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

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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.

## Contents

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## 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 Ceno-Tethys, and tracing the subduction history of this oceanic crust

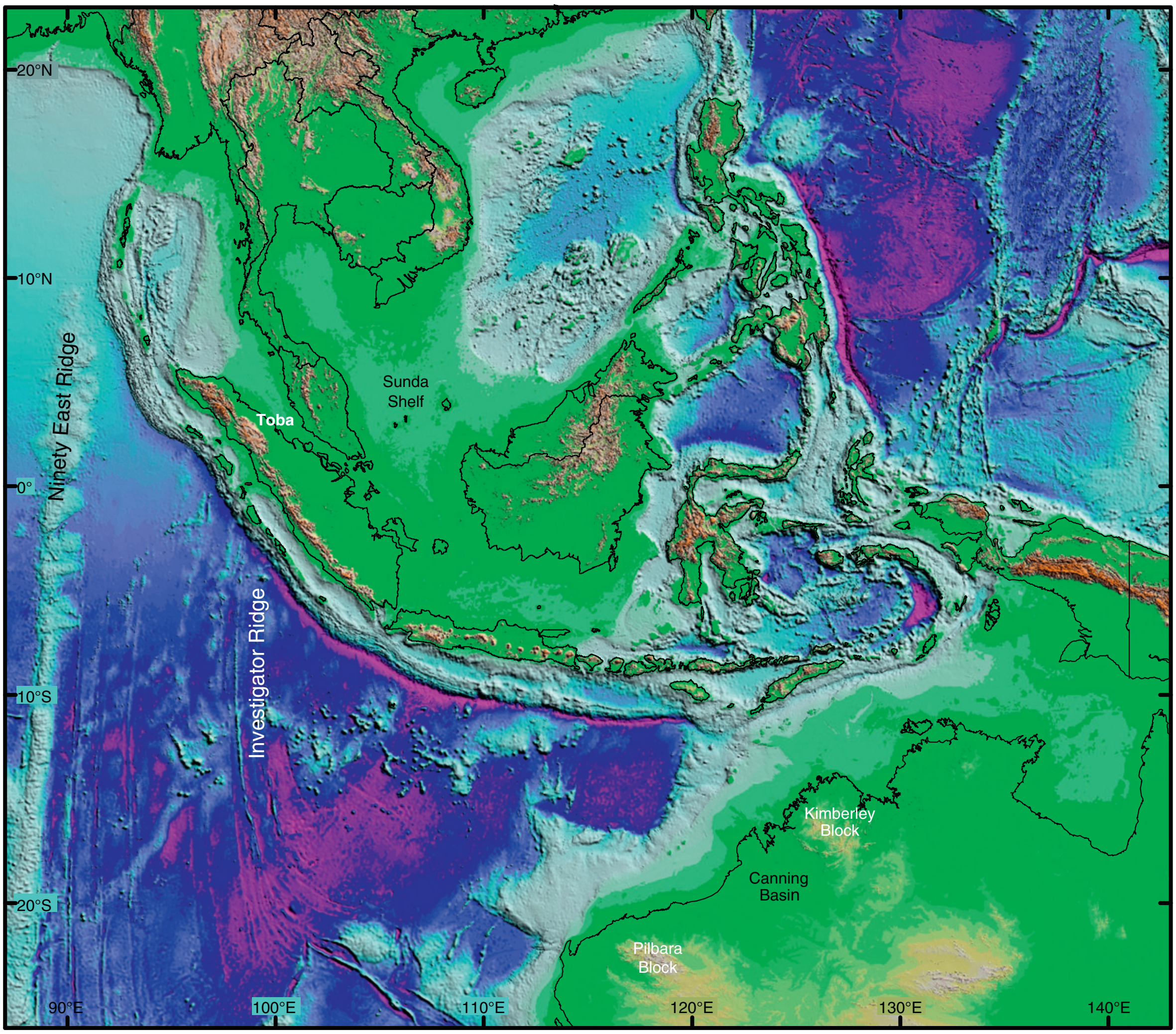

**Fig. 1.** DEM of the region including SE Asia, the Western Pacific, eastern Indian Ocean and Australia from satellite gravity-derived bathymetry combined with SRTM topography (Sandwell and Smith, 2009). The main geographical and tectonic features of the region are identified on Figs. 2, 3 and 4.

