bentong	Early Triassic	Melange includes Lower and Upper Permian limestone clasts. The Main Range 'collisional' 'S' Type granites of peninsular Malaysia range from Late Triassic (230 ± 9 Ma) to earliest Jurassic (207 ± 14 Ma) in age, with a peak of around 210 Ma. Within suture zone are Upper Devonian to Upper Permian deep-marine bedded cherts.
12.	Shan Boundary	Early Cretaceous	Cretaceous thrusts in the back-arc belt. Late Cretaceous age for the Western Belt tin-bearing granites.
13.	Woyla	Late Cretaceous	Cretaceous ophiolites and accretionary complex material.
14.	Meratus	Late Cretaceous	Subduction melange and ophiolite of middle Cretaceous age. Ophiolite obducted in Cenomanian. Suture overlain by Eocene strata.
15.	Boyan	Late Cretaceous	Upper Cretaceous melange.
16.	Changning-Menglian	Late Permian-Late Triassic	Oceanic ribbon-bedded chert-shale sequences have yielded graptolites, conodonts and radiolarians indicating ages ranging from Lower Devonian to Middle Triassic. Limestone blocks and lenses dominantly found within basalt sequence of suture and interpreted as seamount caps, have yielded fusulinids indicative of Lower Carboniferous to Upper Permian ages.
17.	Ailaoshan	Middle Triassic	Ophiolitic rocks are associated with deep-marine sedimentary rocks including ribbon-bedded cherts that have yielded some Lower Carboniferous and Lower Permian radiolarians. Upper Triassic sediments (Carnian conglomerates and sandstones, Norian limestones and Rhaetian sandstones) blanket suture.

Table 5. Palaeozoic and Mesozoic events and their ages in East and SE Asia.

	Palaeozoic Evolution			**Mesozoic Evolution**	
	PROCESS	AGE		PROCESS	AGE
1.	Rifting of South China, North China, Indochina, Tarim and Qaidam from Gondwanaland.	Early Devonian	1.	Suturing of South China with North China and final consolidation of Sundaland	Late Triassic to Early Jurassic
2.	Initial spreading of the Palaeo-Tethys ocean.	Middle/Late Devonian	2.	Rifting of Lhasa, West Burma and Woyla terranes	Late Triassic to Late Jurassic
3.	Amalgamation of South China, Indochina and East Malaya to form Cathaysialand	Late Devonian to Early Carboniferous	3.	Initial spreading of Ceno-Tethys ocean	Late Triassic (Norian) in west (North India) and Late Jurassic in east (NW Australia)
4.	Rifting of Sibumasu and Qiangtang from Gondwanaland as part of the Cimmerian continent	Late Early Permian	4.	Northward drift of Lhasa, West Burma and Woyla terranes	Jurassic to Cretaceous
5.	Initial spreading of Meso-Tethys ocean	Middle Permian	5.	Collision of the Lhasa Block with Eurasia	Cretaceous
6.	Collision and suturing of Sibumasu to Indochina	Latest Permian to Triassic	6.	Accretion of West Burma and Woyla terranes to Sibumasu	Late Early Cretaceous
7.	Initial collision of South and North China and development of Tanlu Fault	Late Permian to Triassic	7.	Suturing of Semitau to SW Borneo	Late Cretaceous

Rifting and separation of terranes from Gondwanaland

Multidisciplinary data suggest that the East and SE Asian terranes were successively rifted and separated from Gondwanaland as three continental slivers in the Devonian, late Early Permian and Late Triassic-Late Jurassic (Metcalfe, 1996a, 1996b, Fig.3). The separation of these slivers of continent was accompanied by the opening (and subsequent closing) of three ocean basins, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys, remnants of which are now to be found along the various suture zones of eastern Asia. The northwards drift of these three continental slivers is to some extent indicated by palaeomagnetic data for the various blocks (see Metcalfe, 1990, 1996a; Van der Voo, 1993; Zhao *et al*., 1996 for details). In addition, recent studies of the NW Shelf of Australia (Colwell *et al*., 1994) have identified major extensional events that can be broadly correlated with the rifting and separation of the Asian terranes (Table 3).

Devonian rifting and separation

South China, North China, Tarim and Indochina were attached to Gondwanaland in the Cambrian to Silurian, but by Carboniferous times were separated from the parent craton (see Metcalfe, 1996a, 1996b for details), suggesting a Devonian rifting and separation of these blocks. This timing is also supported by the presence of a conspicuous Devonian unconformity in South China, and a subsequent Devonian-Triassic passive margin sequence along the southern margin of South China (Nie, 1994). Devonian basin formation in South China has also been shown to be related to rifting (Zhao Xun *et al*., 1996). The splitting of the Silurian Sino-Australian brachiopod province into two sub-provinces and the apparent loss of links between Asian terranes and Australia in the Early Devonian (Rong *et al*., 1995) may be the result of the northwards movement and separation of the Chinese terranes from Gondwanaland.

