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Allochthonous Terrane Processes in Southeast Asia [and Discussion]

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Allochthonous terrane processes in Southeast Asia

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Southeast Asia comprises a complex agglomeration of allochthonous terranes located at the zone of convergence between the Eurasian, Indo-Australian and Philippine Sea plates. The older continental 'core' comprises four principal terranes, South China, Indochina, Sibumasu and East Malaya, derived from Gondwana-Land and assembled between the Carboniferous and the late Triassic. Other terranes (Mount Victoria Land, Sikuleh, Natal, Semitau and S.W. Borneo) were added to this 'core' during the Jurassic and Cretaceous to form 'Sundaland'.

Eastern Southeast Asia (N. and E. Borneo, the Philippines and eastern Indonesia) comprises fragments rifted from the Australian and South China margins during the late Mesozoic and Cenozoic which, together with subduction complexes, island arcs and marginal seas, form a complex heterogeneous basement now largely covered by Cenozoic sediments. Strike–slip motions and complex rotations, due to subduction and rifting processes and the collisions of India with Eurasia and Australia with Southeast Asia, have further complicated the spatial distribution of these Southeast Asian terranes.

A series of palinspastic maps showing the interpreted rift–drift–amalgamation–accretion history of Southeast Asia are presented.

INTRODUCTION

Southeast Asia is a complex composite of allochthonous continental fragments, subduction complexes and small ocean basins located at the zone of convergence between the Eurasian, Indo-Australian and Philippine Sea Plates. The older cratonic core (figure 1) comprises four major continental terranes, South China, Indochina, Sibumasu and East Malaya, bounded by sutures representing former oceans and now recognized along mobile belts by ophiolites, melanges, volcano-plutonic arcs and accompanied by major tectonic faults and lineaments. Details of the rift–drift–amalgamation–accretion history of these four blocks are still contentious due to the lack of sufficient constraining data. It is generally agreed that the major allochthonous terranes of the region had their origin on the northeastern margin of Gondwana-Land in the Southern Hemisphere (Audley-Charles, 1983; Audley-Charles *et al.* 1988; Sengor 1984; Metcalfe 1988; Burrett & Stait 1986, to mention but a few). Major differences of opinion exist, however, regarding the time of rifting of Sibumasu from Gondwana-Land (late Jurassic according to Audley-Charles (1988) and Audley-Charles *et al.* (1988); late Permian according to Sengor *et al.* (1988); late early Permian according to Metcalfe (1988); and late Devonian according to Bunopas (1982) and Burrett & Long (1989). Timings of amalgamation and accretion are equally contentious (e.g. Indochina and South China sutured in the Carboniferous according to Gatinsky *et al.* (1984); in the Late Triassic according to Sengor (1984), Sengor *et al.* (1988); Sibumasu sutured to Indochina and East Malaya in the Permian according to Helmcke (1983, 1985); in the early Triassic according to Mitchell (1989); in the

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late Triassic according to Sengor (1984), Sengor *et al.* (1988); or in the middle–late Cretaceous according to Audley-Charles (1988).

A number of continental terranes were added to the cratonic core of Southeast Asia during the Mesozoic, including the Hainan Island terranes on the northeast (Yu 1989), Mount Victoria Land and the Sikuleh and Natal terranes (figure 1) on the (present) western side (Mitchell 1989; Pulunggono & Cameron 1984) and the Semitau and S.W. Borneo terranes on the southeastern side (Metcalfe 1988, this paper; Williams *et al.* 1986) to form 'Sundaland'. The eastern part of Southeast Asia, east of Sundaland and west of the Philippine Trench and extending from Hainan down to Australia (figure 1), comprises a complex assemblage of continental fragments, stretched continental crust, subduction complexes, island arcs and small ocean basins. The continental fragments in this region appear to be derived from the margin of the South China terrane (Holloway 1981; Taylor & Hayes 1983) or from the Papua New Guinea–N. Queensland margins of Australia (Pigram & Panggabean 1984; Audley-Charles *et al.* 1988).

Cenozoic modification of the region has largely been attributed to expansion and the east and southeast extrusion of Southeast Asia along major left-lateral strike–slip faults consequent

