



Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean

Robert Hall *

SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX, United Kingdom

ARTICLE INFO

Article history:

Received 9 January 2012

Received in revised form 18 April 2012

Accepted 30 April 2012

Available online 15 May 2012

Keywords:

Sundaland

Luconia–Dangerous Grounds

SW Borneo

East Java–West Sulawesi

Subduction

Extension

ABSTRACT

The heterogeneous Sundaland region was assembled by closure of Tethyan oceans and addition of continental fragments. Its Mesozoic and Cenozoic history is illustrated by a new plate tectonic reconstruction. A continental block (Luconia–Dangerous Grounds) rifted from east Asia was added to eastern Sundaland north of Borneo in the Cretaceous. Continental blocks that originated in western Australia from the Late Jurassic are now in Borneo, Java and Sulawesi. West Burma was not rifted from western Australia in the Jurassic. The Banda (SW Borneo) and Argo (East Java–West Sulawesi) blocks separated from western Australia and collided with the SE Asian margin between 110 and 90 Ma, and at 90 Ma the Woyla intra-oceanic arc collided with the Sumatra margin. Subduction beneath Sundaland terminated at this time. A marked change in deep mantle structure at about 110°E reflects different subduction histories north of India and Australia since 90 Ma. India and Australia were separated by a transform boundary that was leaky from 90 to 75 Ma and slightly convergent from 75 to 55 Ma. From 80 Ma, India moved rapidly north with north-directed subduction within Tethys and at the Asian margin. It collided with an intra-oceanic arc at about 55 Ma, west of Sumatra, and continued north to collide with Asia in the Eocene. Between 90 and 45 Ma Australia remained close to Antarctica and there was no significant subduction beneath Sumatra and Java. During this interval Sundaland was largely surrounded by inactive margins with some strike-slip deformation and extension, except for subduction beneath Sumba–West Sulawesi between 63 and 50 Ma. At 45 Ma Australia began to move north; subduction resumed beneath Indonesia and has continued to the present. There was never an active or recently active ridge subducted in the Late Cretaceous or Cenozoic beneath Sumatra and Java. The slab subducted between Sumatra and east Indonesia in the Cenozoic was Cretaceous or older, except at the very western end of the Sunda Arc where Cenozoic lithosphere has been subducted in the last 20 million years. Cenozoic deformation of the region was influenced by the deep structure of Australian fragments added to the Sundaland core, the shape of the Australian margin formed during Jurassic rifting, and the age of now-subducted ocean lithosphere within the Australian margin.

© 2012 Robert Hall. Published by Elsevier B.V. All rights reserved.

Contents

1. Introduction	2
2. Growth of SE Asia: the western core.	4
3. Fragments added to Sundaland since the Triassic and before the Cenozoic	5
3.1. West Burma.	5
3.2. Fragments in Sumatra	6
3.3. Fragments in Borneo.	7
3.4. Meratus suture	9
3.5. West Sulawesi–Sumba	10
3.6. East Java	11
4. Subduction history	12
5. Mesozoic margins	13
5.1. Pacific margin	13
5.2. North Australian margin	16
5.3. West Australian margin	16

* Tel.: +44 1784 443592; fax: +44 1784 434716.

E-mail address: robert.hall@es.rhul.ac.uk.

5.4.	Indian margin	18
5.5.	Asian margin from Burma to the north and west	19
6.	Reconstructions	20
6.1.	160 Ma to 140 Ma	20
6.2.	140 Ma to 110 Ma	21
6.3.	110 Ma collision	22
6.4.	110 Ma to 90 Ma	22
6.5.	90 Ma change	23
6.6.	90 to 45 Ma	24
6.7.	45 Ma to present	26
7.	Christmas Island volcanic province	28
8.	Conclusions	29
	Acknowledgements	32
	Appendix A. Supplementary data	36
	References	37

1. Introduction

This paper updates and extends previous attempts (Hall, 1996, 2002) at reconstructing the SE Asian and West Pacific regions (Fig. 1). The principal features of these Cenozoic models have since been tested using information not used in constructing them (e.g.

Hall and Spakman, 2002; Miller et al., 2006; Richards et al., 2007). The Cenozoic model has been slightly modified but the major changes are the reconstruction of the growth of SE Asia during the Cretaceous which mainly involved modelling the rifting of fragments from the Australian margins, interpreting a spreading history for the Cenozoic Tethys, and tracing the subduction history of this oceanic crust

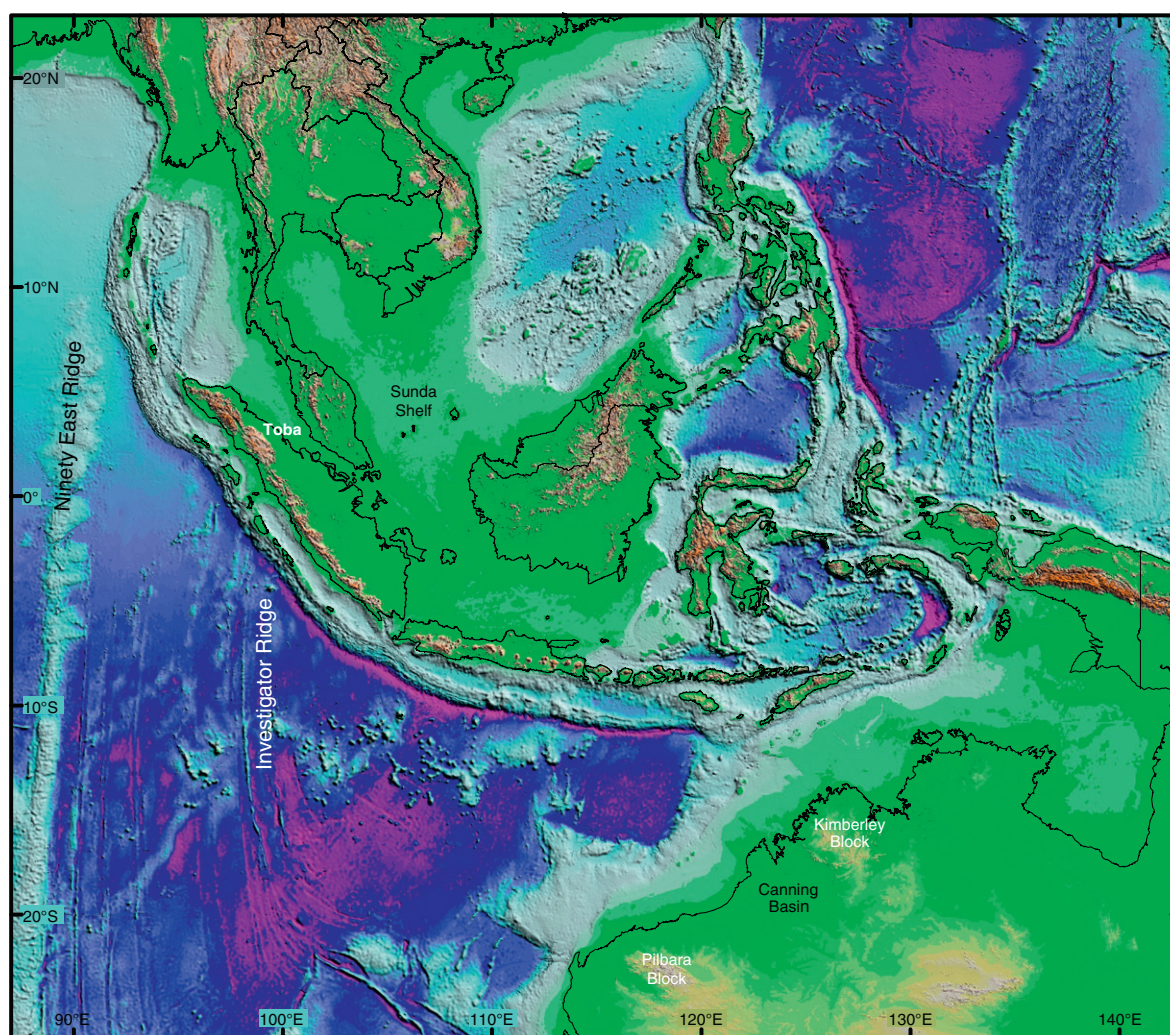


Fig. 1. DEM of the region including SE Asia, the Western Pacific, eastern Indian Ocean and Australia from satellite gravity-derived bathymetry combined with SRTM topography (Sandwell and Smith, 2009). The main geographical and tectonic features of the region are identified on Figs. 2, 3 and 4.

which has been almost completely subducted. Some growth occurred by addition of Asian fragments.

In the earlier papers I discussed the many problems with plate reconstructions and assumptions of rigid fragments which do not need to be repeated. In this region, because of its size, tropical setting, terrain, exposure, and number of studies we still lack detailed information about important matters such as ages of events, boundaries between fragments, nature and thickness of the crust. However, there is enough information to discern the broad features of its history, data sets such as isotopic ages are being improved, and new insights are being acquired from numerous sources such as SRTM and ASTER imagery of land, seismic surveys and multibeam mapping of the sea floor, and seismic tomography. These justify reconstructions that go further back in time, if only to identify problems and provide models for older orogenic belts, and that is what is offered below.

The starting point is a brief summary of the Sundaland core of SE Asia which was broadly in its present form by the end of the Triassic.

I then discuss the fragments that have been added to this core during the Cretaceous, and the different suggestions for their origin. There are some difficulties in unravelling previous interpretations of different blocks. Opinions have changed, even from the same authors, and naming of blocks has been varied. Names of some blocks such as Sibumasu have now become well established (see Metcalfe, 1986, 1988) but a terrane in a similar position was previously given different names (e.g. Shan–Thai, SinoBurMalaya) and included different areas. For other blocks such as West Burma, a similar name has been used in substantially different ways. Next there is a summary of subduction history previously interpreted for SE Asia, principally Indonesia, and the evidence for reconsidering earlier views, followed by a review of the Asian, Australian and Indian margins which explains the fragments interpreted in this model and their original positions. This is followed by an account of the reconstructions which is accompanied by a number of computer animations. Geographical location information is given on Figs. 1 to 4, and the reconstructions are also shown at 5 million year intervals on Figs. 5 to 36 with

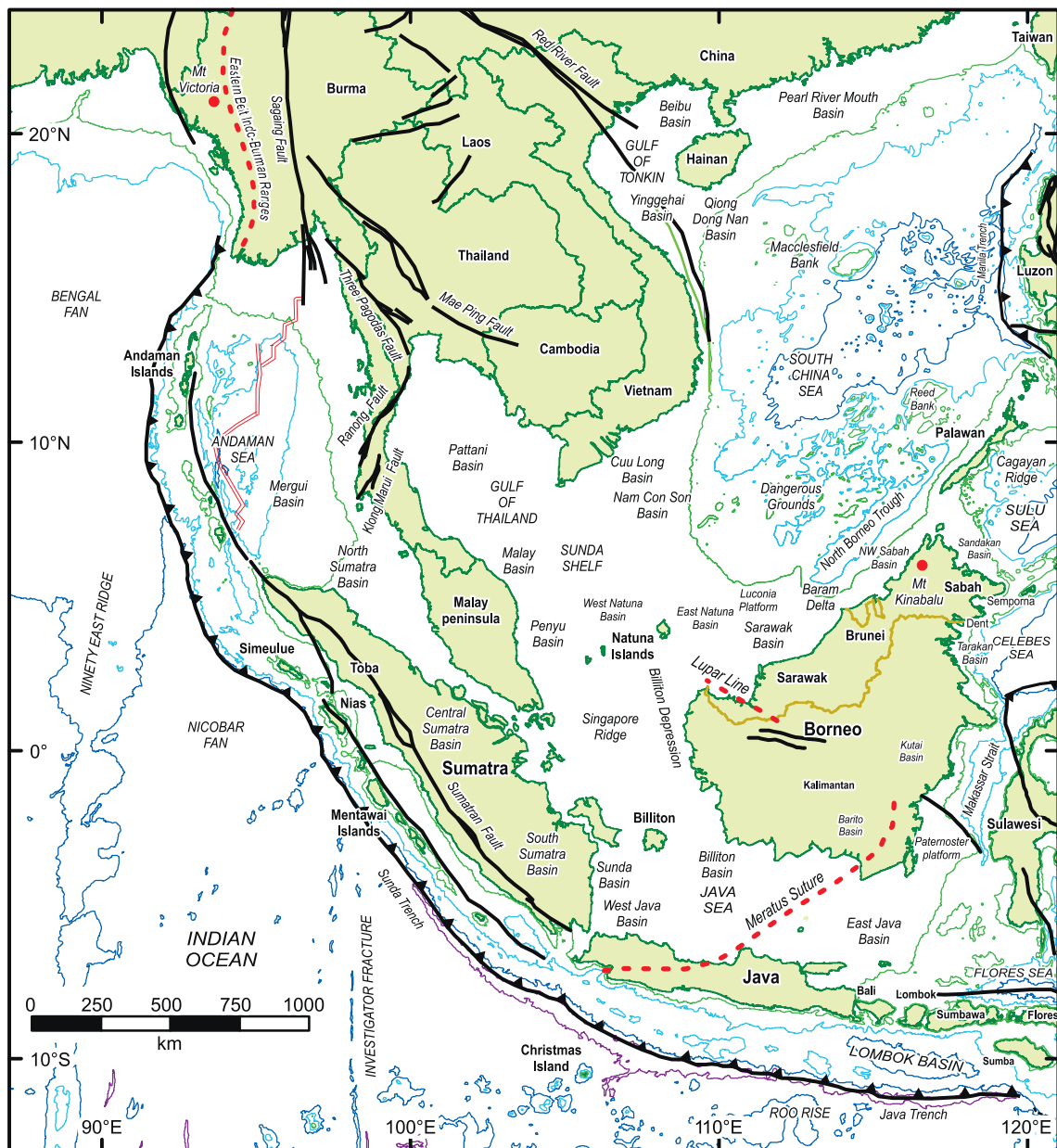


Fig. 2. Principal geographical and tectonic features of Indochina and the Sunda region. Bathymetry is from the [GEBCO \(2003\)](#) digital atlas with contours at 200 m, 2000 m, 4000 m and 6000 m. Double red line shows Andaman Sea spreading centre.

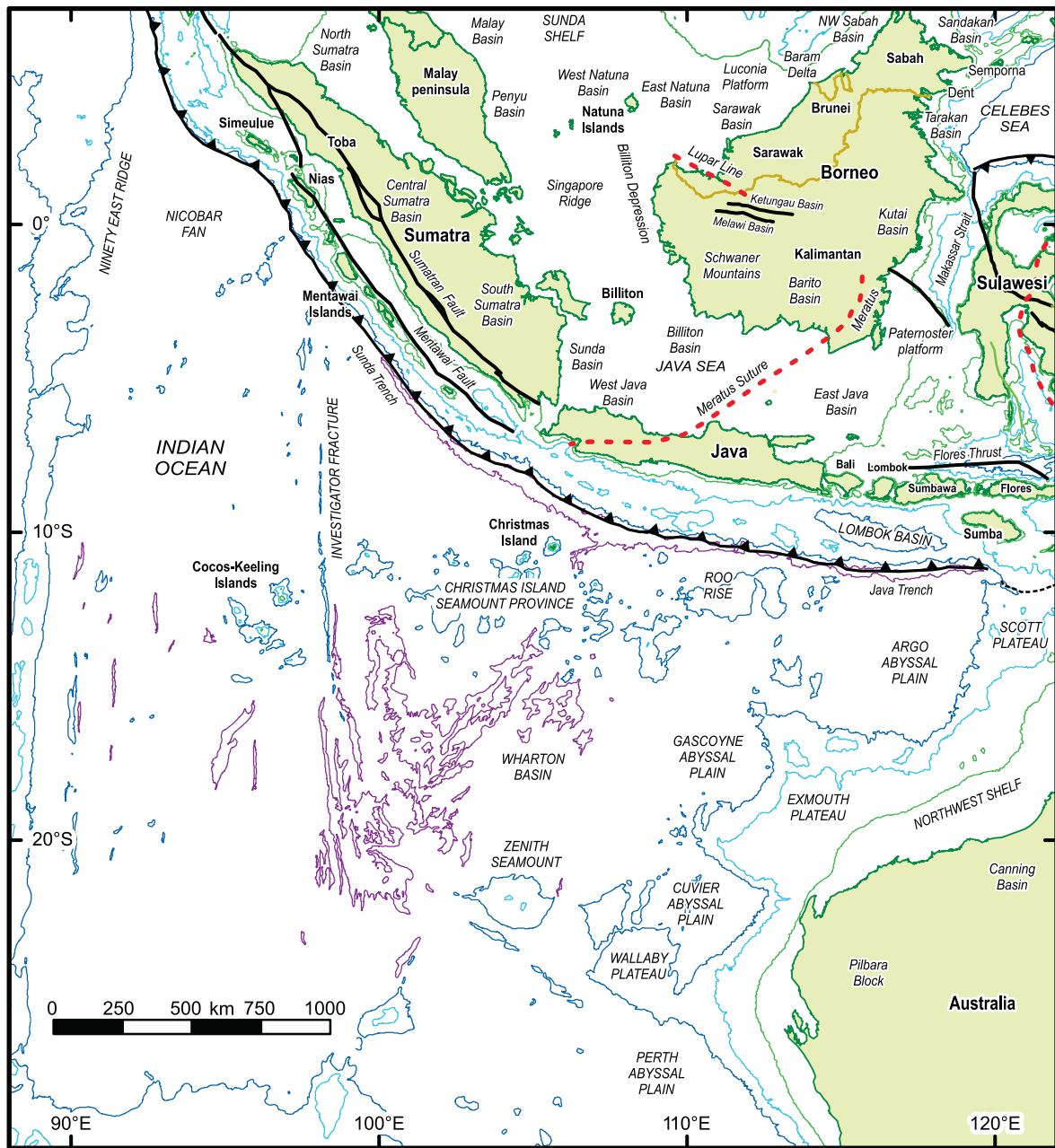


Fig. 3. Principal geographical and tectonic features of the eastern Indian Ocean and western Australia. Bathymetry is from the *GEBCO (2003)* digital atlas with contours at 200 m, 2000 m, 4000 m and 6000 m.

annotation of key features to help the reader. It is expected that the account of the reconstructions will be read together with the computer animations.

2. Growth of SE Asia: the western core

The continental part of SE Asia grew largely by closure of several Tethyan oceans between Gondwana and Asia, and to a lesser extent by addition of material at the east-facing Pacific margin. This formed the continental region commonly called Sundaland which was assembled from blocks rifted from the Gondwana margins, forming a mosaic separated by sutures which typically include arc and ophiolitic rocks. The former positions of many of the blocks that now make up SE Asia within the Gondwana margins are still uncertain. Mesozoic and older reconstructions are based on a variety of evidence including that from palaeomagnetism, lithofacies, faunal

provinces, ages of magmatism and dating of structural events and have many uncertainties, and up to now there have been no really detailed reconstructions, although *Metcalf (1990, 1996, 2009, 2011a,b)* has provided maps for critical intervals during the Palaeozoic and Mesozoic. Reconstructing the intervening Tethyan oceans is also difficult since they have entirely disappeared by subduction. However, although there has been disagreement about the original location, ages of rifting and arrival of blocks (cf. *Audley-Charles, 1988; Metcalfe, 1988*) it is now generally accepted that the western core of Sundaland was assembled from an Indochina–East Malaya block and a Sibumasu block that separated from Gondwana in the Palaeozoic. They amalgamated with the South and North China blocks in the Triassic. The Permian and Triassic granites of the Thai–Malay Tin Belt are the products of associated subduction and post-collisional magmatism (*Hutchison, 1989*). *Sone and Metcalfe (2008)*, *Barber and Crow (2009)*, *Metcalf (2011a,b)* and

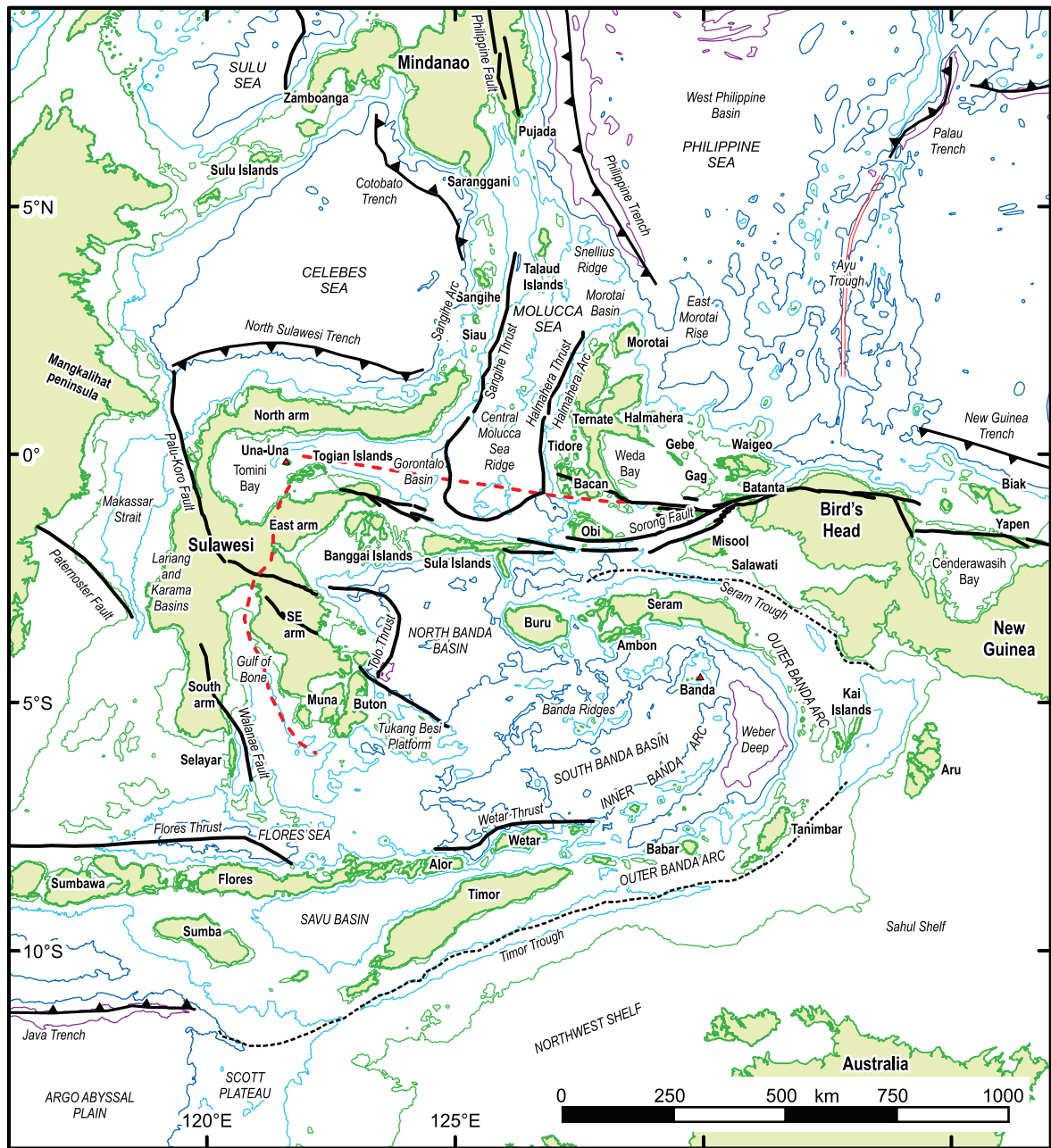


Fig. 4. Principal geographical features of the eastern Indonesia region. Bathymetry is from the [GEBCO \(2003\)](#) digital atlas with contours at 200 m, 2000 m, 4000 m and 6000 m. Double red line shows spreading centre in Ayu Trough. Dashed red line is approximate western and northern limit of Sulu Spur.

[Sevastjanova et al. \(2011\)](#) have added more detail to this relatively simple picture of closure of Palaeo-Tethyan oceans which will no doubt become even more complex as new studies are made. For the purposes of reconstruction in this paper it is sufficient to accept that most of the region that now forms Sumatra, West Java, the Thai-Malay peninsula and most of the present-day Sunda shelf (i.e. Sibumasu, Sukhothai Arc, and Indochina–East Malaya blocks) was part of continental Asia by the end of the Triassic.

3. Fragments added to Sundaland since the Triassic and before the Cenozoic

Other continental fragments were added to Sundaland at different times during the Mesozoic and Early Cenozoic. In the reconstructions presented in this paper I have suggested different locations for the origin of some of the fragments compared to some currently accepted

interpretations, although several of my suggestions have been anticipated by others. In other cases fragments that have been suggested to be continental are now thought not to be continental. In some areas, notably the eastern and northern parts of Sundaland, the basement is not well known as the area east of the Indochina–East Malaya block is now largely submerged or covered with younger rocks. Below I review the fragments that have been interpreted as added during the Mesozoic or early Cenozoic and the different suggestions for their origin and arrival.

3.1. West Burma

West Burma has been identified as a block or plate but this name has been used in different ways by different authors. [Mitchell \(1981\)](#) recognised a Western Burma block that he interpreted as an island arc separated from mainland SE Asia by an oceanic marginal basin which

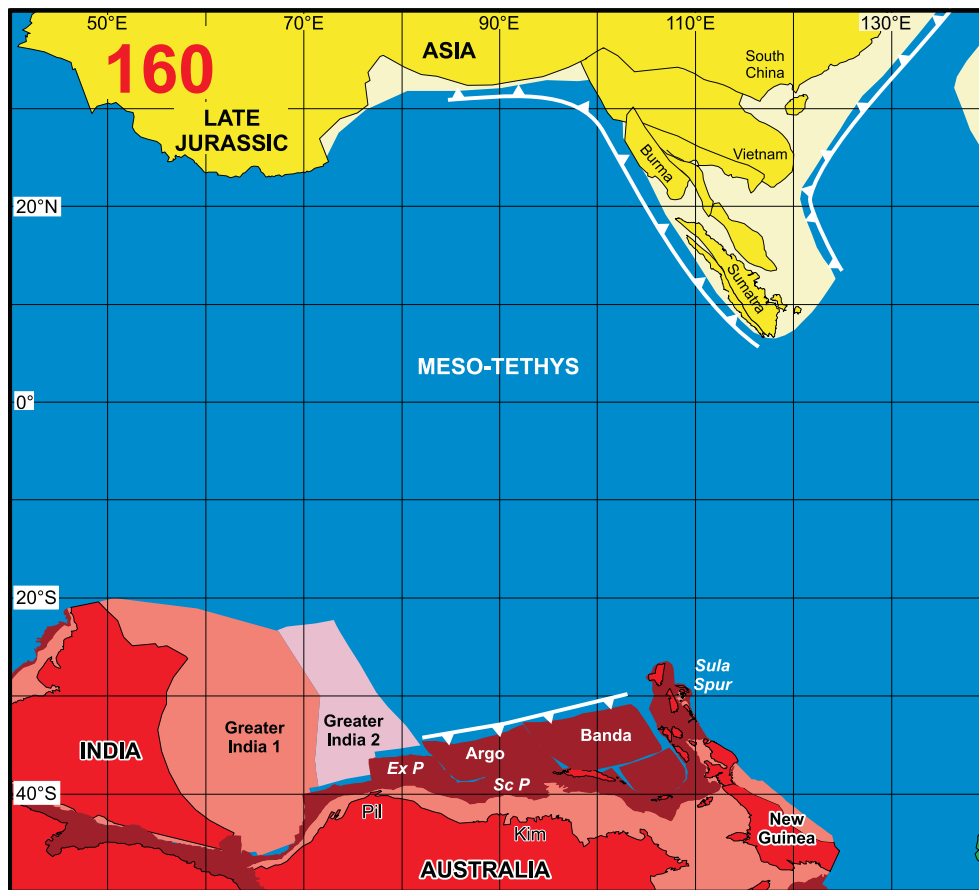


Fig. 5. Reconstruction at 160 Ma. On all reconstructions (Figs. 5 to 38) areas filled with green are mainly arc, ophiolitic, and accreted material formed at plate margins. Areas filled in cyan are submarine arc regions, hot spot volcanic products, and oceanic plateaus. Eurasian crust is coloured in shades of yellow. Areas that were part of Gondwana in the Jurassic are coloured in shades of red. Pil is the Archaean Pilbara block, and the Kim is the Kimberley block. Ex P is Exmouth Plateau, Sc P is Scott Plateau; Argo is the fragment now forms East Java–West Sulawesi, and Banda is the rifted fragment that left the Banda Embayment and now forms SW Borneo. From 160 Ma rifting propagated west.

had closed by the mid Jurassic. Mitchell (1992, 1993) later suggested that the arc, represented by the Mawgyi Nappe in Burma, the Woyla Group in Sumatra and the Meratus ophiolite of SE Borneo, were all parts of northeast-facing intra-oceanic arc, emplaced as nappes onto the western margin of SE Asia in the late Early Cretaceous. Mitchell (1986) proposed a microcontinental fragment that he named Mt. Victoria Land which has a schist basement overlain by Carnian quartz-rich turbidites. He did not identify the origin of the fragment but showed it as separated by an oceanic spreading ridge from the Shan–Thai margin (Sibumasu) in the Late Triassic and thrust underneath the Shan–Thai block in the latest Jurassic or Early Cretaceous. Later Mitchell (1992) argued that Triassic turbidites in Burma were deposited on the southern margin of Asia, which he identified with the Shan–Thai foreland (i.e. Sibumasu), abandoning the separate Mt. Victoria Land block.

At about the same time, West Burma was used as the name of a fragment (Gatinsky and Hutchison, 1986; Hutchison, 1989) that separated from Sibumasu in the Triassic and re-amalgamated with it in the Early Cretaceous. Hutchison (1989) commented that this scenario “is, of course, speculative and it could have been an independent minor continental block” without suggesting where it originated. More recently, Barber and Crow (2009) interpreted West Burma as a continuation of the West Sumatra block. They considered that both West Burma and West Sumatra would have formed part of Indochina by the Early Carboniferous and during the Triassic an elongated slice, including West Sumatra and West Burma, became detached from Cathaysia (Indochina) along a major transcurrent fault and was translated along its western margin to a position outboard of the Sibumasu terrane (Barber and Crow, 2009; Barber et al.,

2005). West Sumatra and West Burma are now separated from one another by the Andaman Sea which opened in the Late Miocene. Thus, for all these authors the Mt. Victoria Land or West Burma block was essentially part of SE Asia from at least the Late Triassic and probably from the Late Palaeozoic.

In contrast, several authors (Audley-Charles, 1991; Metcalfe, 1990; Sengör, 1987; Veevers, 1988) suggested the Mt. Victoria Land block rifted from western Australia in the Jurassic. Metcalfe (1996) later renamed it the West Burma block to avoid confusion with Victoria Land in Antarctica. He suggested that West Burma was derived from NW Australia, and considered “it a good candidate for part of the continental sliver that provided a source for sediments derived from the northwest in Timor during the Triassic, and which must have rifted from Gondwanaland in the Late Jurassic”. This suggestion has since become widely accepted despite the fact that Metcalfe (1996) observed there was “as yet no convincing evidence for the origin of this [West Burma] block”. According to this interpretation West Burma separated from Australia in the Late Jurassic and docked with SE Asia in the Early Cretaceous.

I have accepted the arguments of Mitchell, Hutchison, and Barber and Crow and consider that West Burma was part of SE Asia from the Late Triassic. As explained below, I identify the fragments rifted from western Australia in the Jurassic with SW Borneo and East Java–West Sulawesi.

3.2. Fragments in Sumatra

In the mid Cretaceous the Woyla Group or Nappe was part of an arc (Barber et al., 2005) that was emplaced on the Sumatra margin

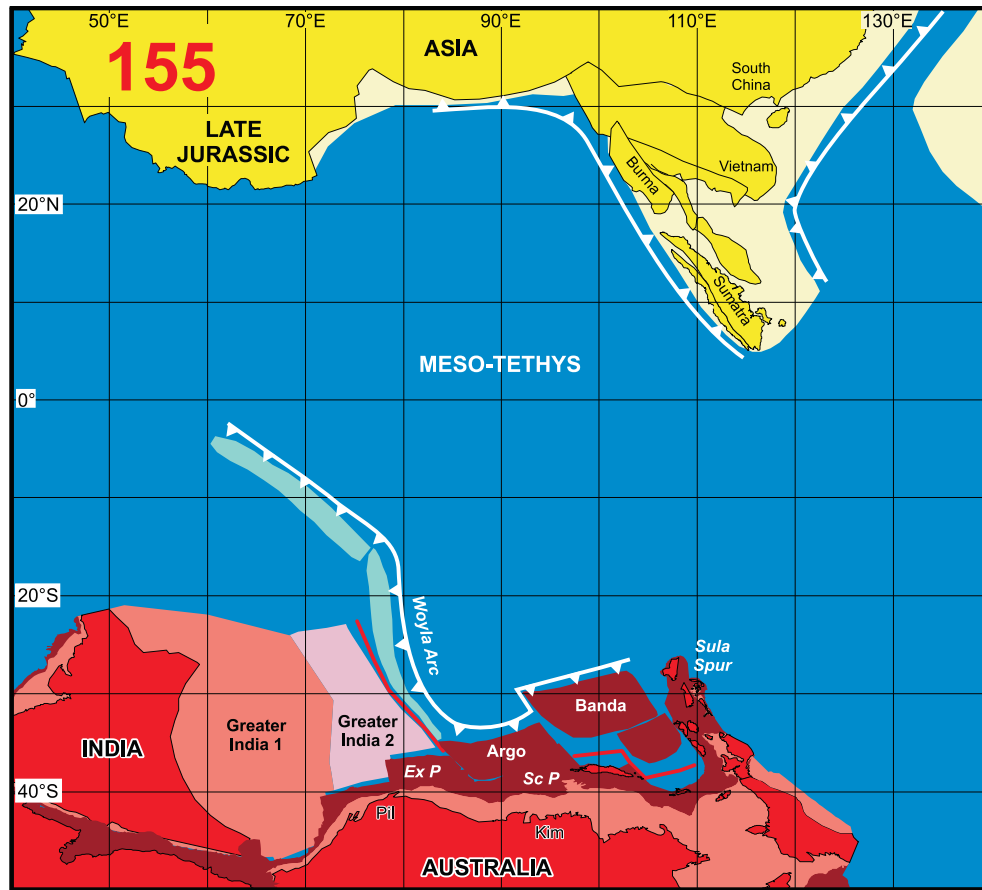


Fig. 6. Reconstruction at 155 Ma. Ocean spreading propagated east and the Woyla intra-oceanic arc formed either at the northern Indian margin, or within the Meso-Tethys north of India. The Tethyan oceans and continental margins west of about 80°E have not been reconstructed.

and there have been suggestions that it includes microcontinental fragments. Cameron et al. (1980) postulated that the western portion of the Woyla Arc overlies an older continental block which they named the Sikuleh Continental Fragment based on a clastic succession of quartzites, grey phyllites and metasilstones beneath the arc, and granites, Tertiary rhyolites and Mo-bearing breccia pipes that cut the arc. Pulunggono and Cameron (1984) proposed that the Natal block was another continental fragment, for which the evidence “is less conclusive”, based largely on the presence of granites that intrude the Woyla Arc. These blocks were suggested to have been fragments rifted from Sundaland or exotic fragments accreted to it. In contrast, Wajzer et al. (1991) and Barber (2000) interpreted the Woyla Group as a Late Jurassic–Early Cretaceous intra-oceanic arc and accretionary complex which became sutured to Sumatra by closure of a Tethyan ocean.