Carboniferous-Permian rifting and Permian separation

There is now substantial evidence for rifting along the northern margin of Gondwanaland in the Carboniferous to Permian (Stöcklin, 1974; Powell, 1976; Falvey and Mutter, 1981; Bird, 1987; Boulin, 1988; Pogue *et al*., 1992; Pillevuit, 1993; Wopfner, 1994; Metcalfe, 1996a, 1996b) accompanied by rift-related magmatism (Veevers and Tawari, 1995). This rifting episode led to the

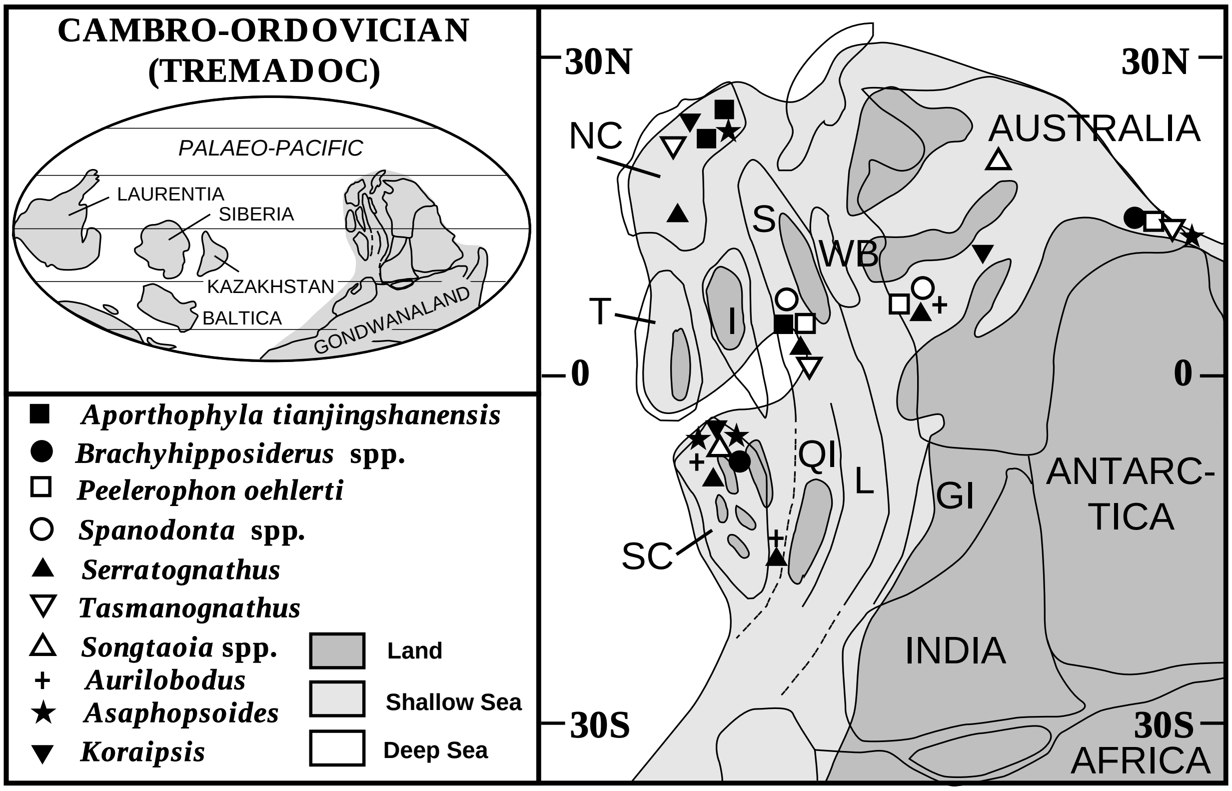


Fig.4. Reconstruction of eastern Gondwanaland for the Cambro-Ordovician (Tremadoc) showing the postulated positions of the East and SE Asian terranes, distribution of land and sea, and shallow-marine fossils that illustrate Asia-Australia connections at this time. NC = North China, SC = South China, T = Tarim, I = Indochina, QI = Qiangtang, L = Lhasa, S = Sibumasu, WB = West Burma, GI = Greater India. Present day outlines are for reference only. Distribution of land and sea for Chinese blocks principally from Wang (1985). Land and sea distribution for Pangaea/Gondwanaland compiled from Golongka *et al.* (1994), Smith *et al.* (1994); and for Australia from Struckmeyer and Totterdell (1990).

late Early Permian separation of the Sibumasu and Qiangtang terranes, as part of the Cimmerian continent, from the Indo-Australian margin of Gondwanaland.