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

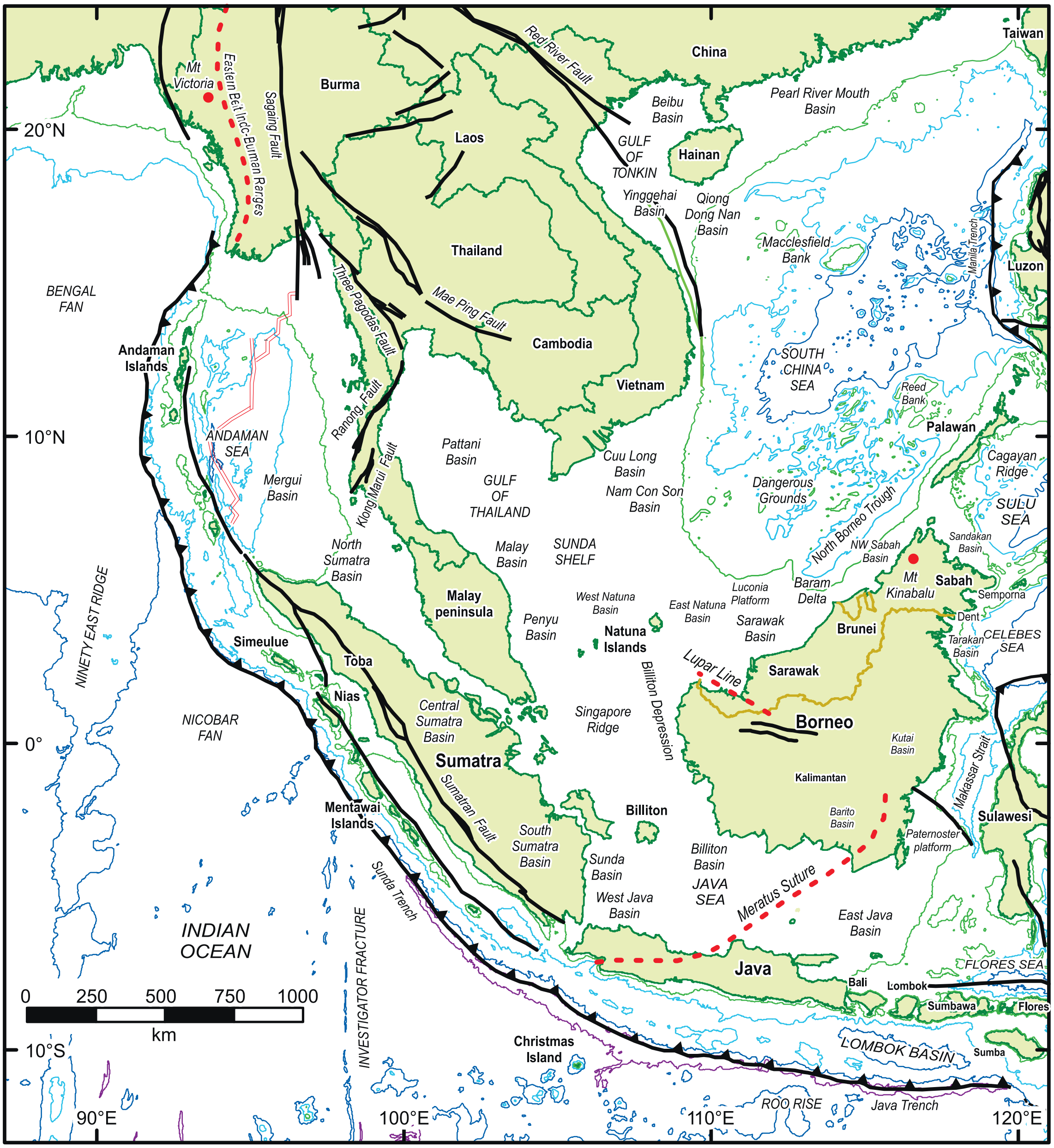

**Fig. 2.** Principal geographical and tectonic features of Indochina and the Sunda region. Bathymetry is from the GEBCO (2003) digital atlas with contours at 200 m, 2000 m, 4000 m and 6000 m. Double red line shows Andaman Sea spreading centre.

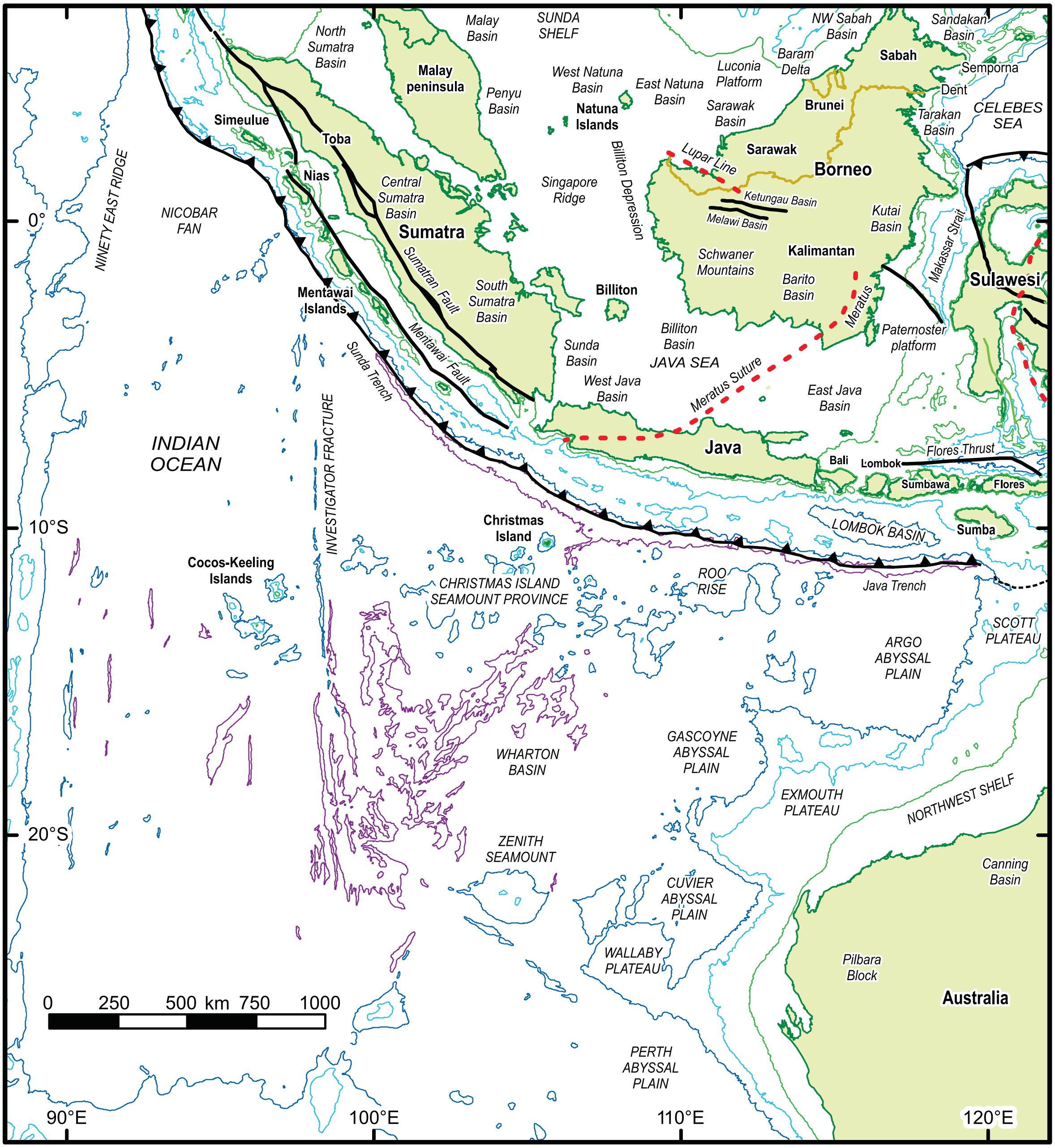

**Fig. 3.** Principal geographical and tectonic features of the eastern Indian Ocean and western Australia. Bathymetry is from the GEBCO (2003) digital atlas with contours at 200 m, 2000 m, 4000 m and 6000 m.

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 Metcalfe (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), Metcalfe (2011a,b) and