Like West Burma the early speculations about microcontinental fragments have since become established in the literature and Metcalfe (1996) suggested the continental fragments had a NW Australian origin. However, Barber (2000) and Barber and Crow (2005) reviewed these proposals and argued that there is no convincing evidence for any microcontinental blocks accreted to the margin of Sundaland in the Cretaceous. They interpreted the Sikuleh and Natal fragments as part of the Woyla intra-oceanic arc that was thrust onto the Sumatran Sundaland margin in the mid Cretaceous. As discussed above, Mitchell (1993) had similarly suggested that the Mawgyi Nappe of West Burma was part of the same intra-oceanic arc thrust onto the Asian margin in the late Early Cretaceous. However, there is one important difference. In Burma, according to Mitchell (1993) the emplacement of the Mawgyi nappe was followed by resumption or continuation of subduction beneath the western Asian

margin indicated by abundant magmatism during the Late Cretaceous and Early Cenozoic, whereas he noted the limited evidence for arc magmatism in Sumatra. I consider that the collision event marked by emplacement of the Woyla Arc and continental fragments further east (Smyth et al., 2007) terminated subduction from about 90 to 45 Ma beneath Sumatra and Java. There is little magmatism in Indonesia during that interval (Hall, 2009) and a widespread regional unconformity that Clements et al. (2011) interpreted as a dynamic topographic response to cessation of subduction.

3.3. Fragments in Borneo

Borneo is a composite region that includes several microcontinental fragments and ophiolitic/arc zones. Hamilton (1970, 1973), Katili (1971) and Haile (1973) recognised very early that western Borneo had ancient subduction zones to the north and south and included microcontinental fragments.

Traditionally, west Borneo has been interpreted as the most ancient part of Borneo (Haile, 1974; van Bemmelen, 1949) and as a fragment of Asian/Cathaysian origin (e.g. Hutchison, 1989; Metcalfe, 1988, 1990, 1996). However, these interpretations assume that all the metamorphic rocks of west Borneo are part of the same basement despite being separated by several sutures. Hamilton (1973, 1979) interpreted much of the area of north Sarawak and offshore as a Tertiary subduction complex, implying west Borneo was part of Sundaland by sometime in the Cretaceous without specifying where it came from or when it was added. It has been generally accepted there was subduction in the Cretaceous beneath Borneo although the interpretation of Cenozoic subduction beneath NW Borneo has

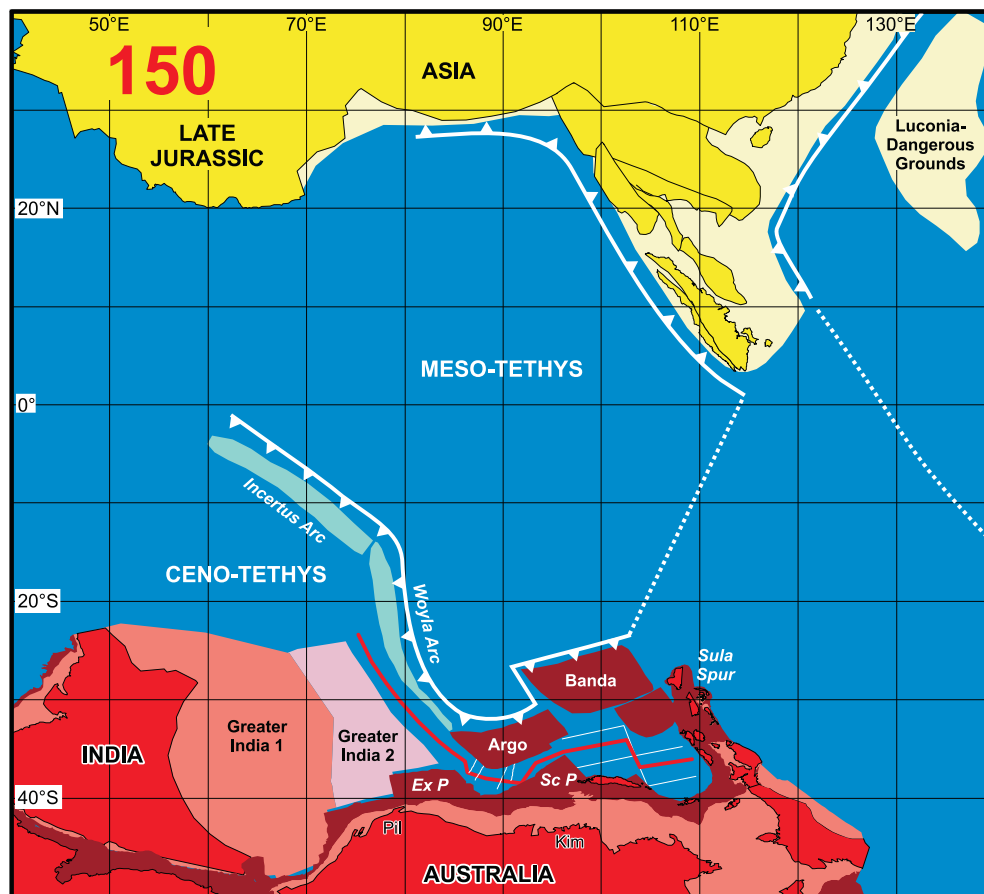


Fig. 7. Reconstruction at 150 Ma. The postulated eastward continuation of the Woyla intra-oceanic arc is named the Incertus Arc. Possible arc terranes that may correspond to this arc are now in Asia and are discussed in the text. Rifting of fragments from the Banda region left the Sula Spur north of the Banda Embayment as the northern extremity of continental Australia.

been challenged by some authors (e.g. Moss, 1998; Williams et al., 1988).

Haile (1973, 1974) divided NW Borneo into 4 zones, from south to north: the West Borneo Basement, and the Kuching, Sibu and Miri Zones. He suggested that geological contrasts between the Kuching and Sibu zones could be interpreted in terms of an Early Cretaceous southward-dipping subduction zone beneath a Borneo microcontinent (West Borneo Basement) although he also drew attention to some characters not typical of former subduction zones. The West Borneo Basement has been considered by some authors as part of Sundaland from the Late Triassic (e.g. Hutchison, 1989) or by others as a separate block added later (e.g. Metcalfe, 1988, 1990, 1996, who named it the SW Borneo block). Both Hutchison and Metcalfe suggested it had a South China origin. Metcalfe originally interpreted it to have moved south after rifting in the Late Cretaceous, opening the Proto-South China Sea, following Ben-Avraham (1973), Ben-Avraham and Emery (1973) and Ben-Avraham and Uyeda (1973). Many workers, including Katili (1973), Hamilton (1973, 1979), Tan (1979), Metcalfe (1988, 1990, 1996), Williams et al. (1988) have suggested broadly south-directed subduction (or west-directed if Borneo was rotated from its present position) beneath Borneo during the Cretaceous and Early Cenozoic.

However, although Borneo has been considered by most authors to have been broadly part of Asia since the Triassic this view has not been universally accepted. In a very early plate tectonic interpretation Luyendyk (1974) suggested that Borneo and Sulawesi had rifted away from Australia in the Late Jurassic but this suggestion seems to have been rejected, overlooked or forgotten. Hall et al. (2009a) proposed that SW Borneo rifted from western Australia in the Late

Jurassic to leave the Banda embayment (Spakman and Hall, 2010) and was added to Sundaland in the Early Cretaceous. The northern edge of the block would have been a south-dipping subduction zone as proposed by many authors (e.g. Hamilton, 1979; Hutchison, 1996; Moss, 1998; Tate, 1991; Williams et al., 1988) south of the Kuching Zone. The suture with Sundaland is suggested to run south from the Natuna area along the structural lineament named the Billiton Depression (Ben-Avraham, 1973; Ben-Avraham and Emery, 1973) and originally interpreted by Ben-Avraham and Uyeda (1973) as a transform fault associated with Cretaceous opening of the South China Sea. The suggestion that SW Borneo is a fragment rifted from Australia in the Late Jurassic has been accepted by Metcalfe (2009, 2011a,b).

North of SW Borneo there are several continental areas that have been assigned to different microcontinental blocks and given different names (e.g. Hutchison, 1989; Metcalfe, 1990, 1996) including the Semitau, Luconia, Spratly Islands–Dangerous Ground, and Kelabit–Longbowan blocks within areas shown as accreted or extended continental crust. It is difficult to determine if all these blocks really deserve the status of independent microcontinents, as the evidence for their age and character is often slight, and some could be relatively rigid high blocks within a stretched continental margin with an older complex history of assembly and orogeny from the Palaeozoic or even earlier. Where there is evidence for their origin (e.g. Haile, 1974; Hutchison, 1989, 2005; Kudrass et al., 1986; Metcalfe, 1988, 1990, 1996; Williams et al., 1988) it supports a east Asian origin for most of the blocks.

Haile (1974) and Gower (1990) suggested important strike-slip movement on the northern boundary of the SW Borneo block and I



Fig. 8. Reconstruction at 145 Ma. The Woyla–Incetus Arc moved northward with the Australian continental Argo and Banda fragments as the Ceno-Tethys widened. In the western Pacific the Luconia–Dangerous Grounds continental fragment had rifted from the Asian margin but its position is very uncertain before 90 Ma.

consider this is supported by observations in northern Kalimantan (Doutch, 1992; Williams et al., 1988). Evidence for the origin of the block is very limited and it is separated from the other blocks by melanges and deformed ophiolites interpreted as representing one or more sutures, including the Boyan zone (Williams et al., 1988) and Lupar Line (Haile, 1973; Tan, 1979, 1982). Interpretations of its Cathaysian origin (e.g. Hutchison, 1989; Metcalfe, 2006, 2009) have relied on correlations across these sutures but there are a few pieces of evidence that favour an Australian origin. The Schwaner Mountains are dominated by Cretaceous granitic rocks which intrude a metamorphic basement suggested to be Permo-Triassic or older (e.g. Hutchison, 2005; Williams et al., 1988) but which is known only to be older than the Cretaceous intrusive rocks, with the exception of a single K–Ar age of 189 ± 2 Ma from a biotite hornfels that is suggested to indicate the minimum age for pre-intrusive regional metamorphism (Pieters and Sanyoto, 1993). Work is in progress to better date the metamorphic rocks.

Alluvial diamonds are found in the Kapuas River of West Kalimantan and the Barito and Meratus areas of SE Kalimantan but their source is unknown. Barron et al. (2008) have suggested the SE Kalimantan diamonds resemble diamonds from eastern Australia and have a subduction origin and there are ultrahigh pressure rocks from the Meratus region (Parkinson et al., 1998) which might contain such diamonds although none have so far been reported. However, this would not explain the Kapuas River diamonds. Metcalfe (2009) has suggested that alluvial diamonds of Burma, Thailand and Sumatra were eroded from Permian glacial-marine diamictites of the Sibumasu block which was rifted from the western Australian part of Gondwanaland. Thus, an alternative explanation for the SW Borneo diamonds is that they

arrived with a different Australian block and have been reworked into river sediments from the basement or its original sedimentary cover. Resemblances to diamonds from NW Australia (Taylor et al., 1990) support this interpretation which does not exclude a subduction origin for some of the SE Kalimantan diamonds. Smith et al. (2009) found that the Borneo diamonds included several groups interpreted to have been reworked from multiple primary sources but that all have characteristics of ancient lithospheric mantle-derived diamonds. It may also be significant that detrital diamonds have not been discovered on Cathaysian blocks in other parts of SE Asia (Metcalfe, 2009).

Devonian limestones are the oldest fossiliferous rocks known from Borneo and occur as float in the Telen River, a tributary of the Mahakam River, in the Upper Kutai basin (Rutten, 1940). The limestones are reported to be blocks in Permian debris flows and schists found nearby are interpreted to be older (Sugiaman and Andria, 1999). The limestones contain coral and stromatoporoid fossils. Hutchison (1989) and Metcalfe (1990) considered these limestones to belong to a separate Mangkalihat microcontinental block, possibly rifted from New Guinea in the Late Jurassic (Metcalfe, 1996). Devonian corals but not stromatoporoids have been reported from New Guinea (Oliver et al., 1995) and from the Canning Basin (Playford, 1980; Wood, 2000) of western Australia.

3.4. Meratus suture

Hamilton (1979) drew a NE–SW line from West Java to the Meratus Mountains of SE Kalimantan (Fig. 2) as the approximate southeast boundary of Cretaceous continental crust and to the east of this line in Java and SE Borneo are ophiolitic, arc rocks and some high pressure-



Fig. 9. Reconstruction at 140 Ma. In the Jurassic and Cretaceous the northern Australian margin was a passive margin. There is evidence of intra-oceanic arcs in the Pacific from the Late Jurassic–Early Cretaceous in the Philippines, Halmahera and New Guinea but their exact positions are unknown. The subduction margin north of the Banda (SW Borneo) block is interpreted to have continued east into the Pacific but well to the north of the passive margin of northern Australia in New Guinea.

low temperature metamorphic rocks. This zone represents subduction beneath Sundaland in the Early Cretaceous. Accretionary-collision complexes resulting from subduction (Katili, 1971, 1973; Parkinson et al., 1998; Sikumbang, 1986, 1990; Sukanto, 1975a,b; Wakita, 2000; Wakita et al., 1994a,b, 1998) include tectonic units formed by oceanic spreading, arc volcanism, oceanic and forearc sedimentation, and metamorphism. The Luk Ulo Complex of Central Java includes serpentinised ultrabasic rocks, basalts, cherts, limestones, siliceous shales, shales, volcanic breccias, and high pressure-low temperature and ultrahigh pressure metamorphic rocks (Parkinson et al., 1998; Wakita, 2000). In West Java similar rocks are exposed to the south of Ciletuh Bay and include serpentinised peridotites, gabbros, pillow basalts, and rare metamorphic rocks such as quartzite and amphibolite (Clements et al., 2009; Schiller et al., 1991).

In Java the age of suturing in this zone is uncertain. K–Ar ages from metamorphic rocks summarised by Parkinson et al. (1998) indicate high pressure-low temperature metamorphism between 117 and 124 Ma, and radiolaria associated with pillow lavas at Luk Ulo are Early Cretaceous (Wakita et al., 1994b). These rocks are overlain by Eocene sediments (Clements et al., 2009; Smyth et al., 2008; Wakita, 2000). In SE Kalimantan Sikumbang (1986, 1990) and Wakita et al. (1998) concluded that arc-continent collision and ophiolite emplacement was completed by about 90 Ma.

3.5. West Sulawesi-Sumba

Hamilton (1979) interpreted the area east of his boundary of Cretaceous continental crust, including East Java and West Sulawesi,

to be underlain by Cretaceous or Early Tertiary melange. However, some authors (e.g. Parkinson et al., 1998; van Leeuwen et al., 2007; Wakita et al., 1996) have since suggested that Gondwana continental fragments that accreted to Sundaland in the Cretaceous underlie parts of SE Kalimantan, western and south Sulawesi which are within the region interpreted by Hamilton (1979) to be melange.

In some areas the basement is now dated, and it is clearly not melange. For example, the western part of the north arm of Sulawesi includes Carboniferous granites (van Leeuwen et al., 2007) that intrude medium to high grade quartzofeldspathic mica schists and gneisses of the Malino Complex, and in the neck are Permo-Triassic granites that intrude the Palu Metamorphic Complex (van Leeuwen and Muhardjo, 2005). In these areas and elsewhere in western Sulawesi there is evidence from inherited zircons, and from chemical characteristics of Cenozoic igneous rocks, of underlying continental basement (Bergman et al., 1996; Elburg and Foden, 1999; Elburg et al., 2003; Polvé et al., 1997, 2001; Priadi et al., 1993, 1994). Jurassic ammonites and bivalves have been reported from South Sulawesi (Sukanto and Westermann, 1993; Sukanto et al., 1990) and Sumba (Roggeveen, 1929) which suggest a continental basement. Geochemistry and palaeomagnetism suggest that Sumba formed part of the Sundaland margin by the Late Cretaceous (Abdullah et al., 2000; Wensink, 1994). $^3\text{He}/^4\text{He}$ ratios suggest that Australian continental crust was involved in genesis of magmas throughout the Inner Banda Arc from the Banda Ridges to Flores (Hilton et al., 1992).

Further north, Plio-Pleistocene basalts and basaltic andesites from the Semporna peninsula of southern Sabah have isotopic characteristics that suggest an ancient, possibly Archaean, component is present

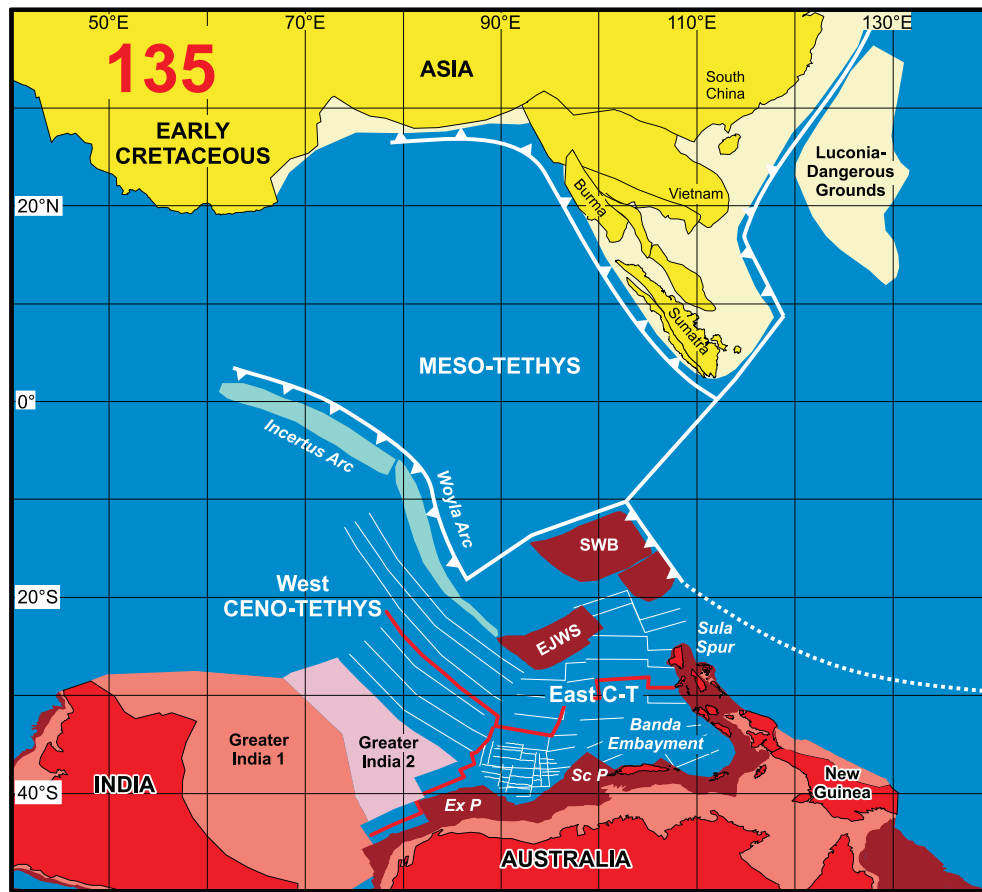


Fig. 10. Reconstruction at 135 Ma. A triple junction formed as India separated from Australia and divided the Ceno-Tethys into West and East (East C-T) parts. The Banda block is identified as SW Borneo (SWB) and the Argo block as East Java–West Sulawesi (EJWS) on this and subsequent figures.

in the Sabah crust (Macpherson et al., 2010). Before Eocene opening of the Celebes Sea south Sabah and NW Sulawesi would have been part of the same block.

Interpreting all these areas of continental crust as part of a single block may be over-simplifying the situation. There are blueschists and other high pressure-low temperature metamorphic rocks known from inliers in South Sulawesi (Maulana et al., 2010; Miyazaki et al., 1996, 1998; Parkinson et al., 1998; Sukanto and Supriatna, 1982) suggesting sutures between blocks. Neogene potassic volcanics in SW Sulawesi do not show the Australian continental isotopic signatures shown by similar volcanic rocks further north in Sulawesi (Elburg et al., 2003) which also could indicate the edge of a block.

3.6. East Java

Only a few areas of basement rocks are known from East Java, but these, and results of oil company drilling offshore, supported Hamilton's (1979) suggestion that the basement of West Java was continental but that further east was Cretaceous or Early Tertiary melange. However, recent studies in East Java show that the southern part of the island is underlain by continental crust and recent studies suggest there may be similar crust beneath the Java Sea and south of East Java in the forearc.

The igneous rocks of the Early Cenozoic Southern Mountains volcanic arc include abundant dacites and rhyolites, and volcanic rock and minor intrusions contain Archaean to Cambrian zircons similar to those of Gondwana crust (Smyth, 2005; Smyth et al., 2007, 2008). East Java and the Malino Complex of NW Sulawesi (van Leeuwen et al., 2007) are so far the only parts of Indonesia where Archaean zircons with ages greater than 3 Ga have been found and

these strongly suggest a West Australian origin for the basement (Smyth et al., 2007).

Offshore seismic data suggest there may be similar crust both to the north beneath the Java Sea (Emmet et al., 2009; Granath et al., 2011) and south of East Java (Deighton et al., 2011). In the Java Sea there is a broadly horizontal regional unconformity at the base of a Cenozoic section and beneath it are synforms containing up to 5–10 km of section which Granath et al. (2011) suggest is of Precambrian to Permo-Triassic age. South of Java the Cenozoic section is about 2 s TWT thick and there is a broadly flat-lying sequence of more than 4 s TWT beneath which Deighton et al. (2011) suggests is Mesozoic or older.

Continental crust has also been suggested to underlie parts of the southern Makassar Straits and East Java Sea between Kalimantan and Java based on basement rocks encountered in exploration wells (Manur and Barraclough, 1994). Hutchison (1989) and Metcalfe (1990) identified a Paternoster block off SE Borneo and a Mangkalihat block further north in East Borneo which were interpreted as underlain by continental basement. Hutchison interpreted the Mangkalihat block as an ancient island arc with some continental basement based on the presence of tin granites (BRGM, 1982; Setiawan and Le Bel, 1987). Maps by Metcalfe (1990, 1996) have suggested that both blocks originated from the New Guinea region.

Ricou (1994) suggested that the Paternoster 'plateau' collided with Borneo in the Paleocene and was derived from the NW Shelf of Australia. Hall et al. (2009a) suggested that the East Java–West Sulawesi block is the Argo block (Powell et al., 1988) which would include the Paternoster platform and possibly the Mangkalihat block. This proposal explains the Palaeozoic to Archaean ages of zircons found in igneous rocks in East Java, which would be expected in

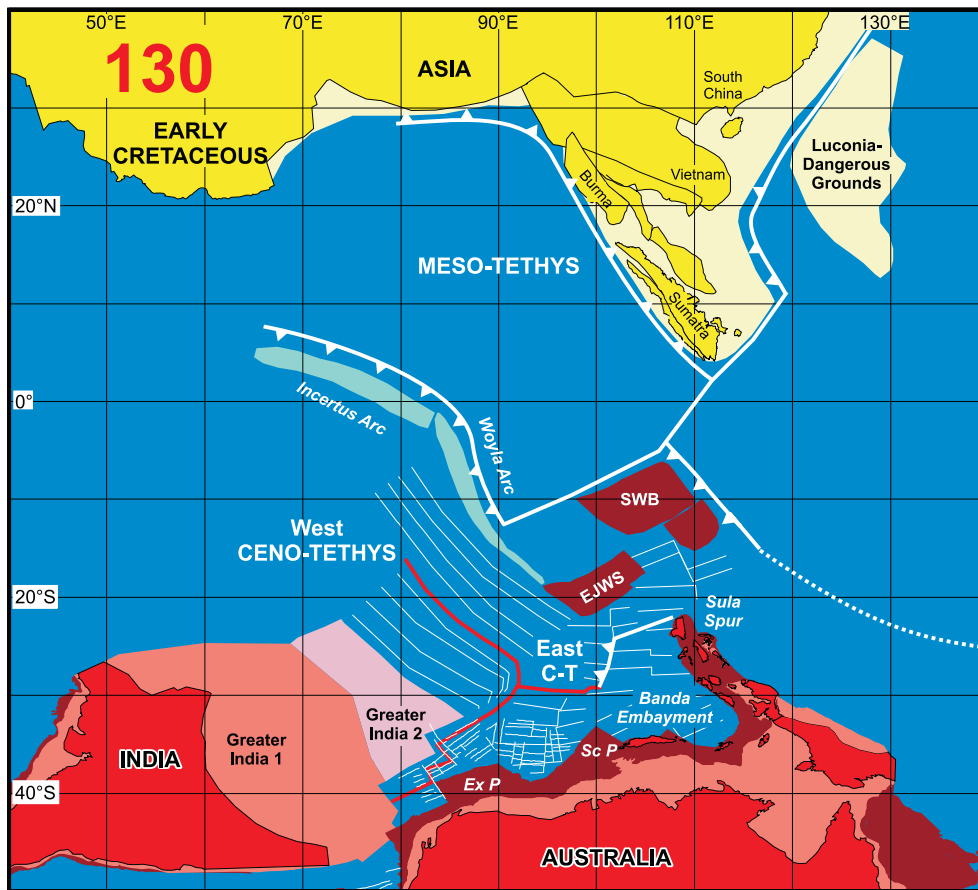


Fig. 11. Reconstruction at 130 Ma. After separation of India from Australia the SW Borneo (SWB) and East Java–West Sulawesi (EJWS) blocks moved NE. A short-lived episode of subduction in the East Ceno-Tethys (East C-T) is inferred for kinematic consistency.

detrital sediments in the offshore continuation of the Canning Basin, although it is further west than proposed for West Sulawesi by van Leeuwen et al. (2007) who also recorded zircons with Archaean ages similar to those of West Australia.

4. Subduction history

Until recently reconstructions of Gondwana breakup and Asian accretion during the Mesozoic have been largely schematic with maps at widely spaced time intervals (e.g. Audley-Charles et al., 1988; Metcalfe, 1988, 1990, 1996). Heine et al. (2004), Heine and Müller (2005) and Whittaker et al. (2007) made the first detailed reconstructions of the ocean basins and used hypothetical Indian Ocean anomalies to speculate on aspects of the Mesozoic history of SE Asia. The reconstructions by Heine et al. (2004) and Heine and Müller (2005) assume that West Burma was rifted from the Australian margin in the Late Jurassic at about 155 Ma and appears to have docked (Heine et al., 2004) at about 70 Ma. For the reasons discussed above, that interpretation is rejected here.

Most previous reconstructions have assumed continuous subduction at the Sumatra–Java margin throughout the Mesozoic and Early Cenozoic. However, although there is good evidence from magnetic anomalies for India's rapid northward movement in the Late Cretaceous and Early Cenozoic, and hence subduction to the north of India, magnetic anomalies south of Australia indicate very slow separation of Australia and Antarctica until about 45 Ma (Royer and Sandwell, 1989). Hence there is no requirement for subduction beneath Indonesia, and the only way in which subduction could have been maintained during the Late Cretaceous and Early Cenozoic is to propose a hypothetical spreading centre between Australia and

Sundaland which moved northward until it was subducted, as suggested by Heine et al. (2004), Heine and Müller (2005) and Whittaker et al. (2007). Ridge subduction is often suggested to produce slab windows associated with volumetrically or compositionally unusual magmatism (e.g. Gorrington and Kay, 2001; Hole et al., 1995; Thorkelson, 1996; Thorkelson and Taylor, 1989). Such a slab window should have swept westward beneath Java and Sumatra during the Late Cretaceous and Paleocene according to the Whittaker et al. (2007) model, but there is no record of magmatism of this age in Java, and almost none in Sumatra (Hall, 2009).

P wave and S wave seismic tomography also indicate a different subduction history north of India compared to that north of Australia. In the mantle below 700 km there is a marked difference in structure west and east of about 100°E (Hall et al., 2008). To the west there are a series of linear high velocity anomalies trending roughly NW–SE interpreted as subducted remnants of Tethyan oceans by van der Voo et al. (1999). East of 100°E there is only a broad elliptical anomaly oriented approximately NE–SW. The position of the deep lower mantle anomaly fits well with that expected from Indian–Australian lithosphere subducted northward at the Java margin since about 45 Ma, and Proto-South China Sea lithosphere subducted southward at the north Borneo trench since 45 Ma, with contributions from several other subduction zones within east Indonesia, such as those associated with the Sulu Arc, and the Sangihe Arc. There is no evidence for a similar series of Tethyan oceans to those subducted north of India, consistent with an absence of subduction during the Late Cretaceous and Paleocene. Therefore, one assumption of this reconstruction is a cessation of subduction beneath the Sundaland margin between about 90 Ma and 45 Ma (Hall, 2009; Hall et al., 2008; Smyth et al., 2008) caused by collision of Gondwana fragments. This is supported

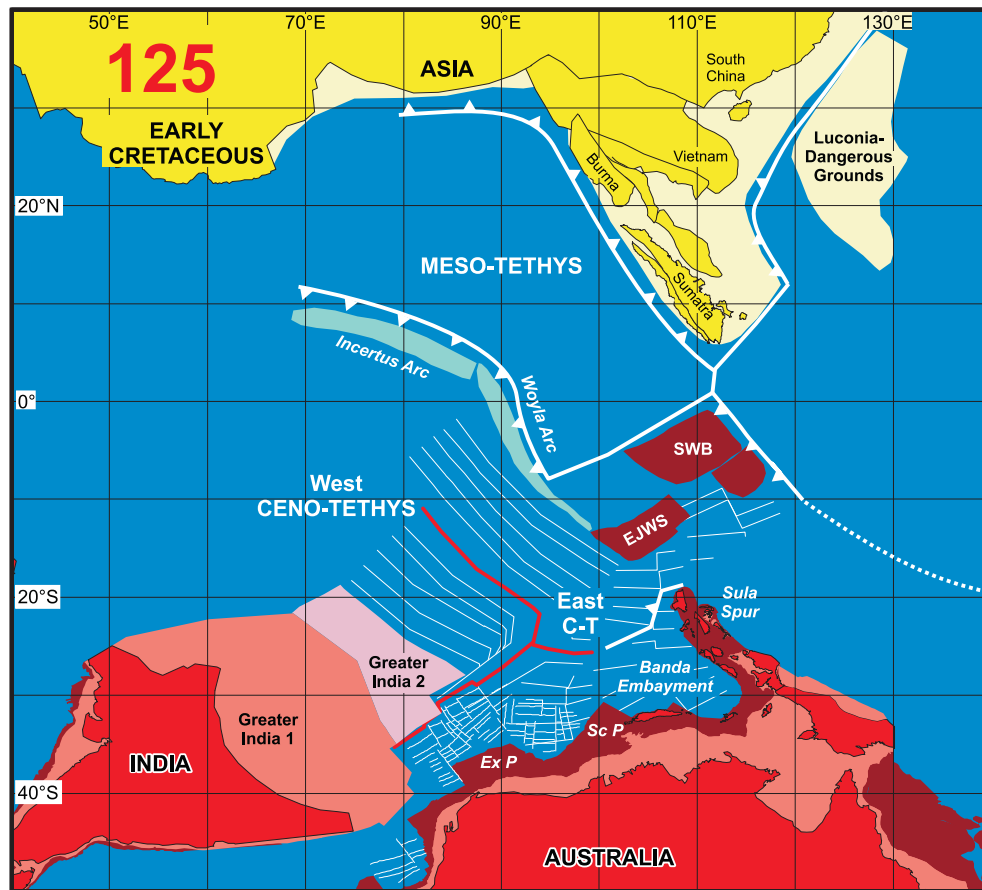


Fig. 12. Reconstruction at 125 Ma. The West Ceno-Tethys continued to widen while the East Ceno-Tethys (East C-T) became slightly smaller.

by the widespread regional unconformity in Sundaland, evidence of uplift, a prolonged interval of erosion and almost complete absence of a marine sedimentary record for the Late Cretaceous and Early Cenozoic which have been interpreted as a dynamic topographic response to termination of subduction (Clements and Hall, 2011; Clements et al., 2011).

5. Mesozoic margins

Interpreting the Mesozoic and Cenozoic collision history of SE Asia requires identifying rifted continental and arc fragments and their original and present locations, as well as reconstructing the oceanic spreading and subduction history. Based on the discussion above I consider that there are Cathaysian/Asian continental fragments east of the East Malaya–Indochina block in the region north of Sarawak, Brunei and Sabah. Small parts of these fragments are known on land in Sarawak and offshore in the Dangerous Grounds and clearly show their Asian origin.