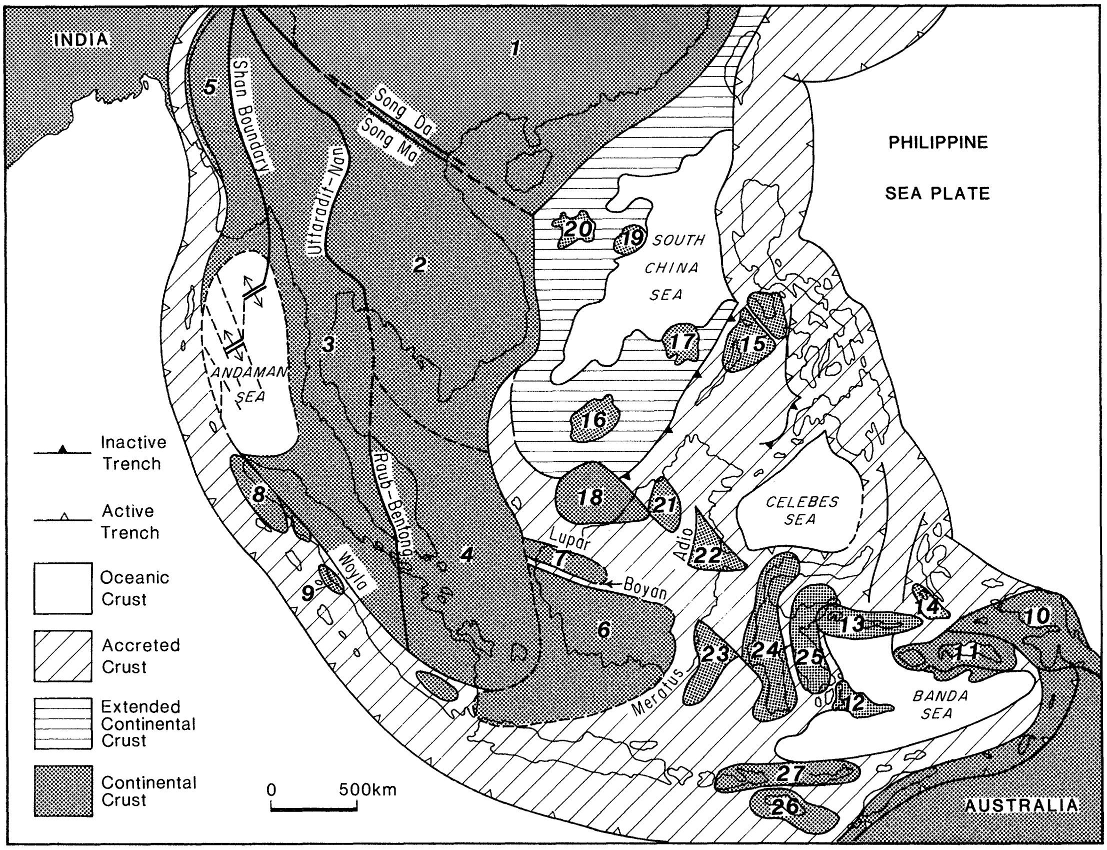

FIGURE 1. Map showing the continental allochthonous terranes and principal sutures of Southeast Asia: 1, South China; 2, Indochina; 3, Sibumasu; 4, East Malaya; 5, Mount Victoria Land; 6, S.W. Borneo; 7, Semitau; 8, Sikuleh; 9, Natal; 10, West Irian Jaya; 11, Buru-Seram; 12, Buton; 13, Bangai-Sula; 14, 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.

upon the collision of India with Eurasia (Tapponier *et al.* 1982; Tapponier *et al.* 1986). An alternative model for the South China Sea region has been put forward by Taylor & Hayes (1980, 1983) and Holloway (1981, 1982) which involves rifting and associated southwards subduction of Mesozoic oceanic crust beneath Borneo. In this model, the North Palawan, Reed Bank, Dangerous Ground, Spratley Islands and Luconia terranes rift from the South China–Indochina margin and travel south by continental stretching in the west and active spreading of the South China Sea in the east. Counter-clockwise rotations of Borneo and the Philippines are proposed in this model and the importance of right-lateral strike–slip motions emphasized.

The allochthonous terranes and their origins

Terranes here considered truly allochthonous are restricted to those continental blocks and fragments (figure 1) which have travelled significant distances from their sites of origin. The South China superterrane comprises at least two welded blocks. Klimetz (1987) proposed three component terranes, the Yangzi Craton, the Jiangnan Terrane, both with Proterozoic basements, and the Cathaysian Terrane, with a pre-Devonian basement. Sengor (1984, 1989), Sengor & Hsu (1984) and Hsu *et al.* (1988) consider it comprises two terranes, the Sichuan Block and the Southeast China Block (or Yangtze and Huanan blocks according to Sengor *et al.* (1988)) which sutured together in the Late Triassic or Jurassic. Wang (1986), Charvet & Faure (1989) and Ren (1989) dispute this late Mesozoic collision and suggest it was in fact a Proterozoic event! The term South China Block is here used to include both the Yangtze and Huanan blocks for the purposes of discussions in this paper. It appears to have its origin in the Western Himalaya–Iran region of Gondwana-Land from where it rifted in the Silurian or Devonian (Lin *et al.* 1985; J.-L. Lin, this Symposium). Indochina is a long stable Pan-African continental block with a pre-Cambrian basement generally overlain by Palaeozoic shallow marine and Mesozoic continental deposits. Its origin is believed to be on the margin of eastern Gondwana-Land (Audley-Charles 1983, 1988). See Metcalfe (1988*a*) for details. The Sibumasu terrane (Metcalfe 1986, 1988*a*) is an elongate continental block with a Proterozoic basement overlain by Palaeozoic shallow marine sequences including late Carboniferous–early Permian glacial-marine diamictites. Mesozoic strata comprise shallow marine and continental deposits with deeper marine sequences developed in certain basins (e.g. Lampang Basin, Semanggol Basin). Sibumasu is regarded to have originated on the northwest margin of Australian Gondwana-Land (Sengor & Hsu 1984; Burrett & Stait 1986; Audley-Charles 1988; Metcalfe 1984, 1986, 1988*a*). The East Malaya terrane has a Proterozoic basement indicated by zircon inheritance age determinations from granites (Liew & McCulloch 1985), but the oldest exposed rocks are Palaeozoic shallow marine strata, overlain by Triassic marine volcaniclastics near its western margin and by Jurassic and Cretaceous continental rocks to the east.

The pre-Mesozoic 'South West Borneo' block of Metcalfe (1986, 1988) is now known to be composite comprising the Semitau Terrane, a small continental block occurring between the Lubok Antu and Boyan accretionary complexes and the South West Borneo block comprising the rest of S.W. Borneo, south of the Boyan melange belt and west of the Meratus accretionary complex. The Mount Victoria Land terrane has a schist basement of pre-Mesozoic age overlain by Triassic turbidites and Cretaceous (Albian) ammonite-bearing shales and limestones in the Indoburman Ranges and by a late Mesozoic–Cenozoic volcanic arc association in the Central

Lowlands of Burma. It is believed to be derived from the N.W. Australian margin of Gondwana-Land. The Sikuleh terrane has a basement of quartzites and phyllites of probable Palaeozoic age, intruded by calc-alkaline granitoids and Tertiary rhyolites and Mo-bearing breccia pipes (Cameron *et al.* 1980). Its origin remains in doubt (Cameron *et al.* 1980) regarding it as a rifted fragment of Sundaland in a marginal basin setting while Pulunggono (1983) and Barber (1985) prefer a subduction complex model with, presumably, a Gondwana-Land origin for Sikuleh. The related Natal terrane and two other probable continental fragments of smaller size located on the southwest margin of Sumatra (figure 1) are also possibly small fragments of Gondwana-Land. Recent work has shown that Hainan Island includes two small continental fragments, the Qiongzhong and Yaxian terranes, that were derived from N.W. Australian Gondwana-Land (Yu 1989). The Palaeozoic sequences on these small blocks are similar to those of N.W. Australia and yield trilobites and other invertebrates endemic to Australia and Gondwana-Land. The sequence also includes Lower Permian glacial-marine diamictites. The Mangkalihat terrane is poorly known but a continental basement is indicated by tin-bearing granitoids, and early Devonian coral-bearing limestones (Rutten 1940). Rocks such as andesite, dacite, radiolarian chert and limestone suggest an old island arc association (Hutchison 1990). The origin of this terrane is unknown but thought likely to be similar to that of the Semitau terrane.