Late Triassic to Late Jurassic rifting and separation

The separation of the Lhasa block from Gondwanaland has been proposed by different authors as occurring either in the Permian or Triassic. A Permian separation has been advocated, either as a part of the Cimmerian continent (Allègre *et al.*, 1984; Metcalfe 1988, 1990) or as a 'Mega-Lhasa' block which included Iran and Afghanistan (Baud *et al.*, 1993). Permian rifting on the North Indian margin and in Tibet (Baud, 1994) is here regarded as being related to the separation of the Cimmerian continental strip which included Iran, Afghanistan and the Qiangtang block of Tibet, but not the Lhasa block. Recent sedimentological and stratigraphical studies in the Tibetan Himalayas and Nepal (Liu, 1992; Liu and Einsele, 1994; von Rad *et al.*, 1994; Ogg and von Rad, 1994) have documented the Triassic rifting and Late Triassic (Norian) separation of the Lhasa Block from northern Gondwanaland. This Late Triassic episode of rifting is also recognised along the NW Shelf of Australia (Colwell *et al.*, 1994) where it continued into the Late Jurassic, resulting in the separation of West Burma and the Woyla terranes (Metcalfe, 1990, 1994, 1996a, 1996b; Görür and Sengör, 1992).

Amalgamation and accretion of terranes

The continental terranes of East and SE Asia have progressively sutured to one another during the Palaeozoic to Cenozoic. Most of the major terranes had coalesced by the end of the Cretaceous and proto SE Asia had formed. The age of welding of one terrane to another can be de-

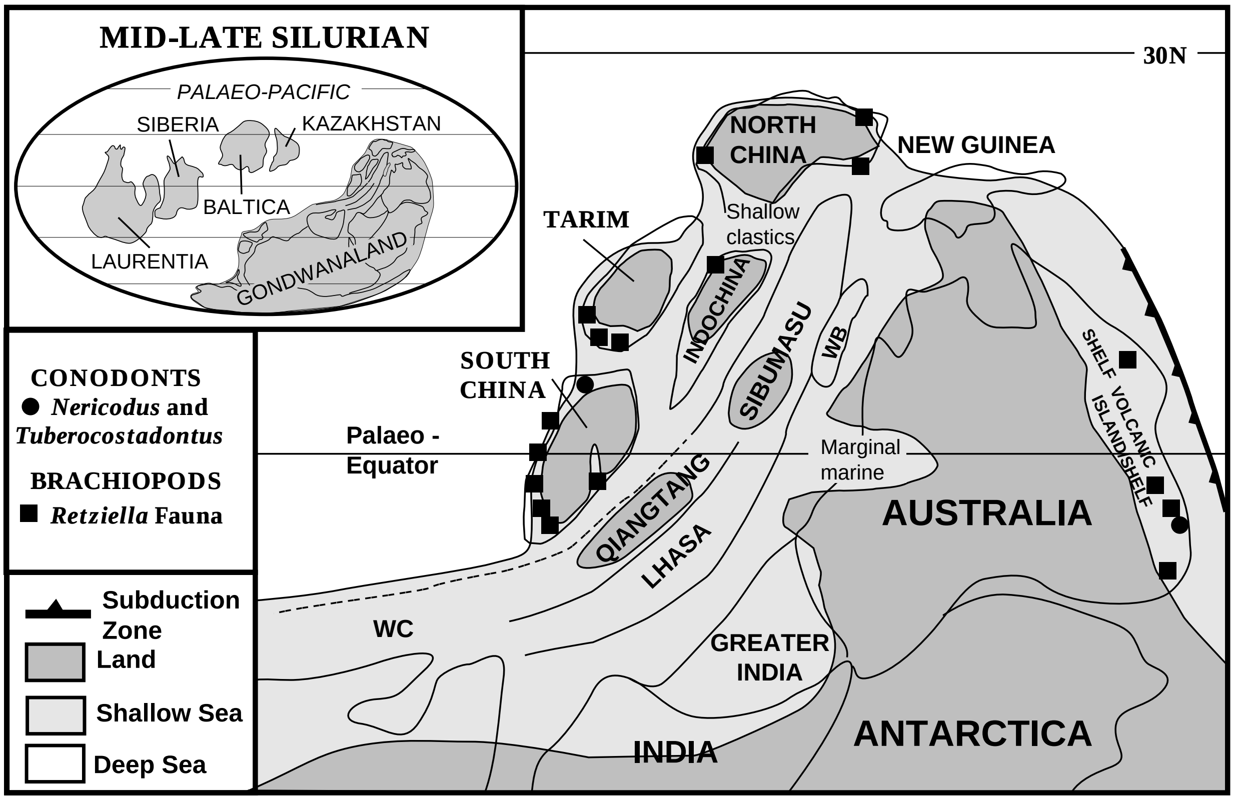


Fig.5. Reconstruction of eastern Gondwanaland for the Mid-Late Silurian showing the postulated positions of the East and SE Asian terranes, distribution of land and sea, and shallow-marine fossils that appear to define an Australasian province at this time. WC = Western Cimmerian Continent, WB = West Burma. Present day outlines are for reference only. Distribution of land and sea for Chinese blocks principally from Wang (1985). Land and sea distribution for Pangaea/Gondwanaland compiled from Golongka *et al.* (1994), Smith *et al.* (1994); and for Australia from Struckmeyer and Totterdell (1990).

termined using the various criteria given in Table 1. When these criteria are applied to the various sutures and terranes of East and SE Asia the interpreted ages of suturing (amalgamation/accretion) are determined as given in Table 4.