Following Hall et al. (2009a) I consider that all other continental fragments have an Australian origin. It is known there was an important episode of rifting around northern Australia in the Jurassic (Audley-Charles et al., 1988; Hamilton, 1979; Metcalfe, 1988; Pigram and Panggabean, 1984; Powell et al., 1988). Several major blocks have been interpreted to have rifted from northwest Australia before India–Australia separation began. Until recently, as discussed above, these rifted fragments had been identified with Mt. Victoria Land/West Burma, or fragments even further north in south Tibet (e.g. Audley-Charles, 1983, 1988; Charlton, 2001). Instead, I identify them with SW Borneo and East Java–West Sulawesi based on the discussion above.

5.1. Pacific margin

The most difficult of all the margins to reconstruct for the Mesozoic and Early Cenozoic is that east of Asia, mainly because most of the evidence is offshore beneath a thick Cenozoic cover, with a little preserved on land in Vietnam, the Natuna Islands, Sarawak and Sabah.

An east-facing Andean margin linked to Pacific subduction is commonly inferred (e.g. Charvet et al., 1994; Taylor and Hayes, 1983). There was widespread granite magmatism in mainland eastern China during the Late Jurassic and Early Cretaceous. For the earlier part of this period a subduction origin is generally accepted but during the Cretaceous the situation is less clear (e.g. Jiang et al., 2009). Cretaceous granites are known in North China but it is debated if they were formed at a subduction margin (e.g. Li and Li, 2007; Lin and Wang, 2006; Yang et al., 2007). For the SE China margin Jahn et al. (1976) argued that there was a Cretaceous (120–90 Ma) thermal episode related to west-directed Pacific subduction. In South China around Hong Kong acid magmatism ceased in the Early Cretaceous (Sewell et al., 2000). It is not known if acid magmatism continued in a belt to the east, because this area is offshore. Knittel (2010) reported 83 Ma rhyolites in Mindoro suggested to have formed in the South China margin before a continental fragment rifted from Southeast China in the Oligocene as a result of the opening of the South China Sea. Early Cretaceous granites are reported from Vietnam (Nguyen et al., 2004; Thuy et al., 2004) with youngest ages of 88 Ma. If these are subduction-related it implies a trench somewhere beneath the present South China Sea. Zhou et al. (2008) used geophysical data to propose that a Jurassic–Early Cretaceous subduction complex can be traced south from Taiwan along the present northern margin of the South China Sea and was displaced to Palawan by opening of the South China Sea. This restoration of the Early

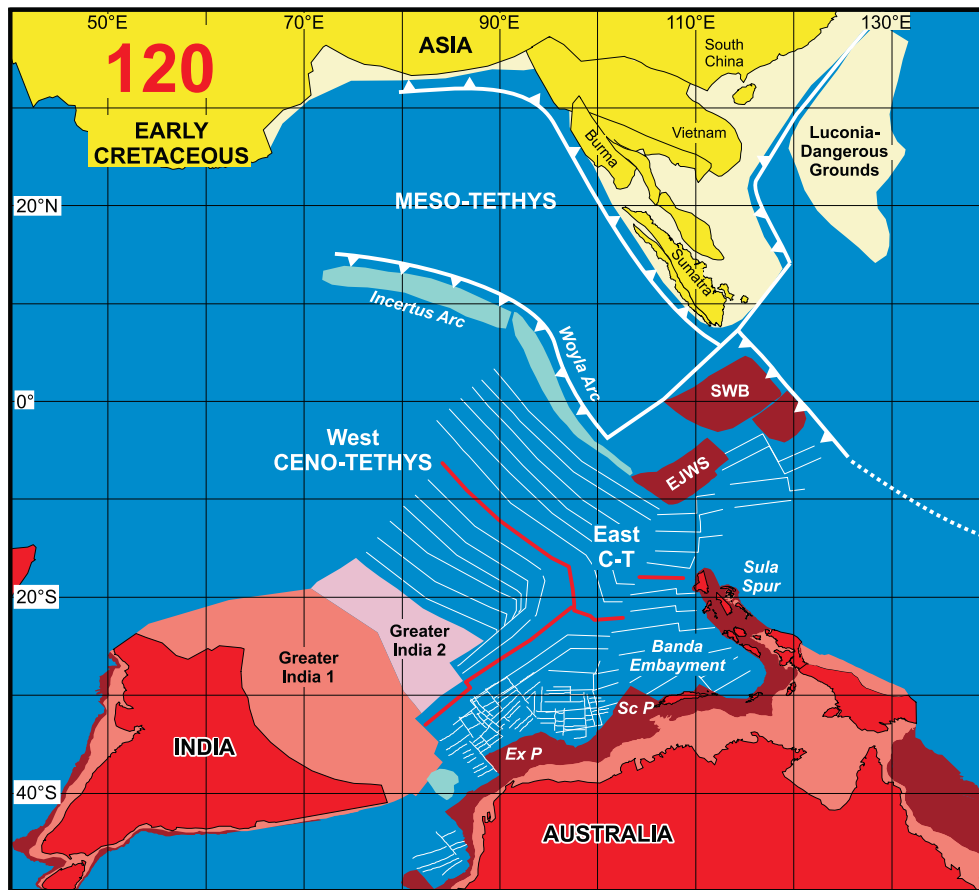


Fig. 13. Reconstruction at 120 Ma. SW Borneo (SWB) was close to the SE Asia Sundaland margin and is interpreted to have moved along a strike-slip boundary at the Billiton depression.

Cretaceous margin would account for subduction-related granites in Vietnam but it is not clear where to continue this belt, or even if it did continue south. Some authors have traced this subduction margin or belt of granites into Borneo (e.g. Fyhn et al., 2010b; Hamilton, 1979; Wakita and Metcalfe, 2005; Williams et al., 1988) with the implicit or explicit assumption that SW Borneo was part of Sundaland by this time.

Several workers have suggested collision of continental fragments with the Asian margin during the Cretaceous. Faure et al. (1989) and Charvet et al. (1994) proposed Cretaceous collision of a West Philippine block with the Asian margin in SE China. Zhou et al. (2008) interpreted a block that continued much further south from SE China into Sarawak, that collided in the Cretaceous, which they named Cathaysia. Dredged samples (Kudrass et al., 1986) from the Dangerous Grounds indicate the presence of continental material, including Upper Triassic to Lower Jurassic sandstones with plant remains, with east Asian affinities. Fyhn et al. (2010b) inferred a fragment they called the Luconia block which sutured to SE Asia in the early Cenozoic. Hutchison (1996) introduced the term Sarawak Orogeny for an inferred collision between a continental block and SW Borneo in the Late Eocene. I consider there is good evidence for a continental block, here termed the Luconia–Dangerous Grounds block, of east Asian origin but suggest it docked in the early Late Cretaceous and there was no Sarawak Orogeny, as discussed further below.

There is little evidence anywhere of subduction-related magmatism younger than about 80 Ma and the Late Cretaceous after 80 Ma was a period of rifting and extension of the South China margin (e.g. Taylor and Hayes, 1983; Zhou et al., 2008). As noted above, many authors have suggested west- or south-directed subduction beneath

northern Borneo in the Late Cretaceous and Early Cenozoic (e.g. Hamilton, 1979; Tate, 1991; Taylor and Hayes, 1983; Williams et al., 1988) but Moss (1998) drew attention to problems with a subduction-related interpretation for what he termed the Rajang–Embaluh Group. Hutchison (1996) also observed that the subduction history inferred by Tan and Lamy (1990) and Hazebroek and Tan (1993), from Late Cretaceous to Late Eocene, is not marked by subduction-related post-Paleocene volcanic arcs in Borneo and suggested subduction had ceased by 60 Ma (Hutchison, 2010). Moss (1998) suggested that subduction had ceased by about 80 Ma after arrival of micro-continental fragments now beneath the Luconia Shoals and Sarawak leaving a remnant ocean and a foreland basin in northern Borneo. This explains the absence of subduction-related magmatism but does not account for the Late Eocene deformation considered by Hutchison (1996) to record the Sarawak Orogeny.

Hutchison (1996) originally proposed the deep water sediments of the Rajang Group were deformed during the Sarawak Orogeny in the Late Eocene at about 45 Ma, but in later papers at about 37 Ma (Hutchison, 2004, 2005). The orogeny was interpreted to be synchronous with the collision of India and Asia (Hutchison, 2005) and possibly linked to collision of a Balingian–Luconia continental block with SW Borneo (Hutchison, 2010). He interpreted the latter collision to have followed southwards subduction beneath SW Borneo which terminated by about 60 Ma although compression and uplift apparently did not occur until more than 15 Ma after the block arrived at the trench.

Hutchison (1996) dated the orogeny from a regional unconformity described by Borneo Geological Survey geologists who recognised an episode of folding in the Late Eocene (Haile, 1962; Kirk, 1957; Wolfenden, 1960), which occurred before 37 Ma and was a

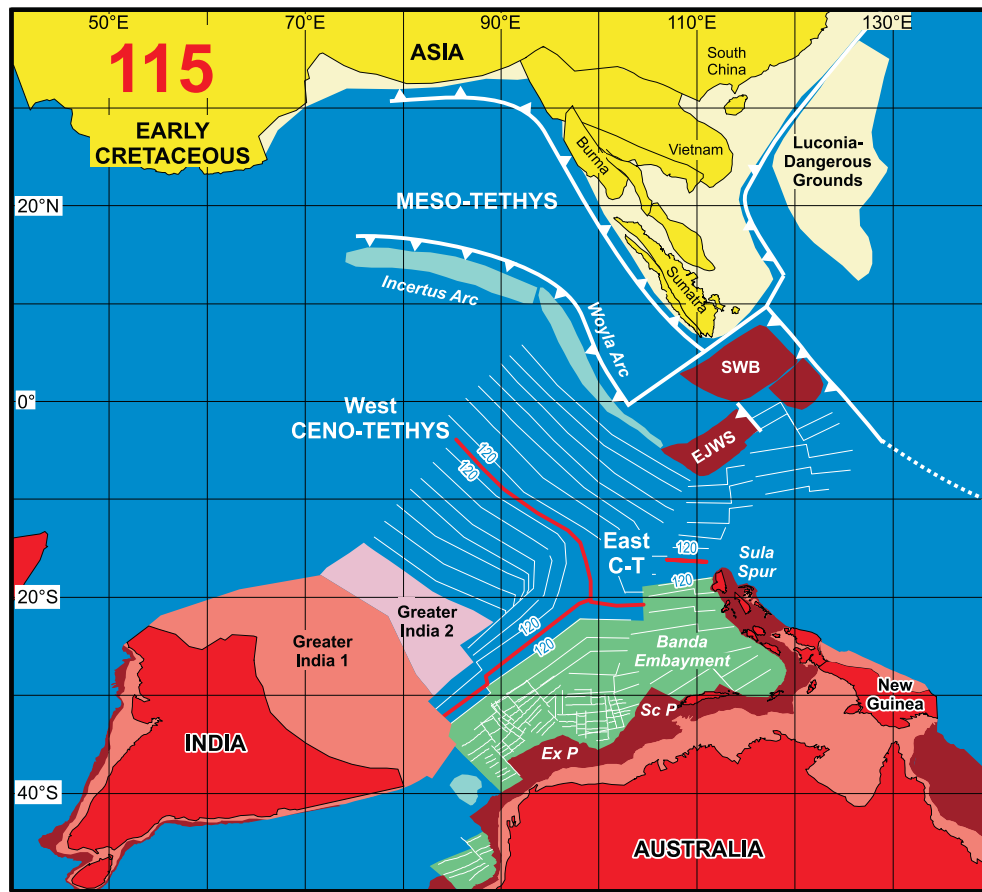


Fig. 14. Reconstruction at 115 Ma. SW Borneo (SWB) was close to its final position and subduction began between it and the East Java–West Sulawesi (EJWS) blocks based on metamorphic ages from the Meratus Suture in Java and SE Kalimantan. In the Ceno-Tethys selected anomalies are numbered with their age. On this and subsequent figures Jurassic and Early Cretaceous oceanic crust older than 120 Ma to the west of Australia is shaded green.

late event in a long Late Cretaceous to Eocene history of deformation. The original reports reveal some uncertainty in the age of the unconformity. Wolfenden (1960) reported Upper Eocene limestones unconformably above low-grade slates and phyllites assumed to be Eocene based on a very poor fauna including no pre-Tertiary foraminifera. Haile and Ho (1991), reproduced in Hutchison (2005), showed folded turbidites overlain by undated conglomerates. Adams and Haak (1962) reported Upper Eocene limestones above a steeply dipping sequence of Cretaceous turbidites. All that can be inferred with confidence is that Wolfenden (1960) showed the unconformity is older than uppermost Eocene, Haile and Ho (1991) did not date it, and Adams and Haak (1962) showed it was older than about 40 Ma. Wolfenden (1960) noted the absence of a marked angular unconformity in some areas and commented that the “stratigraphic evidence is difficult to reconcile with the concept of an Upper Eocene orogeny that caused the entire... Rajang Group to be folded” and observed that “deformation accompanied deposition”.

The idea of syn-depositional deformation has suggested to some authors that the Rajang Group was an accretionary prism (e.g. Tan, 1979, 1982) related to southward subduction. Hutchison (1996, 2005, 2010) argued that older parts of the Rajang Group were accretionary but that subduction ceased in the Paleocene before most of the turbidites were deposited. For the younger turbidites he followed Moss (1998) who suggested they were deposited in a remnant ocean basin, although Moss had specifically excluded an accretionary setting and argued that subduction had ceased in the Late Cretaceous.

Hutchison (2005) interpreted the unconformities to be synchronous with the collision of India with Asia but his 37 Ma age for the Sarawak Orogeny (Hutchison, 2004, 2005, 2010) is significantly

younger than his Paleocene to Early Eocene preferred collision age, and most other estimates of India–Asia collision age (e.g. Chen et al., 2010; Green et al., 2008; Leech et al., 2005; Najman et al., 2010; Rowley, 1996), except for the c. 34 Ma age of Aitchison et al. (2007a) which he discounted (Hutchison, 2010).

No authors provide Cretaceous–Paleocene reconstructions but Hutchison (2010) drew one map that shows an independent block, bounded by faults, that moved southwards during the Late Cretaceous to collide at the Lupar Line in Sarawak. Such a block would not explain the continuation of the Lupar Line eastwards into Kalimantan, nor is there any driving force for its movement, and the volcanic arc to the south that would be expected by the subduction suggested by Hutchison is missing.

The Lupar Line marks the southerly termination of the deep water Rajang Group rocks, although this was disputed by Hutchison (1996). Pieters and Supriatna (1990) showed the “Turbidite basin” terminates to the south at a linear zone of “Oceanic basement and overlying sediments” that can be traced from the Lupar River Lubok Antu Melange Belt of Sarawak (Tan, 1979) into Kalimantan. Douch (1992) showed the Cretaceous–Eocene ‘flysch’ terminating in a similar way. It appears that the Lupar Line is a profound structure, also associated with linear gravity and magnetic anomalies (Pieters and Supriatna, 1990; Williams et al., 1988). However, it lacks many of the features expected in a long-lived south-dipping subduction zone (Haile, 1973) which could be explained if it were a major strike-slip fault as suggested by Haile (1973).

It is impossible to reconcile the many different interpretations, few of which provide palaeogeographic reconstructions, but it is difficult to do better simply because there is so little evidence, and critical

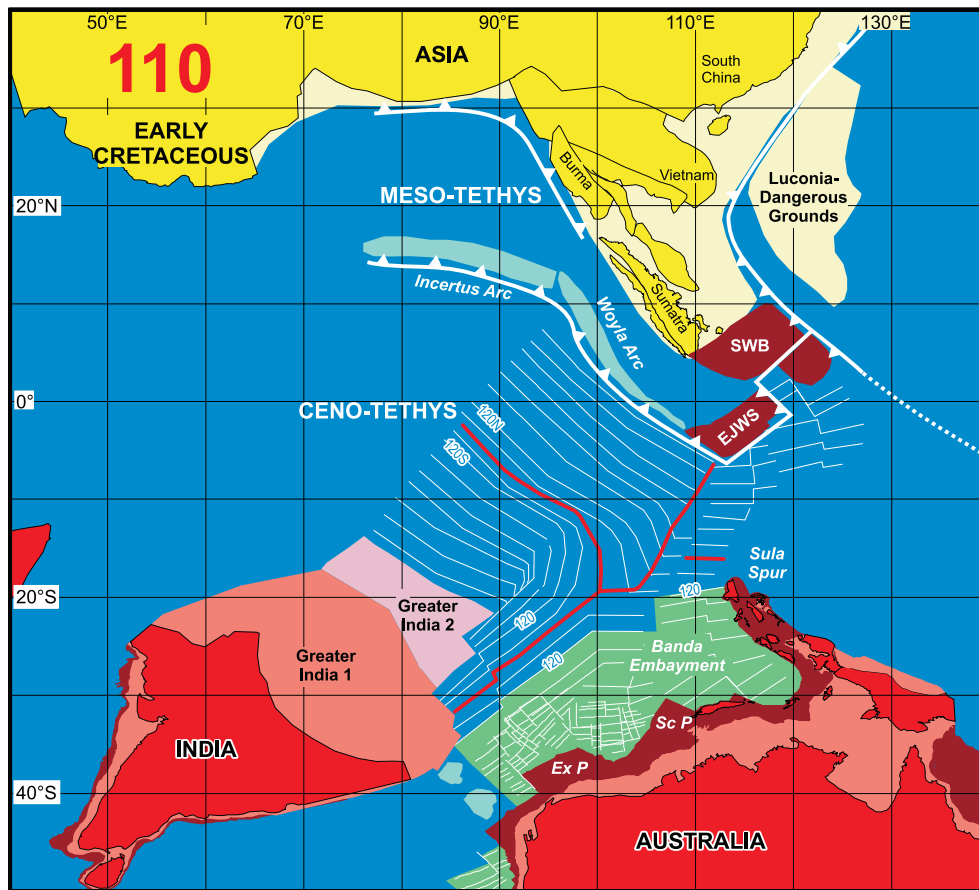


Fig. 15. Reconstruction at 110 Ma. SW Borneo (SWB) completed docking with the Sundaland margin. Spreading ended in the Ceno-Tethys between India and the Woyla-Incertus Arc. Subduction polarity flipped from south- to north-directed at the Woyla-Incertus Arc and the Ceno-Tethys began to subduct northwards. The India-Australia spreading centre propagated north as India moved north.

areas are offshore. I follow earlier authors in suggesting an east-facing Andean-type subduction margin close to the present Asian margin until the early Late Cretaceous, at about 90–80 Ma, when subduction terminated. I have assumed that this subduction ceased due to arrival of the Luconia–Dangerous Grounds block that included the area of offshore Sarawak often described as Luconia, the Dangerous Grounds and parts of the offshore northern South China Sea continental margin. An important difference from earlier interpretations is that the granites of Borneo are not interpreted to be the result of the Asian margin magmatism but are the result of south-directed subduction beneath the SW Borneo block as it moved north from Australia. East or west-directed subduction could have continued in the area that now includes south and offshore Vietnam (Fyhn et al., 2010a, 2010b), and on land and offshore Sarawak, into the early Cenozoic, and the simplest hypothesis to explain this is westward movement of a fragment along the Lupar Line, probably during the Late Cretaceous and early Cenozoic. This could imply a small remnant of oceanic crust to the west of the Luconia–Dangerous Grounds block eliminated during this interval.

5.2. North Australian margin

There is little information available to reconstruct the northern Australian margin in New Guinea and the adjacent Pacific further north before the Eocene. By the Early Jurassic New Guinea appears to have been a passive continental margin but the age of ocean crust to the north is unknown. There is some magmatism indicated by K–Ar and zircon fission track dating in central New Guinea (Page, 1976), the Bird's Head (Lunt and Djaafar, 1991; Sutriyono,

1999) and Misool (Visser and Hermes, 1962) during the Late Cretaceous which includes basalts on Misool and granites elsewhere. There is little to indicate this is subduction-related as the stratigraphy (Pieters et al., 1983; Pigram and Panggabean, 1984; Visser and Hermes, 1962) of New Guinea suggests a relatively quiet tectonic environment. There is considerable evidence for Mesozoic intra-Pacific oceanic arcs north of Australia in the Philippine Sea, the Philippines, Halmahera and northern New Guinea (e.g. Davies and Jaques, 1984; Hall et al., 1988; Karig, 1983; Klein and Kobayashi, 1981; Lewis et al., 1982; Tokuyama, 1985). Palaeomagnetic data (Ali and Hall, 1995; Hall et al., 1995) show the Halmahera Arc was close to the equator in the Late Cretaceous but this is insufficient to make a reconstruction and the positions of the other arcs at the time of formation are unknown.

5.3. West Australian margin

Reconstructing the early history of the Indian Ocean has always been difficult since almost all Mesozoic ocean floor has been subducted at the Sunda Trench. Some oceanic crust that formed soon after rifting of fragments is still preserved close to western and northern Australia. A remnant is left in the Argo Abyssal Plain which is Late Jurassic in age (Gradstein, 1992) and magnetic anomalies indicate two phases of spreading in the Late Jurassic and Early Cretaceous (Fullerton et al., 1989; Powell and Luyendyk, 1982). To the west there is oceanic crust in the Wharton Basin south of Java but this formed during the Cretaceous Quiet Zone (Fullerton et al., 1989) and anomalies there are not clear (Shreider et al., 1996). Magnetic anomalies remain off west Australia but identifying the fragments

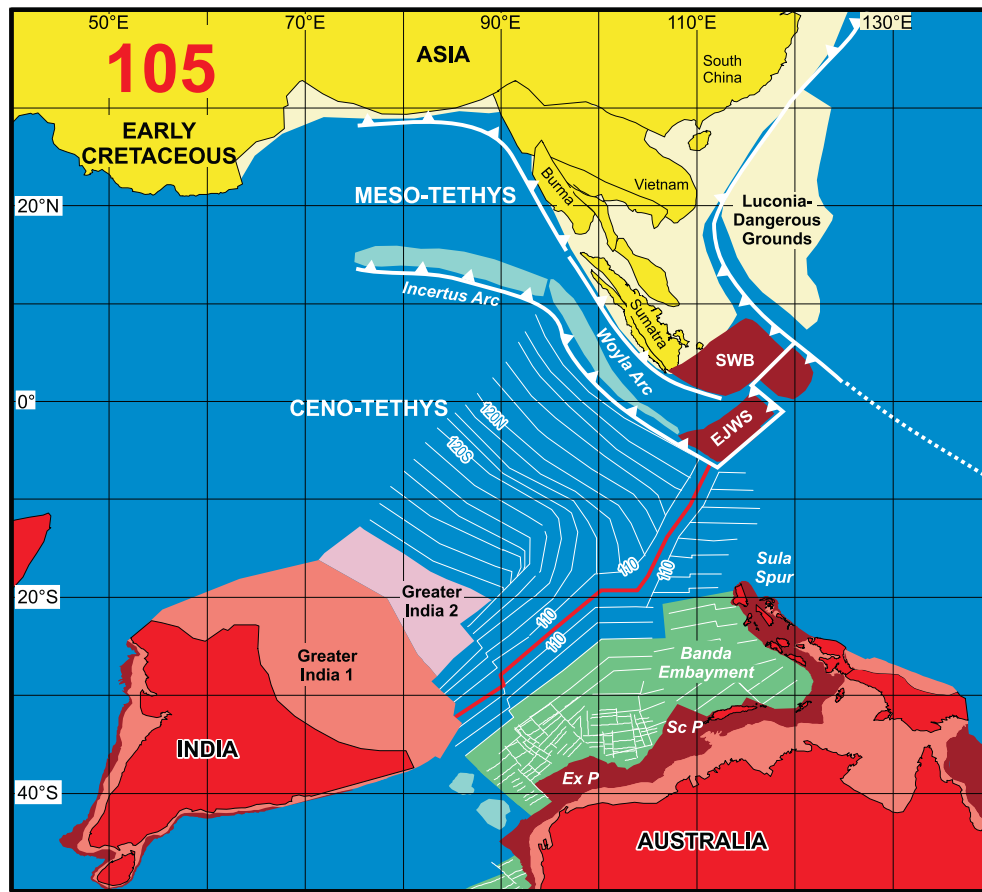


Fig. 16. Reconstruction at 105 Ma. East Java–West Sulawesi (EJWS) converged with SW Borneo (SWB). Spreading had ceased in the Ceno-Tethys between India and the Woyla–Incertus Arc but continued at the India–Australia spreading centre.

that rifted, leaving these anomalies in their wake, and their present position is controversial. Most authors have suggested that rifting propagated west and south (Fullerton et al., 1989; Pigram and Panggabean, 1984; Powell et al., 1988; Robb et al., 2005) from the Banda region but Heine et al. (2002, 2004) and Heine and Müller (2005) have argued that rifting propagated in the opposite direction. I have preferred interpretations of SW-propagating rifting based on the earlier papers, and the discussion by Robb et al. (2005) of the Heine and co-workers' interpretations.

The Heine et al. (2002, 2004) and Heine and Müller (2005) models were constructed with the assumption of West Burma as the rifted fragment, and its surmised Cretaceous collision age. As discussed above there is now more evidence and agreement that West Burma has been part of the Asian margin since the Triassic, and it favours Borneo, East Java and West Sulawesi as the fragments rifted from Australia.

SW Borneo is interpreted here as a block that separated from the Banda embayment. This is consistent with evidence for its origin discussed above, such as detrital diamonds and its size. The SW Borneo block has its northern limit at about the position of the Boyan zone and to the north are fragments of ophiolitic and Asian continental material accreted to it during the Cretaceous. The zone between the Boyan zone and Lupar Line appears to include fragments of both Asian and SW Borneo origin which may have been mixed and deformed with a wide WNW–ESE strike-slip zone. The suture between SW Borneo and Sundaland is along the Billiton Depression (Ben-Avraham, 1973; Ben-Avraham and Uyeda, 1973). A small Inner Banda block is shown on the reconstructions and is interpreted to move mainly with the SW Borneo block, but to have moved relative to it during the collision, and is speculated to now underlie part of

Sabah. This block could be dispensed with by allowing stretching of the Banda region as it rifted, and deformation after it docked, but this is difficult to include in a rigid plate model.

The East Java–West Sulawesi block is interpreted to come from further south in the West Australian margin. This is supported by the Archaean ages of zircons from East Java (Smyth et al., 2007) and NW Sulawesi (van Leeuwen et al., 2007). The East Java–West Sulawesi block collided at about 90 Ma. The age of collision is interpreted from ages of radiolaria in rocks associated with basic igneous rocks that represent accreted oceanic crust and sedimentary cover (e.g. Wakita et al., 1994a,b, 1998), the age of high pressure–low temperature (HP–LT) metamorphic rocks in accretionary complexes (Parkinson et al., 1998), ages of subduction-related magmatism, ages of post-collisional rocks (Sikumbang, 1986, 1990; Yuwono et al., 1988a,b), and the widespread paucity of magmatism in Sumatra, Java and Borneo after about 80 Ma until the Eocene (Hall, 2009). East Java–West Sulawesi may be more complex than a single fragment. There could be another continental block beneath southernmost Sulawesi, Sumba and Flores (e.g. Hilton et al., 1992) since high pressure–low temperature metamorphic rocks are known from South Sulawesi suggesting a suture between East Java–West Sulawesi and a continental fragment to the southeast (e.g. Hasan, 1990, 1991; Parkinson et al., 1998; Sikumbang, 1986, 1990; Wakita et al., 1996). Another suture would explain the isotopic signature of Australian continental crust seen in most West Sulawesi volcanic rocks, but absent in South Sulawesi (Elburg et al., 2003). Manur and Barraclough (1994) interpreted the area from SE Kalimantan to Sulawesi to include several continental fragments separated by sutures or highly extended crust. Evidence from modern Atlantic continental margins shows that rifting and extension may lead to multiple blocks which

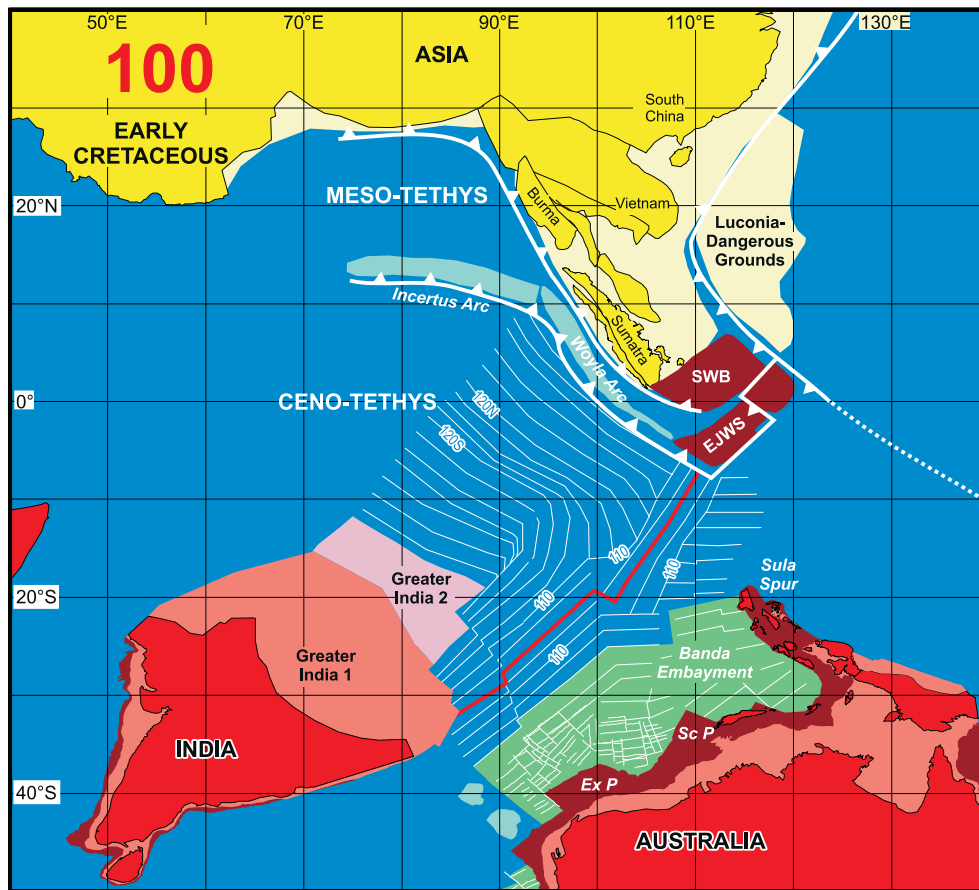


Fig. 17. Reconstruction at 100 Ma. The Ceno-Tethys was gradually reduced in area by subduction north of India but widened between India and Australia.

are still effectively part of a single hyper-extended terrane (Peron-Pinvidic and Manatschal, 2010). Therefore, in this reconstruction a single East Java–West Sulawesi block is a simplified entity that includes all continental crust from the Meratus Suture to Sumba and Flores.

The age of separation of the blocks is interpreted from their reconstructed positions in the West Australia margin. Late Jurassic oceanic crust (older than 155 Ma; Gradstein, 1992) preserved in the Argo abyssal plain is southwest of the Banda embayment which implies slightly older rifting of the Banda embayment. Anomalies off West Australia indicate the oldest oceanic crust there is about 132 Ma (Robb et al., 2005) which record the separation of India from Australia. I have assumed a simple model of separation of the SW Borneo block from the Banda embayment at 160 Ma, separation of the East Java–West Sulawesi block from the Exmouth Plateau at 155 Ma, and beginning of separation of Greater India from Australia at 140 Ma.

SW Borneo was part of Sundaland by the Early Cretaceous (Hamilton, 1979) but the exact age of arrival is uncertain. SW Borneo must have accreted to Sundaland before the arrival of the East Java–West Sulawesi block since it is inboard of it and is interpreted to have left the Australian margin first. Its area and shape fit well into the Banda embayment south of the Sula Spur and north of Timor. An alternative reconstruction with the SW Borneo block originally situated further southwest of the East Java–West Sulawesi block as suggested by Granath et al. (2011) proved impossible to model without a very complex movement history. In contrast, the positions chosen satisfy the evidence for the origins of the blocks discussed earlier, and their rifting and accretion can be modelled in a simple way. The SW Borneo fragment is interpreted to have arrived at the Sunda margin at about 110 Ma and continued moving north along a strike-slip

suture until about 90 Ma. The East Java–West Sulawesi block is proposed to have docked at 90 Ma, leading to widespread uplift of Sundaland (Clements et al., 2011) and cessation of magmatism by 80 Ma (Hall, 2009). The Late Jurassic–Early Cretaceous Woyla Arc (Barber, 2000; Barber et al., 2005; Wajzer et al., 1991) collided with the Sumatra margin between 98 and 92 Ma (M.J. Crow, pers. comm., 2008) at the same time as docking of the East Java–West Sulawesi block.

5.4. Indian margin

The pre-collision extent of India has implications for the age of India–Asia collision which continues to be controversial (e.g. Aitchison et al., 2007a; Chen et al., 2010; Dupont-Nivet et al., 2010; Green et al., 2008; Henderson et al., 2011; Khan et al., 2009; Leech et al., 2005; Najman et al., 2010; Rowley, 1996). It is not the intention of this paper to enter into that controversy. However, there are a number of issues concerning India that are relevant to reconstruction of SE Asia. The extent of Greater India (Veevers et al., 1975) is important when reconstructing the blocks that rifted from the Australian margin, the Woyla intra-oceanic arc must have been between northern India and Sumatra during the Early Cretaceous (Barber et al., 2005), there is the difference in subduction history to east and west of 110°E (Hall et al., 2008) outlined above, and there is now a linear anomaly in the lower mantle beneath India interpreted by van der Voo et al. (1999) as a Tethyan subduction zone, which could represent an India–arc collision (Ali and Aitchison, 2008; Hall et al., 2009a).