The other pre-Mesozoic continental terranes of the region comprise a number of small continental blocks of either South China or Australian affinities and origin. The terranes showing affinities to South China include the Paracel Islands terrane which has a Palaeozoic and possibly Pre-Cambrian basement with a thin sedimentary cover; the poorly known Macclesfield Bank terrane with a presumed Palaeozoic or older basement; the Spratley Islands–Dangerous Ground–Reed Bank terranes which have a presumed Palaeozoic basement overlain by slightly metamorphosed deltaic sandstones and siltstones and dark green mudstones with plants and bivalves of Triassic and Jurassic age; the North Palawan Block which has a late Palaeozoic basement of Middle Permian fusulinid limestones and Middle Triassic cherts in North Palawan, and a metamorphic complex of mica schist, slate, quartzite and marble in Mindoro; and the Luconia and Kelabit-Longbowan terranes which are stable areas with shallow marine Tertiary reef limestones or fluvio-deltaic deposits surrounded by pene-contemporaneous deeper-water sediments. The Luconia area also exhibits high geothermal gradients and the Kelabit-Longbowan area has numerous salt springs indicating subsurface salt deposits (Hutchison 1989).

The pre-Mesozoic terranes derived from the Australian margin include West Irian Jaya (Pigram & Panggabean 1984), with a basement of Palaeozoic metasedimentary rocks and an origin in the Papua New Guinea or N. Queensland section of Gondwana-Land. The Buru–Seram terrane has a basement of low to medium grade metamorphics overlain by siltstones, mudstones and reefal limestones of Triassic age. The reef facies of Seram, the Asinepe Limestone, is treated as allochthonous by Audley-Charles *et al.* (1979). The terrane is believed derived from Papua New Guinea (Pigram & Panggabean 1984). The Obi–Bacan, Bangai–Sula and Buton terranes have basements of metamorphics intruded by late Palaeozoic granitoids on Obi–Bacan and Bangai–Sula, overlain by middle Jurassic shales, and sandstones of Jurassic and Cretaceous age on Obi–Bacan, and Triassic volcanics and shallow marine strata on Bangai–Sula and Buton respectively. The basements of these blocks resemble the eastern part of the Birds Head and Central Papua New Guinea, from where they are believed to be derived

(Pigram & Panggabean 1984). The Sumba continental fragment has a Mesozoic basement of carbonaceous strata with Jurassic and Cretaceous ammonoids and bivalves overlain by Miocene pelagic chalk. It is believed to have its origin on the N.W. Australian margin and was carried north by the spreading of the Argo Abyssal Plain (Chamalaun *et al.* 1982).

Southeast Asian sutures and their ages

The principal sutures are shown in figure 1. The ages range from Carboniferous to Tertiary reflecting the long and complex accretionary history of the area.

Song Ma and Song Da sutures

The boundary between the Indochina and South China Blocks is marked by the Song Ma–Song Da zone. Various workers recognise two suture zones, the Song Ma and Song Da sutures of Palaeozoic and Mesozoic age respectively (Tran 1979; Gatinsky *et al.* 1985; Sengor 1984, 1986; Sengor *et al.* 1988). Triassic sequences in the Song Da and other Triassic basins of this zone have been regarded as superimposed rift basins by Tran (1979) and Gatinsky *et al.* (1984), but have alternatively been interpreted as an accretionary complex by Sengor (1984). The question as to whether South China and Indochina were welded in the Palaeozoic along the Song Ma suture or in the Triassic along the Song Da zone remains unresolved. Following my previous papers, I here favour the Palaeozoic suturing along the Song Ma suture. The age of the Song Ma suture is indicated to be early Carboniferous by Devonian–early Carboniferous ophiolite and melange ages, early-middle Carboniferous folding and large-scale thrusting and by blanketing strata of middle Carboniferous age. Indochina and South China were therefore probably amalgamated by the middle Carboniferous and together with East Malaya formed 'Cathaysialand' (Gatinsky *et al.* 1984; Lin 1987).

Uttaradit–Nan and Raub–Bentong sutures

These two sutures, regarded as contiguous by most authors, form the boundary between the Sibumasu Block and the Indochina and East Malaya Blocks. The age of these sutures is still contentious. The traditional view is that they are late Triassic in age (Ridd 1980; Mitchell 1981; Sengor 1984) but an earlier suturing in the Permian has been suggested by Helmcke (1985) and in the early Triassic by Mitchell (1989) and Cooper *et al.* (1989). An early Triassic rather than a Permian age is here favoured. The Raub–Bentong suture is also here considered to be probably of early Triassic age. Melange in the Raub area contains limestone clasts of early and late Permian age (Chakraborty & Metcalfe 1987; Metcalfe 1989). Blanketing strata is of late Triassic–Jurassic age and the ages of the S-type collisional Main Range Granites are latest Triassic and early Jurassic. The structural data recently reported from Peninsular Malaysia by Harbury *et al.* (1990) does not necessarily preclude a Triassic suturing of western and eastern Malaya along the Bentong–Raub suture.

Shan boundary suture

Also known as the Mandalay or Sagaing suture it forms the boundary between the Mount Victoria Land Block and Sibumasu. Mitchell (1989) has suggested a late Jurassic or early Cretaceous collision between Mount Victoria Land and Sibumasu. A Cretaceous suturing is here favoured in view of the Cretaceous aged thrusts in the back-arc belt (Mitchell 1990) and the late Cretaceous age for the Western Belt tin-bearing granites. This would also better agree with the age of closure of the Banggong Co-Nu Jiang ocean (Sengor *et al.* 1988).