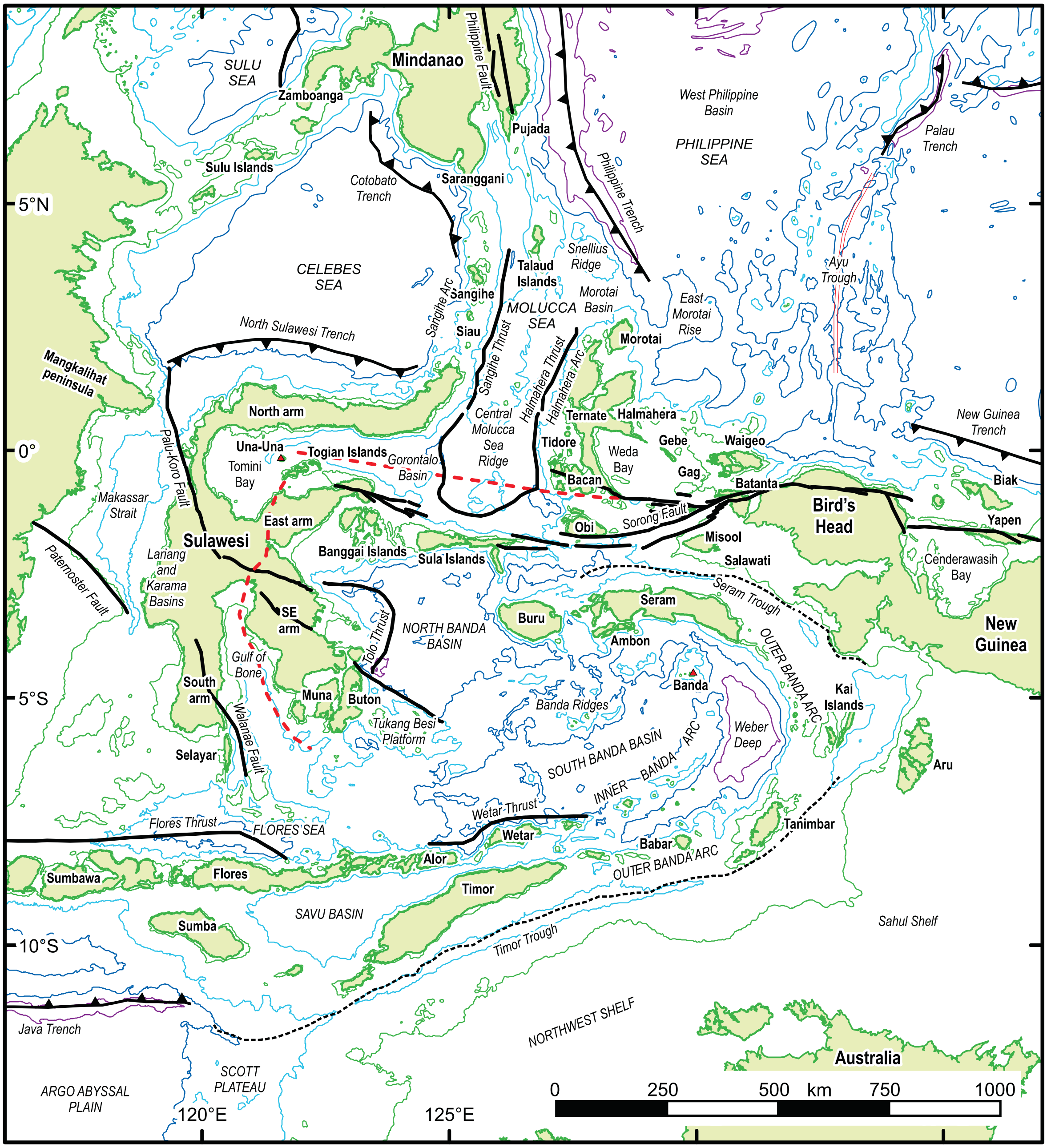

**Fig. 4.** Principal geographical features of the eastern Indonesia region. Bathymetry is from the GEBCO (2003) digital atlas with contours at 200 m, 2000 m, 4000 m and 6000 m. Double red line shows spreading centre in Ayu Trough. Dashed red line is approximate western and northern limit of Sulu Spur.

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

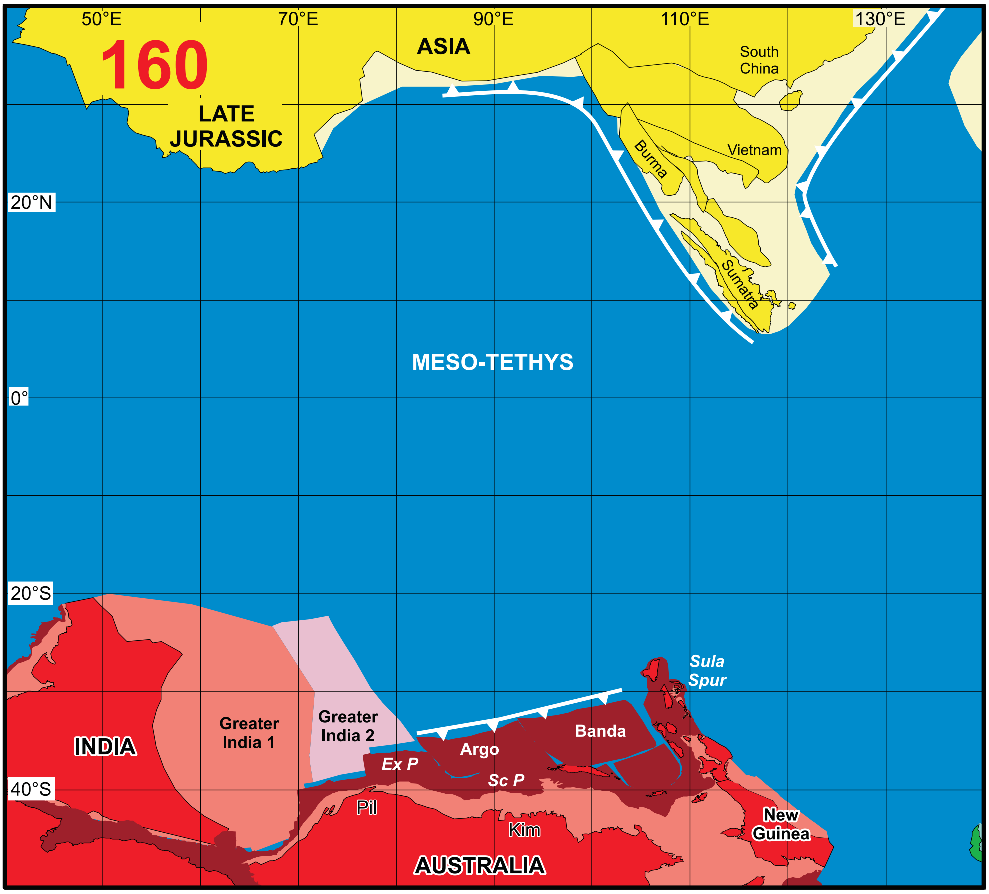

**Fig. 5.** Reconstruction at 160 Ma. On all reconstructions (Figs. 5 to 38) areas filled with green are mainly arc, ophiolitic, and accreted material formed at plate margins. Areas filled in cyan are submarine arc regions, hot spot volcanic products, and oceanic plateaus. Eurasian crust is coloured 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