Powell et al. (1988) discussed in some detail various positions for the margins of Greater India. Ali and Aitchison (2005) reviewed most suggestions that have been made subsequently. They concluded that

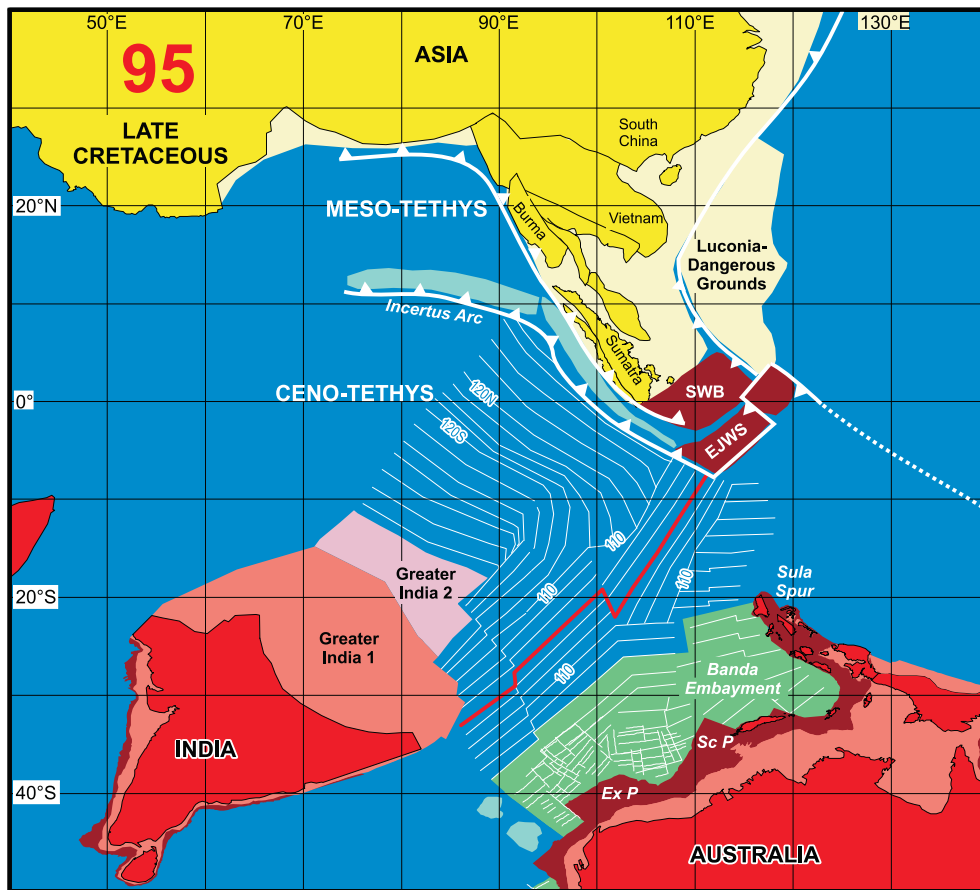


Fig. 18. Reconstruction at 95 Ma. The Ceno-Tethys continued to be subducted north of India but widened between India and Australia.

the northern limit of Greater India was the Wallaby–Zenith Fracture Zone and suggested there was continental crust beneath the Wallaby and Zenith seamounts, in contrast to others (Colwell et al., 1994; Robb et al., 2005) who suggested that the seamounts are basaltic. This is the preferred limit of Greater India for many authors. In contrast, others have traced Greater India as far north as the Cape Range Fracture Zone at the southern edge of the Exmouth Plateau (e.g. Greater India 5 of Powell et al., 1988) or to the Platypus Spur at the northern edge of the Exmouth Plateau (e.g. Lee and Lawver, 1995). Both limits to Greater India are shown on the reconstructions. Greater India 1 is almost the same Greater India as that used by Hall (2002) and its northern limit is the Wallaby–Zenith Fracture Zone advocated by Ali and Aitchison (2005). The northern limit of Greater India 2 is aligned with the Platypus Spur as suggested by Lee and Lawver (1995). The limit of Greater India 5 of Powell et al. (1988) is approximately midway between these two suggestions.

The Woyla intra-oceanic arc (Barber et al., 2005) was initiated at about 160 Ma and collided with the Sumatra margin at about 90 Ma. Its position during this interval is not known but I suggest that it was formed by the westward propagation of rifting that separated the SW Borneo and East Java–West Sulawesi blocks from the NW Australian margin. This is a very simple model that explains the Woyla Arc history and could be tested by palaeomagnetic work. A possible consequence of this interpretation is that if the arc continued west into the Indian Ocean it would have been in the position consistent with an India–arc collision at about 55 Ma which would account for the linear lower mantle tomographic anomaly as discussed further below.

Determining how the different fragments reached their present position is a challenge and the model presented below shows my interpretation of how this occurred.

5.5. Asian margin from Burma to the north and west

This paper makes no claims about or any attempt to seriously reconstruct the margin from Burma northwards. The Asian margin north of the India collision is drawn schematically at the position of the Main Boundary Thrust (Aitchison et al., 2007a; Green et al., 2008). The positions of the southern boundary of Asia and the northern boundary of Greater India, continue to be vexed questions and the only plate reconstructions are those of Replumaz and Tapponnier (2003), and van Hinsbergen et al. (2011a) which show many continental blocks between India and Asia. The Replumaz and Tapponnier (2003) reconstruction treats most of SE Asia including Borneo as a single rigid fragment (see also Replumaz et al., 2004) and has several problems summarised in Hall et al. (2008), for example some of the large blocks interpreted to be extruded as a result of the collision overlap before the Oligocene. van Hinsbergen et al. (2011a) avoid the overlaps and their reconstruction focuses on Greater India, which is the largest so far suggested, and its effects on Asia. They reconstruct only the western part of the region that is the concern of this paper. The most obvious difference between their model and that presented in this paper for southern Sundaland is an abrupt rotation of Sumatra and a large southward rollback of the Sunda Trench between 30 and 20 Ma. This appears to be a consequence of rotations of linked rigid blocks south of the Red River Fault in the van Hinsbergen et al. (2011a) model. There is no evidence to support an advance of the Sunda Trench at this time and it is not obvious how such rollback would be accommodated further east, north of Java. A plausible way to reconcile the reconstructions is to accommodate the consequences of India–Asia convergence by internal deformation within Indochina, and potentially further south.

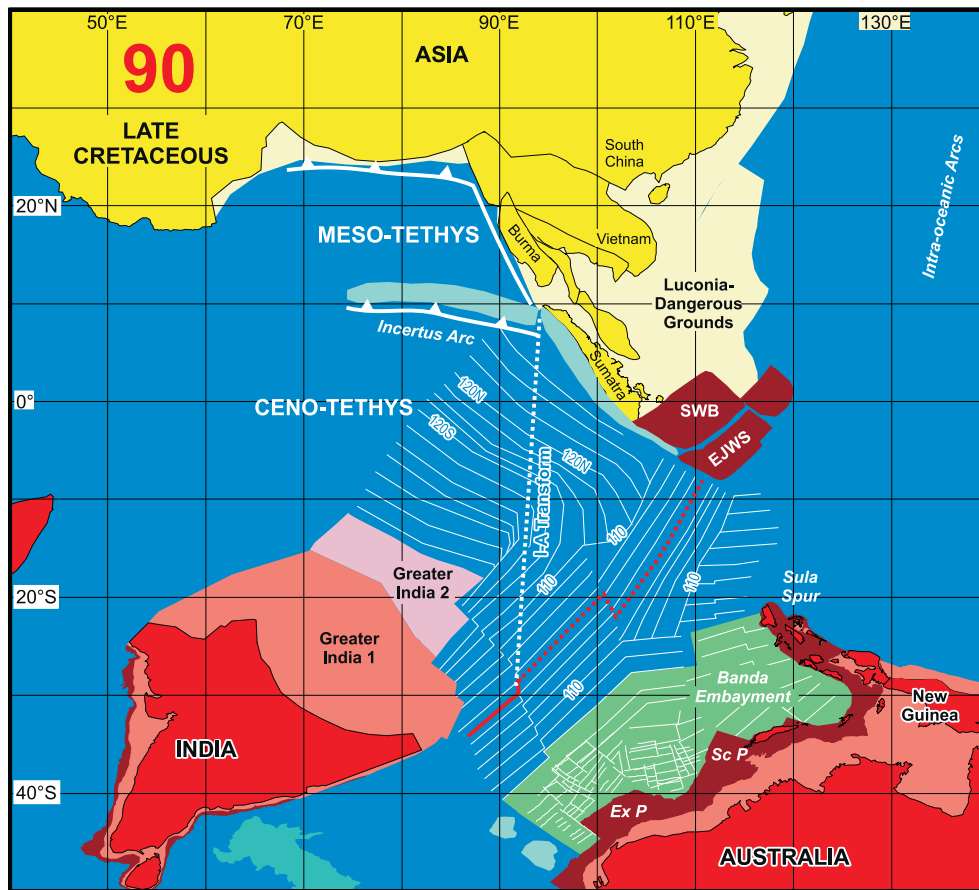


Fig. 19. Reconstruction at 90 Ma. There were major changes in the Ceno-Tethys and at its margins. The India–Australia spreading centre died and as India continued to move north a new transform was initiated to form the new India–Australia plate boundary. The Woyla Arc and East Java–West Sulawesi (EJWS) blocks both docked at the Sundaland margin between Sumatra and Borneo, and the boundary between EJWS and SWB was the Meratus Suture. Part of the Inner Banda block was pushed north and now underlies Sabah and part of northern Borneo. The Luconia–Dangerous Grounds continental fragment docked with the Asian margin and became part of Sundaland.

Here I simply note that if there was a collision at the generally preferred age of about 50 Ma, or even earlier (e.g. Aitchison et al., 2007a; Chen et al., 2010; Dupont-Nivet et al., 2010; Green et al., 2008; Henderson et al., 2011; Khan et al., 2009; Leech et al., 2005; Najman et al., 2010; Rowley, 1996), either India was even larger than Greater India 2 (the solution chosen by van Hinsbergen et al., 2011a,b) or the southern margin of Asia must have been significantly south of the present position of the Main Boundary Thrust. For this reason, in earlier reconstructions (Hall, 1996, 2002) which used Greater India 1, I had schematically drawn the Asian margin several hundred kilometres south of the position shown on the reconstructions in this paper.

6. Reconstructions

The reconstructions were made using the ATLAS computer program (Cambridge Paleomap Services, 1993) and the plate motion model for the major plates of Hall (2002). The model uses the Indian–Atlantic hotspot frame of Müller et al. (1993) from 0 to 120 Ma and a palaeomagnetic reference frame before 120 Ma using poles provided by A.G. Smith (pers. comm., 2001). The model now incorporates about 170 fragments, compared to approximately 60 of Hall (1996) and 120 of Hall (2002). Here, the model of Hall (2002) is extended back to 160 Ma and a spreading history in the now-subducted Tethys and Indian Oceans has been constructed, based on the inferred age of rifting of blocks from NW and western Australia, their interpreted positions in SE Asia, and evidence from SE Asia about timing of magmatism and collision. Movements of Australia and India are from Royer and Sandwell (1989). Some changes have been made to the

Cenozoic reconstructions, notably for the Indian Ocean from 55 to 45 Ma, and for the Banda region (Spakman and Hall, 2010). I have followed Metcalfe (1996) in naming the different Tethyan ocean strands (Figs. 5 to 36).

Animations of the reconstructions that accompany the following section can be downloaded from http://searg.rhul.ac.uk/FTP/tecto_2012/ or from <http://dx.doi.org/10.1016/j.tecto.2012.04.021>. There are 4 animations in formats including Powerpoint ppt files and QuickTime mov files. They include *waus_breakup_2012* which runs from 160 Ma to the present at 1 Ma intervals, *waus_breakup_2012_5Ma* which runs from 160 Ma to the present at 5 Ma intervals, *xmas_island_volcanism* which runs from 160 Ma to the present at 1 Ma intervals and plots ages of volcanic rocks from the Christmas Island volcanic province (Hoernle et al., 2011) discussed below, and *banda_2012* is an animation of the eastern Indonesian region and runs from 30 Ma to the present.

6.1. 160 Ma to 140 Ma

Rifting in the Banda and Argo regions began at about 160 Ma (Fullerton et al., 1989) and is interpreted to have begun earlier in the east, and propagated west (Fig. 5). The SW Borneo and Sabah blocks rifted to form the Banda embayment leaving the Sula Spur (Klompé, 1954; Stille, 1945) to its north. The East Java–West Sulawesi block rifted away leaving the Argo abyssal plain which is now north of the Exmouth Plateau and west of the Scott Plateau. The reconstruction implies that rifting followed the initiation of south-directed subduction at the north Gondwana margin. After separation of the East Java–West Sulawesi block the Ceno-Tethys spreading centre

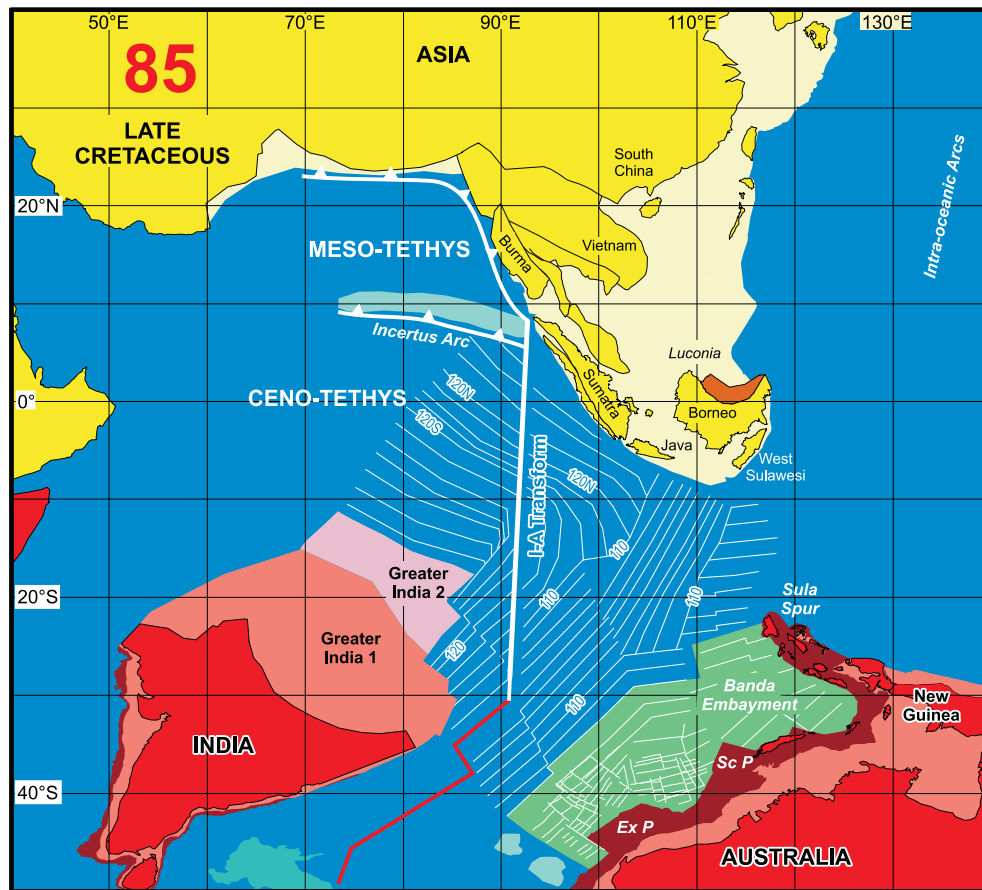


Fig. 20. Reconstruction at 85 Ma. Subduction had ceased all round Sundaland. India and Australia continued to separate by spreading on a ridge south of India with strike-slip motion along the I-A Transform.

propagated west to form the Woyla Arc either along the Greater India 2 continent–ocean boundary or as an intra-oceanic arc at the southern edge of the Meso-Tethys (Fig. 6). At present there are no data that can locate the Woyla Arc more precisely but this model leads to a simpler reconstruction than an intra-oceanic position further north which would require additional subduction zones and/or transforms. The Woyla Arc is speculated to have continued west into another intra-oceanic arc, here named the Incertus Arc. Possible candidates for this arc are the Spontang Arc (Pedersen et al., 2001), the Zedong Terrane of southern Tibet (Aitchison et al., 2007b) which is an intra-oceanic arc formed in the Late Jurassic, or the Kohistan–Ladakh Arc which may have been in an equatorial position in the Late Cretaceous and could have collided with India in the Early Paleocene (Khan et al., 2009; Petterson, 2010). The significance of this arc is discussed further below.

The reconstructions use the simplest possible interpretation of ocean crust formation, generally with symmetrical spreading. The orientation and age of the magnetic anomalies in the Ceno-Tethys was inferred from preserved oceanic crust close to western Australia, and the requirement that the Banda and Argo fragments arrive at the Sundaland margin at 110 Ma and 90 Ma. This is essentially an Occam's Razor approach. No old oceanic crust is preserved in the Banda embayment so the initial movement of the SW Borneo fragment is determined by the orientation and size of the Sula Spur, and implies a re-orientation of the spreading direction at about 150 Ma (Fig. 7). The movement of the East Java–West Sulawesi fragment (Fig. 8) is determined by the preserved magnetic anomalies of the Argo abyssal plain and the assumption of symmetrical spreading.

It is possible that the actual history of spreading was more complicated. Anomalies preserved in the Argo region (Fullerton et al., 1989)

show that in the Early Cretaceous there was at least one change in ridge orientation, and south of the Exmouth Plateau there were repeated ridge jumps in the Early Cretaceous (Robb et al., 2005). If the identification of Late Jurassic anomalies in the Wharton Basin (Barckhausen et al., 2008) proves correct a more complex model will be required, but with relatively small modifications, such as other India–Australia ridge jumps, asymmetrical spreading at the mid-ocean ridge, or small shifts in the position of the transform boundary that developed after 90 Ma (see below).

The Luconia–Dangerous Grounds block was derived from east Asia, indicated by dredged material offshore and the geology of Sarawak discussed above, but when and where it separated from Asia is not known and its position on the reconstructions from 160 Ma is schematic. If it is accepted that the granite belt of South China and Vietnam represents a Jurassic–Early Cretaceous subduction margin (e.g. Charvet et al., 1994; Taylor and Hayes, 1983) either this block was rifted away from the Asian margin somewhere to the north of South China, or it could be a block separated by a backarc basin from the Asian margin during subduction at the palaeo-Pacific margin further east. An alternative is that the granite belt does not have a subduction origin but may be the product of regional extension at the east Asian margin as advocated for North China (e.g. Li and Li, 2007; Lin and Wang, 2006; Lin et al., 2008; Yang et al., 2007).

6.2. 140 Ma to 110 Ma

India began to separate from Australia at about 140 Ma (Fig. 9). The new spreading centre between Australia and India implies a ridge–ridge–ridge triple junction with the three spreading centres active until 110 Ma. The narrow zone of old oceanic crust that today

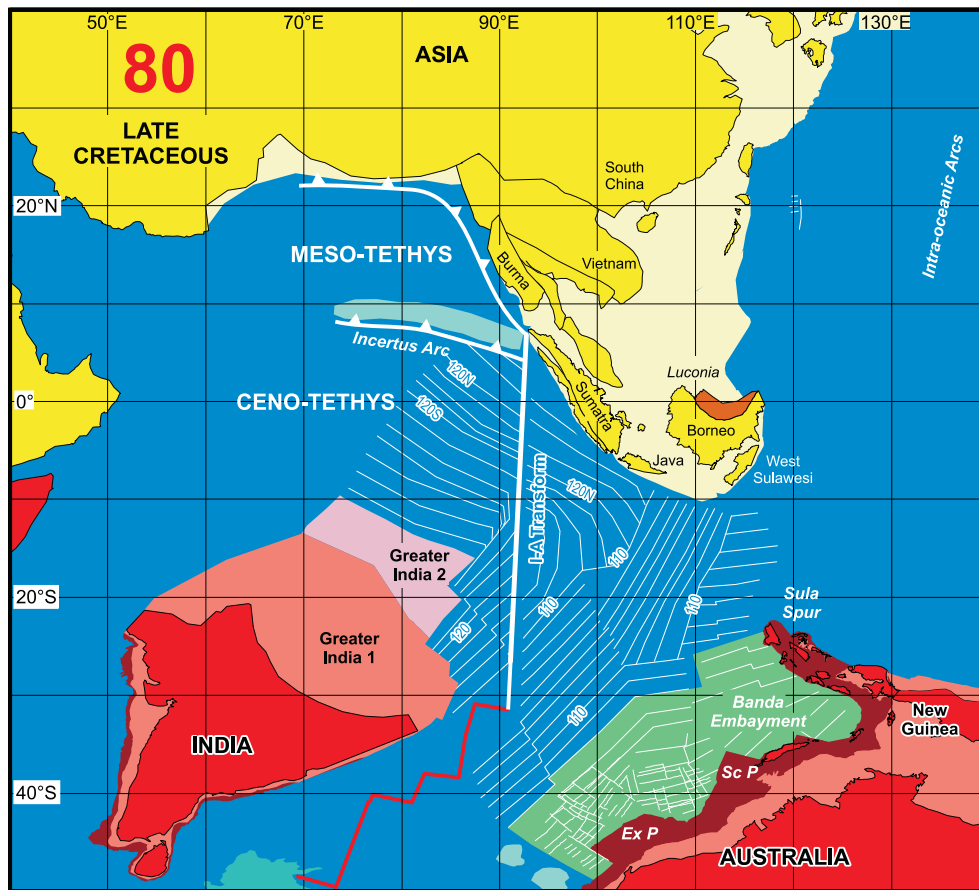


Fig. 21. Reconstruction at 80 Ma. India's rate of northward motion increased. Localised magmatic activity is known from the Bird's Head and central New Guinea during the Late Cretaceous. It seems unlikely that this was subduction-related but it may reflect strike-slip movements or extension within the northern Australian margin.

remains off west Australia records a complex spreading history with a series of ridge jumps back to the continent–ocean boundary between 132 Ma and 120 Ma (Robb et al., 2005) before an inferred final spreading centre was established close to the former Indian continent–ocean boundary. After the formation of the triple junction (Fig. 10) the western Ceno-Tethys had a simple symmetrical spreading history, but the model implies a short-lived interval (c. 10 Ma) of subduction in the eastern Ceno-Tethys between 130 (Fig. 11) and 124 Ma (Fig. 12) followed by a resumption of spreading until 110 Ma (Figs. 13 and 14). On the reconstructions oceanic crust older than 120 Ma between the Perth abyssal plain and the Banda embayment is coloured pale green from 120 to 0 Ma so that the subduction history of the Banda embayment can be seen more clearly.

6.3. 110 Ma collision

SW Borneo, East Java–West Sulawesi and the Woyla Arc moved northwards as the subduction hinge rolled back and the Ceno-Tethys ocean widened to the south of them. In the early Cretaceous the SW Borneo block was close to the Sundaland margin (Fig. 14) and is suggested to have moved along it on a NE–SW transform fault at the Billion Depression suture of Ben-Avraham (1973). The age of final suturing of this block is uncertain. It must have arrived earlier than the East Java–West Sulawesi block which was in place by about 90 Ma. There is discontinuity in radiolaria ages in cherts from the Lubok Antu melange from Sarawak during the Aptian–Albian (Jasin, 2000) which suggests an interval between 125 and 100 Ma. In the model presented here the block docked to form part of Sundaland at 110 Ma (Fig. 15). The 110 Ma age chosen is arbitrary

but there would be no significant difference to the model if an older age such as 120 Ma were used.

Mitchell (1992, 1993) interpreted the Mawgyi Nappe in Burma as a northeast-facing intra-oceanic arc emplaced onto the western margin of SE Asia in the Early Cretaceous. He correlated this event with collisions of the Woyla Arc in Sumatra and the Meratus of SE Borneo, but these are now known to be early Late Cretaceous events. This could indicate a diachronous collision starting earlier in Burma and progressing southeastwards but I suggest instead that the Burma events may be correlated with the collision of the SW Borneo block at 110 Ma. It seems unlikely to me that the Mawgyi Nappe is a continuation of the Woyla Arc. However, this reconstruction is primarily concerned with the rifting of fragments from western Australia, the Sundaland region and Indonesia and there is insufficient information for the region from Burma to India to reconstruct it adequately, so this part of the model should be regarded as schematic.

6.4. 110 Ma to 90 Ma

After collision of the SW Borneo block there was subduction polarity flip and a new subduction zone was initiated on its south side (Fig. 15) which closed the ocean that remained between the Woyla Arc–East Java–West Sulawesi and Sundaland from Sumatra to SW Borneo (Figs. 16 to 19). An Early Cretaceous active margin ran from Sumatra into West Java and continued northeast through SE Borneo into West Sulawesi and is marked by ophiolites and HP–LT subduction-related metamorphic rocks in Central Java, the Meratus Mountains of SE Borneo and West Sulawesi (e.g. Hamilton, 1979; Parkinson et al., 1998; Sikumbang, 1986, 1990). K–Ar ages of HP–LT metamorphic rocks compiled by Parkinson et al. (1998) from

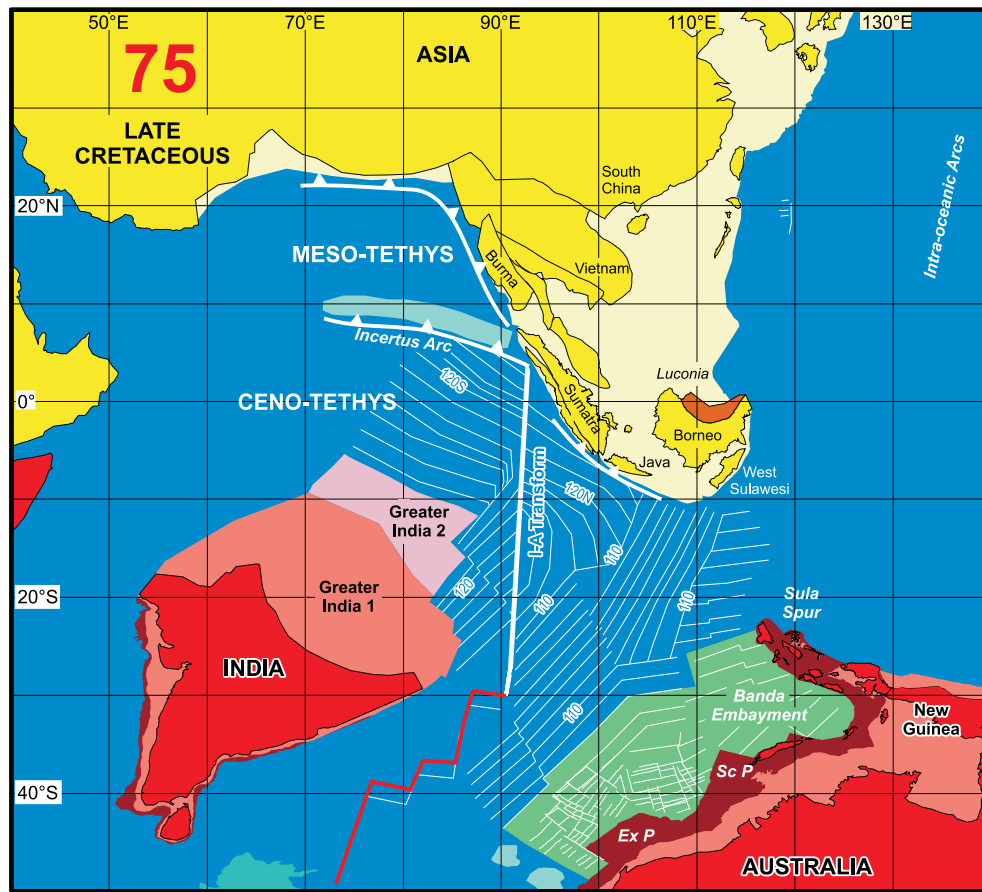


Fig. 22. Reconstruction at 75 Ma. India's rapid northward movement continued. During this interval there was no major northward movement of Australia relative to Sundaland but there could have been small amounts of localised subduction at the Sundaland margin between Sumatra and Java due to slow spreading south of Australia.

the Luk Ulo complex, Java range from 124 to 110 Ma, and those from the Meratus from 119 to 108 Ma, suggest subduction was underway on the south side of the SW Borneo block during this interval.

After 110 Ma the model interprets north-dipping subduction on the south side of the Woyla-Incertus Arc (Fig. 15) and it is possible that backarc basins formed above this subduction zone on the north side of the arc. Ophiolitic plagiogranite with a 95 Ma age from the Andaman Islands is suggested to have formed above a subduction zone (Pedersen et al., 2010) and would be a candidate for such a backarc basin.

The intra-oceanic Woyla Arc collided with the Sumatran margin in the early Late Cretaceous (Fig. 19) adding arc and ophiolitic rocks to the southern margin of Sumatra (Barber et al., 2005) at the same time as the East Java–West Sulawesi fragment accreted to Sundaland (Smyth et al., 2007) and West Sulawesi (van Leeuwen et al., 2007). The age of this collision is inferred to be approximately 90 Ma, although the collision could have been diachronous, and an age between about 92 and 80 Ma is possible, as indicated by ages of cherts in melanges (e.g. Wakita et al., 1994a,b, 1998) and the beginning of a widespread hiatus in magmatism (e.g. Barber et al., 2005; Hall, 2009; McCourt et al., 1996; Williams et al., 1988). In SE Borneo the inferred suture is a transpressional strike-slip boundary which may have been reactivated in the late Cenozoic. The present Meratus Mountains currently form a relatively narrow linear elevated region separating the Barito and Asem-Asem basins which formed a broad subsiding region from the Eocene until the Late Miocene (Witts et al., 2011). Cross-sections (e.g. Satyana and Silitonga, 1994) across the mountains suggest a strike-slip-related flower structure.

It is worth considering what the southern Sundaland margin was like during the Early Cretaceous until the termination of subduction.

This model represents it in a very simple way with two large blocks and two main sutures, with a possible third suture not shown which could have crossed south Sulawesi. It was probably much more complex. Subduction rollback is commonly associated with extension and fragmentation of the upper plate. If the present complexity between Sulawesi and New Guinea is any guide, after complete elimination of the present Banda Basins and juxtaposition of Sundaland and Australia, eastern Indonesia will be characterised by several oceanic/arc zones separating numerous continental fragments that record multiple phases of collision and extension. The southern Sundaland margin was probably similar in the Early Cretaceous.

6.5. 90 Ma change

The collision at the south Sundaland margin (Fig. 19) coincided with the cessation of acid magmatism in Vietnam (Nguyen et al., 2004) and an interpreted change to extensional tectonics in the South China margin (e.g. Zhou et al., 2008). In this model the Luconia–Dangerous Grounds block is suggested to have become part of the Sundaland margin at about 90 Ma. Because most of the critical region is offshore, it is very difficult at present to do more than speculate about the latest Cretaceous and Early Cenozoic history of eastern Sundaland. In Sarawak there is an abrupt change from poorly dated terrestrial sediments south of the Lupar Line to deep water sediments of the Rajang Group to the north. As discussed above, the Lupar Line is often considered to be an important suture but Haile (1973) argued that it lacked some features expected in a former subduction zone. Strike-slip movement on the Lupar Line with a west-moving block to the north could account for observations in northern Borneo (e.g. Douth, 1992; Gower, 1990; Haile, 1974; Williams et al.,

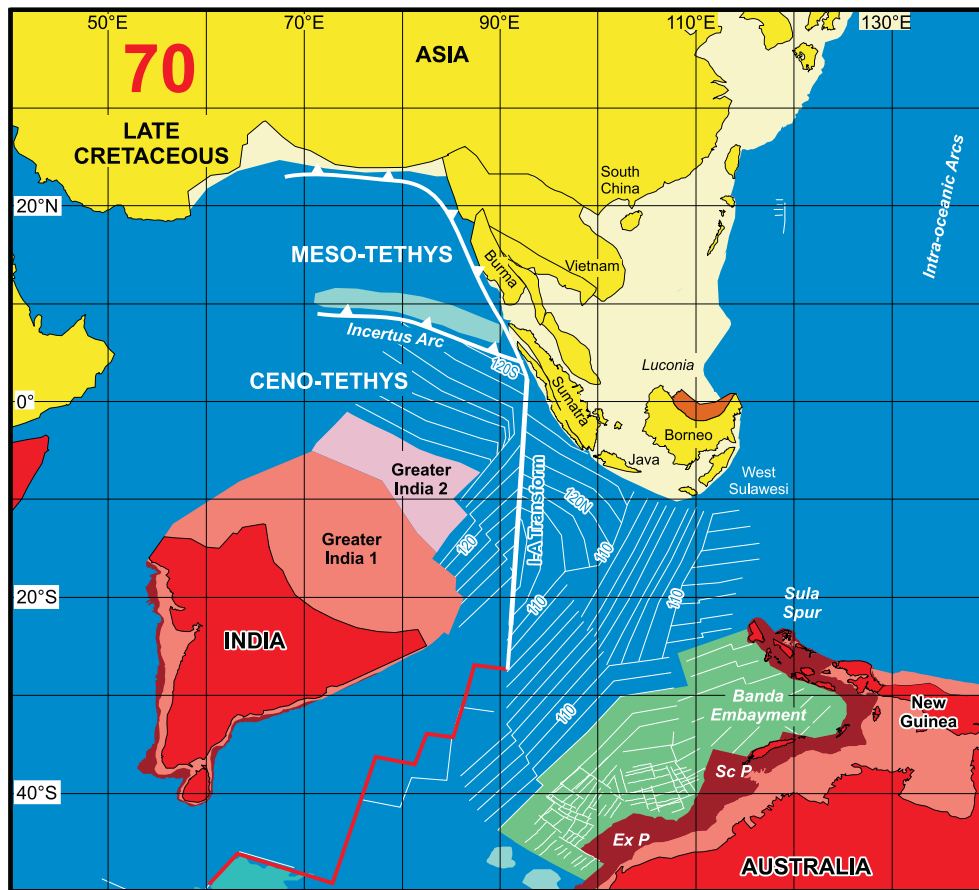


Fig. 23. Reconstruction at 70 Ma. The northward trace of the subducted I-A transform was beneath northern Sumatra and the Thai peninsula. Localised magmatism is reported from northern Sumatra and the Ranong and Khlong Marui faults in southern Thailand were active during the Late Cretaceous and Paleocene, parallel to this orientation, suggesting deformation in the upper plate above the subducted transform.