Woyla suture

Cameron *et al.* (1980) proposed a late Jurassic–early Cretaceous opening of a marginal basin on the southwest margin of Sumatra and the rifting of the Sikuleh and Natal blocks from Sundaland followed by a late Cretaceous closure and suturing. An alternative hypothesis, made by Pulungono (1983) and Barber (1985) involving subduction processes in the Cretaceous and a derivation of the Sikuleh and Natal blocks from Gondwana-Land with a late Cretaceous suturing, is here proposed and is supported by the palaeomagnetic data (see below).

Boyan and Lupar sutures

Recent data from West Kalimantan (Williams *et al.* 1986; Williams & Harahap 1987) indicate a late Cretaceous short-lived subduction which produced the Boyan Melange and which ceased due to clogging by the Semitau Terrane in the late Cretaceous. Subduction then jumped and continued behind the Semitau Block along the Lupar Line producing the Lubok Antu Melange and the Sarawak accretionary prism. The Lubok Antu Melange and accretionary wedge turbidites of the Lupar suture yield early Eocene ages from both clasts and matrix. Tan (1982) and Taylor & Hayes (1983) have suggested that subduction continued into the Miocene but Williams & Harahap have proposed that the Oligocene–early Miocene intrusive rocks in northwest Borneo represent post-subduction intrusions. This would constrain the age of the suture as probably Oligocene. A mid-Miocene age for the suture, consequent upon the arrival of the Luconia terrane, seems more attractive considering that the South China Sea began its spreading in the mid-Oligocene. In that case the I-type small Oligocene and Miocene intrusions of northwest Borneo would have to be related to a north migrated subduction front as suggested by Hamilton (1979). The precise age of the Lupar suture cannot at present be determined but falls in the range late Eocene to mid-Miocene. The age of structural inversion observed in the Malay and West Natuna basins around 25 Ma (Oligocene–Miocene boundary) may be indicative of the cessation of southwest directed subduction beneath Borneo.

Meratus suture

Subduction melange and ophiolite of the Meratus Mountains appears to be of Middle Cretaceous age (Hamilton 1979) and is overlain by Eocene strata. Obduction of ophiolite occurred in the Cenomanian, related to an arc-continent collision (Sikumbang 1986). The Meratus suture is therefore of late Cretaceous age and it may have been a continuation of the Woyla suture in Sumatra.

Palaeomagnetic data

All available palaeomagnetic data for Southeast Asia was reviewed by Haile & Briden (1982) and the rather restricted and quality-variable nature of the database was all too evident. Since that time significant contributions to the palaeomagnetic database have been made and an Apparent Polar Wander Path (APWP) has been constructed for the South China Block and palaeolatitudes and senses and amounts of rotation for other terranes are also better known.

Palaeolatitudes

Palaeolatitude plots against time for the South China, Indochina, East Malaya and Sibumasu Blocks are given in figure 2. All four terranes show rapid northward movement during the Permo–Triassic followed by a Jurassic–early Cretaceous southwards drift, a mid-late Cretaceous northwards motion and a Tertiary southwards movement to their present latitudes. The remarkably similar pattern of north–south movements for all four blocks since the Permian suggests that they were in the same plate tectonic regime during that period. It is also clear from these plots that the Sibumasu block travelled rapidly from southern to northern palaeolatitudes during middle Permian–early Triassic times. This is consistent with the proposed early Permian rifting of this block from Australian Gondwana-Land. The sudden southwards movements experienced by all four blocks in the Jurassic–early Cretaceous immediately postdates the collision with North China which took place in the latest Triassic–early Jurassic (Sengor 1985; Lin *et al.* 1985; Lin & Fuller 1990). The database for the other Southeast Asian terranes is too limited to construct palaeolatitude variation diagrams. There are no data for the Mount Victoria Land block. Data from the Semitau terrane include two contrasting Triassic palaeolatitudes of 10.5° S and 17° N (Sunata & Wahyono 1990) and