Palaeozoic and Mesozoic regional evolution

The Palaeozoic and Mesozoic evolution of SE Asia involved three successive episodes of rifting and separation of continental terranes from the margin of Gondwanaland, their northwards drift and their amalgamation/accretion to form proto East and SE Asia. The various Palaeozoic and Mesozoic evolutionary events of the region are summarised in Table 5. In order to illustrate the various processes and the changing continent-ocean configurations during the Palaeozoic and Mesozoic, palaeogeographic reconstructions for the Palaeozoic and Mesozoic are presented and briefly discussed below.

Cambro-Ordovician (Tremadoc) reconstruction

This reconstruction (Fig.4) shows the proposed relative positions of the East and SE Asian continental terranes on the Indian-Australian margin of Gondwanaland forming a 'Greater Gondwanaland'. The proposed positions are based on palaeobiogeographic, tectonostratigraphic and palaeomagnetic data. The reconstruction also shows the distribution of land, shallow sea and deep sea, compiled from numerous sources. Late Cambrian and Ordovician shallow-marine faunas define an 'Australasian Province' and suggest continental connection between the Asian blocks and Australia at this time. Some of the genera and species providing close links between the Asian blocks and Australia are also plotted on this figure. The deep-marine gulf between South China and Tarim/Indochina was possibly the result of rifting at this time, also recorded by major intracontinental extension on the Australian NW Shelf (Colwell *et al.*, 1994).