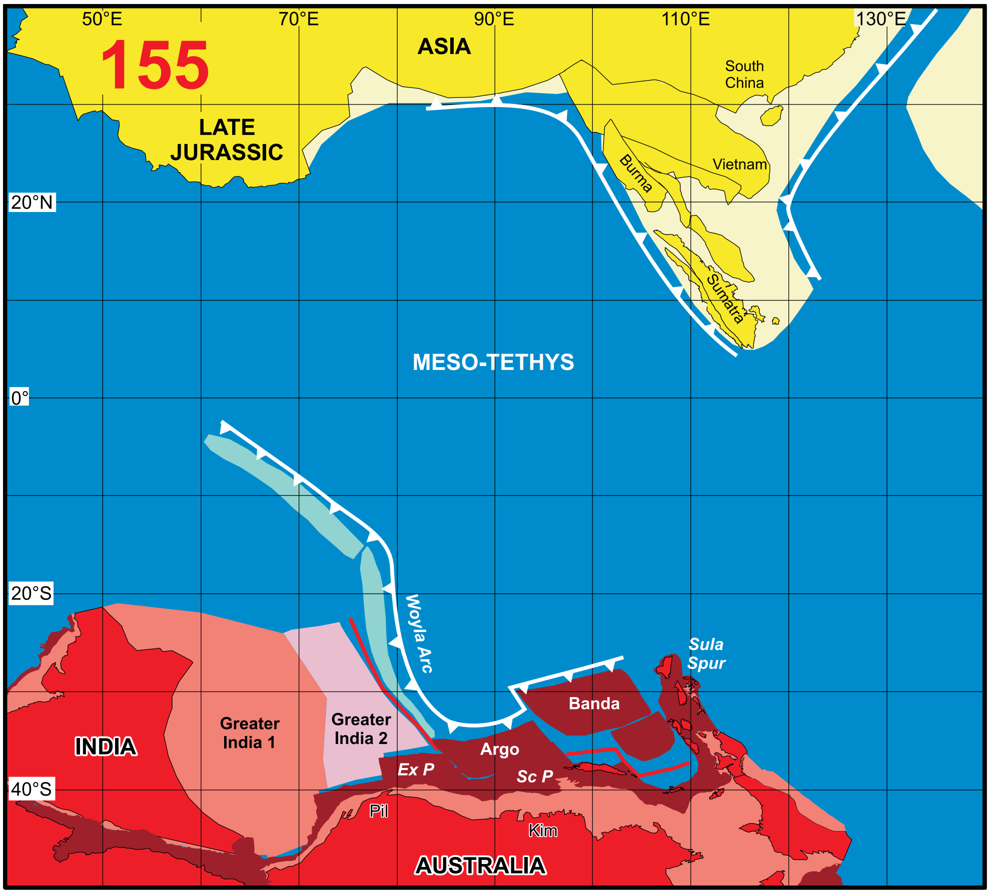

**Fig. 6.** Reconstruction at 155 Ma. Ocean spreading propagated east and the Woyla intra-oceanic arc formed either at the northern Indian margin, or within the Meso-Tethys north of India. The Tethyan oceans and continental margins west of about 80°E have not been reconstructed.

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 metasiltstones 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

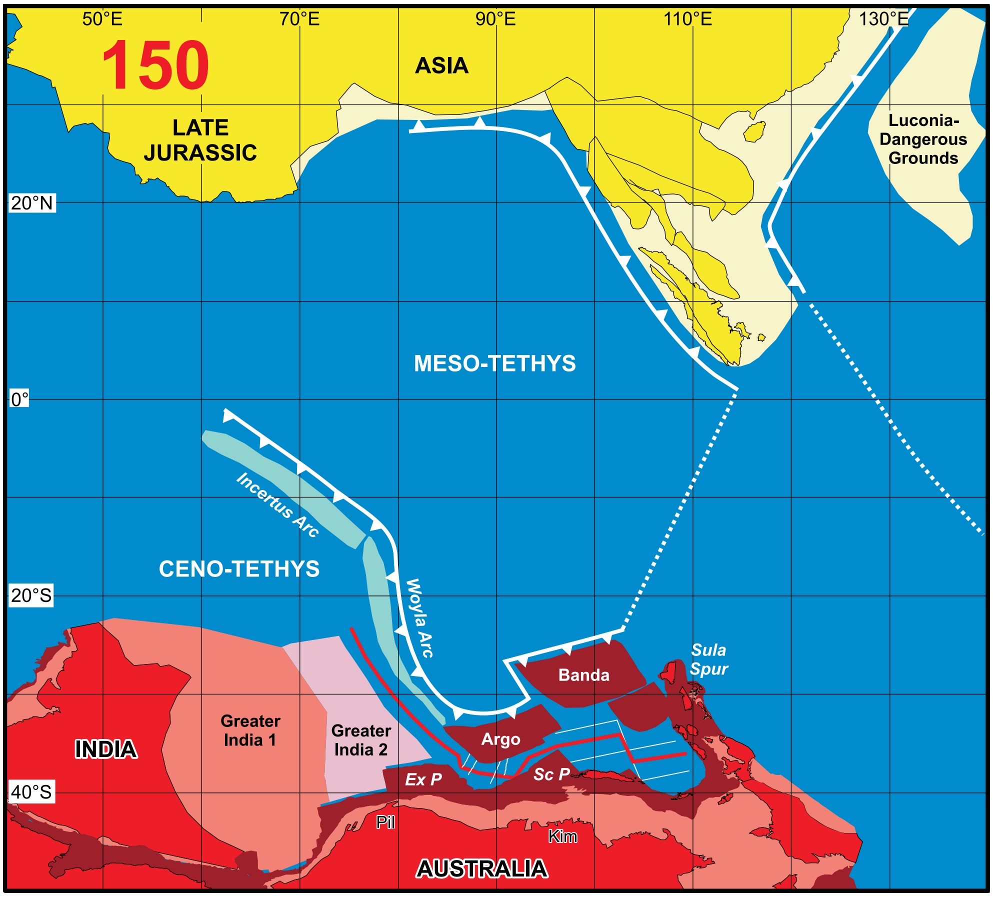

**Fig. 7.** Reconstruction at 150 Ma. The postulated eastward continuation of the Woyla intra-oceanic arc is named the Incertus Arc. Possible arc terranes that may correspond to this arc are now in Asia and are discussed in the text. Rifting of fragments from the Banda region left the Sula Spur north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