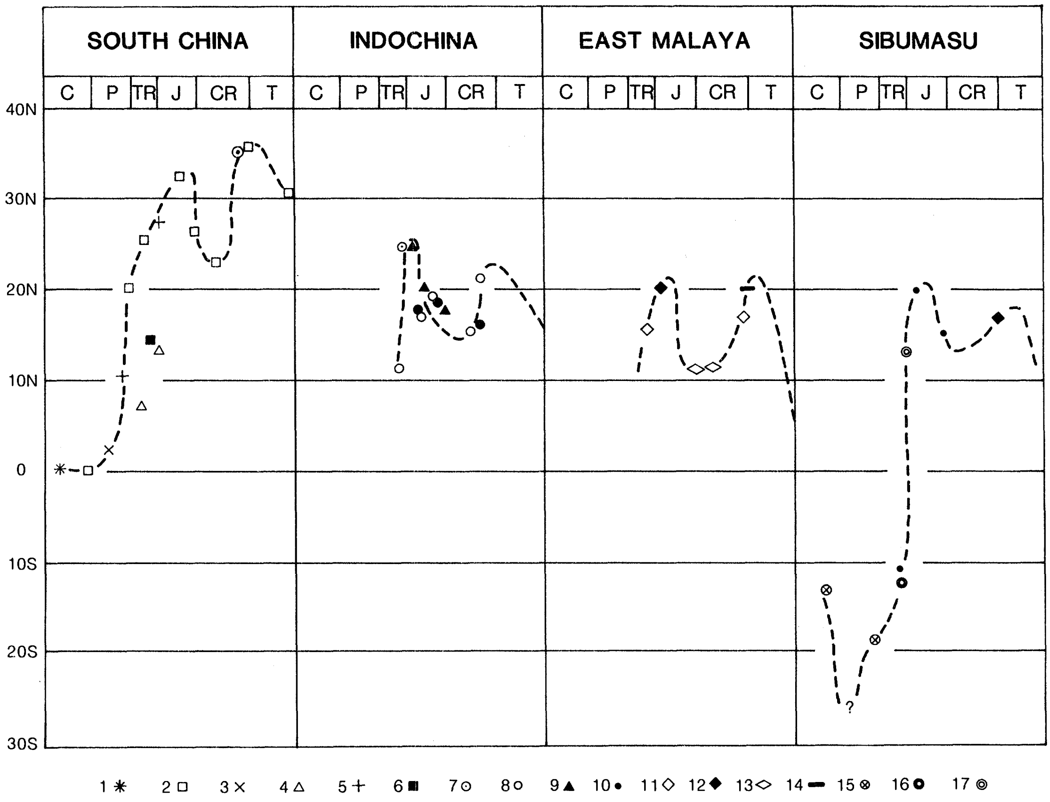

FIGURE 2. Palaeolatitude–time plots for the South China, Indochina, East Malaya and Sibumasu terranes from Carboniferous to Tertiary. Sources of data are: 1, Lin (1987); 2, Lin *et al.* (1985); 3, McElhinny *et al.* (1981); 4, Opdyke *et al.* (1986); 5, Sasajima & Maenaka (1987); 6, Chan *et al.* (1984); 7, Achache *et al.* (1983); 8, Marante & Vella (1986); 9, Achache & Courtillot (1985); 10, Bunopas *et al.* (1989*a*, *b*); 11, McElhinny *et al.* (1974); 12, E. A. Schmidtke & M. Fuller (personal communication); 13, Haile & Khoo (1980); 14, Haile *et al.* (1983); 15, Bunopas (1982); 16, Sasajima *et al.* (1978); 17, Haile (1979).

equatorial palaeolatitudes from Jurassic to the present (Schmidtke *et al.* 1990). The South West Borneo terrane appears to have been located on or very close to the equator since the Jurassic (Haile *et al.* 1977; Sunata & Wahyono 1990). Palaeomagnetic data for other small terranes in the region is very limited and confined generally to isolated sample sites. Haile (1979) reported some late Triassic and early Cretaceous data from localities in Sumatra which are located on the Sikuleh terrane. These results indicate that the Sikuleh terrane was at 26° S in the late Triassic and at about 10° S in the late Mesozoic. These results are consistent with the proposed derivation from Gondwana-Land in the late Jurassic. Data from West Sulawesi indicates southern palaeolatitudes in the Cretaceous (Sasajima *et al.* 1980; Haile 1978) which support the interpreted derivation from N.W. Australia in the late Jurassic. Data from the Sumba terrane indicate a Jurassic palaeolatitude of 25° S (Otofuji *et al.* 1981) and 14° S in the late Cretaceous (Chamalaun & Sunata 1982). This supports an Australian rather than a Sundaland origin for Sumba. Palaeomagnetic data from the Yaxian terrane of Hainan gives a Cambrian palaeolatitude of 6.7° S which would be consistent with a derivation from Australian Gondwana-Land. An early Permian palaeolatitude of 5 °N for the Echa Formation of the Qiongzhong terrane of Hainan, which contains glacial-marine diamictites, appears to be in conflict with an Australian origin suggested by stratigraphy and palaeobiogeography (Yu 1989).

Rotations

Variations of declination with age indicate sense and amount of rotation for a particular terrane and are potentially very useful in unravelling or constraining palaeotectonics. The Indentor–Extrusion model for Cenozoic tectonics in Southeast Asia (Molnar & Tapponier 1975; Tapponier *et al.* 1982) implies the east and southeast extrusion of the region consequent upon the collision of India with Eurasia and requires significant clockwise rotations for a number of the Southeast Asian terranes. Alternative models (see, for example, Holloway 1981, 1982; Taylor & Hayes 1980, 1983) require counterclockwise rotations for some of the same blocks. It therefore becomes crucial that palaeomagnetic data be assessed to test these models. The South China Block has rotated about 30° clockwise (cw) since the Cretaceous according to Achache *et al.* (1983). The Indochina Block shows evidence of 47° cw rotation since the Lower Cretaceous (Achache *et al.* 1983) and 37° cw rotation since the late Cretaceous (Bunopas *et al.* 1989*a*). The Sibumasu Block has rotated about 55° cw since the early Cretaceous, much of that rotation occurring around the Cretaceous–Tertiary boundary (Bunopas *et al.* 1989*b*). This data is in general consistent with the Extrusion model, particularly as these blocks have also moved southwards during the Tertiary (figure 2). However, Cretaceous data from the South West Borneo Block, the Semitau Block and from East Malaya all show counterclockwise (ccw) rotations of between 30° and 50° since the late Cretaceous (Haile 1979; Schmidtke *et al.* 1990; Sunata & Wahyono 1990). ccw rotation of Luzon in the Eocene–Oligocene followed by rapid ccw rotation in the Miocene are reported by Fuller *et al.* (1983) and Fuller *et al.* (1990) which appears to support the Holloway model. The ccw rotations for Borneo and East Malaya also appear to contradict the Indentor Extrusion model. Results of ongoing palaeomagnetic studies in the region by Fuller and co-workers should provide more constraints on the Cenozoic tectonic models for Southeast Asia and these are eagerly awaited.

Apparent Polar Wander Paths

Comparisons of APWPs of the Southeast Asian Blocks with each other and with APWPs of Eurasia and Gondwana-Land should allow the timings of rifting and amalgamation or accretion to be constrained. Unfortunately, an insufficient database for Southeast Asia does not permit such comparisons at present. Only the South China Block has a fairly well-constrained APWP (Lin *et al.* (1985) and comparisons are hence limited to individual poles from Southeast Asia with APWPs for Eurasia, Gondwana-Land and South China.

ALLOCHTHONOUS TERRANE PROCESSES

Fundamental factors in elucidating the terrane processes of the region and for constraining palaeogeographic maps are the timings of rifting of terranes from their parent cratons, the positions and relative rotations of terranes during their pre-rift, drift, and post-drift histories, the timings of suturing (amalgamation and accretion) and post-suturing structural and tectonic modifications. Criteria used to identify or constrain the timings and positions of terranes are varied in type and reliability. The main criteria used in timing the rifting of terranes are ocean floor ages and magnetic stripe data, divergence of APWPs and palaeolatitudes from continental palaeomagnetism, age of associated rift volcanics and intrusions, regional unconformities, ages of major block faulting episodes and associated slumping, development of different biotic provinces on separating blocks. The palaeopositions of continental terranes during their drift may be estimated from well-constrained palaeomagnetism which will give palaeolatitudes and sense and amount of rotation relative to present. Stratigraphical and palaeontological data may also be indicative of palaeolatitude or proximity to other continental regions. Many criteria have been used to date the suturing of one terrane to another including ophiolite obduction ages, ages of melanges, ages of stitching plutons, ages of subduction-related and collisional-related plutons, ages of and chemical or isotopic changes in volcanic arcs, convergence of APWPs, loops or disruptions in individual APWPs, age of blanketing strata, palaeobiogeography, structural geology (e.g. age of thrusting, nappe formation), stratigraphic sequences (e.g. pelagic-flysch-molasse). Application of the above criteria allows the rift–drift–suture processes for the Southeast Asian terranes to be worked out and these are discussed below.