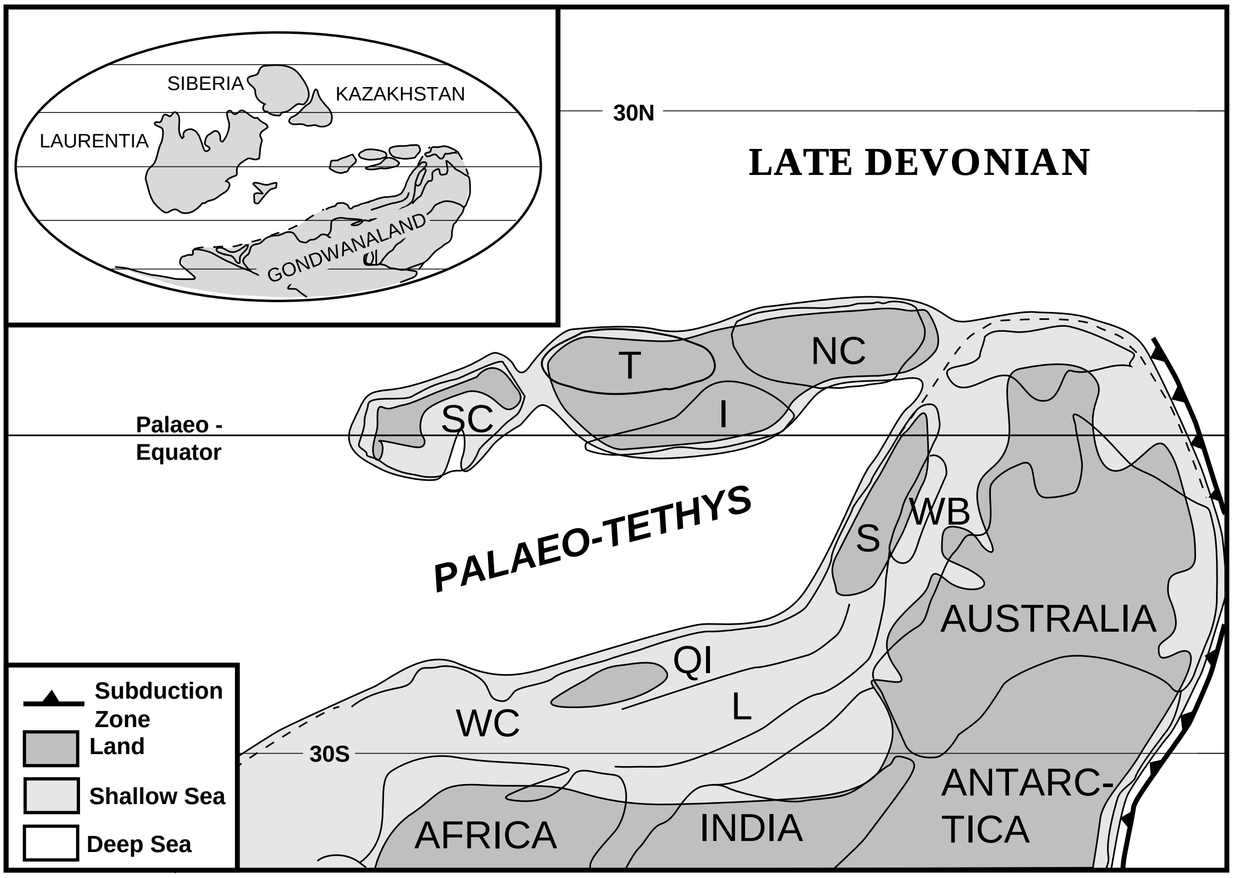


Fig.6. Reconstruction of eastern Gondwanaland for the Late Devonian showing the postulated positions of the East and SE Asian terranes, distribution of land and sea, and opening of the Palaeo-Tethys ocean at this time. Present day outlines are for reference only. Distribution of land and sea for Chinese blocks principally from Wang (1985). Land and sea distribution for Pangaea/Gondwanaland compiled from Golongka *et al.* (1994), Smith *et al.* (1994); and for Australia from Struckmeyer and Totterdell (1990). Symbols as for Figs.4 and 5.

Mid-Late Silurian reconstruction

The East and SE Asian terranes were still located in the same relative positions on the margin of Gondwanaland (Fig.5). However, northern Gondwanaland was relatively more emergent with the trans-Australian Larapintine seaway disappearing, and the previously completely or partly submerged North China, Tarim, and South China regions becoming emergent and largely land areas. Shallow-marine faunas continue to represent an Australasian province, exemplified by the *Retziella* brachiopod fauna (Rong *et al.*, 1995). The distribution of the distinctive conodonts *Nericodus* and *Tuberocostadontus* also indicates connections between South China and Australia at this time (Nicoll and Metcalfe, 1994).

Late Devonian

By Late Devonian times (Fig.6) the Palaeo-Tethys ocean had already opened between a continental sliver comprising North China, Indochina, Tarim and South China, and northern Gondwanaland. This is evident from the presence of Upper Devonian ribbon-bedded cherts in the Palaeo-Tethyan suture segments of Asia, and the fact that the separating continental terranes show no post-Devonian Gondwanaland affinities. The proposed clockwise rotation and separation of the main Chinese terranes and Indochina from Gondwanaland, and the opening of the Palaeo-Tethys, are consistent with a reported rapid anticlockwise rotation of mainland Gondwanaland at this time (Chen *et al.*, 1993). It is suggested here that an eastern conti-