1988), limited subduction to the west, and suggestions of Paleocene suturing of the Luconia block (Fyhn et al., 2010b).

The most important change at 90 Ma was the termination of subduction beneath Sundaland which did not resume until 45 Ma (Hall, 2009). It is from this time that Sundaland became an almost completely elevated and emergent continental region surrounded by inactive margins. Clements et al. (2011) suggest this was a dynamic topographic response to termination of subduction beneath Sundaland.

Further west, north of India, subduction continued and in fact India's northward motion accelerated in the Late Cretaceous. I speculated above that the Woyla Arc continued west into the Incertus Arc. If there was a subduction polarity flip from SW- to NE-dipping at this arc and a change to subduction at its south side at this time the Incertus Arc would have been in the position to collide with the northern margin of India, whether Greater India 1 or 2 is preferred, at about 55 Ma (see below).

6.6. 90 to 45 Ma

The change from subduction north of India west of about 110°E to no subduction north of Australia to the east was accommodated by a transform boundary between India and Australia (Fig. 19). This is a requirement that follows from the India-Australia plate motions determined by Royer and Sandwell (1989) not a feature created in this model. The position of the fault is inferred by the extent of the Woyla Arc in Sumatra and by the change in deep mantle structure at about 110°E.

Between 90 and 75 Ma (Figs. 20 to 22) the boundary was a leaky transform with very slight extension of the order of a few tens of kilometres. From 75 to 55 Ma (Figs. 23 to 26) the boundary was convergent, with the amount of convergence increasing northwards from about 10°S. This implies either subduction of the Indian Plate beneath the Australian Plate or vice-versa. The amount is small and would have been approximately 500 km at the northern end of the transform boundary. Since this region of the Indian and Australian Plates was entirely subducted beneath north Sumatra before 10 Ma it is impossible to know what was the polarity of this subduction zone. However, it is possible that its final remnants could be the enigmatic N–S striking slab dipping steeply east that lies beneath Burma (Guzman-Speziale and Ni, 2000; Ni et al., 1989; Satyabala, 1998, 2000) implying India subducted beneath Asia.

Watkinson et al. (2008, 2011a) have shown that there was ductile dextral deformation on the Khlong Marui and Ranong Faults in southern Thailand before 81 Ma, and later between 59 and 49 Ma. There was a major phase of dextral shear between 45 and 37 Ma, followed then by sinistral brittle deformation after 37 Ma. The early deformation in the shear zones is much older than India-Asia collision and they were situated in the upper plate above the subducting active transform fault from 90 to 45 Ma (Watkinson et al., 2008). It is suggested that the shear zones formed at the position where there was a change from subduction north of India to no subduction north of Australia.

The reconstructions could also account for the very early ages suggested for India-Asia collision (55 Ma or older) by collision between the Incertus intra-oceanic arc and the northern margin of Greater India (Fig. 26). Arc-continent collision terminated subduction

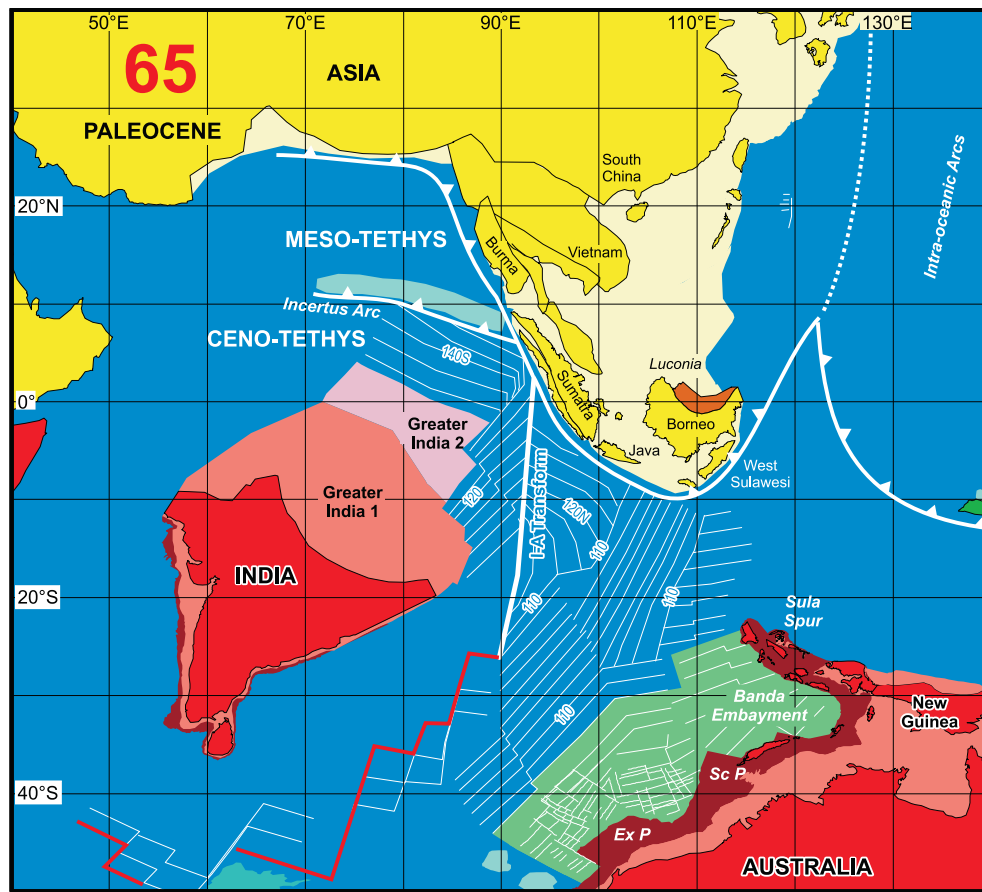


Fig. 24. Reconstruction at 65 Ma. There was a brief episode of NW-directed subduction marked by volcanic activity in Sumba and West Sulawesi. There were many intra-oceanic arcs in the Pacific in the Late Cretaceous but their positions are uncertain. Arcs that later collided with New Guinea are speculated to have been situated above a north-dipping subduction zone.

at this position, the arc was carried north with India and may be in Asia as the Spontang Arc (Pedersen et al., 2001), the Zedong Terrane (Aitchison et al., 2007b) or Kohistan-Ladakh Arc (Khan et al., 2009; Petterson, 2010). Each of these suggestions has problems. The Spontang Arc was too far south at 80 Ma when it is suggested to have collided with the Indian margin, little is known of the position of the Zedong Terrane, and the Kohistan–Ladakh Arc has a deformation history older than 75 Ma (Petterson and Windley, 1992) usually considered to be due to collision of the arc with the Asian margin. Petterson (2010) has reviewed many of the suggested scenarios for intra-oceanic arcs north of India which cannot be resolved here. Whichever arc collided with India it is suggested that the subducted slab broke off, was over-ridden by India, and the slab has now sunk deep in the lower mantle where it is visible as the prominent linear anomaly trending NW–SE (Aitchison et al., 2007a; Hall et al., 2008; van der Voo et al., 1999) particularly clear at depths around 1100 km.

Because all the crust south of Sundaland was oceanic and has been subducted it has been difficult to judge the character of the Late Cretaceous–Paleocene Sundaland margins because there are no anomalies and there is little geological evidence on land. Many authors (e.g. Audley-Charles et al., 1988; Barber et al., 2005; Metcalfe, 1988, 1990, 1996) have depicted subduction schematically, or assumed it for reconstructions older than 45 Ma (e.g. Hall, 1996, 2002; Lee and Lawver, 1995).

Pedersen et al. (2010) dated trondhjemitic zircons from the South Andaman ophiolite at 95 Ma which they interpret to mark initiation of new subduction from Cyprus to the Andamans, and also further east to Sumatra and Java. They assume the ophiolitic basement rocks in the Sumatran forearc are Paleocene to Eocene based on the

fact that they are unconformably overlain by “Late Oligocene–Miocene turbidites and carbonates”. However, on Nias the ophiolitic basement rocks include Upper Cretaceous and Eocene pelagic limestones (Samuel et al., 1997) and it is more likely that the ophiolitic rocks of the Sumatran forearc are correlatives of the Woyla intra-oceanic arc and do not mark the initiation of subduction, but were emplaced during collision of the Woyla Arc at about 90 Ma. The tectonic setting during the remarkable interval of ophiolite formation in the Tethys from Cyprus to the Andamans in the Cretaceous is still controversial (e.g. Agard et al., 2007; Dilek and Furnes, 2009; Dilek and Robinson, 2003; Nicolas and Boudier, 2011; Smith, 2006) and perhaps does mark initiation of a new subduction zone west of Sumatra although Mitchell (1993) previously identified the Early Cretaceous as a period of ophiolite emplacement during collision from Burma to Sumatra. However, as discussed above and elsewhere (Hall, 2009; Hall et al., 2009a) after about 90 Ma there is no record of subduction in Sumatra and Java and it is therefore unlikely that subduction was initiated there at 95 Ma, rather that this age records an event in the Andamans and further west.

As discussed above, Heine et al. (2004), Heine and Müller (2005) and Whittaker et al. (2007) have made reconstructions using hypothetical Indian Ocean anomalies but their predictions of the nature of plate boundaries are inconsistent with the geology of Sumatra and Java. One would generally expect significant igneous activity to accompany subduction, and during periods of slab window subduction there should be a record of abundant and possibly compositionally unusual magmatism. It would be unusual for igneous activity to cease for 35 million years along a subduction boundary more than 2000 km in length. However, the period 80 to 45 Ma (Figs. 21 to 28)

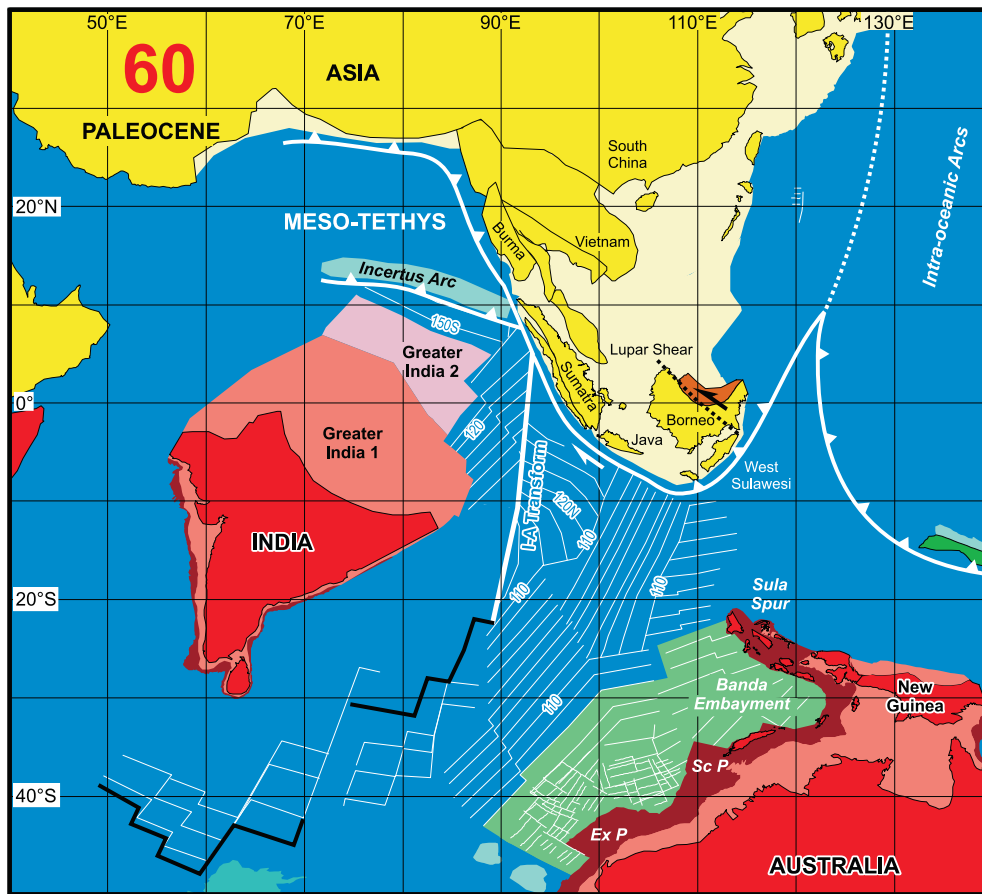


Fig. 25. Reconstruction at 60 Ma. The NW-directed subduction beneath Sumba and West Sulawesi was possibly linked to strike-slip motion along the Lupar Line in Sarawak and in Kalimantan along faults parallel to basement structures, contributing to formation of basins such as the Ketungau and Melawi Basins in NW Kalimantan. The reconstruction suggests a strike-slip margin from Java to Sumatra accompanied by some extension of the Sundaland margin in south Sumatra.

is marked by an almost complete absence of a volcanic and plutonic record in Java and Sumatra (Hall, 2009). Furthermore, the Whittaker et al. (2007) model predicts quite different intervals of extension and compression in the Sundaland margins from those observed. For example, it is claimed that in Java the interval of 60 to 50 Ma “corresponds with a known period of extension” when in fact this is an interval with almost no geological record in Java. Whittaker et al. (2007) observe that their “reconstructions from 50 Ma show an advancing upper plate in Sumatra suggesting that a compressive regime should have existed, however extension is observed from geological evidence”.

The predictions of the model presented here for the Sundaland margins of Indonesia are very different. For the period 90 Ma to 45 Ma the rotation model is no different from that of Hall (2002), but with the addition of the hypothetical anomalies that were constructed from the inferred movement of the SW Borneo, East Java–West Sulawesi and Woyla fragments it is possible to see and examine the implications for the Sundaland margins. Around most of Sundaland, except north of Sumatra, there was no subduction during most of the 90 Ma to 45 Ma interval (Figs. 19 to 28). Australia was not moving north and there was an inactive margin south of Sumatra and Java until 70 Ma. Thus, no significant igneous activity is expected, as observed. There could have been some subduction in north Sumatra, west of the India–Australia transform boundary, where there is a record of minor Paleocene volcanic activity (Crow, 2005). From 70 Ma (Fig. 23) the model predicts slight extension until 65 Ma (Fig. 24) and then significant dextral strike-slip motion at the Sumatra and Java margin (Fig. 25). Further east it predicts NW-directed subduction beneath Sumba and West Sulawesi between 63 Ma and 50 Ma

(Figs. 26 to 27). In the latest Cretaceous and Paleocene there was calc-alkaline volcanism in Sumba and West Sulawesi which has been interpreted as subduction-related (e.g. van Leeuwen, 1981; Hasan, 1990; Abdullah et al., 2000; Elburg et al., 2002; see Hall, 2009, for review) which fits well with the model.

It is difficult to interpret how the latest Cretaceous and Paleocene NW-directed subduction zone continued north into the Pacific (Figs. 24 to 26). Extension is recorded in the East Asian margin in the Late Cretaceous but it is possible there was a west-dipping subduction system very far to the east. There are many small Upper Cretaceous volcanic arc fragments remaining in Halmahera (Hall et al., 1988), the Philippines (e.g. Karig, 1983; Lewis et al., 1982), the Philippine Sea (Klein and Kobayashi, 1981; Tokuyama, 1985) to Kamchatka (Levashova et al., 1998). At the moment it is impossible to reconstruct the Cretaceous–Paleocene West Pacific with any detail. It is clear that there were many intra-oceanic arcs within the Pacific basin but their polarities and positions are very uncertain.

6.7. 45 Ma to present

For the period after 45 Ma (Figs. 28 to 36), there are a few differences between the model presented here and that of Hall (2002). The reconstruction of the Proto-South China Sea has changed slightly to incorporate new information. The deeper rift structures in Sarawak and offshore Sarawak indicate that the Luconia shelf was part of Sundaland by the Eocene (Hutchison, 2005). As discussed above the Sarawak Orogeny of Hutchison (1996, 2004, 2005) is interpreted as the final phase of deformation in a remnant basin, not a collisional event. There was a major reorganisation of plate boundaries at

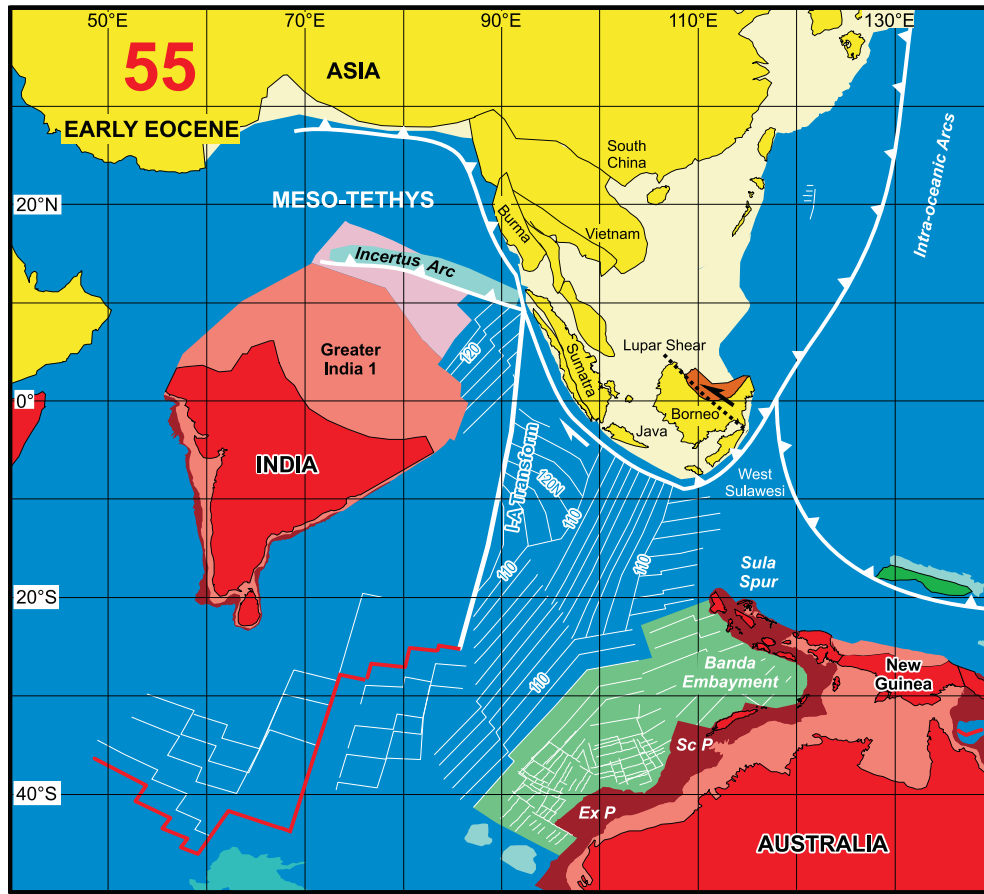


Fig. 26. Reconstruction at 55 Ma. India is interpreted to have collided with the Incertus Arc at about this time, which then became accreted to the north India margin. The orientation of the arc is very uncertain and the age of collision is equally compatible with Greater India 1 or 2.

45 Ma and this is suggested to have terminated strike-slip movement on the Lupar Line and initiated south-directed subduction of the Proto-South China Sea beneath northern Borneo (Hall et al., 2008). The Luconia shelf is interpreted to have been in its present position relative to Sarawak but there must have been some relative movement within the Luconia–Dangerous Grounds block, perhaps along the West Baram Line (cf. Clift et al., 2008) to allow subduction of the Proto-South China Sea between the Eocene and Early Miocene (Figs. 28 to 33). There are also small differences in the reconstruction of the Celebes Sea and its subduction history to allow for northward subduction beneath the Sulu Arc (Hall and Wilson, 2000; Hutchison et al., 2000). The north Makassar Straits are interpreted to be underlain by continental not oceanic crust (Hall et al., 2009b).

The Philippines remain as they were reconstructed in the 2002 model and is one of many areas of the model where better reconstructions are required but too little information is available, although new studies show a more complex model will be required (e.g. Dimalanta et al., 2006; Yumul et al., 2006, 2008, 2009). Queano et al. (2007) collected new palaeomagnetic data from Luzon and argued that the Hall (2002) model should be modified to place Luzon in the southern hemisphere with the rest of the Philippines. This solution had been rejected by Hall (1996) because of overlaps with Sulawesi and the Celebes Sea, which remain and are acknowledged by Queano et al. (2007), and because the palaeomagnetic data then available were considered to favour a northern hemisphere position although there were differences of interpretation by different palaeomagnetists. Queano et al. (2007) consider that their new data support a modification of the reconstruction but at present I find their proposal unconvincing. First, although they suggest new reconstructions

for the Paleogene they have only one mean palaeolatitude at 40 ± 8 Ma for which it is not possible to identify the hemisphere, as they recognise. Second, their interpreted latitude change for the Neogene is also consistent with a northern hemisphere position for Luzon. Third, their model does not account for the observed collision of a South China continental fragment with Luzon by 15 Ma (Fig. 34). However, this does not exclude the possibility that parts of eastern Luzon could have moved with the Philippine Sea Plate (e.g. Ishida et al., 2011) and been juxtaposed with western Luzon during the Neogene.

The present subduction beneath Java began at about 45 Ma (Fig. 28) and has been almost perpendicular to the Java Trench. The subducted slab dips steeply at more than 60° and may be locally overturned between 300 and 600 km depth beneath Java and south Sumatra (Schöffel and Das, 1999) and this probably reflects the Early Cretaceous age of the slab being subducted in this sector. Further west beneath Sumatra subduction becomes markedly oblique and relative motion of India–SE Asia is partitioned into trench-normal subduction and trench-parallel movement on the Sumatran and other strike-slip faults. Tomographic studies by Pesicek et al. (2008, 2010) show the dip on the slab is much lower beneath north and central Sumatra which they interpret as a fold in the subducted slab; an alternative is that the slab is torn. The reconstruction model of this paper (Figs. 28 to 36) offers a simple explanation for the fold or tear which is the difference in age of crust across the former I-A transform which has been subducted since 45 Ma. At 45 Ma (Fig. 28) the age difference across the transform was small. By 25 Ma the age difference was about 50 million years (Fig. 32) and this has remained the age difference since then. Thus to the west the lithosphere would be significantly colder, thicker and denser.

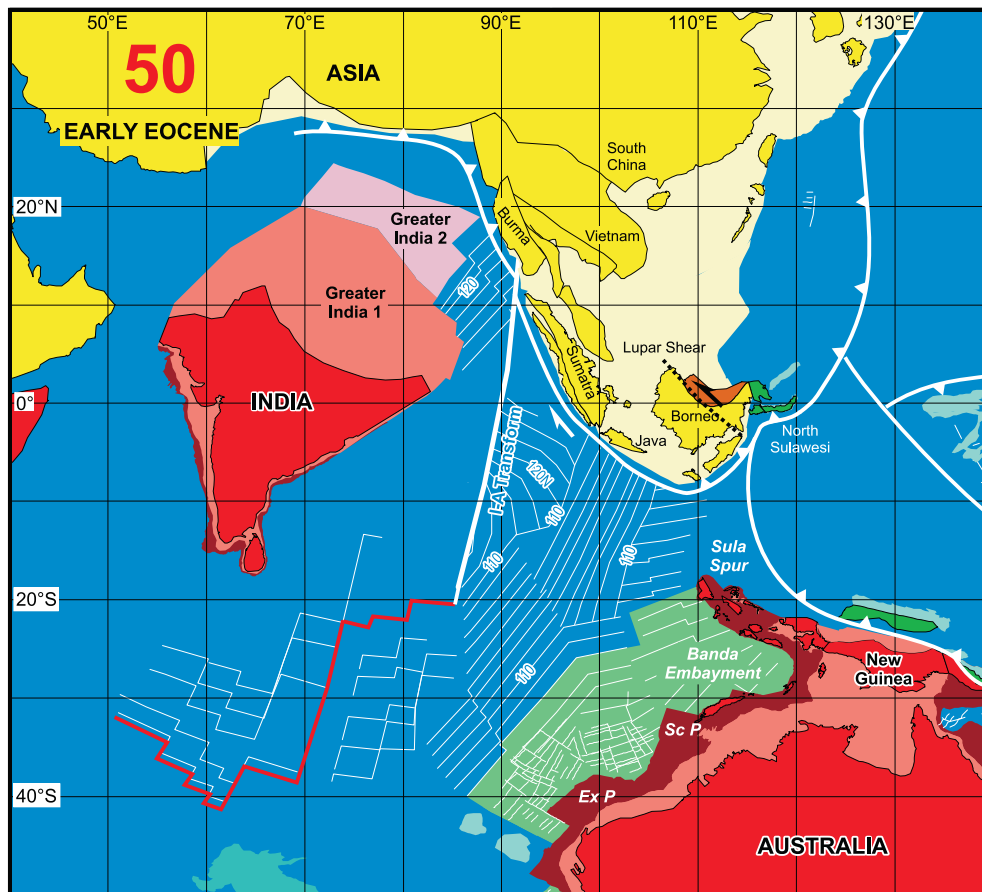


Fig. 27. Reconstruction at 50 Ma. The Philippine Sea Plate had begun to form by spreading within Cretaceous arcs and the Sepik terranes arrived at the New Guinea margin.

The location of Toba caldera and the very shallow forearc region above the intersection with the subducted Investigator Ridge (Fig. 1) suggests a link between them but the ridge is not a particularly prominent bathymetric feature. Alternatively, a recent tear due to the stresses induced by the difference in lithosphere age and character across the subducted transform could account for hot mantle rise beneath this part of Sumatra.

The reconstruction of the Banda region has been improved (Figs. 33 to 36), based in part on detailed identification of ocean floor anomalies (Hinschberger et al., 2000, 2001) and new information on structures in eastern Indonesia (e.g. Watkinson et al., 2011b). Jurassic rifting of the SW Borneo block left the Sula Spur continental promontory and this extended west from New Guinea north of the Banda oceanic embayment within the Australian continental margin. The shape of the embayment and the age of oceanic lithosphere within it were major influences on Australia–Sundaland collision during the Neogene.

The first contact of the Sula Spur and the Asian margin was soon after 25 Ma in north Sulawesi (Fig. 32). The embayment was surrounded by a passive continental margin but at about 15 Ma (Fig. 34) the Java Trench propagated east at the continent–ocean boundary along the northern edge of the embayment. The remaining oceanic lithosphere then fell away into the mantle and the subduction hinge rolled back into the embayment. Many authors have identified the importance of subduction rollback in the Neogene development of the Banda Arc (e.g. Charlton, 2000; Hall, 1996, 2002; Hamilton, 1976, 1979; Harris, 1992, 2003, 2006; Hinschberger et al., 2005; Milsom, 2001) but there have been no detailed reconstructions of the eastern Indonesia region except Hall (1996, 2002) and Hinschberger et al. (2005). Recent mapping using multibeam and seismic data offshore with SRTM and ASTER imagery on land (e.g. Ferdian et al., 2010;

Spencer, 2010, 2011; Watkinson et al., 2011b) is revealing different structures in eastern Indonesia from those previously interpreted. The present reconstruction departs from previous models in largely eliminating the slicing of continental fragments from northern New Guinea, proposing instead that the continental fragments now dispersed in eastern Indonesia represent fragmentation during extension of the Sula Spur, and modelling them as moving southwards or southeast, not west, in the late Neogene. The reconstruction of eastern Indonesia (Spakman and Hall, 2010) is very slightly modified in the animation included with this paper and its history is discussed at greater length in Hall (2011).

In this model rollback into the Banda embayment began at 15 Ma (Fig. 37). Volcanic activity in the western Banda Arc began at about 12 Ma. The tear along the northern oceanic–continent boundary stalled or ceased at about 6 Ma near west Seram, juxtaposing continental crust and hot mantle by delamination (Spakman and Hall, 2010), causing melting and metamorphism, later exhumed. In Timor and Sumba the arc–continent collision age of about 4 Ma is marked by a cessation of volcanic activity in the Inner Banda Arc in Wetar and Alor by 3 Ma (Abbott and Chamalaun, 1981; Scotney et al., 2005) and by the rapid uplift that followed collision bringing deep marine sedimentary rocks to their present positions well above sea level (e.g. Audley-Charles, 2011; Fortuin et al., 1997). The very young volcanoes in the eastern part of arc from Damar to Banda (Abbott and Chamalaun, 1981; Honthaas et al., 1998, 1999) record the latest and final stage of rollback that formed the Weber Deep.

7. Christmas Island volcanic province

During the final stages of preparation of this paper valuable new information was published about the Christmas Island volcanic

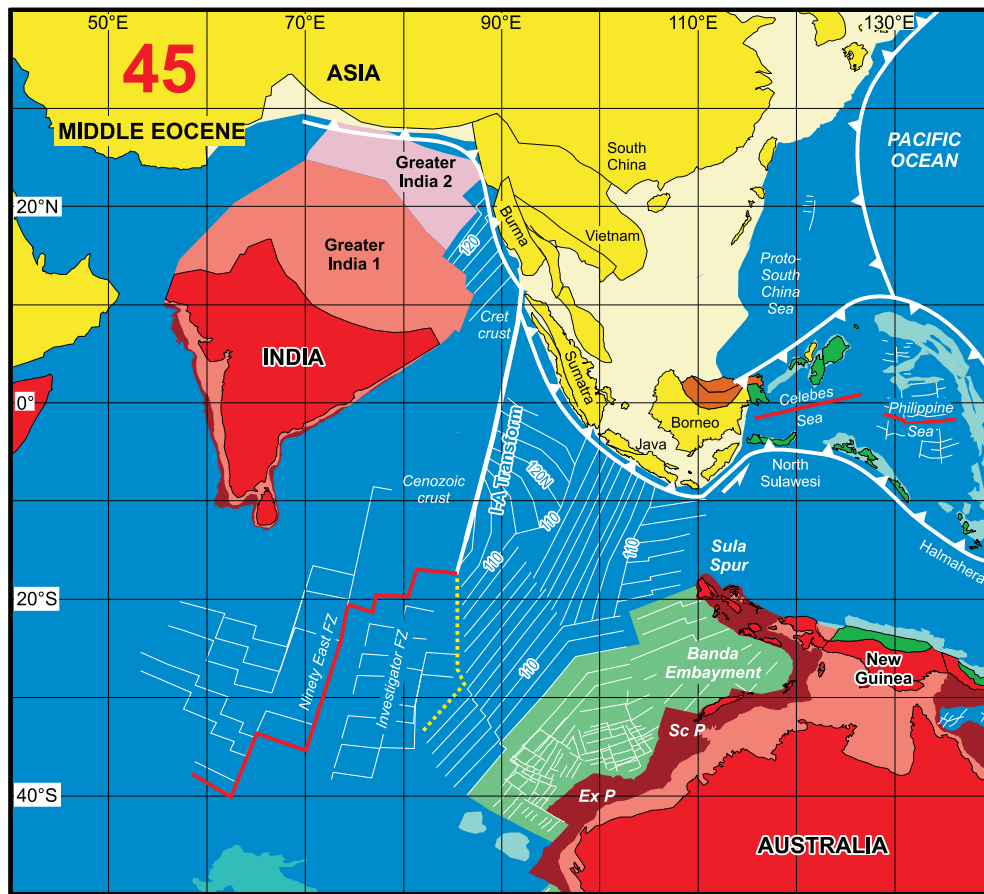


Fig. 28. Reconstruction at 45 Ma. Australia began to move northwards and new subduction zones were initiated all round Sundaland. The Proto-South China Sea began to subduct southwards at the Sabah margin. The Celebes and Philippine Sea were spreading in a backarc setting. The Ceno-Tethys was subducted northwards from Sumatra to Halmahera.

province in the Indian Ocean south of Java (Hoernle et al., 2011) about which almost nothing was previously known. From a tectonic viewpoint Hoernle et al. suggest three important conclusions: that the seamount province formed close to a new mid-ocean ridge at the position where West Burma began separating from Australia and India; that high $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of volcanic rocks indicate a contribution from Archaean continental lithosphere; and that a stationary mantle plume could account for volcanic activity at 136 Ma and 115–94 Ma, but not at 93–70 Ma, 56–47 Ma and 4 Ma.

In this paper I have argued that the fragments that separated from Australia are not to be found in West Burma but in SW Borneo and East Java–West Sulawesi. The data of Hoernle et al. (2011) are plotted on selected reconstructions of this paper (Fig. 38) and are shown in a complete reconstruction animation (xmas_island_volcanism). These reconstructions support the interpretation of Hoernle et al. that the volcanism occurred close to a new mid-ocean ridge, but it was the ridge between Australia and East Java–West Sulawesi. Archaean crust is present south of the spreading centre in the Pilbara and Kimberley blocks of western Australia, and Archaean zircons with ages up to 3.5 Ga are present in East Java (Smyth et al., 2007) and West Sulawesi (van Leeuwen et al., 2007). Triassic sandstones in the Mt Victoria area of the supposed West Burma block have not yet been sampled for zircon analysis, but detrital zircon studies in Burma that could expect to sample such rocks contain no zircons older than 2.8 Ga (Allen et al., 2008; Bodet and Schärer, 2000). The reconstructions also suggest that a stationary plume could account for volcanic activity at 136 Ma, 115–94 Ma, 93–70 Ma, and 44–37 Ma. Volcanic activity in the Cocos-Keeling Province and at the Outside

Seamount is not explained by a plume and is more likely to be related to transform faults. The 4 Ma Christmas Island Upper Volcanics cannot be accounted for by a plume and are probably related to stresses in the bending subducting slab as it approached the trench.

8. Conclusions

SE Asia was built largely from continental fragments that separated from Gondwana and have amalgamated from the Palaeozoic onwards. The core of Sundaland, including the East Malaya–Indochina, Sukhothai Arc, Sibumasu, and West Sumatra blocks (Barber et al., 2005; Metcalfe, 2011a,b) was in place by the end of the Triassic. In this model there is no West Burma block rifted in the Jurassic and added during the Cretaceous. West Burma is interpreted to have been part of the Asian margin from the Carboniferous and since the Triassic has moved only along strike-slip faults within the margin (Barber and Crow, 2009).