Palaeozoic processes

The first event in the history of the Southeast Asian terranes was the Palaeozoic rifting of South China, Indochina, East Malaya and S.W. Borneo from Gondwana-Land. The precise age of rifting is not known but thought to be Silurian or Devonian by Lin (1987, this Symposium). The presence of a regional unconformity of late Devonian–early Carboniferous age supports a Devonian rifting. These blocks then amalgamated by late early Carboniferous times to form a superterrane referred to as the East Asian Continent by Gatinsky *et al.* (1984) and Cathaysialand by Lin (1989) on which the Cathaysian flora developed during the Carbo–Permian. This superterrane was located in low northern equatorial latitudes during the Carboniferous (Lin 1987; see figure 3*a*). In the late early to Middle Permian, a major rifting phase occurred on the northeast Gondwana-Land margin (Powell 1976; Bird 1987; Audley-Charles 1988) indicating that a substantial continental fragment (or fragments) separated from Gondwana-Land at that time. Audley-Charles (1988) suggested that the blocks rifting at this

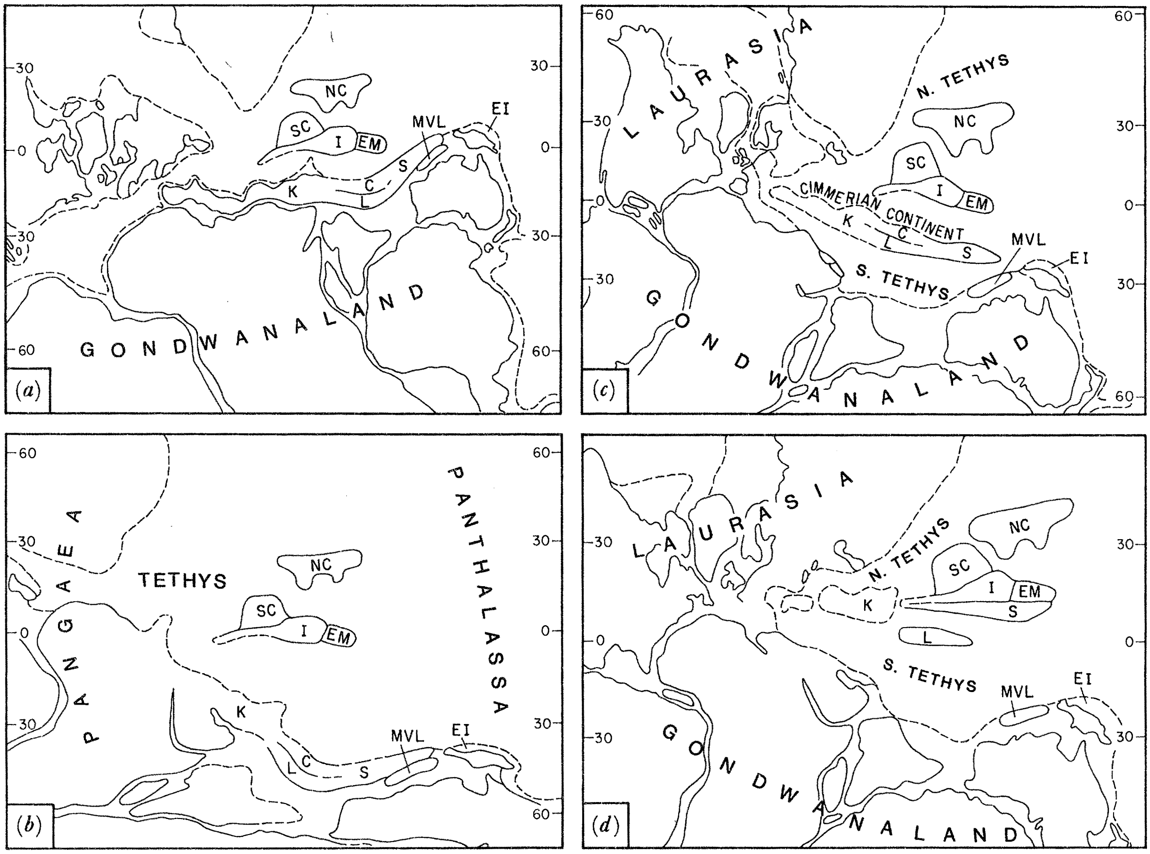

FIGURE 3. Palaeogeographic reconstructions for (*a*) early Carboniferous, (*b*) early early Permian, (*c*) middle–late Permian and (*d*) late Triassic. Based on the reconstructions of Smith *et al.* (1981) and partly after Metcalfe (1988). Present day outlines are for reference only. NC = North China, SC = South China, I = Indochina, EM = East Malaya, K = Kreios, C = Changtang, L = Lhasa, S = Sibumasu, MVL = Mount Victoria Land, EI = Eastern Indonesian terranes.

time were Iran, North Tibet (Changtang) and Indochina, thus leaving Sibumasu as a source for the Triassic intracratonic basin deposits seen in Timor. Metcalfe (1988), however, suggested that it was in fact the Sibumasu, Lhasa and Changtang blocks (along with other terranes that comprised the Cimmerian continent of Sengor) which rifted from Gondwana at that time. That view is still held and the source for the Triassic intracratonic basin sediments in Timor is believed to be Mount Victoria Land. Sibumasu must have remained attached or close to N.W. Australia until the early Permian (figure 3*b*) as indicated by early Permian glacial-marine deposits, cool-water faunas and faunas with N.W. Australian affinities (Metcalfe 1988). The middle–late Permian and early Triassic faunas of Sibumasu show affinities to Cathaysialand and to northern Tethys province types (Metcalfe 1988*a*, *b*) indicating that Sibumasu had already rifted from Gondwana-Land. This is supported by the palaeomagnetic data. During its travel northwards across the Tethys, the Cimmerian continent fragmented both longitudinally and latitudinally separating the Lhasa and Changtang–Sibumasu blocks and separating the Western Cimmerian Continent in Turkey and Iran from the Southeast Asian and Tibetan terranes (figure 3*c*). In late Permian times, Sibumasu began its collision with Cathaysialand and the suturing to Indochina and East Malaya was largely completed by the early Triassic (see above).