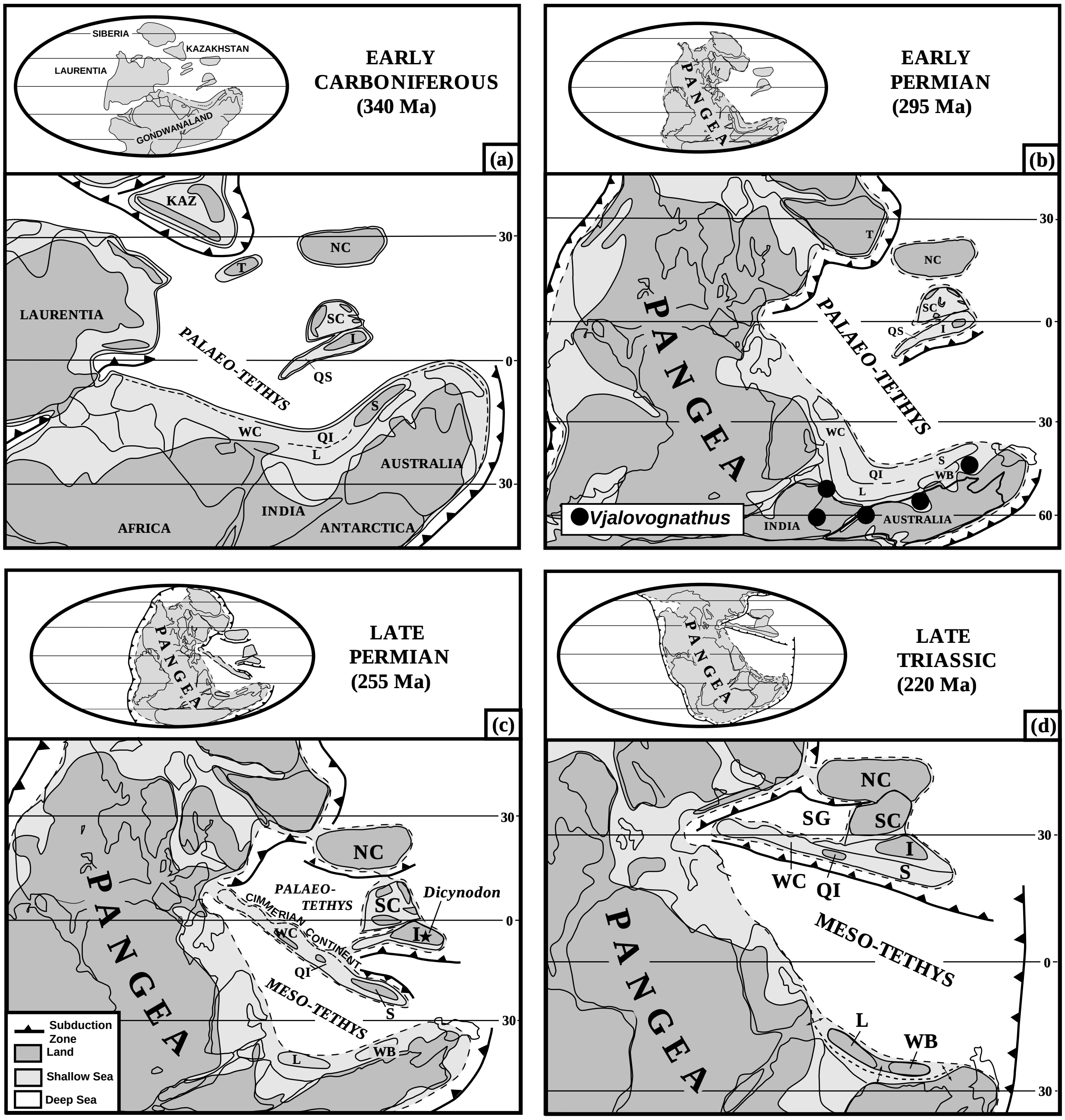


Fig. 7. Palaeogeographic reconstructions of the Tethyan region for (a) Early Carboniferous, (b) Early Permian, (c) Late Permian and (d) Late Triassic showing relative positions of the East and SE Asian terranes and distribution of land and sea. The distribution of the Lower Permian cold-water tolerant conodont genus *Vjalovognathus*, and the location of the Late Permian *Dicynodon* from Laos are also shown. Present day outlines are for reference only. Distribution of land and sea for Chinese blocks principally from Wang (1985). Land and sea distribution for Pangaea/Gondwanaland compiled from Golongka *et al.* (1994), Smith *et al.* (1994); and for Australia from Struckmeyer and Totterdell (1990). Symbols as for Figs.4 and 5.

nental connection was maintained between the rifting sliver and Gondwanaland which may explain the migration of and similarities between Late Devonian sinolepids of South China and Australia. A Middle to Late Devonian connection between South China and Indochina is also possibly indicated by the recent discovery on the Indochina block of upper Middle Devonian yunnanolepid antiarchs (Tong-Dzuy Thanh *et al.*, 1996), formerly known only from the

Silurian-Lower Devonian of the South China block. The age disparity of these yunnanolepid faunas may also be interpreted as a possible Siluro-Devonian connection between South China and Indochina and subsequent isolation of Indochina and South China from each other by late Middle Devonian (Young and Janvier, 1997). The development of essentially endemic fish faunas on South China in the Early Devonian may have resulted from the formation of a deep-water marine barrier (but not necessarily continental separation) between South China and Tarim/Indochina during the rifting from Gondwanaland, the vestiges of this remaining as a shallow-marine seaway in the Late Devonian.

Early Carboniferous

Northeastern Gondwanaland was still in low southern latitudes (Fig.7a). Gondwanaland had rotated clockwise and initial collision between Gondwanaland and Laurentia was occurring. Siberia and Kazakhstan were nearing collision with each other and Tarim was about to accrete to them. South China and Indochina had amalgamated along the Song Ma suture zone but a narrow ocean still existed between the Qamdo-Simao extension of Indochina and South China. This narrow ocean closed in the Middle Triassic to form the Ailaoshan suture.