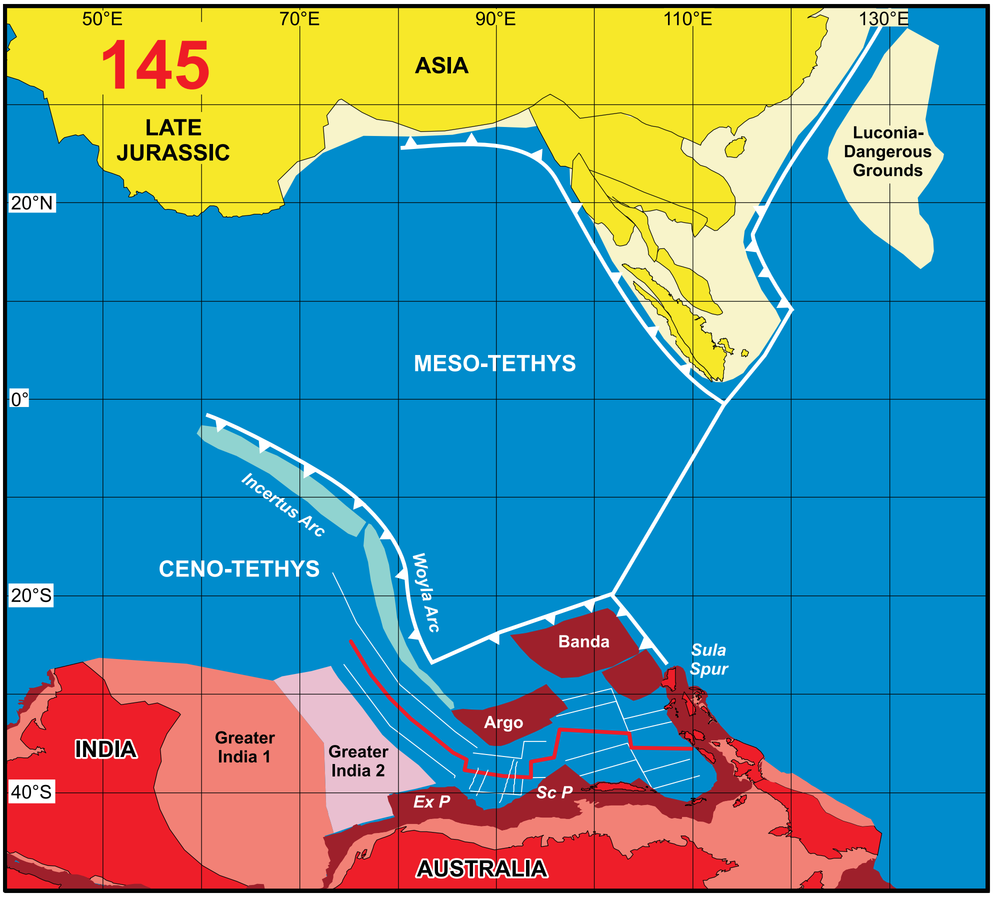

**Fig. 8.** Reconstruction at 145 Ma. The Woyla–Incertus Arc moved northward with the Australian continental Argo and Banda fragments as the Ceno-Tethys widened. In the western Pacific the Luconia–Dangerous Grounds continental fragment had rifted from the Asian margin but its position is very uncertain 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; Sukamto, 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 quartzo-feldspathic 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 (Sukamto and Westermann, 1993; Sukamto 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). $^3$He/$^4$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

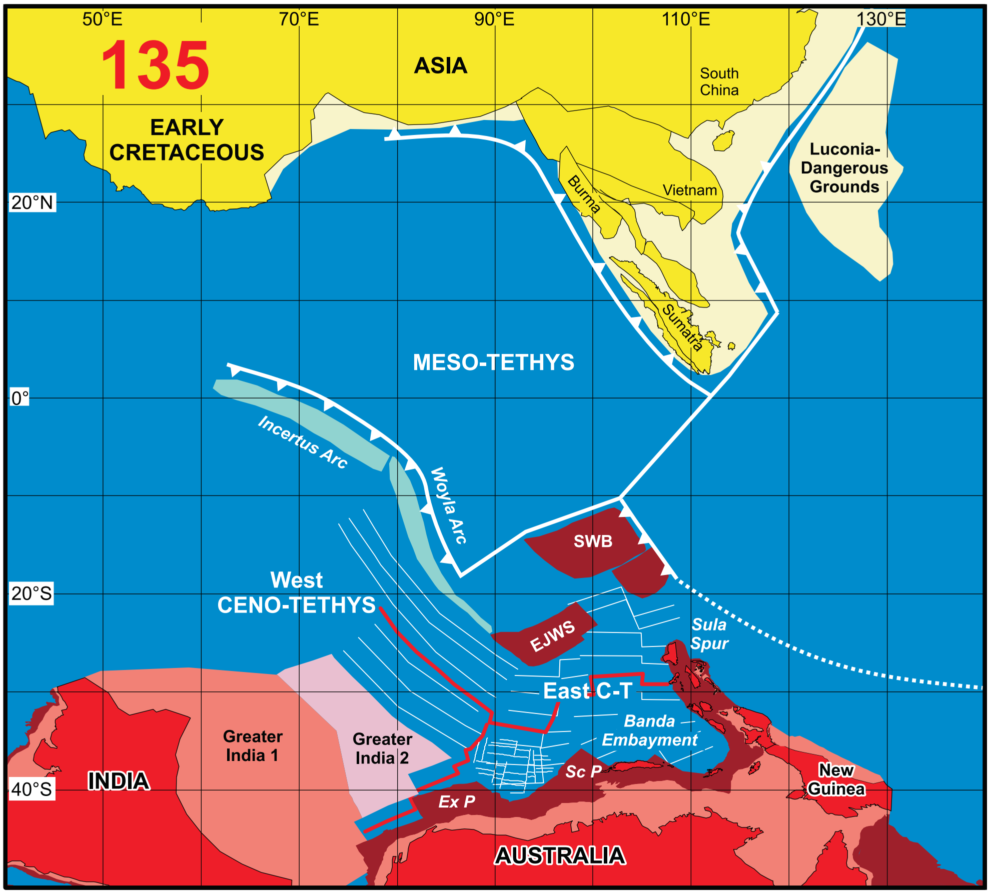

**Fig. 10.** Reconstruction at 135 Ma. A triple junction formed as India separated from Australia and divided the Ceno-Tethys into West and East (East C-T) parts. The Banda block is identified as SW Borneo (SWB) and the Argo block as East Java–West Sulawesi (EJWS) on this and subsequent figures.

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; Sukamto 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