Mesozoic processes

Granites generated during or post the collision between Sibumasu and Indochina–East Malaya were emplaced in the latest Triassic to early Jurassic (Liew & Page 1985; Cobbing *et al.* 1986; Darbyshire 1987) which would indicate an early Triassic or earlier age for the collision considering that there may be up to 30 Ma time difference between the generation and emplacement of collisional granites (England & Thompson 1986). The late Triassic–early Jurassic period saw the collision of Cathaysialand with North China and an overall consolidation of the Southeast Asian cratonic 'core'. The Indosinian orogeny was the result of this collision and final consolidation. The Triassic basins were largely closed at this time and continental deposits were widespread over large parts of the Southeast Asian craton during the Jurassic and Cretaceous. The final suturing of mainland Southeast Asia to Eurasia probably occurred in the early–middle Jurassic. A further period of rifting occurred on the north-eastern margin of Gondwana-Land during the late Jurassic and another sliver of the cratonic margin separated at this time. This sliver included the Mount Victoria Land, Sikuleh, Natal, Mangkalihat, West Sulawesi and Sumba terranes along with other unidentified continental crust (including the Banda allochthon of Audley-Charles?). As Neotethys (Tethys III) opened up in the late Jurassic, the Banggong Co-Nu Jian ocean (Tethys II) continued to subduct beneath Eurasia and the Lhasa block finally collided with the Changtang and Sibumasu terranes in the late Jurassic–early Cretaceous (figure 4*a*). The Mount Victoria Land, Sikuleh and Natal terranes continued their northward travel during the Cretaceous (figure 4*b*) and had sutured to Sibumasu by the late Cretaceous (figure 4*c*). A short-lived subduction in the late Cretaceous brought together the Semitau and South West Borneo terranes along the Boyan Suture and the Philippine arc was in its incipiancy. There was also a significant clockwise rotation of 'Sundaland' during the late Cretaceous and India travelled rapidly northwards towards its collision with Eurasia.

Cenozoic processes

During the last decade, the Indentor–Extrusion model for the Cenozoic of Southeast Asia (Molnar & Tapponier 1975; Tapponier *et al.* 1982; Tapponier *et al.* 1986) achieved wide acceptance amongst geologists working in the region. The model proposes the migration of a prograding zone of deformation across Asia which occurs concurrently with the northward moving India–Eurasia collision front and the successive activation of several large left-lateral strike–slip faults. During the late Eocene to Miocene (40–20 Ma), 'Sundaland' was pushed sideways and extruded to the east and southeast rotating clockwise by about 25° during the Oligocene to early Miocene simultaneous with the opening of the South China Sea. Later in the Miocene, Tibet and China moved several hundred kilometres to the east and the opening of the South China Sea stopped but 'Sundaland' continued to rotate clockwise a further 40° in sympathy with the South China Block. The opening of the Andaman Sea was proposed to be the result of the eastwards motion of the Southeast Asian Blocks relative to India and as a possible counterpart to the South China Sea (Tapponier *et al.* 1986). The main large left-lateral strike–slip faults that have accommodated these movements in Southeast Asia have been identified as the Altyn Tagh-Kun Lun and Red River faults. The main test of the extrusion model comes from recognition of major left-lateral movements along these faults and in