Continental fragments were added to the Sundaland core during the Cretaceous from north and south. Asian-origin fragments were added to form the Luconia–Dangerous Grounds region north of the Lupar Line, and may have been modified by strike-slip movements along the northern Sundaland margin in the Early Cenozoic. By the mid Eocene the Luconia–Dangerous Grounds block was part of the shallow Sunda Shelf. Rifting of the Asian margin that accompanied elimination of the Proto-South China Sea and formed the present South China Sea, partially fragmented the South China margin leaving extended continental crust on the south side of the South China Sea. This extended continental crust underthrust the active margin of

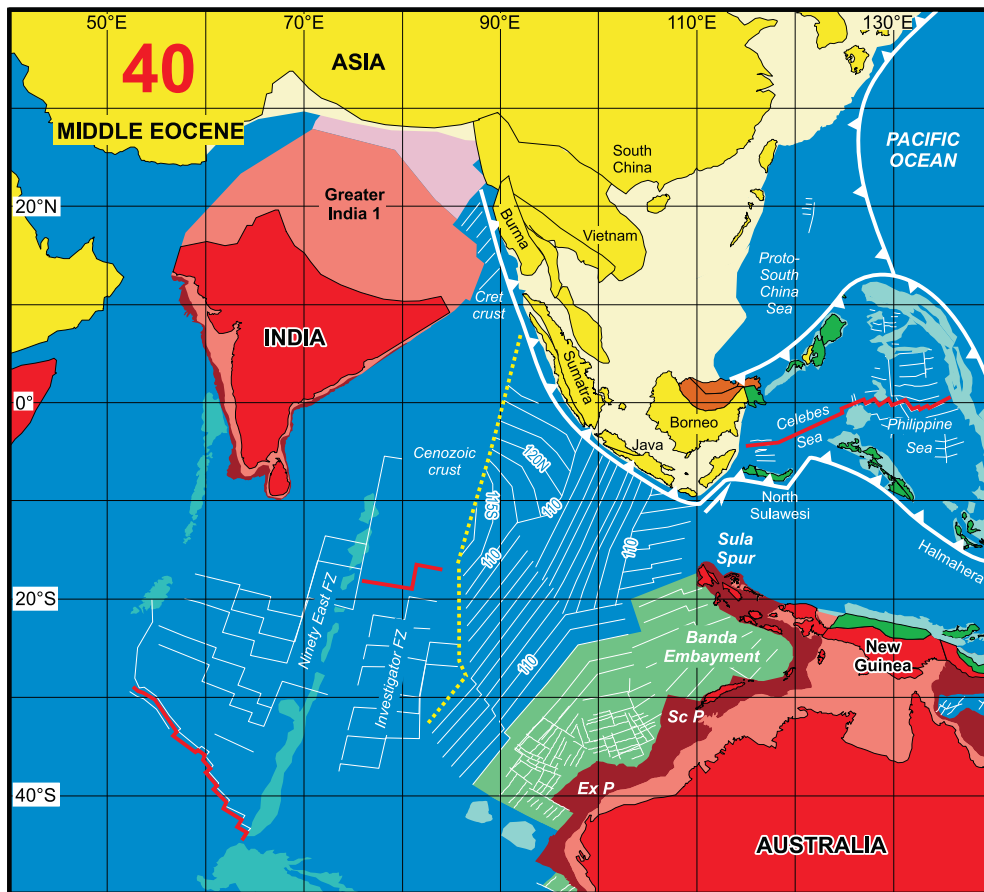


Fig. 29. Reconstruction at 40 Ma. India's movement slowed. The yellow dashed line shows the position of the subducting I-A transform. At the north end of the transform the crust was similar in age on each side of the fault. Further south the age difference increased. Close to the spreading centre south of India the crust to the west was about 40 Ma old whereas to the east it was about 120 Ma old.

the Sabah–Cagayan Arc in the Early Miocene during the final stages of Proto-South China Sea subduction. A relatively short-lived elevated mountain range stretched from Borneo to Palawan formed by the collision but this was quickly reduced during the Miocene, partly by erosion, but mainly by extension caused by rollback at the north side of the Celebes Sea that formed the Dent–Semporna–Sulu Arc and Sulu Sea backarc basin.

Australian-origin fragments were added to form SW Borneo and East Java–West Sulawesi. The SW Borneo–Sundaland boundary is the Billiton depression and was a strike-slip suture. The east boundary of the SW Borneo block is also a strike-slip boundary with the East Java–West Sulawesi from 110 to 90 Ma, and this may explain why the Meratus suture has been reactivated as an elongate narrow mountain belt resembling a strike-slip-related flower structure in SE Borneo. These blocks account for the areas of continental crust rifted from the Australian margin and fit into the areas where there is now increasing evidence for continental basement in Indonesia.

The East Java–West Sulawesi block may be underlain by Archaean basement as suggested by Smyth et al. (2007, 2008) but could also include sedimentary and metamorphic rocks (up to Triassic age) which contain zircons inherited from Archaean, Proterozoic and Palaeozoic basement in western Australia. This would also account for the range of ages in the zircon data. Work is underway to characterise the basement of the SW Borneo block.

The Australian blocks also brought with them structures that influenced Cenozoic deformation of Java, Borneo, and Sulawesi. Deep structural trends, now oriented approximately NW–SE, are

often identified across the whole of Borneo and commonly traced southeastwards into Sulawesi and north towards the Dangerous Grounds. Many of these features show no sign of having been active faults during most of the Cenozoic, some may have been reactivated at intervals during the Cenozoic but most are not active faults today, although they are commonly represented in this way on maps. However, they do appear to have influenced the development of the region during the Cenozoic, and there are indications of changing basement character, depth to basement and changes in sedimentary thicknesses across them. The model provides two possible explanations for them. They could be basement features inherited from Australia where there are deep ancient structures that can be traced offshore across the NW Shelf and western Australia, for example from the Canning or Browse Basins (Brown et al., 1984; Eyles et al., 2001; Goncharov, 2004). An alternative, or additional, explanation is that these faults were active during the phase of Late Cretaceous–Paleocene subduction beneath Sumba and West Sulawesi. Their orientation means that they may have formed or been reactivated at this stage as they were parallel to the NW-directed plate convergence direction. From 45 Ma there was a major change to broadly NE-directed convergence as Australia began to move north and because of their orientation movement on them would have ceased. This would explain why they influence Cenozoic development but, in most cases, do not appear to have been active structures.

The Woyla Arc initiated close to the northern edge of India. If the initial rifting did occur along the continent–ocean boundary there could have been some small microcontinental fragments brought

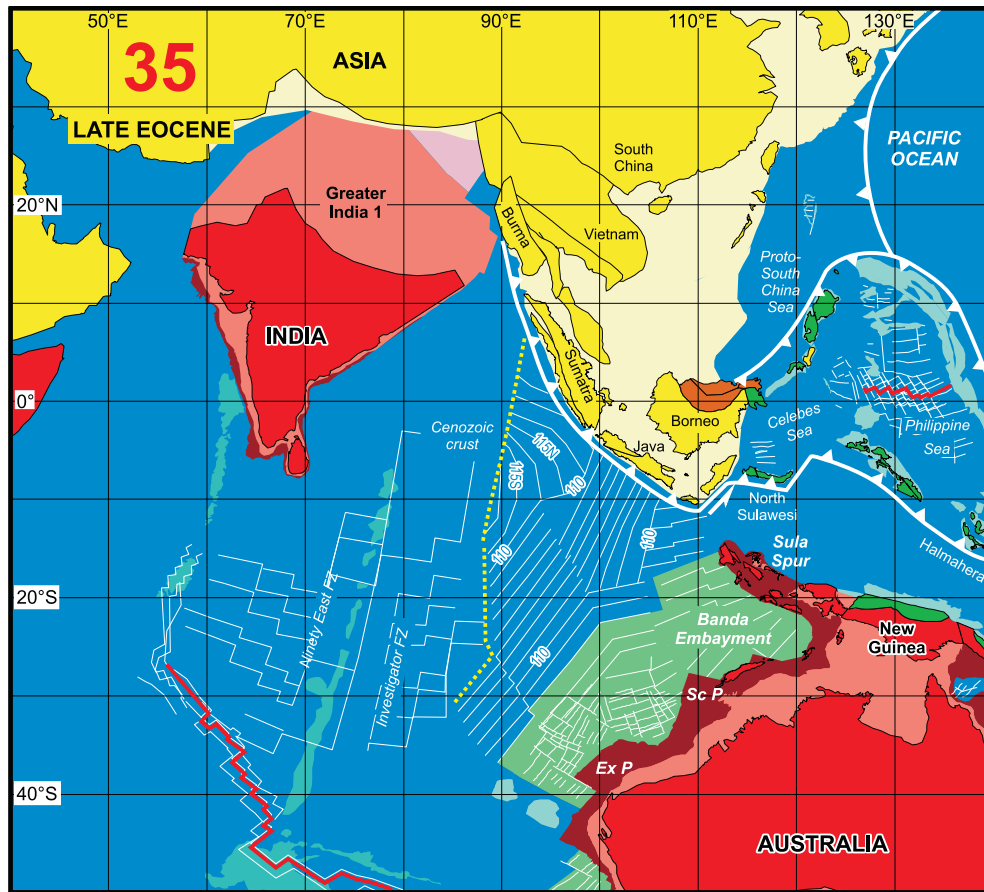


Fig. 30. Reconstruction at 35 Ma. The Proto-South China Sea narrowed by south-directed subduction beneath northern Borneo and the Cagayan Arc.

north with it, such as Sikuleh and Natal, but I follow Barber and Crow (2005) in assuming there are none. The arc collided with the Sumatra margin at about 90 Ma. The model of the Woyla Arc fits well with what is known of its history (M.J. Crow, pers. comm., 2008) and its Cretaceous position could be better constrained by palaeomagnetic studies as suggested by Barber et al. (2005). The model is the simplest possible but if it is discovered that the Woyla Arc formed further north in the Tethys a more complex model of oceanic spreading will be required. The 110 Ma collision of the SW Borneo block caused a reversal of polarity at the Woyla-Incertus Arc which later led India to collide with the arc at about 55 Ma. The western continuation of the Woyla Arc into the proposed Incertus Arc fits very well with the position of the major linear high velocity anomaly in the deep mantle interpreted as a subduction zone that India has passed over.

An important difference between this model and previous perceptions of the Indonesian region is in the history of subduction. Although for many years it has been understood that arcs have been active at different times in different parts of the region (e.g. Hamilton, 1970, 1979, 1988; Hutchison, 1989; Katili, 1971, 1973) there has been widespread assumption that subduction was broadly continuous and simply shifted to different places. The term Great Indonesian Arc has been used (Harris, 2006; Lytwyn et al., 2001) for the concept of a long-lived arc that stretched from Sumatra into the Pacific. There is no such arc in this model. The 90 Ma collisions of the Woyla Arc and the East Java–West Sulawesi block terminated subduction at the Sundaland margins. Collisional thickening and dynamic topographic responses to termination of subduction both contributed to an enlarged emergent Sundaland continent from this time. The period from about 90 to 45 Ma was mainly a time of

erosion, non-deposition, and sediment recycling with little igneous activity. From 63 Ma to 50 Ma there was some subduction beneath the SE corner of Sundaland due to NW-directed plate convergence, between NW Sulawesi and Sumba. However, major subduction did not resume until 45 Ma, as Australia began to move north, and sedimentary basins began to form across the region in response to the regional stresses that then developed (Hall, 2009; Hall and Morley, 2004). The Sumatra–Java Arc became active from the Middle Eocene, as did the Sulawesi North Arm Arc, but between them the Sulawesi–Sumba arc activity ceased. Western Sulawesi was not the site of igneous activity during the Paleogene and there was no arc linking Java to the North Arm of Sulawesi. The Walanae Fault in South Sulawesi appears to be a fundamental structure formed at or close to a continental margin which from the Late Eocene to Early Miocene was a transform boundary in the model. The reconstructions suggest that this fault may be traced north within the Sundaland margin into the Palu–Koro Fault. It is possible that both of these are ancient faults that have been repeatedly reactivated, as appears to be the case for many other major faults in Indochina and East Asia.

Even in the Miocene there was no subduction-related Great Indonesian Arc east of Java. Miocene to Recent igneous activity in western Sulawesi was extension-related rather than subduction- or collision-related. The Banda Arc is a young arc built largely on continental crust. From Flores to Wetar this was continental crust that was added to Sundaland in the Cretaceous, but east of Wetar was crust that was stretched during Banda subduction rollback. The fragmentation of the Sula Spur in this model is interpreted as due to extension driven by rollback into the Banda embayment and is very different from the earlier reconstructions, which assumed slicing of

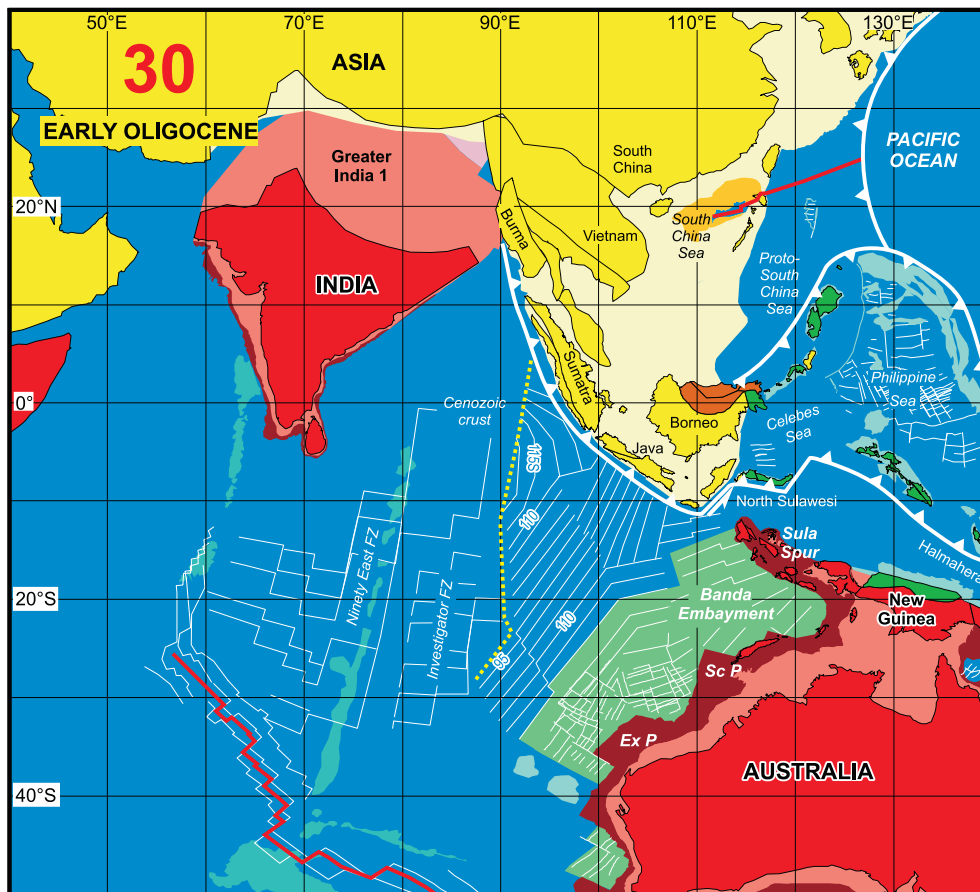


Fig. 31. Reconstruction at 30 Ma. South China Sea oceanic crust formation was underway.

continental fragments from northern New Guinea, which then collided with Sulawesi.

A key feature of the model presented in this paper is that there was never an active or recently active ridge subducted beneath Sumatra and Java as suggested previously (e.g. Hall, 2002; Whittaker et al., 2007). In fact, the slab subducted in the Cenozoic between Sumatra and east Indonesia was always Cretaceous or older, except at the very western end of the Sunda Arc beneath north Sumatra and the Andamans, where Cenozoic lithosphere has been subducted since about 20 Ma. Age contrasts of the lithosphere across the I-A transform can explain the geometry of the subducted slab beneath Sumatra and would also account for a tear that caused Toba volcanism and elevation of the Sumatra forearc. The reconstructions presented here also account well for the new age data acquired from the Christmas Island volcanic province and most volcanism there could be explained by a stationary hotspot. The reconstructions suggest that this hotspot could be implicated in the tectonic development as its position coincides with the triple junction that developed at 135 Ma, and is close to the end of the I-A transform initiated at 90 Ma.

Subduction has been the major influence on the development of the region. However, although there has been considerable growth, little material has been added by subduction accretion, or by accretion of oceanic plateaus or seamounts. Despite the many arcs, igneous activity seems to have contributed little new crust. Subduction-driven rollback is a clear feature of the reconstructions at numerous stages. The importance of rollback is now widely accepted around the world but in SE Asia, particularly Indonesia, it is still common to interpret the region in terms of collision. The major growth of the region has been by addition of continental fragments but many of the

important features we observe today, from Sundaland, Borneo, Sulawesi to the Banda Arc reflect extension mainly driven by subduction.

Tectonic reconstructions are useful at appropriate scales, encourage useful new insights (e.g. Dewey and Casey, 2011), and may highlight problems and processes. However, it is also clear that the upper crust deforms in a complex way that cannot be modelled well using rigid fragments, by 'plate tectonics' at an increasingly micro-plate scale (Hall, 2011). Modelling the region requires deformable fragments for which currently few tools and rules exist. Thus, the reconstructions here should be considered a first order approximation rather than a literal description of the region.

Acknowledgements

This work has been supported mainly by the SE Asia Research Group at Royal Holloway, funded by a consortium of oil companies. Financial support has also been provided at times by the Royal Society, the London University Central Research Fund, and the Natural Environment Research Council. I thank members of the research group who over many years have added to our knowledge of the region, and I have listed some of the numerous colleagues who have helped us here but I am aware that the list could be much longer and to those omitted I apologise. These include Jason Ali, Jonathan Aitchison, Mike Audley-Charles, Peter Baillie, Tony Barber, Diane Cameron, Ben Clements, Mike Crow, Mike Cottam, John Decker, Ian Deighton, Chris Elders, Marnie Forster, Tom Fraser, Piri Hall, Charles Hutchison, Gordon Lister, Jeff Malaihollo, Colin Macpherson, Ian Metcalfe, Bob Morley, Chris Morley, Gary Nichols, Brian Rosen, Lawrence Rush, Inga Sevastjanova, Nafrizal Sikumbang, Alan Smith,

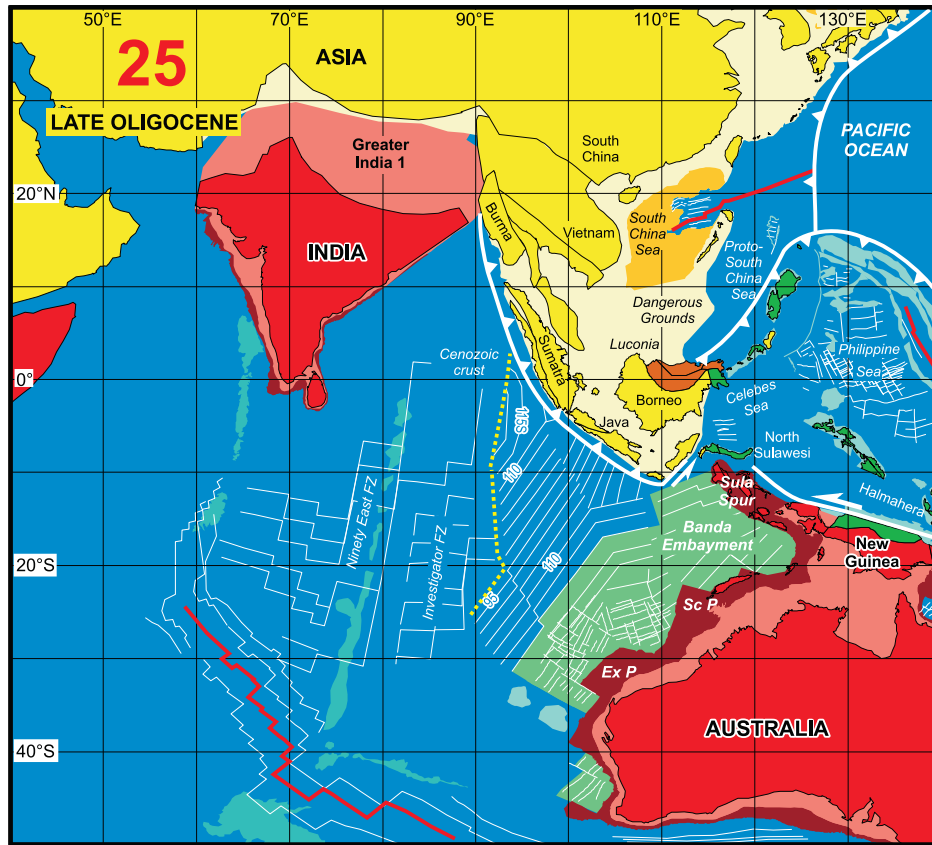


Fig. 32. Reconstruction at 25 Ma. The Sula Spur was about to make contact with the Sulawesi North Arm volcanic arc marking the beginning of collision of Australia and SE Asia. The Philippine Sea Plate began to rotate clockwise with strike-slip motion along the northern New Guinea margin following arc-continent collision in eastern New Guinea.

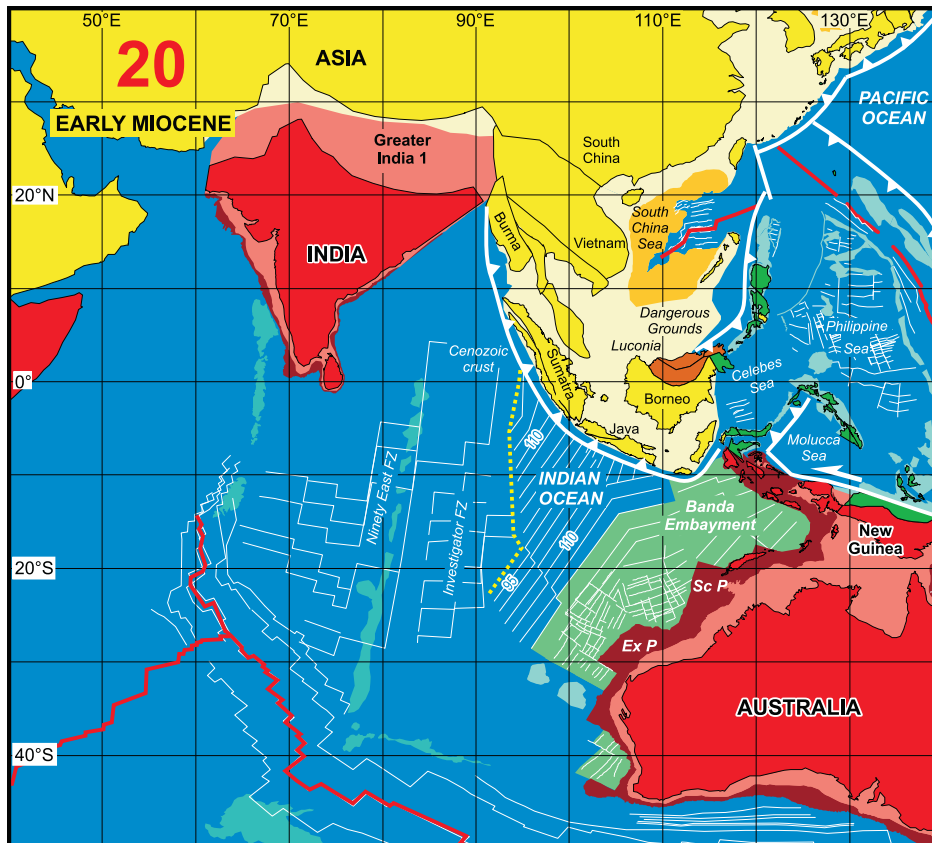


Fig. 33. Reconstruction at 20 Ma. Proto-South China Sea subduction beneath Sabah terminated and South China Sea spreading was about to end.

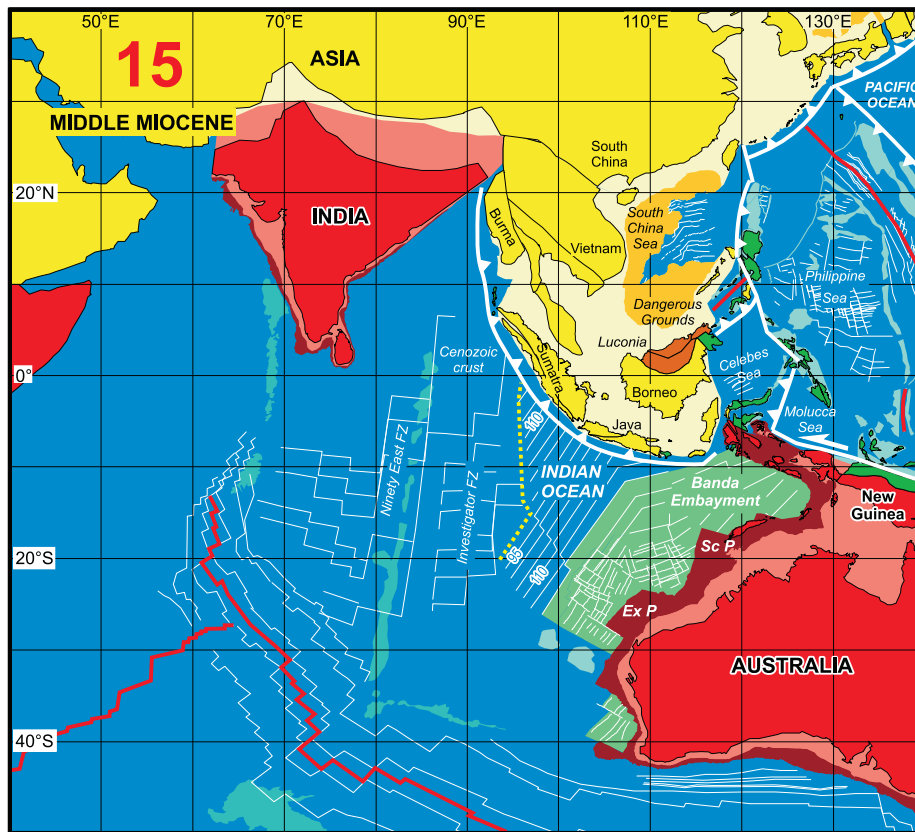


Fig. 34. Reconstruction at 15 Ma. Collision of the Cagayan Arc and the Palawan microcontinent was complete. Subduction rollback of the Celebes Sea caused spreading of the Sulu Sea in a backarc setting. The Java Trench subduction zone began to roll back into the Banda Embayment beginning extension of the Sundaland margin in Sulawesi and the Sula Spur. Across the former I-A Transform (yellow dashed line) there was a very large age difference of crust being subducted beneath North and Central Sumatra.

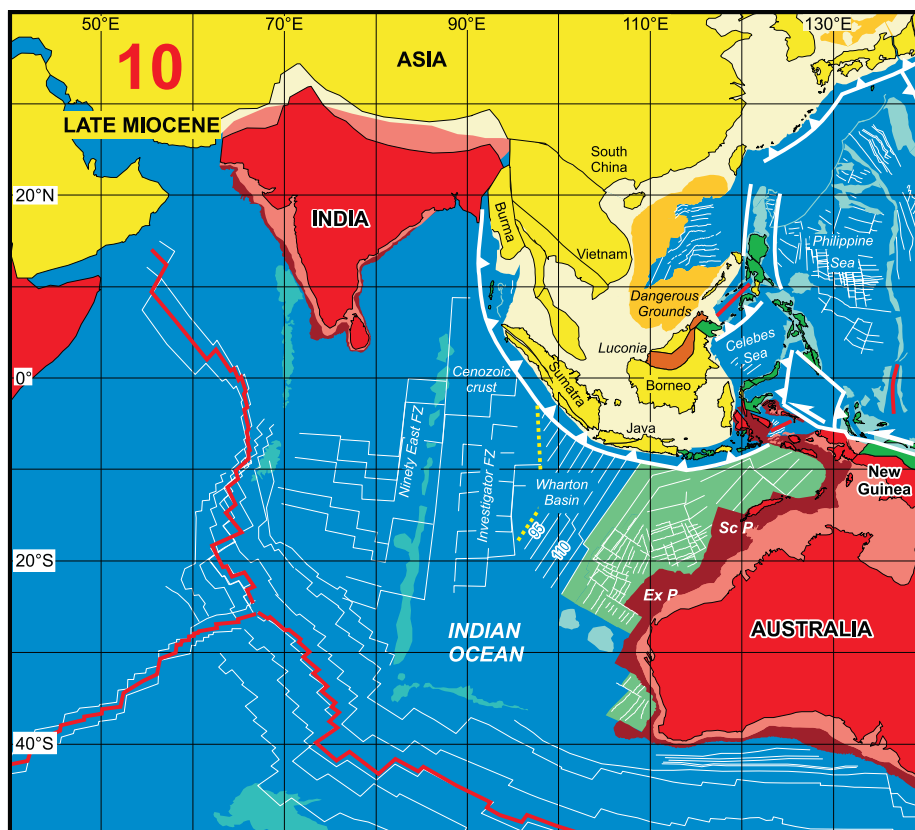


Fig. 35. Reconstruction at 10 Ma. Rollback into the Banda Embayment caused extension of the Sula Spur to form the North Banda Sea. Andaman Sea spreading was underway.

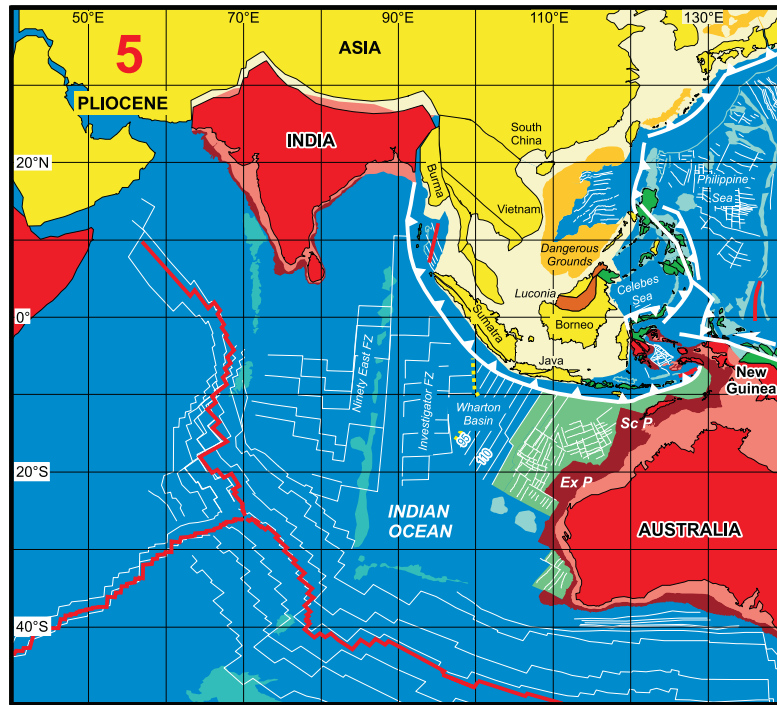


Fig. 36. Reconstruction at 5 Ma. Rollback into the Banda Embayment caused extension to form the South Banda Sea. Molucca Sea subduction was almost complete and the Halmahera and Sangihe Arcs were about to collide.

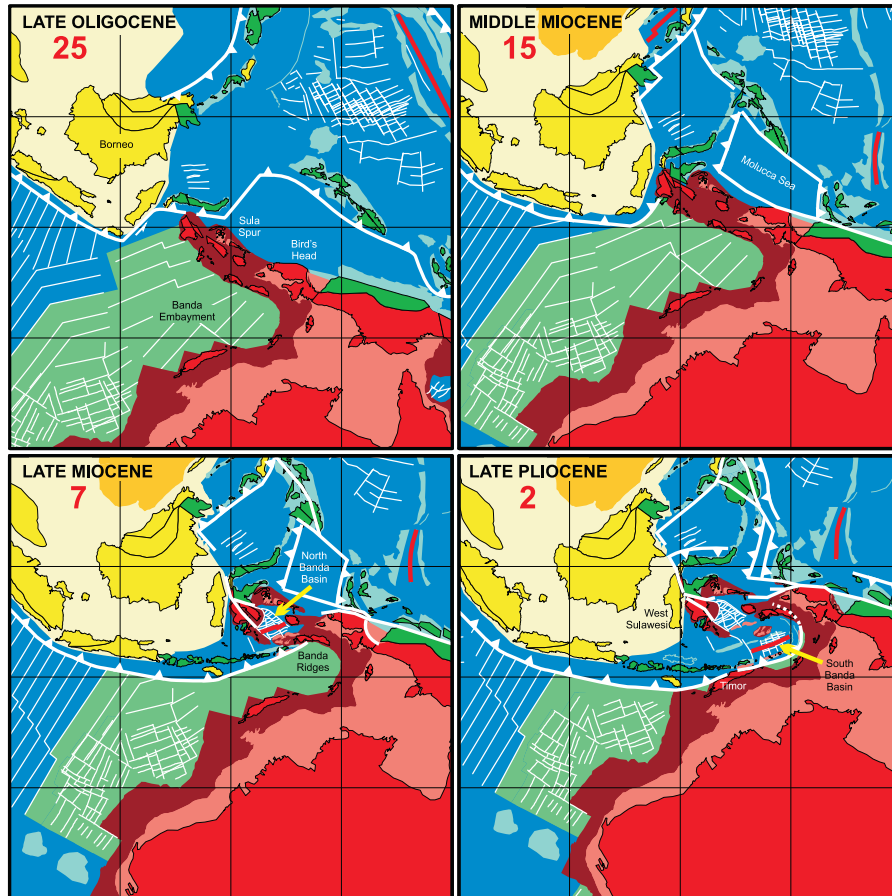


Fig. 37. Details of Banda reconstruction showing Australia–SE Asia collision began in the Early Miocene when the Sula Spur collided with the North Sulawesi volcanic arc. Subduction rollback began at about 15 Ma into the Jurassic Banda Embayment causing extension of the Sula Spur. The first stage of extension formed the North Banda Sea between 12 and 7 Ma and remnants of the Sula Spur were carried southeast above the subduction hinge. The Banda volcanic arc is built partly on these fragments which were further extended as the arc split and the South Banda Basin formed, leaving remnants of continental crust and arc rocks in the Banda Ridges between the North and South Banda Basins. Fragments of continental crust are found today in the Banda forearc in small islands east of Timor and on Timor in the Aileu Complex.