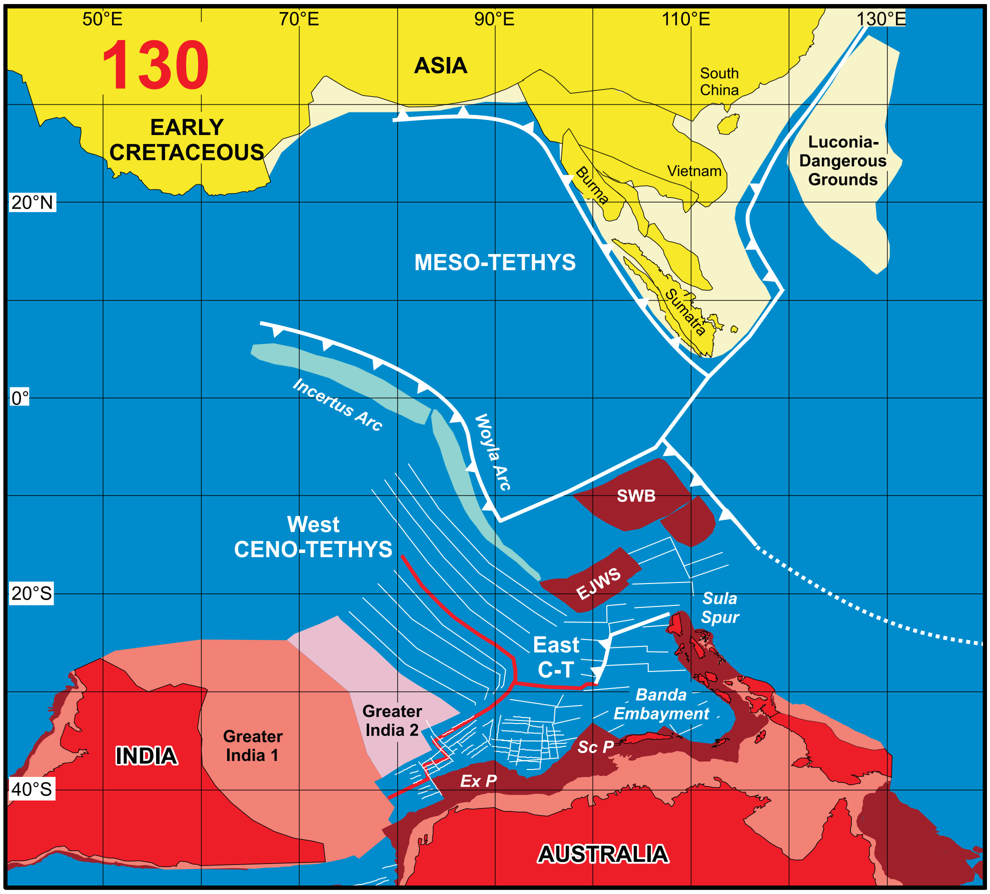

**Fig. 11.** Reconstruction at 130 Ma. After separation of India from Australia the SW Borneo (SWB) and East Java–West Sulawesi (EJWS) blocks moved NE. A short-lived episode of subduction in the East Ceno-Tethys (East C-T) is inferred for kinematic consistency.

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. Gorring 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

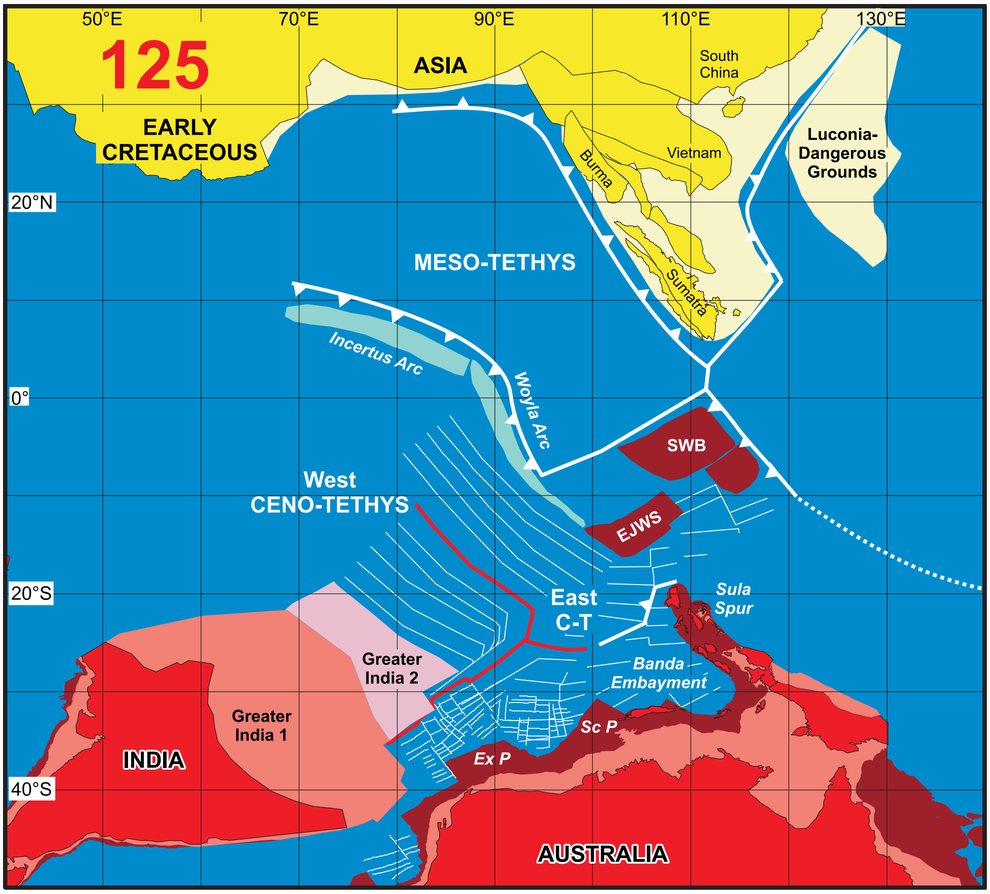

**Fig. 12.** Reconstruction at 125 Ma. The West Ceno-Tethys continued to widen while the East Ceno-Tethys (East C-T) became slightly smaller.