Early Permian

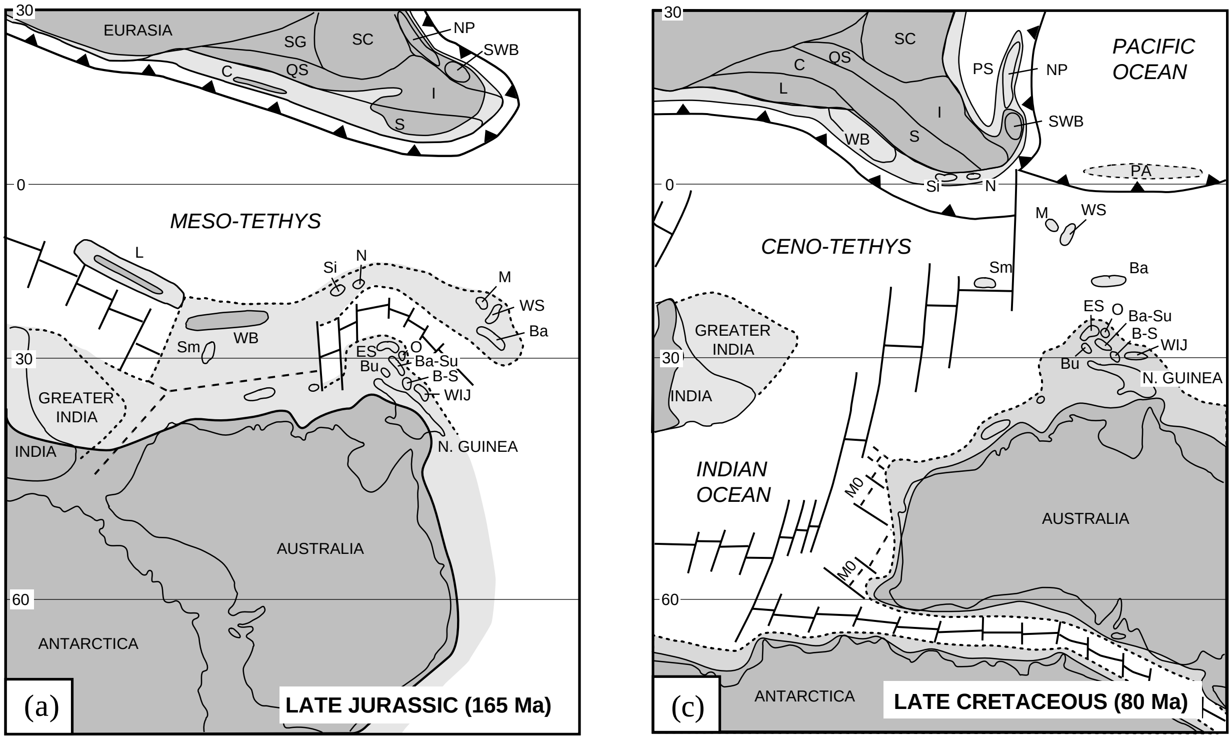
During the Late Carboniferous (Fig.7b) Gondwanaland continued to rotate clockwise sending eastern Gondwanaland into high southern palaeolatitudes and amalgamation with Laurentia, Siberia and Kazakhstan, and producing the supercontinent Pangaea. Gondwanaland was glaciated during the Late Carboniferous and Early Permian, and cold marine conditions with glacial-marine deposits were experienced on the northeastern margin of Gondwanaland. These cold conditions generally precluded the presence of warm water faunas on this part of the Gondwanaland margin, including the conodonts. Recently, however, some poor conodont faunas have been discovered in the Lower Permian rocks of Western Australia which include the cold-water tolerant genus *Vjalovognathus*, which defines an eastern peri-Gondwanaland cold-water conodont province (Metcalfe and Nicoll, 1995).

Late Permian

During the late Early Permian the Sibumasu and Qiangtang terranes, as part of the Cimmerian Continent, separated from Gondwanaland and the Meso-Tethys ocean basin opened behind it. The Palaeo-Tethys ocean continued to be subducted and destroyed beneath Laurasia, North China, and the amalgamated Indochina/South China. By Late Permian times (Fig.7c), South China was probably already in initial contact with North China (Yin and Nie, 1993), which itself may also have made initial contact with Laurasia. The Cimmerian continental sliver probably also had connections with Laurasia at its western end and also with the Qamdo-Simao part of Indochina. These various connections allowed the migration of the Pangaean dicynodont genus *Dicynodon* across to Indochina where its occurrence in the Late Permian has recently been confirmed (Battail *et al.*, 1995). The changing pattern of Permian brachiopod provincialism in the western Pacific, where blocks belonging to the Cimmerian continent contain distinct Cimmerian Province and Sibumasu Sub-Province faunas in the Sterlitamakian to Early Kungurian and then Cathaysian faunas in the Kazanian, is believed to be primarily the result of the separation and northwards drift of the Cimmerian continent in the Permian (Archbold and Shi, 1996).

Late Triassic

By Late Triassic times (Fig.7d) the main Palaeo-Tethyan branch between Sibumasu and Indochina had closed by their collision to form the Lancangjiang, Changning-Menglian, Uttaradit-Nan-Sra Kaeo, and Bentong-Raub suture zones of China, Thailand, and peninsular Malaysia. The Palaeo-Tethys oceanic lithosphere between the Cimmerian continent and Laurasia/North China continued to be subducted northwards during the Triassic, and South China collided with North China along the Qinling-Dabei suture, the resulting orogenic mountains providing huge amounts of sediment into the Songpan Ganzi accretionary complex constructed on the disappearing Palaeo-Tethyan oceanic crust (Nie *et al.*, 1995). The remnant narrow oceanic basin between Qamdo-Simao and South China was also closed during the Middle Triassic to form the Ailaoshan suture. The northwards drift of the Sibumasu terrane (and the Cimmerian continent) is also indicated by the available palaeomagnetic data (Van der Voo, 1993; Metcalfe,