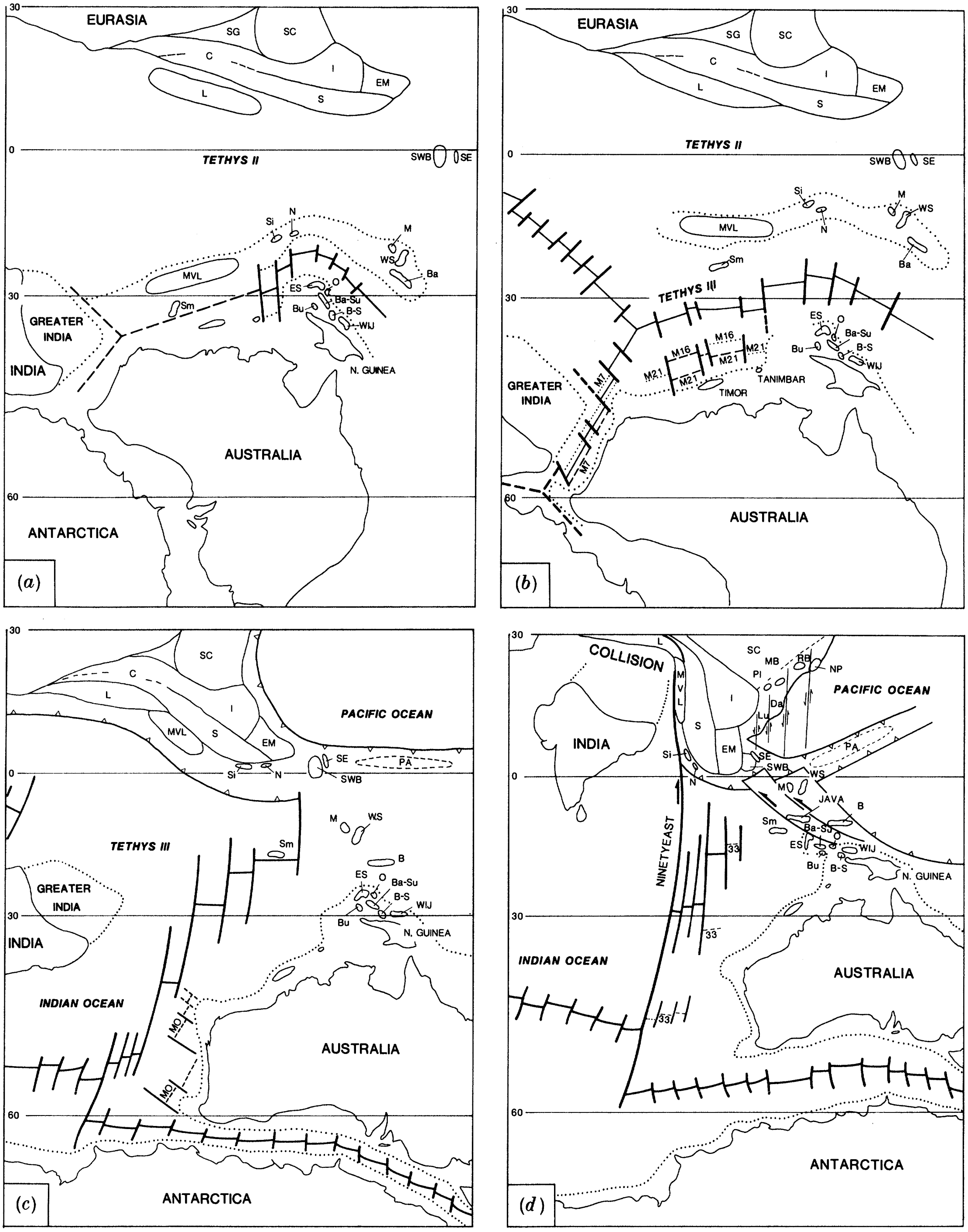

FIGURE 4. Palaeogeographic reconstructions for (*a*) late Jurassic, (*b*) early Cretaceous, (*c*) late Cretaceous and (*d*) late Eocene. SG = Songpan Gangzi accretionary complex, SWB = South West Borneo, SE = Semitau, Si = Sikuleh, N = Natal, M = Mangkalihat, WS = West Sulawesi, Ba = Banda Allochthon, ES = East Sulawesi, O = Obi-Bacan, Ba-Su = Bangai-Sula, Bu = Buton, B-S = Buru-Seram, WIJ = West Irian Jaya. Other terrane symbols as in figure 3. Partly after Smith *et al.* (1981), Audley-Charles (1988) and Audley-Charles *et al.* (1989). Present day outlines are for reference only.

demonstrating the necessary progressive clockwise rotations and southeast movements of the Southeast Asian Blocks.

Alternative models have been put forward for the South China Sea region by Taylor & Hayes (1980, 1983) and Holloway (1981, 1982) where the South China Sea develops due to rifting of the South China–Indochina margin and consumption of Mesozoic oceanic crust by southwards subduction beneath Borneo and the Pacific plate. They also propose that substantial continental crust attenuation took place on the South China margin between the latest Cretaceous and earliest Palaeocene. This rift onset would be too old to be due to the collision of India with Eurasia. They also propose that the spreading in the South China Sea was essentially north–south and that the Philippine arc and Borneo underwent significant counterclockwise rotations. The North Palawan, Reed Bank and Luconia–Dangerous Ground–Spratley Islands terranes travelled south during Mid-Oligocene to early Miocene times. Cessation of subduction to the south in Mid-Miocene times is indicated by an unconformity on Palawan and Holloway (1982) has proposed diachronieity of the suture as collision of blocks with Borneo progressively inactivates the subduction zone from west to east. Hence, the Taylor & Hayes–Holloway model proposes an essentially local closed system for the South China Sea.

Tapponier *et al.* (1986), however, consider the South China Basin an Atlantic-type marginal basin bounded by passive continental margins to the north and south. Clockwise rotations of the South China (30°), Indochina (47°), and Sibumasu (55°) since the Cretaceous (see above) are consistent with the extrusion model. Borneo, the Philippines and East Malaya however show clear counterclockwise rotations since the Cretaceous (see above) which support the Taylor & Hayes–Holloway model. Further detailed palaeomagnetic work is required, along with structural data on strike–slip faults to constrain the models for the Cenozoic evolution of Southeast Asia. What is clear, however, is that the North Palawan, Reed Bank and Luconia–Dangerous Ground–Spratley terranes were detached from the South China margin in the Middle Oligocene, travelled south during the spreading of the South China Sea and collided with, and/or were underthrust beneath, Borneo and Palawan during the Miocene (Hinz & Schluter 1983; Mohammad *et al.* 1987; Tan & Lamy 1989).

Fragments of the North Australian margin (Mangkalihat, West Sulawesi, etc.) that rifted in the Jurassic continued to move northwards during the Cenozoic along with Australia and were translated north and west by major transcurrent faults in a kind of bacon-slicer mechanism between the Australian and Pacific plates (figure 4*d*). This mechanism also moved fragments of the New Guinea margin of Australia (West Irian Jaya, Buru-Seram, Buton, Bangai-Sula, East Sulawesi) westwards along major fault dislocations (the Sorong fault being a recently active one). Proto-Borneo was formed when the Mangkalihat and Paternoster terrane (then part of the West Sulawesi block) sutured to the other Borneo blocks along the Adio and Meratus sutures. The collision between Southeast Asia and the Australian craton began with the collision of West and East Sulawesi at around 15 Ma (late Miocene) and continued with the collisions of Seram and Timor at 5 and 3 Ma respectively (Audley-Charles *et al.* 1988).

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Discussion

E. Irving, F.R.S. (*Pacific Geoscience Centre, Sydney, Canada*). How does Dr Metcalfe distinguish between north and south latitudes determined palaeomagnetically from Triassic rocks?

I. Metcalfe. There are some Jurassic and Cretaceous results that suggest that the rotation of Peninsular Malaysia reverses between the Triassic and Cretaceous. These results are from dykes in eastern Malaya and from sediments in the Tekai region of Pahang. If this interpretation is correct, then the polarity is determined and the Malay Peninsular is in the Northern Hemisphere. This problem is not finally resolved and is the subject of present studies.