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

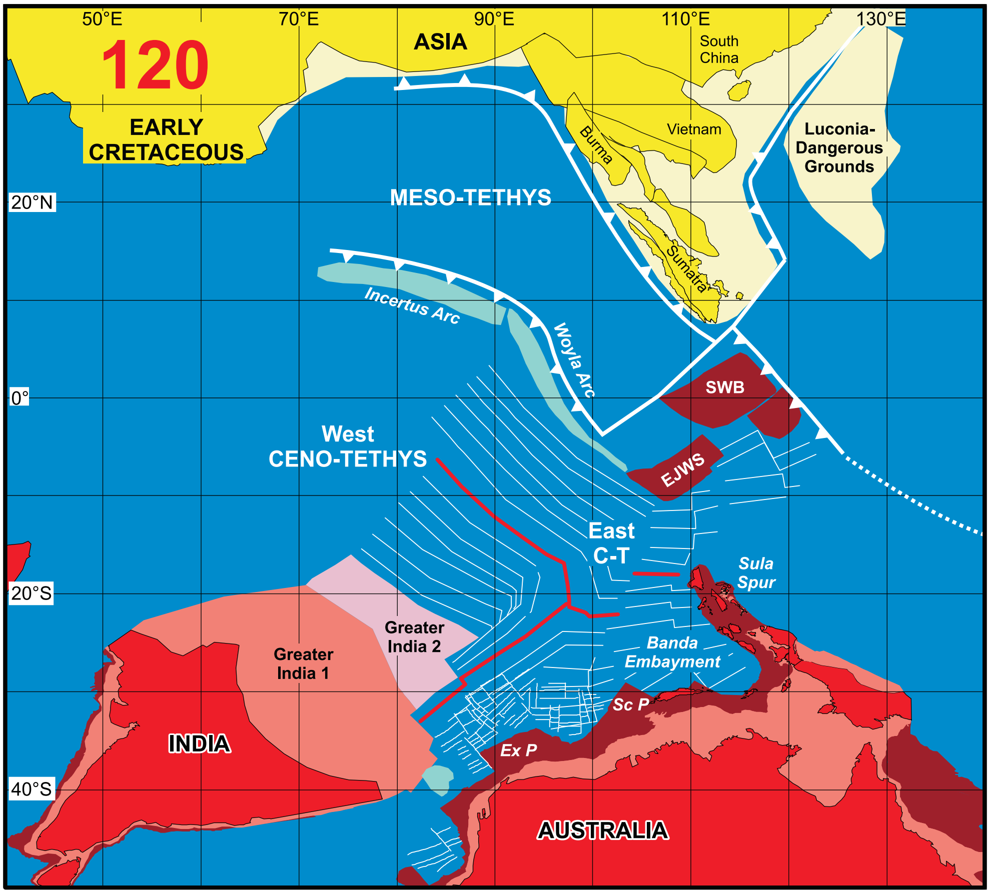

**Fig. 13.** Reconstruction at 120 Ma. SW Borneo (SWB) was close to the SE Asia Sundaland margin and is interpreted to have moved along a strike-slip boundary at the Billiton depression.

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

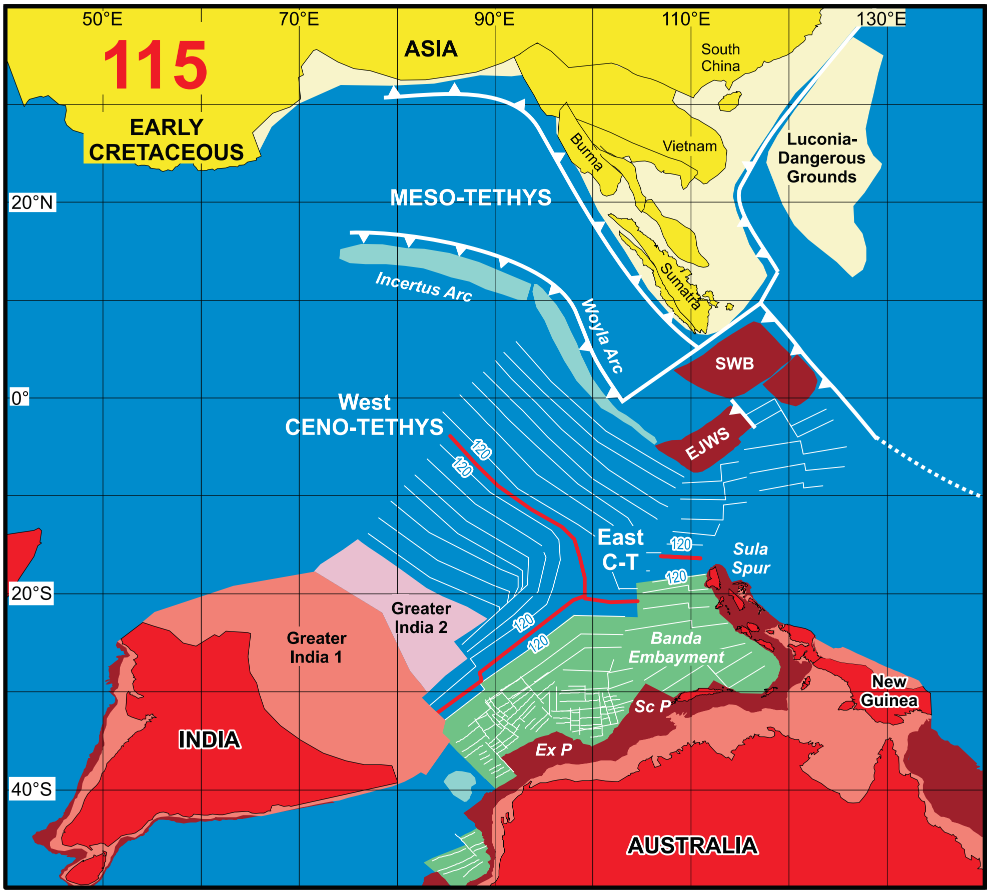

**Fig. 14.** Reconstruction at 115 Ma. SW Borneo (SWB) was close to its final position and subduction began between it and the East Java–West Sulawesi (EJWS) blocks based on metamorphic ages from the Meratus Suture in Java and SE Kalimantan. In the Ceno-Tethys selected anomalies are numbered with their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

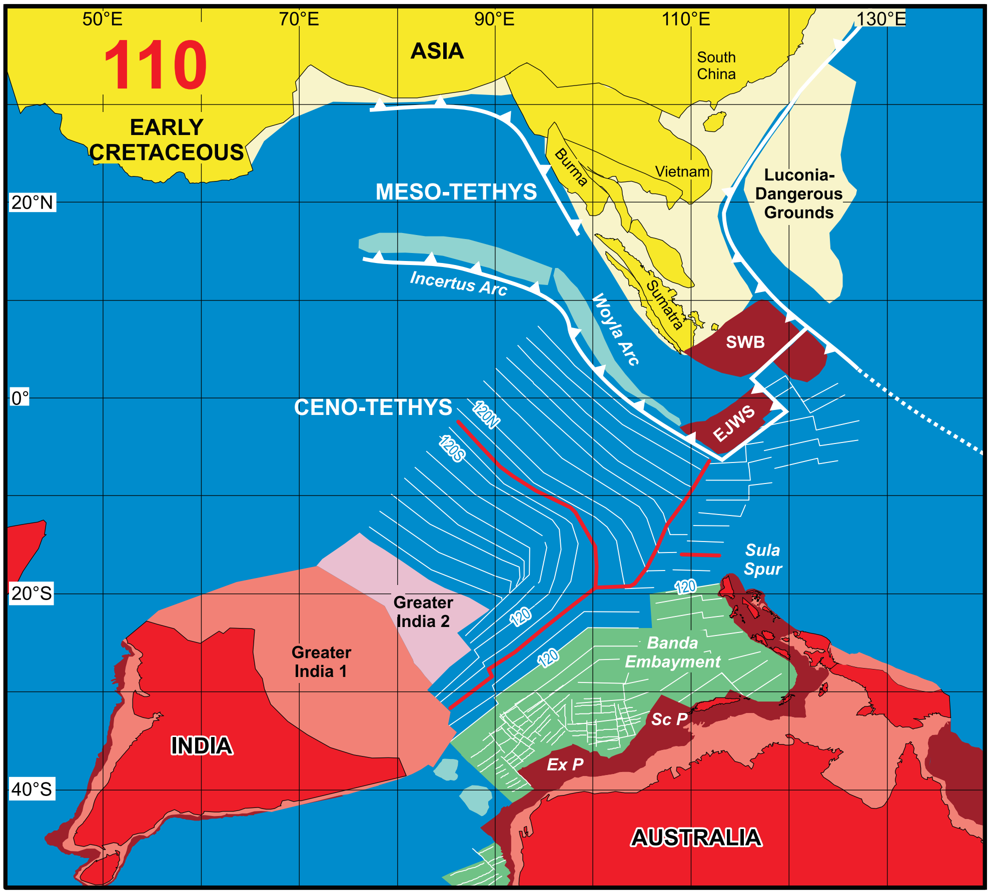

**Fig. 15.** Reconstruction at 110 Ma. SW Borneo (SWB) completed docking with the Sundaland margin. Spreading ended in the Ceno-Tethys between India and the Woyla–Incertus Arc. Subduction polarity flipped from south- to north-directed at the Woyla–Incertus Arc and the Ceno-Tethys began to subduct northwards.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