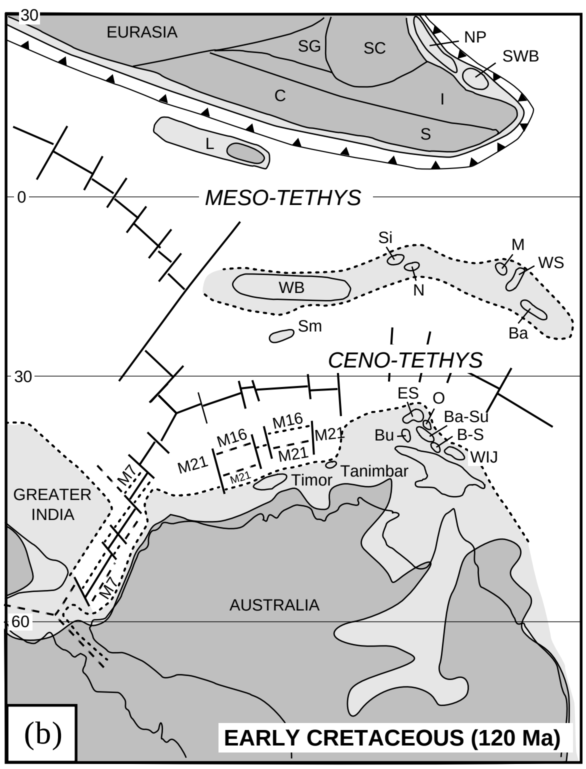


Fig.8. Palaeogeographic reconstructions for Eastern Tethys in (a) Late Jurassic, (b) Early Cretaceous, and (c) Late Cretaceous showing distribution of land and sea. SG = Songpan Ganzi accretionary complex, SWB = South West Borneo (includes Semitau), NP = North Palawan and other small continental fragments now forming part of the Philippines basement, Si = Sikuleh, N = Natal, M = Mangkalihat, WS = West Sulawesi, Ba = Banda allochthon, ES = East Sulawesi, O = Obi-Bacan, Ba-Su = Banggai-Sula, Bu = Buton, B-S = Buru-Seram, WIJ = West Irian Jaya, Sm = Sumba, PA = Incipient Philippine Arc, PS = Proto-South China Sea. M numbers represent Indian Ocean magnetic anomalies. Other terrane symbols as in Figs.4 and 5. Modified from Metcalfe (1990) and partly after Smith *et al.* (1981), Audley-Charles (1988) and Audley-Charles *et al.* (1988). Present day outlines are for reference only. Distribution of land and sea for Chinese blocks principally from Wang (1985). Land and sea distribution for Pangaea/Gondwanaland compiled from Golongka *et al.* (1994), Smith *et al.* (1994); and for Australia from Struckmeyer and Totterdell (1990).

1993, 1996; Zhao et al., 1996) and the changing provincial patterns of Permian brachiopod distributions (Archbold and Shi, 1996; Shi and Archbold, 1998 this volume).

Late Jurassic

Rifting of the northern margin of Gondwanaland had resumed by Late Triassic times and the Lhasa block separated from Gondwanaland by the Norian (Liu, 1992; Liu and Einsele, 1994; von Rad *et al.*, 1994; Ogg and von Rad, 1994). By Oxfordian times (Fig.8a) West Burma and other small continental terranes now located in south west Sumatra (Sikuleh, Natal and Bengkulu blocks), Borneo (Mangkalihat block) and

Sulawesi (West Sulawesi) had separated from northwest Australian Gondwanaland.

Early Cretaceous

During the Late Jurassic and Early Cretaceous (Fig.8b) the Lhasa block and the West Burma continental sliver drifted northwards towards proto-East and SE Asia. By late Early Cretaceous times, the Lhasa block collided with Eurasia forming the Banggong suture zone. Incipient ocean spreading also occurred between India and Australia during the Early Cretaceous as Gondwanaland began its final breakup.

Late Cretaceous

By Late Cretaceous times (Fig.8c) the West Burma, Sikuleh and Natal blocks had accreted to proto-Sundaland along the Shan Boundary and Woyla sutures. The SW Borneo block and the North Palawan block (plus other small continental fragments now forming part of the basement of the Philippines) were separating from Indochina/South China by back-arc spreading and opening of the Proto-South China Sea. The Philippine oceanic island arc was probably initiated at this time. India was well on its way northwards towards its collision with Eurasia, and Australia was moving slowly northwards and separating from Antarctica.

Acknowledgements

I would like to thank Professor Robert Hall and the Organising Committee of the Biogeography and Geological Evolution of SE Asia meeting for support to attend and present this paper at the meeting in London. I would also like to thank Professors Neville Haile and Robert Hall, and an anonymous referee for constructive review of the paper. I would also like to thank the Australian Research Council for continued funding under its Large Grant Scheme for research on East and SE Asia.

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