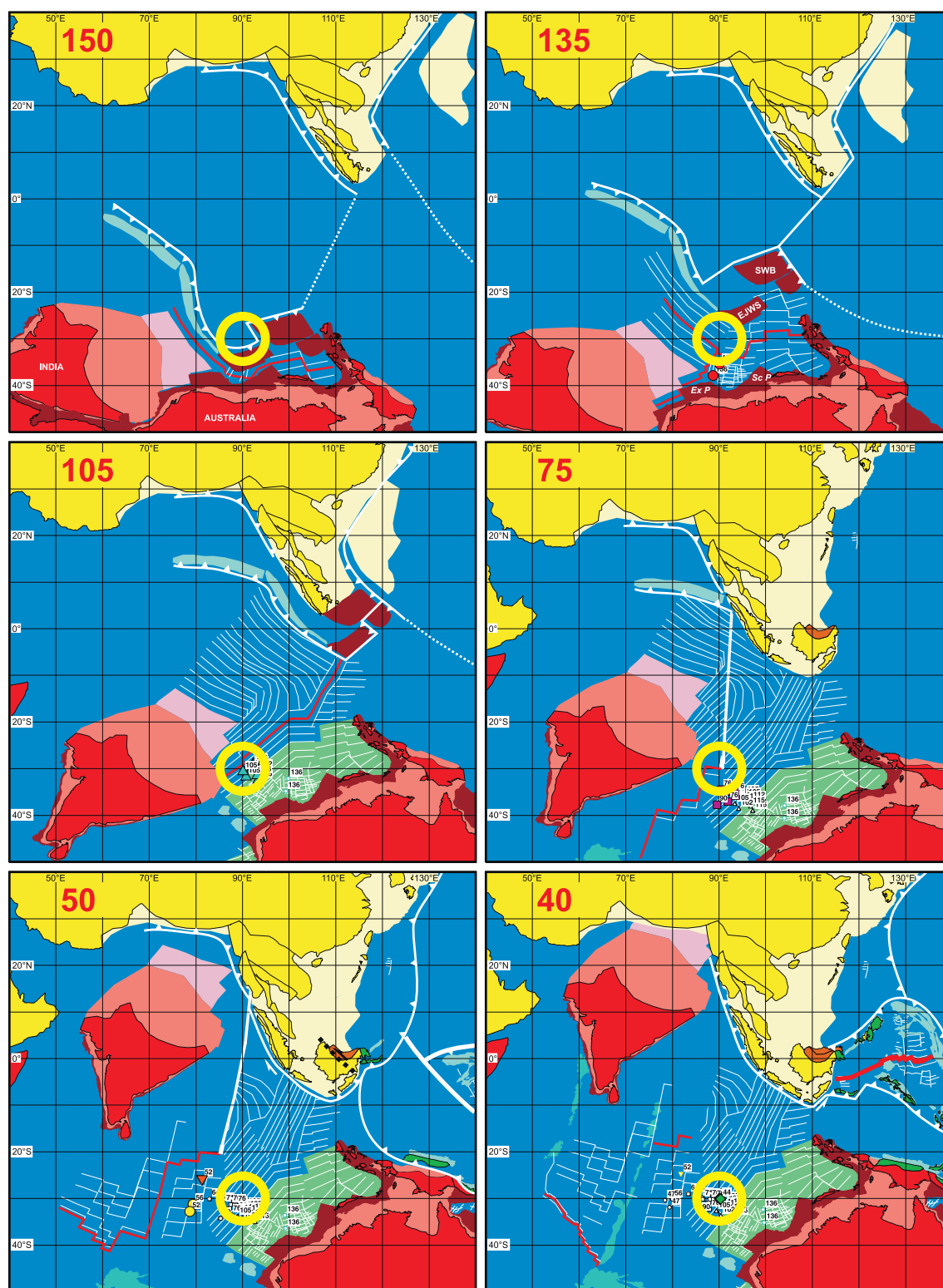


Fig. 38. Reconstructions of the Christmas Island Volcanic Province plotting location and ages of volcanic rocks dated by Hoernle et al. (2011) on the reconstructions of this paper. Larger coloured symbols indicate active magmatism and smaller white symbols show the location of samples after magmatism ceased. Numbers are ages. The oldest rocks are 136 Ma. Most samples appear to have erupted a few million years after formation of ocean crust at the ridge. Magmatic episodes at about 135 Ma, 105 Ma, 75 Ma and 40 Ma appear to be close to a stationary mantle feature shown as the yellow circle. In contrast, Paleogene magmatism (56–47 Ma) of the Cocos-Keeling Province and Outsider Seamount appears to be more closely related to transforms south of the Indian Ocean spreading centre.

Helen Smyth, Wim Spakman, Simon Suggate, Mike Sullivan, Sahat Tobing, Phil Teas, Marco van Hattum, Theo van Leeuwen, Ian Watkinson and Duncan Witts. Ian Metcalfe and Chris Morley made helpful comments on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.tecto.2012.04.021>.

References

- Abbott, M.J., Chamalaun, F.H., 1981. Geochronology of some Banda Arc volcanics. In: Barber, A.J., Wiryosujono, S. (Eds.), *The Geology and Tectonics of Eastern Indonesia: Geological Research and Development Centre, Bandung, Special Publication*, 2, pp. 253–268.
- Abdullah, C.I., Rampnoux, J.-P., Bellon, H., Maury, R.C., Soeria-Atmadja, R., 2000. The evolution of Sumba Island (Indonesia) revisited in the light of new data on the geochronology and geochemistry of the magmatic rocks. *Journal of Asian Earth Sciences* 18, 533–546.
- Adams, C.G., Haak, R., 1962. The stratigraphical succession in the Batu Gading area, Middle Baram, North Sarawak. In: Haile, N.S. (Ed.), *The Geology and Mineral Resources of the Suai-Baram area, North Sarawak: Geological Survey Department, British Territories in Borneo, Memoir*, 13, pp. 141–150.
- Agard, P., Jolivet, L., Vrielynck, B., Burov, E., Monié, P., 2007. Plate acceleration: the obduction trigger? *Earth and Planetary Science Letters* 258, 428–441.
- Aitchison, J.C., Ali, J.R., Davis, A.M., 2007a. When and where did India and Asia collide? *Journal of Geophysical Research* 112, B05423. <http://dx.doi.org/10.1029/2006JB004706>.
- Aitchison, J.C., McDermid, I.R.C., Ali, J.R., Davis, A.M., Zyabrev, S.V., 2007b. Shoshonites in southern Tibet record Late Jurassic rifting of a Tethyan intraoceanic island arc. *Journal of Geology* 115, 197–218.
- Ali, J.R., Aitchison, J.C., 2005. Greater India. *Earth-Science Reviews* 72, 169–188.
- Ali, J.R., Aitchison, J.C., 2008. Gondwana to Asia: plate tectonics, paleogeography and the biological connectivity of the Indian sub-continent from the Middle Jurassic through latest Eocene (166–35 Ma). *Earth-Science Reviews* 72, 145–166.
- Ali, J.R., Hall, R., 1995. Evolution of the boundary between the Philippine Sea Plate and Australia: palaeomagnetic evidence from eastern Indonesia. *Tectonophysics* 251, 251–275.
- Allen, R., Najman, Y., Carter, A., Barford, D., Bickle, M.J., Chapman, H.J., Garzanti, E., Vezzoli, G., Ando, S., Parrish, R.R., 2008. Provenance of the Tertiary sedimentary rocks of the Indo-Burman Ranges, Burma (Myanmar): Burman arc or Himalayan-derived? *Journal of the Geological Society of London* 165, 1045–1057.
- Audley-Charles, M.G., 1983. Reconstruction of eastern Gondwanaland. *Nature* 306, 48–50.
- Audley-Charles, M.G., 1988. Evolution of the southern margin of Tethys (North Australian region) from early Permian to late Cretaceous. In: Audley-Charles, M.G., Hallam, A. (Eds.), *Gondwana and Tethys Geological Society of London Special Publication* 37, 79–100.
- Audley-Charles, M.G., 1991. Tectonics of the New Guinea area. *Annual Reviews of Earth and Planetary Sciences* 19, 17–41.
- Audley-Charles, M.G., 2011. Tectonic post-collision processes in Timor. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia-Asia collision Geological Society of London Special Publication* 355, 241–266.
- Audley-Charles, M.G., Ballantyne, P.D., Hall, R., 1988. Mesozoic–Cenozoic rift-drift sequence of Asian fragments from Gondwanaland. *Tectonophysics* 155, 317–330.
- Barber, A.J., 2000. The origin of the Woyla Terranes in Sumatra and the Late Mesozoic evolution of the Sundaland margin. *Journal of Asian Earth Sciences* 18, 713–738.
- Barber, A.J., Crow, M.J., 2005. Chapter 4: Pre-Tertiary stratigraphy. In: Barber, A.J., Crow, M.J., Milsom, J.S. (Eds.), *Sumatra: Geology, Resources and Tectonic Evolution: Geological Society London Memoir*, 31, pp. 24–53.
- Barber, A.J., Crow, M.J., 2009. The structure of Sumatra and its implications for the tectonic assembly of Southeast Asia and the destruction of Paleotethys. *Island Arc* 18, 3–20.
- Barber, A.J., Crow, M.J., de Smet, M.E.M., 2005. Chapter 14: Tectonic evolution. In: Barber, A.J., Crow, M.J., Milsom, J.S. (Eds.), *Sumatra: Geology, Resources and Tectonic Evolution: Geological Society London Memoir*, 31, pp. 234–259.
- Barckhausen, U., Gibbons, A., Hoernle, K., Werner, R., Hauff, F., Mueller, D.R., 2008. Sea-floor spreading anomalies of the south-eastern Indian Ocean revisited. *American Geophysical Union, Fall Meeting 2008, abstract T53G-04*.
- Barron, L., Mernagh, T.P., Pogson, R., Barron, B.J., 2008. Alluvial ultrahigh pressure (UHP) macrodiamond at Copeton/Bingara (Eastern Australia), and Cempaka (Kalimantan, Indonesia). 9th International Kimberlite Conference, Extended Abstract, 9IKC-A-00039, pp. 1–3.
- Ben-Avraham, Z., 1973. Structural framework of the Sunda shelf and vicinity. PhD Thesis, Woods Hole Oceanographic Institute & MIT, 269 pp.
- Ben-Avraham, Z., Emery, K.O., 1973. Structural framework of Sunda Shelf. *Bulletin of the American Association of Petroleum Geologists* 57, 2323–2366.
- Ben-Avraham, Z., Uyeda, S., 1973. The evolution of the China Basin and the Mesozoic paleogeography of Borneo. *Earth and Planetary Science Letters* 18, 365–376.
- Bergman, S.C., Coffield, D.Q., Talbot, J.P., Garrard, R.J., 1996. Tertiary tectonic and magmatic evolution of Western Sulawesi and the Makassar Strait, Indonesia: evidence for a Miocene continent–continent collision. In: Hall, R., Blundell, D.J. (Eds.), *Tectonic Evolution of SE Asia Geological Society of London Special Publication* 106, 391–430.
- Bodet, F., Schärer, U., 2000. Evolution of the SE-Asian continent from U–Pb and Hf isotopes in single grains of zircon and baddeleyite from large rivers. *Geochimica et Cosmochimica Acta* 64, 2067–2091.
- BRGM, 1982. Geological mapping and mineral exploration in northeast Kalimantan 1979–1982, Final Report. *Rapport du Bureau de Recherches Géologique et Minière*.
- Brown, S.A., Bosserio, I.M., Jackson, K.S., Spence, K.W., 1984. The geological evolution of the Canning Basin—implications for petroleum exploration. In: Purcell, P.G. (Ed.), *Proceedings Canning Basin Symposium. Petroleum Exploration Society of Australia*, pp. 85–96.
- Cambridge Paleomap Services, 1993. ATLAS version 3.3. Cambridge Paleomap Services, P.O. Box 246, Cambridge, U.K.
- Cameron, N.R., Clarke, M.C.G., Aldiss, D.T., Aspden, J.A., Djunuddin, A., 1980. The geological evolution of northern Sumatra. *Proceedings Indonesian Petroleum Association 9th Annual Convention*, pp. 149–187.
- Charlton, T.R., 2000. Tertiary evolution of the Eastern Indonesia Collision Complex. *Journal of Asian Earth Sciences* 18, 603–631.
- Charlton, T.R., 2001. Permo-Triassic evolution of Gondwanan eastern Indonesia, and the final Mesozoic separation of SE Asia from Australia. *Journal of Asian Earth Sciences* 19, 595–617.
- Charvet, J., Lapiere, H., Yu, Y., 1994. Geodynamic significance of the Mesozoic volcanism of southeastern China. *Journal of Southeast Asian Earth Sciences* 9, 387–396.
- Chen, J., Huang, B., Sun, L., 2010. New constraints to the onset of the India-Asia collision: paleomagnetic reconnaissance on the Linzizong Group in the Lhasa Block, China. *Tectonophysics* 489, 189–209.
- Clements, B., Hall, R., 2011. A record of continental collision and regional sediment flux for the Cretaceous and Palaeogene core of SE Asia: implications for early Cenozoic palaeogeography. *Journal of the Geological Society* 168, 1187–1200.
- Clements, B., Hall, R., Smyth, H.R., Cottam, M.A., 2009. Thrusting of a volcanic arc: a new structural model for Java. *Petroleum Geoscience* 15, 159–174.
- Clements, B., Burgess, P.M., Hall, R., Cottam, M.A., 2011. Subsidence and uplift by slab-related mantle dynamics: a driving mechanism for the late Cretaceous and Cenozoic evolution of continental SE Asia. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia-Asia collision Geological Society of London Special Publication* 355, 37–51.
- Clift, P., Lee, G.H., Duc, N.A., Barckhausen, U., Long, H.V., Zhen, S., 2008. Seismic reflection evidence for a Dangerous Grounds miniplate: no extrusion origin for the South China Sea. *Tectonics* 27. <http://dx.doi.org/10.1029/2007TC002216>.
- Colwell, J.B., Symonds, P.A., Crawford, A.J., 1994. The nature of the Wallaby (Cuvier) Plateau and other igneous provinces of the west Australian margin. *AGSO Journal of Australian Geology and Geophysics* 15, 137–156.
- Crow, M.J., 2005. Chapter 8: Tertiary volcanicity. In: Barber, A.J., Crow, M.J., Milsom, J.S. (Eds.), *Sumatra: Geology, Resources and Tectonic Evolution: Geological Society London Memoir*, 31, pp. 98–119.
- Davies, H.L., Jaques, A.L., 1984. Emplacement of ophiolite on Papua New Guinea. In: Gass, I.G., Lippard, S.J., Shelton, A.W. (Eds.), *Ophiolites and Oceanic Lithosphere Geological Society of London Special Publication* 14, 341–349.
- Deighton, I., Hancock, T., Hudson, G., Tamannai, M., Conn, P., Oh, K., 2011. Infill seismic in the southeast Java Forearc Basin: implications for petroleum prospectivity. *Proceedings Indonesian Petroleum Association 35th Annual Convention, IPA11-G-068*.
- Dewey, J.F., Casey, J.F., 2011. The origin of obducted large-slab ophiolite complexes. In: Brown, D., Ryan, P.D. (Eds.), *Arc-Continent Collision. Frontiers in Earth Sciences. Springer-Verlag, Berlin, Heidelberg*, pp. 431–444.
- Dilek, Y., Furnes, H., 2009. Structure and geochemistry of Tethyan ophiolites and their petrogenesis in subduction rollback systems. *Lithos* 113, 1–20.
- Dilek, Y., Robinson, P.T. (Eds.), 2003. *Ophiolites in Earth History Geological Society of London Special Publication* 218.
- Dimalanta, C.B., Suerte, L.O., Yumul, G.P., Tamayo, R.A., Ramos, E.G.L., 2006. A Cretaceous supra-subduction oceanic basin source for Central Philippine ophiolitic basement complexes: geological and geophysical constraints. *Geosciences Journal* 10, 305–320.
- Douth, H.F., 1992. Aspects of the structural histories of the Tertiary sedimentary basins of East, Central and West Kalimantan and their margins. *BMR Journal of Australian Geology and Geophysics* 13, 237–250.
- Dupont-Nivet, G., van Hinsbergen, D.J.J., Torsvik, T.H., 2010. Persistently low Asian palaeolatitudes: implications for the India–Asia collision history. *Tectonics* 29, TC5016. <http://dx.doi.org/10.1029/2008TC002437>.
- Elburg, M., Foden, J., 1999. Sources for magmatism in central Sulawesi: geochemical and Sr–Nd–Pb isotopic constraints. *Chemical Geology* 156, 67–93.
- Elburg, M., van Leeuwen, T., Foden, J., Muhardjo, 2002. Origin of geochemical variability by arc–continent collision in the Biru area, Southern Sulawesi (Indonesia). *Journal of Petrology* 43, 581–606.
- Elburg, M., van Leeuwen, T., Foden, J., Muhardjo, 2003. Spatial and temporal isotopic domains of contrasting igneous suites in western and northern Sulawesi, Indonesia. *Chemical Geology* 199, 243–276.
- Emmet, P.A., Granath, J.W., Dinkelman, M.G., 2009. Pre-Tertiary sedimentary “keels” provide insights into tectonic assembly of basement terranes and present-day petroleum systems of the East Java Sea. *Proceedings Indonesian Petroleum Association 33rd Annual Convention, IPA09-G-046* 1–11.
- Eyles, N., Eyles, C.H., Neil Apak, S., Carlsen, G.M., 2001. Permian–Carboniferous tectonostratigraphic evolution and petroleum potential of the northern Canning basin, Western Australia. *Bulletin of the American Association of Petroleum Geologists* 85, 989–1006.
- Faure, M., Marchadier, Y., Rangin, C., 1989. Pre Eocene synmetamorphic structure in the Mindoro Romblon Palawan area, West Philippines, and implications for the history of Southeast Asia. *Tectonics* 8, 963–979.
- Ferdian, F., Watkinson, I.M., Hall, R., 2010. A structural re-evaluation of the North Banggai-Sula area, eastern Sulawesi. *Proceedings Indonesian Petroleum Association 34th Annual Convention, IPA10-G-009* 1–20.
- Fortuin, A.R., van der Werff, W., Wensink, H., 1997. Neogene basin history and paleomagnetism of a rifted and inverted forearc region, on- and offshore Sumba, Eastern Indonesia. *Journal of Asian Earth Sciences* 15, 61–88.
- Fullerton, L.G., Sager, W.W., Handschumacher, D.W., 1989. Late Jurassic–Early Cretaceous evolution of the eastern Indian Ocean adjacent to northwest Australia. *Journal of Geophysical Research* 94, 2937–2954.
- Fyhn, M.B.W., Boldreel, L.O., Nielsen, L.H., 2010a. Escape tectonism in the Gulf of Thailand: Paleogene left-lateral pull-apart rifting in the Vietnamese part of the Malay Basin. *Tectonophysics* 483, 365–376.
- Fyhn, M.B.W., Pedersen, S.A.S., Boldreel, L.O., Nielsen, L.H., Green, P.F., Dien, P.T., Huyen, L.T., Frei, D., 2010b. Palaeocene–early Eocene inversion of the Phuquoc-Kampot

- Som Basin: SE Asian deformation associated with the suturing of Luconia. *Journal of the Geological Society of London* 167, 281–295.
- Gatinsky, Y.G., Hutchison, C.S., 1986. Cathaysia, Gondwanaland and the Paleotethys in the evolution of continental Southeast Asia. *Bulletin of the Geological Society of Malaysia* 20, 179–199.
- GEBCO, 2003. IHO-UNESCO, General Bathymetric Chart of the Oceans Digital Edition, <http://www.gebco.net/>.
- Goncharov, A., 2004. Basement and crustal structure of the Bonaparte and Browse basins, Australian northwest margin. *Proceedings of the Timor Sea Symposium*, Northern Territory Geological Survey Australia, Special Publication 1, 551–566.
- Gorring, M.L., Kay, S.M., 2001. Mantle processes and sources of Neogene slab window magmas from Southern Patagonia, Argentina. *Journal of Petrology* 42, 1067–1094.
- Gower, R.J.W., 1990. Early Tertiary plate reconstructions for the South China Sea region: constraints from northwest Borneo. *Journal of Southeast Asian Earth Sciences* 4, 29–35.
- Gradstein, F.M., 1992. 43. Legs 122 and 123, northwestern Australian margin—a stratigraphic and paleogeographic summary. In: Gradstein, F.M., Ludden, J.N., et al. (Eds.), *Proceedings of the Ocean Drilling Program Scientific Results* 123, 801–816.
- Granath, J.W., Christ, J.M., Emmet, P.A., Dinkelman, M.G., 2011. Pre-Cenozoic sedimentary section and structure as reflected in the JavaSPAN crustal-scale PSDM seismic survey, and its implications regarding the basement terranes in the East Java Sea. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia-Asia collision* Geological Society of London Special Publication 355, 53–74.
- Green, O.R., Searle, M.P., Corfield, R.I., Corfield, R.M., 2008. Cretaceous–Tertiary carbonate platform evolution and the age of the India–Asia collision along the Ladakh Himalaya (Northwest India). *Journal of Geology* 116, 331–353.
- Guzman-Speziale, M., Ni, J.F., 2000. Comment on “Subduction in the Indo-Burma region: is it still active?” by S. P. Satyabala. *Geophysical Research Letters* 27, 1065–1066.
- Haile, N.S., 1962. The Geology and Mineral Resources of the Suai-Baram area, North Sarawak. Geological Survey Department, British Territories in Borneo, Memoir, 13, 176 pp.
- Haile, N.S., 1973. The recognition of former subduction zones in Southeast Asia. In: Tarling, D.H., Runcorn, S.K. (Eds.), *Implications of continental drift to the Earth Sciences*, 2. Academic Press, London, pp. 885–891.
- Haile, N.S., 1974. Borneo. In: Spencer, A.M. (Ed.), *Mesozoic–Cenozoic Orogenic Belts* Geological Society of London Special Publication 4, 333–347.
- Haile, N.S., Ho, C.K., 1991. Geological Field Guide: Sibul-Miri traverse, Sarawak (24 September–1 October 1991). *Petronas Petroleum Research Institute*, 37 pp.
- Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D.J. (Eds.), *Tectonic Evolution of SE Asia* Geological Society of London Special Publication 106, 153–184.
- Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. *Journal of Asian Earth Sciences* 20, 353–434.
- Hall, R., 2009. Hydrocarbon basins in SE Asia: understanding why they are there. *Petroleum Geoscience* 15, 131–146.
- Hall, R., 2011. Australia–SE Asia collision: plate tectonics and crustal flow. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia–Asia collision* Geological Society of London Special Publication 355, 75–109.
- Hall, R., Morley, C.K., 2004. Sundaland Basins. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D.E. (Eds.), *Continent–Ocean Interactions within the East Asian Marginal Seas*. : Geophysical Monograph, 149. American Geophysical Union, Washington, D.C., pp. 55–85.
- Hall, R., Spakman, W., 2002. Subducted slabs beneath the eastern Indonesia–Tonga region: insights from tomography. *Earth and Planetary Science Letters* 201, 321–336.
- Hall, R., Wilson, M.E.J., 2000. Neogene sutures in eastern Indonesia. *Journal of Asian Earth Sciences* 18, 787–814.
- Hall, R., Audley-Charles, M.G., Banner, F.T., Hidayat, S., Tobing, S.L., 1988. Basement rocks of the Halmahera region, eastern Indonesia: a Late Cretaceous–Early Tertiary arc and fore-arc. *Journal of the Geological Society of London* 145, 65–84.
- Hall, R., Ali, J.R., Anderson, C.D., 1995. Cenozoic motion of the Philippine Sea Plate: palaeomagnetic evidence from eastern Indonesia. *Tectonics* 14, 1117–1132.
- Hall, R., van Hattum, M.W.A., Spakman, W., 2008. Impact of India–Asia collision on SE Asia: the record in Borneo. *Tectonophysics* 451, 366–389.
- Hall, R., Clements, B., Smyth, H.R., 2009a. Sundaland: basement character, structure and plate tectonic development. *Proceedings Indonesian Petroleum Association 33rd Annual Convention*, IPA09-G-134 1–27.
- Hall, R., Cloke, I.R., Nur'Aini, S., Puspita, S.D., Calvert, S.J., Elders, C.F., 2009b. The North Makassar Straits: what lies beneath? *Petroleum Geoscience* 15, 147–158.
- Hamilton, W., 1970. Tectonic map of the Indonesian region, a progress report. U.S. Geological Survey Open File Report, 29 pp.
- Hamilton, W., 1973. Tectonics of the Indonesian region. In: Tarling, D.H., Runcorn, S.K. (Eds.), *Implications of Continental Drift to the Earth Sciences*, 2. Academic Press, London, pp. 879–884.
- Hamilton, W., 1976. Subduction in the Indonesian region. *Proceedings Indonesian Petroleum Association 5th Annual Convention*, pp. 3–24.
- Hamilton, W., 1979. Tectonics of the Indonesian region. U.S. Geological Survey Professional Paper, 1078, 345 pp.
- Hamilton, W., 1988. Plate tectonics and island arcs. *Geological Society of America Bulletin* 100, 1503–1527.
- Harris, R.A., 1992. Peri-collisional extension and the formation of Oman-type ophiolites in the Banda arc and Brooks Range. In: Parson, L.M., Murtin, B.J., Browning, P. (Eds.), *Ophiolites and their Modern Oceanic Analogues* Geological Society of London Special Publication 60, 301–325.
- Harris, R., 2003. Geodynamic patterns of ophiolites and marginal basins in the Indonesian and New Guinea regions. In: Dilek, Y., Robinson, P.T. (Eds.), *Ophiolites in Earth History* Geological Society of London Special Publication 218, 481–506.
- Harris, R., 2006. Rise and fall of the Eastern Great Indonesian arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor. *Gondwana Research* 10, 207–231.
- Hasan, K., 1990. The Upper Cretaceous flysch succession of the Balangbaru Formation, Southwest Sulawesi, Indonesia. PhD Thesis, University of London, 337 pp.
- Hasan, K., 1991. Upper Cretaceous flysch succession of the Balangbaru Formation, Southwest Sulawesi. *Proceedings Indonesian Petroleum Association 20th Annual Convention*, pp. 183–208.
- Hazebroek, H.P., Tan, D.N.K., 1993. Tertiary tectonic evolution of the NW Sabah Continental Margin. *Bulletin of the Geological Society of Malaysia* 33, 195–210.
- Heine, C., Müller, R.D., 2005. Late Jurassic rifting along the Australian North West Shelf: margin geometry and spreading ridge configuration. *Australian Journal of Earth Sciences* 52, 27–39.
- Heine, C., Müller, R.D., Norvick, M.S., 2002. Revised tectonic evolution of the Northwest Shelf of Australia and adjacent abyssal plains. In: Keep, M., Moss, S. (Eds.), *The Sedimentary Basins of Western Australia*, 3. Petroleum Exploration Society of Australia, Perth, pp. 955–957.
- Heine, C., Müller, R.D., Gaina, C., 2004. Reconstructing the Lost Eastern Tethys Ocean Basin: convergence of the SE Asian Margin and marine gateways. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D.E. (Eds.), *Continent–Ocean Interactions within the East Asian Marginal Seas*. : Geophysical Monograph, 149. American Geophysical Union, Washington, D.C., pp. 37–54.
- Henderson, A.L., Najman, Y., Parrish, R., Mark, D.F., Foster, G.L., 2011. Constraints to the timing of India–Eurasia collision: a re-evaluation of evidence from the Indus Basin sedimentary rocks of the Indus–Tsangpo Suture Zone, Ladakh, India. *Earth-Science Reviews* 106, 265–292.
- Hilton, D.R., Hoogewerff, J.A., van Bergen, M.J., Hammerschmidt, K., 1992. Mapping magma sources in the east Sunda–Banda arcs, Indonesia: constraints from Helium isotopes. *Geochimica et Cosmochimica Acta* 56, 851–859.
- Hinschberger, F., Malod, J.-A., Rehault, J.-P., Dymont, J., Honthaas, C., Villeneuve, M., Burhanuddin, S., 2000. Origine et evolution du bassin Nord-Banda (Indonesie): apport des donnees magnetiques. *Comptes Rendus de l'Academie des Sciences, Paris* 331, 507–514.
- Hinschberger, F., Malod, J.A., Dymont, J., Honthaas, C., Rehault, J.P., Burhanuddin, S., 2001. Magnetic lineations constraints for the back-arc opening of the Late Neogene South Banda Basin (eastern Indonesia). *Tectonophysics* 333, 47–59.
- Hinschberger, F., Malod, J.-A., Rehault, J.-P., Villeneuve, M., Royer, J.-Y., Burhanuddin, S., 2005. Late Cenozoic geodynamic evolution of eastern Indonesia. *Tectonophysics* 404, 91–118.
- Hoernle, K., Hauff, F., Werner, R., van den Bogaard, P., Gibbons, A.D., Conrad, S., Müller, R.D., 2011. Origin of Indian Ocean Seamount Province by shallow recycling of continental lithosphere. *Nature Geoscience* 4, 883–887. <http://dx.doi.org/10.1038/ngeo1331>.
- Hole, M.J., Saunders, A.D., Rogers, G., Sykes, M.A., 1995. The relationship between alkaline magmatism, lithospheric extension and slab window formation along continental destructive plate margins. In: Smellie, J.L. (Ed.), *Volcanism Associated with Extension at Consuming Plate Margins* Geological Society of London Special Publication 81, 265–285.
- Honthaas, C., Rehault, J.-P., Maury, R.C., Bellon, H., Hemond, C., Malod, J.-A., Cornee, J.-J., Villeneuve, M., Cotten, J., Burhanuddin, S., Guillou, H., Arnaud, N., 1998. A Neogene back-arc origin for the Banda Sea basins: geochemical and geochronological constraints from the Banda ridges (East Indonesia). *Tectonophysics* 298, 297–317.
- Honthaas, C., Maury, R.C., Priadi, B., Bellon, H., Cotten, J., 1999. The Plio–Quaternary Ambon arc, Eastern Indonesia. *Tectonophysics* 301, 261–281.
- Hutchison, C.S., 1989. Geological Evolution of South-East Asia, 13. Oxford Monographs on Geology and Geophysics. Clarendon Press, 376 pp.
- Hutchison, C.S., 1996. The ‘Rajang Accretionary Prism’ and ‘Lupar Line’ problem of Borneo. In: Hall, R., Blundell, D.J. (Eds.), *Tectonic Evolution of SE Asia* Geological Society of London Special Publication 106, 247–261.
- Hutchison, C.S., 2004. Marginal basin evolution: the southern South China Sea. *Marine and Petroleum Geology* 21, 1129–1148.
- Hutchison, C.S., 2005. Geology of North-West Borneo. Elsevier, 444 pp.
- Hutchison, C.S., 2010. Oroclines and paleomagnetism in Borneo and South-East Asia. *Tectonophysics* 496, 53–67.
- Hutchison, C.S., Bergman, S.C., Swauger, D.A., Graves, J.E., 2000. A Miocene collisional belt in north Borneo: uplift mechanism and isostatic adjustment quantified by thermochronology. *Journal of the Geological Society of London* 157, 783–793.
- Ishida, K., Suzuki, S., Yumul Jr., G.P., Dimalanta, C.B., 2011. Middle Eocene low-paleolatitude radiolarian evidence for the Cabog Formation, Central East Luzon, Philippine Mobile Belt. *Gondwana Research* 19, 61–70.
- Jahn, B.-M., Chen, P.Y., Yen, T.P., 1976. Rb–Sr ages of granitic rocks in southeastern China and their tectonic significance. *Geological Society of America Bulletin* 87, 763–776.
- Jasin, B., 2000. Significance of Mesozoic radiolarian chert in Sabah and Sarawak. *Proceedings Geological Society of Malaysia Annual Conference*, pp. 123–130.
- Jiang, Y.H., Jiang, S.Y., Dai, B.Z., Liao, S.Y., Zhao, K.D., Ling, H.F., 2009. Middle to late Jurassic felsic and mafic magmatism in southern Hunan province, southeast China: implications for a continental arc to rifting. *Lithos* 107, 185–204.
- Karig, D.E., 1983. Accreted terranes in the northern part of the Philippine archipelago. *Tectonics* 2, 211–236.
- Katili, J.A., 1971. A review of the geotectonic theories and tectonic maps of Indonesia. *Earth-Science Reviews* 7, 143–163.
- Katili, J.A., 1973. Geochronology of west Indonesia and its implication on plate tectonics. *Tectonophysics* 19, 195–212.

- Khan, S.D., Walker, D.J., Hall, S.A., Burke, K.C., Shah, M.T., Stockli, L., 2009. Did the Kohistan–Ladakh island arc collide first with India? *Geological Society of America Bulletin* 121, 366–384.
- Kirk, H.J.C., 1957. The geology and mineral resources of the Upper Rajang and adjacent areas. British Territories Borneo Region Geological Survey, Memoir, 8. 181 pp.
- Klein, G.de V., Kobayashi, K., 1981. Geological summary of the north Philippine Sea based on Deep Sea Drilling Project Leg 58 results. In: Klein, G.de V., Kobayashi, K., et al. (Eds.), *Deep Sea Drilling Project, Initial Reports*, 58. US Government Printing Office, Washington, pp. 951–961.
- Klompé, T.H.F., 1954. The structural importance of the Sula Spur (Indonesia). *Indonesian Journal of Natural Sciences* 110, 21–40.
- Knittel, U., 2010. 83 Ma rhyolite from Mindoro—evidence for Late Yanshanian magmatism in the Palawan Continental Terrane (Philippines). *Island Arc* 19, 1–9.
- Kudrass, H.R., Wiedecke, M., Cepek, P., Kreuzer, H., Müller, P., 1986. Mesozoic and Cenozoic rocks dredged from the South China Sea (Reed Bank area) and Sulu Sea and their significance for plate-tectonic reconstructions. *Marine and Petroleum Geology* 3, 19–30.
- Lee, T.-Y., Lawver, L.A., 1995. Cenozoic plate reconstruction of Southeast Asia. *Tectonophysics* 251, 85–138.
- Leech, M.L., Singh, S., Jain, A.K., Klempner, S.L., Manickavasagam, R.M., 2005. The onset of India–Asia collision: early, steep subduction required by the timing of UHP metamorphism in the western Himalaya. *Earth and Planetary Science Letters* 234, 83–97.
- Levashova, N.M., Shapiro, M.N., Bazhenov, M.L., 1998. Late Cretaceous paleomagnetic data from the Median Range of Kamchatka, Russia: tectonic implications. *Earth and Planetary Science Letters* 163, 235–246.
- Lewis, S.D., Mrzowski, C.L., Hayes, D.E., 1982. The origin of the West Philippine Basin by inter-arc spreading. In: Balce, G.R., Zanolari, A.S. (Eds.), *Geology and Tectonics of the Luzon–Marianas Region*, Philippine SEATAR Committee, Special Publication, pp. 31–52.
- Li, Z.-X., Li, X.-H., 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: a flat-slab subduction model. *Geology* 35, 179–182.
- Lin, W., Wang, Q., 2006. Late Mesozoic extensional tectonics in the North China block: a crustal response to subcontinental mantle removal? *Bulletin de la Société Géologique de France* 177, 287–297.
- Lin, W., Faure, M., Monié, P., Schärer, U., Panis, D., 2008. Mesozoic extensional tectonics in Eastern Asia: the South Liaodong Peninsula Metamorphic Core Complex (NE China). *Journal of Geology* 116, 134–154.
- Lunt, P., Djaafar, R., 1991. Aspects of the stratigraphy of western Irian Jaya and implications for the development of sandy facies. *Proceedings Indonesian Petroleum Association 20th Annual Convention*, pp. 107–124.
- Luyendyk, B.P., 1974. Gondwanaland dispersal and the early formation of the Indian Ocean. In: Luyendyk, B.P., Davies, T.A. (Eds.), *Deep Sea Drilling Project, Initial Reports*, 26. US Government Printing Office, Washington, pp. 945–952.
- Lytwyn, J., Rutherford, E., Burke, K., Xia, C., 2001. The geochemistry of volcanic, plutonic and turbiditic rocks from Sumba, Indonesia. *Journal of Asian Earth Sciences* 19, 481–500.
- Macpherson, C.G., Chiang, K.K., Hall, R., Nowell, G.M., Castillo, P.R., Thirlwall, M.F., 2010. Plio-Pleistocene intra-plate magmatism from the southern Sulu Arc, Semporna peninsula, Sabah, Borneo: implications for high-Nb basalt in subduction zones. *Journal of Volcanology and Geothermal Research* 190, 25–38.
- Manur, H., Barraclough, R., 1994. Structural control on hydrocarbon habitat in the Bawean area, East Java Sea. *Proceedings Indonesian Petroleum Association 23rd Annual Convention*, pp. 129–144.
- Maulana, A., Ellis, D.J., Christy, A.G., 2010. Petrology, geochemistry and tectonic evolution of the South Sulawesi basement rocks, Indonesia. *Proceedings Indonesian Petroleum Association 34th Annual Convention*, IPA10-G-192 1–26.
- McCourt, W.J., Crow, M.J., Cobbing, E.J., Amin, T.C., 1996. Mesozoic and Cenozoic plutonic evolution of SE Asia: evidence from Sumatra, Indonesia. In: Hall, R., Blundell, D.J. (Eds.), *Tectonic Evolution of SE Asia*. Geological Society of London Special Publication 106, 321–335.
- Metcalfe, I., 1986. Late Palaeozoic palaeogeography of Southeast Asia: some stratigraphical, palaeontological and palaeomagnetic constraints. *Bulletin of the Geological Society of Malaysia* 19, 153–164.
- Metcalfe, I., 1988. Origin and assembly of Southeast Asian continental terranes. In: Audley-Charles, M.G., Hallam, A. (Eds.), *Gondwana and Tethys*. Geological Society of London Special Publication 37, 101–118.
- Metcalfe, I., 1990. Allochthonous terrane processes in Southeast Asia. *Philosophical Transactions of the Royal Society of London A331*, 625–640.
- Metcalfe, I., 1996. Pre-Cretaceous evolution of SE Asian terranes. In: Hall, R., Blundell, D.J. (Eds.), *Tectonic Evolution of SE Asia*. Geological Society of London Special Publication 106, 97–122.
- Metcalfe, I., 2006. Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: the Korean Peninsula in context. *Gondwana Research* 9, 24–46.
- Metcalfe, I., 2009. Late Palaeozoic and Mesozoic tectonic and palaeogeographical evolution of SE Asia. In: Buffetaut, E., Cuny, G., Le Loeuff, J., Suteethorn, V. (Eds.), *Late Palaeozoic and Mesozoic Ecosystems in SE Asia*. Geological Society of London Special Publication 315, 7–23.
- Metcalfe, I., 2011a. Palaeozoic–Mesozoic History of SE Asia. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia–Asia collision*. Geological Society of London Special Publication 355, 7–35.
- Metcalfe, I., 2011b. Tectonic framework and Phanerozoic evolution of Sundaland. *Gondwana Research* 19, 3–21.
- Miller, M.S., Kennett, B.L.N., Toy, V.G., 2006. Spatial and temporal evolution of the subducting Pacific plate structure along the western Pacific margin. *Journal of Geophysical Research* 111, B02401. <http://dx.doi.org/10.1029/2005JB003705>.
- Milson, J., 2001. Subduction in eastern Indonesia: how many slabs? *Tectonophysics* 338, 167–178.
- Mitchell, A.H.G., 1981. Phanerozoic plate boundaries in mainland S.E. Asia, the Himalaya and Tibet. *Journal of the Geological Society of London* 138, 109–122.
- Mitchell, A.H.G., 1986. Mesozoic and Cenozoic regional tectonics and metallogenesis in mainland SE Asia. *Bulletin Geological Society of Malaysia* 20, 221–239.
- Mitchell, A.H.G., 1992. Late Permian–Mesozoic events and the Mergui group Nappe in Myanmar and Thailand. *Journal of SE Asian Earth Sciences* 7, 165–178.
- Mitchell, A.H.G., 1993. Cretaceous–Cenozoic tectonic events in the western Myanmar (Burma)–Assam region. *Journal of the Geological Society of London* 150, 1089–1102.
- Miyazaki, K., Zulkarnain, I., Sopaheluwan, J., Wakita, K., 1996. Pressure–temperature conditions and retrograde paths of eclogites, garnet–glaucophanite rocks and schists from South Sulawesi, Indonesia. *Journal of Metamorphic Geology* 14, 549–563.
- Miyazaki, K., Sopaheluwan, J., Zulkarnain, I., Wakita, K., 1998. A jadeite–quartz–glaucophanite rock from Karangsambung, central Java, Indonesia. *Island Arc* 7, 223–230.
- Moss, S.J., 1998. Embaluh group turbidites in Kalimantan: evolution of a remnant oceanic basin in Borneo during the Late Cretaceous to Palaeogene. *Journal of the Geological Society of London* 155, 509–524.
- Müller, R.D., Royer, J.-Y., Lawver, L.A., 1993. Revised plate motions relative to hotspots from combined Atlantic and Indian Ocean hotspot tracks. *Geology* 21, 275–278.
- Najman, Y., Appel, E., Boudagher-Fadel, M., Bown, P., Carter, A., Garzanti, E., Godin, L., Han, J., Liebke, U., Oliver, G., Parrish, R., Vezzoli, G., 2010. Timing of India–Asia collision: geological, biostratigraphic, and palaeomagnetic constraints. *Journal of Geophysical Research* 115, B12416. <http://dx.doi.org/10.1029/2010JB007673>.
- Nguyen, T.T.B., Satir, M., Siebel, W., Chen, S., 2004. Granitoids in the Dalat zone, southern Vietnam: age constraints on magmatism and regional geological implications. *International Journal of Earth Sciences* 93, 329–340.
- Ni, J.F., Guzman-Speziale, M., Bevis, M., Holt, W.E., Wallace, T.C., Seager, W.R., 1989. Accretionary tectonics of Burma and the three-dimensional geometry of the Burma subduction zone. *Geology* 17, 68–71.
- Nicolas, A., Boudier, F., 2011. Structure and dynamics of ridge axial melt lenses in the Oman ophiolite. *Journal of Geophysical Research* 116, B03103. <http://dx.doi.org/10.1029/2010JB007934>.
- Oliver, W.A., Pedder, A.E.H., Weiland, R.J., Quarles Van Ufford, A., 1995. Middle Palaeozoic corals from the southern slope of the Central Ranges of Irian Jaya, Indonesia. *Alcheringa* 19, 1–15.
- Page, R.W., 1976. Geochronology of igneous and metamorphic rocks in the New Guinea Highlands. Australian Bureau of Mineral Resources, *Geology and Geophysics Bulletin* 162, 1–117.
- Parkinson, C.D., Miyazaki, K., Wakita, K., Barber, A.J., Carswell, D.A., 1998. An overview and tectonic synthesis of the pre-Tertiary very high-pressure metamorphic and associated rocks of Java, Sulawesi and Kalimantan, Indonesia. *Island Arc* 7, 184–200.
- Pedersen, R.B., Searle, M.P., Corfield, R.I., 2001. U–Pb zircon ages from the Spontang Ophiolite, Ladakh Himalaya. *Journal of the Geological Society of London* 158, 513–520.
- Pedersen, R.B., Searle, M.P., Carter, A., Bandopadhyay, P.C., 2010. U–Pb zircon age of the Andaman ophiolite: implications for the beginning of subduction beneath the Andaman–Sumatra arc. *Journal of the Geological Society of London* 167, 1105–1112.
- Peron-Pinvidic, G., Manatschal, G., 2010. From microcontinents to extensional allochthons: witnesses of how continents rift and break apart? *Petroleum Geoscience* 16, 189–197.
- Pesicek, J.D., Thurber, C.H., Widiyantoro, S., Engdahl, E.R., DeShon, H.R., 2008. Complex slab subduction beneath northern Sumatra. *Geophysical Research Letters* 35, L20303. <http://dx.doi.org/10.1029/2008GL035262>.
- Pesicek, J.D., Thurber, C.H., Widiyantoro, S., Zhang, H., DeShon, H.R., Engdahl, E.R., 2010. Sharpening the tomographic image of the subducting slab below Sumatra, the Andaman Islands and Burma. *Geophysical Journal International* 182, 433–453.
- Petterson, M.G., 2010. A review of the geology and tectonics of the Kohistan island arc, north Pakistan. In: Kusky, T.M., Zhai, M.-G., Xiao, W. (Eds.), *The evolving continents: understanding processes of continental growth*. Geological Society of London Special Publication 338, 287–327.
- Petterson, M.G., Windley, B.F., 1992. The field relationships, geochemistry and petrogenesis of the Cretaceous basalt Jutal dykes, Kohistan, northern Pakistan. *Journal of the Geological Society of London* 149, 107–114.
- Pieters, P.E., Sanyoto, P., 1993. Geology of the Pontianak/Nangataman Sheet area, Kalimantan: 1:250,000. Geological Research and Development Centre, Bandung, Indonesia.
- Pieters, P.E., Supriatna, S., 1990. Geological Map of West, Central and East Kalimantan Area. Scale 1:1,000,000. Geological Research and Development Centre, Bandung, Indonesia.
- Pieters, P.E., Pigram, C.J., Trail, D.S., Dow, D.B., Ratman, N., Sukanto, R., 1983. The stratigraphy of western Irian Jaya. *Bulletin Geological Research and Development Centre, Bandung* 8, 14–48.
- Pigram, C.J., Panggabean, H., 1984. Rifting of the northern margin of the Australian continent and the origin of some microcontinents in eastern Indonesia. *Tectonophysics* 107, 331–353.
- Playford, P.E., 1980. Devonian Great Barrier Reef of Canning Basin, Western Australia. *American Association of Petroleum Geologists Bulletin* 64, 814–840.
- Polvé, M., Maury, R.C., Bellon, H., Rangin, C., Priadi, B., Yuwono, S., Joron, J.L., Atmadja, R.S., 1997. Magmatic evolution of Sulawesi (Indonesia): constraints on the Cenozoic geodynamic history of the Sundaland active margin. *Tectonophysics* 272, 69–92.
- Polvé, M., Maury, R.-C., Vidal, P., Priadi, B., Bellon, H., Soeria-Atmadja, R., Joron, J.-L., Cotten, J., 2001. Melting of lower continental crust in a young post-collision setting: a geochemical study of Plio–Quaternary acidic magmatism from central Sulawesi (Indonesia). *Bulletin de la Société Géologique de France* 172, 333–342.
- Powell, T.S., Luyendyk, B.P., 1982. The sea-floor spreading history of the eastern Indian Ocean. *Marine Geophysical Researches* 5, 225–247.
- Powell, C.M., Roots, S.R., Veevers, J.J., 1988. Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean. *Tectonophysics* 155, 261–283.

- Priadi, B., Polve, M., Maury, R., Soeria-Atmadja, R., Bellon, H., 1993. Geodynamic implications of Neogene potassic calc alkaline magmatism in central of Sulawesi: geochemical and isotopic constraints. *Proceedings of the 22nd Annual Convention of the Indonesian Association of Geologists (IAGI)*, pp. 59–81.
- Priadi, B., Polve, M., Maury, R.C., Bellon, H., Soeria-Atmadja, R., Joron, J.L., Cotten, J., 1994. Tertiary and Quaternary magmatism in Central Sulawesi: chronological and petrological constraints. *Journal of Southeast Asian Earth Sciences* 9, 81–93.
- Pulunggono, A., Cameron, N.R., 1984. Sumatran microplates, their characteristics and their role in the evolution of the Central and South Sumatra Basins. *Proceedings Indonesian Petroleum Association 13th Annual Convention*, pp. 121–144.
- Queano, K.L., Ali, J.R., Milsom, J., Aitchison, J.C., Pubellier, M., 2007. North Luzon and the Philippine Sea Plate motion model: insights following paleomagnetic, structural, and age-dating investigations. *Journal of Geophysical Research* 112, B05101. <http://dx.doi.org/10.1029/2006JB004506>.
- Replumaz, A., Tapponnier, P., 2003. Reconstruction of the deformed collision zone between India and Asia by backward motion of lithospheric blocks. *Journal of Geophysical Research* 108. <http://dx.doi.org/10.1029/2001JB000661>.
- Replumaz, A., Karason, H., van der Hilst, R.D., Besse, J., Tapponnier, P., 2004. 4-D evolution of SE Asia's mantle from geological reconstructions and seismic tomography. *Earth and Planetary Science Letters* 221, 103–115.
- Richards, S., Lister, G., Kennett, B., 2007. A slab in depth: three-dimensional geometry and evolution of the Indo-Australian plate. *Geochemistry, Geophysics, Geosystems* 8. <http://dx.doi.org/10.1029/2007GC001657>.
- Ricou, L.E., 1994. Tethys reconstructed—plates, continental fragments and their boundaries since 260 Ma from Central America to Southeastern Asia. *Geodinamica Acta* 7, 169–218.
- Robb, M.S., Taylor, B., Goodliffe, A.M., 2005. Re-examination of the magnetic lineations of the Gasconne and Cuvier Abyssal Plains, off NW Australia. *Geophysical Journal International* 163, 42–55.
- Roggeveen, P.M., 1929. Jurassic in the island of Sumba. *Proceedings Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam* 32, 512–514.
- Rowley, D.B., 1996. Age of initiation of collision between India and Asia: a review of stratigraphic data. *Earth and Planetary Science Letters* 145, 1–13.
- Royer, J.-Y., Sandwell, D.T., 1989. Evolution of the eastern Indian Ocean since the Late Cretaceous: constraints from Geosat altimetry. *Journal of Geophysical Research* 94, 13755–13782.
- Rutten, M.G., 1940. On Devonian limestones with *Clathrodictyon* cf. *spatiosum* and *Heliolites porosus* from eastern Borneo. *Proceedings Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam* 43, 1061–1064.
- Samuel, M.A., Harbury, N.A., Bakri, A., Banner, F.T., Hartono, L., 1997. A new stratigraphy for the islands of the Sumatran Forearc, Indonesia. *Journal of Asian Earth Sciences* 15, 339–380.
- Sandwell, D.T., Smith, W.H.F., 2009. Global marine gravity from retracked Geosat and ERS-1 altimetry: ridge segmentation versus spreading rate. *Journal of Geophysical Research* 114, B01411. <http://dx.doi.org/10.1029/2008JB006008>.
- Satyabala, S.P., 1998. Subduction in the Indo-Burma region: is it still active? *Geophysical Research Letters* 25, 3189–3192.
- Satyabala, S.P., 2000. Reply to comment on “Subduction in the Indo-Burma region: is it still active?” by S. Satyabala. *Geophysical Research Letters* 27, 1067–1068.
- Satyaana, A.H., Silitonga, P.D., 1994. Tectonic reversal in East Barito Basin, South Kalimantan: consideration of the types of inversion structures and petroleum significance. *Proceedings Indonesian Petroleum Association 23rd Annual Convention*, pp. 57–74.
- Schiller, D.M., Garrad, R.A., Prasetyo, L., 1991. Eocene submarine fan sedimentation in southwest Java. *Proceedings Indonesian Petroleum Association 20th Annual Convention*, pp. 125–182.
- Schöffel, H.J., Das, S., 1999. Fine details of the Wadati-Benioff zone under Indonesia and its geodynamic implications. *Journal of Geophysical Research* 104, 13101–13114.
- Scotney, P.M., Roberts, S., Herrington, R.J., Boyce, A.J., Burgess, R., 2005. The development of volcanic hosted massive sulfide and barite gold orebodies on Wetar Island, Indonesia. *Mineralium Deposita* 40, 76–99.
- Sengör, A.M.C., 1987. Tectonics of the Tethysides: orogenic collage development in a collisional setting. *Annual Reviews of Earth and Planetary Sciences* 15, 213–244.
- Setiawan, B., Le Bel, L.M., 1987. Discovery of a new tin province, Long Laai area, east Kalimantan, Indonesia. In: Hutchison, C.S. (Ed.), *Exploration and evaluation techniques for Tin/Tungsten granites in Southeast Asia and the western Pacific region*. *Proceedings of ICGP Project 220 Meeting*, September 1986, SEATRAD Centre, Ipoh, Malaysia, pp. 61–82.
- Sevastjanova, I., Clements, B., Hall, R., Belousova, E.A., Griffin, W.L., Pearson, N., 2011. Granitic magmatism, basement ages, and provenance indicators in the Malay Peninsula: insights from detrital zircon U–Pb and Hf-isotope data. *Gondwana Research* 19, 1024–1039.
- Sewell, R.J., Campbell, S.D.G., Fletcher, C.J.N., Lai, K.W., Kirk, P.A., 2000. The Pre-Quaternary Geology of Hong Kong. *Hong Kong Geological Survey, Geological Memoir* 181 pp.
- Shreider, A.A., Stenszinski, S.B., Lygin, V.A., 1996. Chronology of the bottom of the Wharton Basin. *Physics of the Solid Earth* 31, 864–869.
- Sikumbang, N., 1986. Geology and tectonics of Pre-Tertiary rocks in the Meratus Mountains, South-East Kalimantan, Indonesia. PhD Thesis, University of London 401 pp.
- Sikumbang, N., 1990. The Geology and tectonics of the Meratus Mountains, South Kalimantan, Indonesia. *Geologi Indonesia. Journal of the Indonesian Association of Geologists* 13, 1–31.
- Smith, A.G., 2006. Tethyan ophiolite emplacement, Africa to Europe motions, and Atlantic spreading. In: Robertson, A.H.F., Mountakis, D. (Eds.), *Tectonic Development of the Eastern Mediterranean Region*. *Geological Society of London Special Publication* 260, 11–34.
- Smith, C.B., Bulanova, G.P., Kohn, S.C., Milledge, J., Hall, A.E., Griffin, B.J., Pearson, G., 2009. Nature and genesis of Kalimantan diamonds. *Lithos* 112S, 822–832.
- Smyth, H.R., 2005. Eocene to Miocene basin history and volcanic history in East Java, Indonesia. PhD Thesis, University of London, 476 pp.
- Smyth, H.R., Hamilton, P.J., Hall, R., Kinny, P.D., 2007. The deep crust beneath island arcs: inherited zircons reveal a Gondwana continental fragment beneath East Java, Indonesia. *Earth and Planetary Science Letters* 258, 269–282.
- Smyth, H.R., Hall, R., Nichols, G.J., 2008. Early Cenozoic volcanic arc history of East Java, Indonesia: the stratigraphic record of eruptions on a continental margin in a tropical setting. In: Draut, A.E., Clift, P.D., Scholl, D.W. (Eds.), *Formation and Applications of the Sedimentary Record in Arc Collision Zones*. *Geological Society America Special Publication* 436, 199–222.
- Sone, M., Metcalfe, I., 2008. Parallel Tethyan sutures in mainland Southeast Asia: new insights for Palaeo-Tethys closure and implications for the Indosinian orogeny. *Comptes Rendus Geosciences* 340, 166–179.
- Spakman, W., Hall, R., 2010. Surface deformation and slab–mantle interaction during Banda Arc subduction rollback. *Nature Geoscience* 3, 562–566. <http://dx.doi.org/10.1038/ngeo917>.
- Spencer, J.E., 2010. Structural analysis of three extensional detachment faults with data from the 2000 Space-Shuttle Radar Topography Mission. *GSA Today* 20, 4–10. <http://dx.doi.org/10.1130/GSATG59A>.
- Spencer, J.E., 2011. Gently dipping normal faults identified with Space Shuttle radar topography data in central Sulawesi, Indonesia, and some implications for fault mechanics. *Earth and Planetary Science Letters* 308, 267–276.
- Stille, H., 1945. Die tektonische Entwicklung der hinterindischen Festlands- und Inselgebiete. In: Stille, H., Lotze, F. (Eds.), *Die tektonische Entwicklung der pazifischen Randgebiete II*. *Geotektonische Forschungen* 7/8, 34–153.
- Sugiaman, F., Andria, L., 1999. Devonian carbonate of Telen River, East Kalimantan. *Berita Sedimentologi* 10, 18–19.
- Sukanto, R., 1975a. The structure of Sulawesi in the light of plate tectonics. *Regional Conference on the Geology and Mineral Resources of Southeast Asia*, Jakarta, 4–7 August 1975, pp. 121–141.
- Sukanto, R., 1975b. Geological map of Indonesia, Ujung Pandang 1:1,000,000. *Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung, Indonesia*.
- Sukanto, R., Supriatna, S., 1982. The geology of the Ujung Pandang, Benteng and Sinjai quadrangles, Sulawesi 1:250,000. *Geological Research and Development Centre, Bandung, Indonesia*, pp. 20.
- Sukanto, R., Westermann, G.E.G., 1993. Indonesia and Papua New Guinea. In: Westermann, G.E.G. (Ed.), *The Jurassic of the Circum-Pacific*. *Cambridge University Press*, pp. 181–193.
- Sukanto, R., Setyogroho, B., Atmawinata, S., Aziz, S., Jamal, B., Suharsono, Mangga, S.A., 1990. The Jurassic rocks in Indonesia. *Bulletin Geological Research and Development Centre Bandung Indonesia* 14, 1–16.
- Sutriyono, E., 1999. Structure and Thermochronology of the Bird's Head of Irian Jaya, Indonesia. PhD Thesis, La Trobe University, Australia, 321 pp.
- Tan, D.N.K., 1979. Lupa Valley, west Sarawak. *Geological Survey of Malaysia, Report* 13.
- Tan, D.N.K., 1982. Lubok Antu Melange, Lupa Valley, West Sarawak: a Lower Tertiary subduction complex. *Bulletin of the Geological Society of Malaysia* 15, 31–46.
- Tan, D.N.K., Lamy, J.M., 1990. Tectonic evolution of the NW Sabah continental margin since the Late Eocene. *Bulletin of the Geological Society of Malaysia* 27, 241–260.
- Tate, R.B., 1991. Cross-border correlation of geological formations in Sarawak and Kalimantan. *Bulletin of the Geological Society of Malaysia* 28, 63–96.
- Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea Basin. In: Hayes, D.E. (Ed.), *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2: Geophysical Monograph Series*, 27. *American Geophysical Union*, pp. 23–56.
- Taylor, W.R., Jaques, A.L., Ridd, M., 1990. Nitrogen-defect aggregation characteristics of some Australasian diamonds: time–temperature constraints on the source regions of pipe and alluvial diamonds. *American Mineralogist* 75, 1290–1310.
- Thorkelson, D.J., 1996. Subduction of diverging plates and the principles of slab window formation. *Tectonophysics* 255, 47–63.
- Thorkelson, D.J., Taylor, R.P., 1989. Cordilleran slab windows. *Geology* 17, 833–836.
- Thuy, N.T.B., Satir, M., Siebel, W., Venneman, T., Long, T.V., 2004. Geochemical and isotopic constraints on the petrogenesis of granitoids from the Dalat zone, southern Vietnam. *Journal of Asian Earth Sciences* 23, 467–482.
- Tokuyama, H., 1985. Dredged igneous rocks from the Amami Plateau. In: Shiki, T. (Ed.), *Geology of the Northern Philippine Sea*. *Tokai University Press*, pp. 50–56.
- van Bemmelen, R.W., 1949. *The Geology of Indonesia*. *Government Printing Office, Nijhoff, The Hague*. 732 pp.
- van der Voo, R., Spakman, W., Bijwaard, H., 1999. Tethyan subducted slabs under India. *Earth and Planetary Science Letters* 171, 7–20.
- van Hinsbergen, D.J.J., Kapp, P., Dupont-Nivet, G., Lippert, P.C., DeCelles, P.G., Torsvik, T.H., 2011a. Restoration of Cenozoic deformation in Asia and the size of Greater India. *Tectonics* 30, TC5003. <http://dx.doi.org/10.1029/2011TC002908>.
- van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P.V., Gassmüller, R., 2011b. Acceleration and deceleration of India–Asia convergence since the Cretaceous: roles of mantle plumes and continental collision. *Journal of Geophysical Research* 116, B06101. <http://dx.doi.org/10.1029/2010JB008051>.
- van Leeuwen, T.M., 1981. The geology of southwest Sulawesi with special reference to the Biru area. In: Barber, A.J., Wirjosujono, S. (Eds.), *The Geology and Tectonics of Eastern Indonesia: Geological Research and Development Centre, Bandung, Special Publication*, 2, pp. 277–304.
- van Leeuwen, T., Muhardjo, 2005. Stratigraphy and tectonic setting of the Cretaceous and Paleogene volcanic–sedimentary successions in northwest Sulawesi, Indonesia: implications for the Cenozoic evolution of Western and Northern Sulawesi. *Journal of Asian Earth Sciences* 25, 481–511.

- van Leeuwen, T.M., Allen, C.M., Kadarusman, A., Elburg, M., Michael Palin, J., Muhandjo, Suwijanto, 2007. Petrologic, isotopic, and radiometric age constraints on the origin and tectonic history of the Malino Metamorphic Complex, NW Sulawesi, Indonesia. *Journal of Asian Earth Sciences* 29, 751–777.
- Veevers, J.J., 1988. Morphotectonics of Australia's northwestern margin—a review. In: Purcell, P.G., Purcell, R.R. (Eds.), *The North West Shelf Proceedings of Petroleum Exploration Society of Australia Symposium*. PESA, Perth, WA, pp. 19–27.
- Veevers, J.J., Powell, C.M., Johnson, B.D., 1975. Greater India's place in Gondwanaland and in Asia. *Earth and Planetary Science Letters* 27, 383–387.
- Visser, W.A., Hermes, J.J., 1962. Geological results of the exploration for oil in Netherlands New Guinea. *Verhandelingen Koninklijk Nederlands Geologisch en Mijnbouwkundig Genootschap, Geologische Serie* 20, 1–265.
- Wajzer, M.R., Barber, A.J., Hidayat, S., Suharsono, 1991. Accretion, collision and strike-slip faulting: the Woyla Group as a key to the tectonic evolution of North Sumatra. *Journal of Southeast Asian Earth Sciences* 6, 447–461.
- Wakita, K., 2000. Cretaceous accretionary–collision complexes in central Indonesia. *Journal of Asian Earth Sciences* 18, 739–749.
- Wakita, K., Metcalfe, I., 2005. Ocean plate stratigraphy in East and Southeast Asia. *Journal of Asian Earth Sciences* 24, 679–702.
- Wakita, K., Munasari, S.J., Zulkarnain, I., Miyazaki, K., 1994a. Early Cretaceous tectonic events implied in the time-lag between age of radiolarian chert and its metamorphic basement in the Bantimala area, South Sulawesi, Indonesia. *The Island Arc* 3, 90–102.
- Wakita, K., Munasri, Widoyoko, B., 1994b. Cretaceous radiolarians from the Luk-Ulo Melange Complex in the Karangsambung area, Central Java, Indonesia. *Journal of Southeast Asian Earth Sciences* 9, 29–43.
- Wakita, K., Sopaheluwakan, J., Miyazaki, K., Zulkarnain, I., Munasri, 1996. Tectonic evolution of the Bantimala Complex, South Sulawesi, Indonesia. In: Hall, R., Blundell, D.J. (Eds.), *Tectonic evolution of SE Asia*. Geological Society of London Special Publication 106, 353–364.
- Wakita, K., Miyazaki, K., Zulkarnain, I., Sopaheluwakan, J., Sanyoto, P., 1998. Tectonic implications of new age data for the Meratus complex of south Kalimantan, Indonesia. *Island Arc* 7, 202–222.
- Watkinson, I., Elders, C., Hall, R., 2008. The kinematic history of the Khlong Marui and Ranong Faults, southern Thailand. *Journal of Structural Geology* 30, 1554–1571.
- Watkinson, I., Elders, C., Batt, G., Jourdan, F., Hall, R., McNaughton, N.J., 2011a. The timing of strike-slip shear along the Ranong and Khlong Marui faults, Thailand. *Journal of Geophysical Research* 116, B09403. <http://dx.doi.org/10.1029/2011jb008379>.
- Watkinson, I.M., Hall, R., Ferdian, F., 2011b. Tectonic re-interpretation of the Banggai-Sula–Molucca Sea margin, Indonesia. In: Hall, R., Cottam, M.A., Wilson, M.E.J. (Eds.), *The SE Asian Gateway: History and Tectonics of the Australia-Asia collision*. Geological Society of London Special Publication 355, 203–224.
- Wensink, H., 1994. Paleomagnetism of rocks from Sumba: tectonic implications since the Late Cretaceous. *Journal of Southeast Asian Earth Sciences* 9, 51–65.
- Whittaker, J.M., Müller, R.D., Sdrolias, M., Heine, C., 2007. Sunda-Java trench kinematics, slab window formation and overriding plate deformation since the Cretaceous. *Earth and Planetary Science Letters* 255, 445–457.
- Williams, P.R., Johnston, C.R., Almond, R.A., Simamora, W.H., 1988. Late Cretaceous to Early Tertiary structural elements of West Kalimantan. *Tectonophysics* 148, 279–298.
- Witts, D., Hall, R., Morley, R.J., BouDagher-Fadel, M.K., 2011. Stratigraphy and sediment provenance, Barito basin, Southeast Kalimantan. *Proceedings Indonesian Petroleum Association 35th Annual Convention*, IPA11-G-054 1–18.
- Wolfenden, E.B., 1960. *The Geology and Mineral Resources of the Lower Rajang Valley and Adjoining Areas, Sarawak*. British Territories Borneo Region Geological Survey Department, Memoir, 11. 167 pp.
- Wood, R., 2000. Palaeoecology of a Late Devonian back reef: Canning Basin, Western Australia. *Palaeontology* 43, 671–703.
- Yang, J.-H., Wu, F.-Y., Chung, S.-L., Lo, C.-H., Wilde, S.A., Davis, G.A., 2007. Rapid exhumation and cooling of the Liaonan metamorphic core complex: inferences from $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology and implications for Late Mesozoic extension in the eastern North China Craton. *Bulletin of the Geological Society of America* 119, 1405–1414.
- Yumul, G.P., Dimalanta, C.B., Tamayo, R.A., Zhou, M.F., 2006. Geology and geochemistry of the Rapu-Rapu Ophiolite Complex, Eastern Philippines: possible fragment of the Proto-Philippine Sea Plate. *International Geology Review* 48, 329–348.
- Yumul, G.P., Dimalanta, C.B., Maglambayan, V.B., Marquez, E.J., 2008. Tectonic setting of a composite terrane: a review of the Philippine island arc system. *Geosciences Journal* 12, 7–17.
- Yumul, G.P., Dimalanta, C.B., Marquez, E.J., Queaño, K.L., 2009. Onland signatures of the Palawan microcontinental block and Philippine mobile belt collision and crustal growth process: a review. *Journal of Asian Earth Sciences* 34, 610–623.
- Yuwono, Y.S., Bellon, H., Maury, R.C., Soeria-Atmadja, R., 1988a. Tertiary and Quaternary geodynamic evolution of S Sulawesi: constraints from the study of volcanic units. *Geologi Indonesia* 13, 32–48.
- Yuwono, Y.S., Priyomarsono, S., Maury, R.C., Rampnoux, J.P., Soeria, A.R., Bellon, H., Chotin, P., 1988b. Petrology of the Cretaceous magmatic rocks from Meratus Range, Southeast Kalimantan. *Journal of Southeast Asian Earth Sciences* 2, 15–22.
- Zhou, D., Sun, Z., Chen, H., Xu, H., Wang, W., Pang, X., Cai, D., Hu, D., 2008. Mesozoic paleogeography and tectonic evolution of South China Sea and adjacent areas in the context of Tethyan and Paleo-Pacific interconnections. *Island Arc* 17, 186–207.