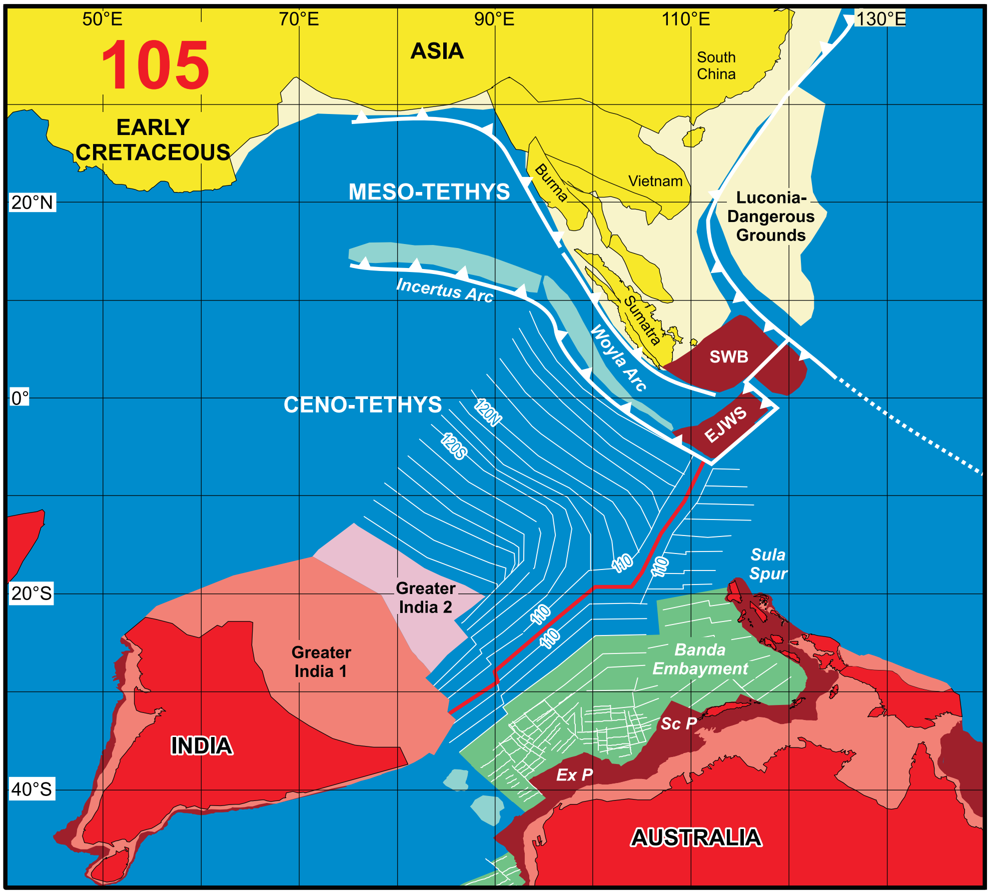

**Fig. 16.** Reconstruction at 105 Ma. East Java–West Sulawesi (EJWS) converged with SW Borneo (SWB). Spreading had ceased in the Ceno-Tethys between India and the Woyla–Incertus Arc but continued at the India-Australia spreading centre.

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

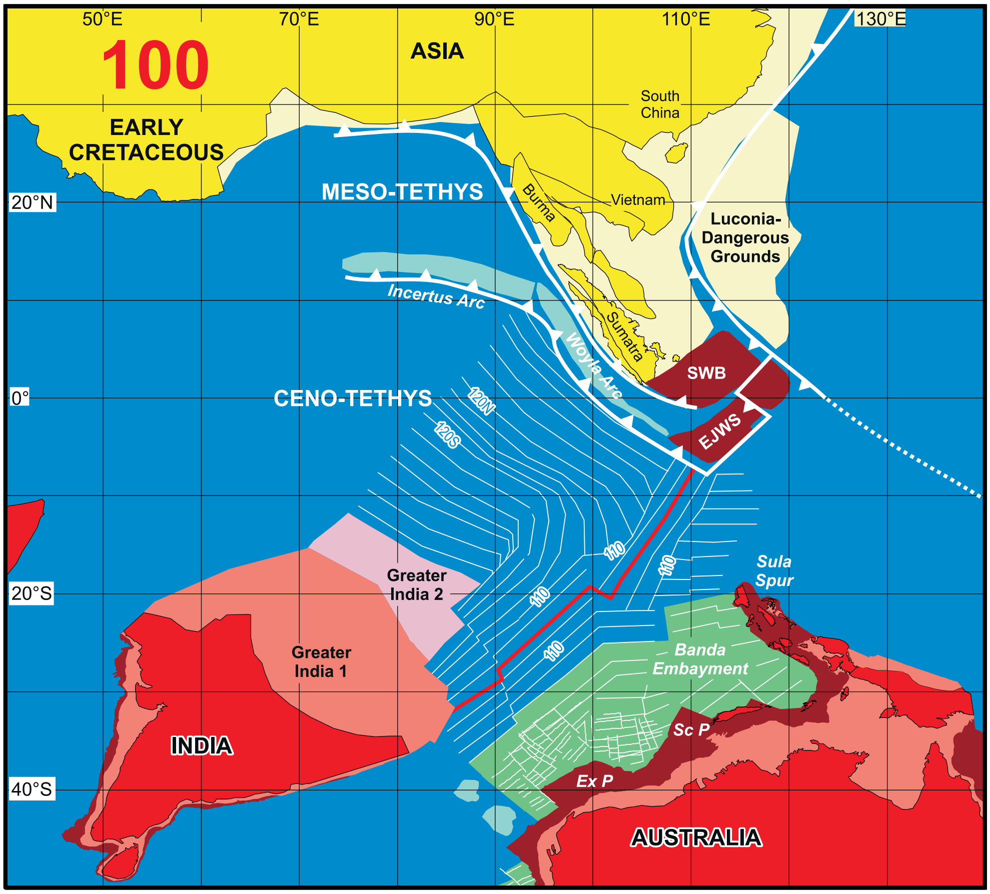

**Fig. 17.** Reconstruction at 100 Ma. The Ceno-Tethys was gradually reduced in area by subduction north of India but widened between India and Australia.

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

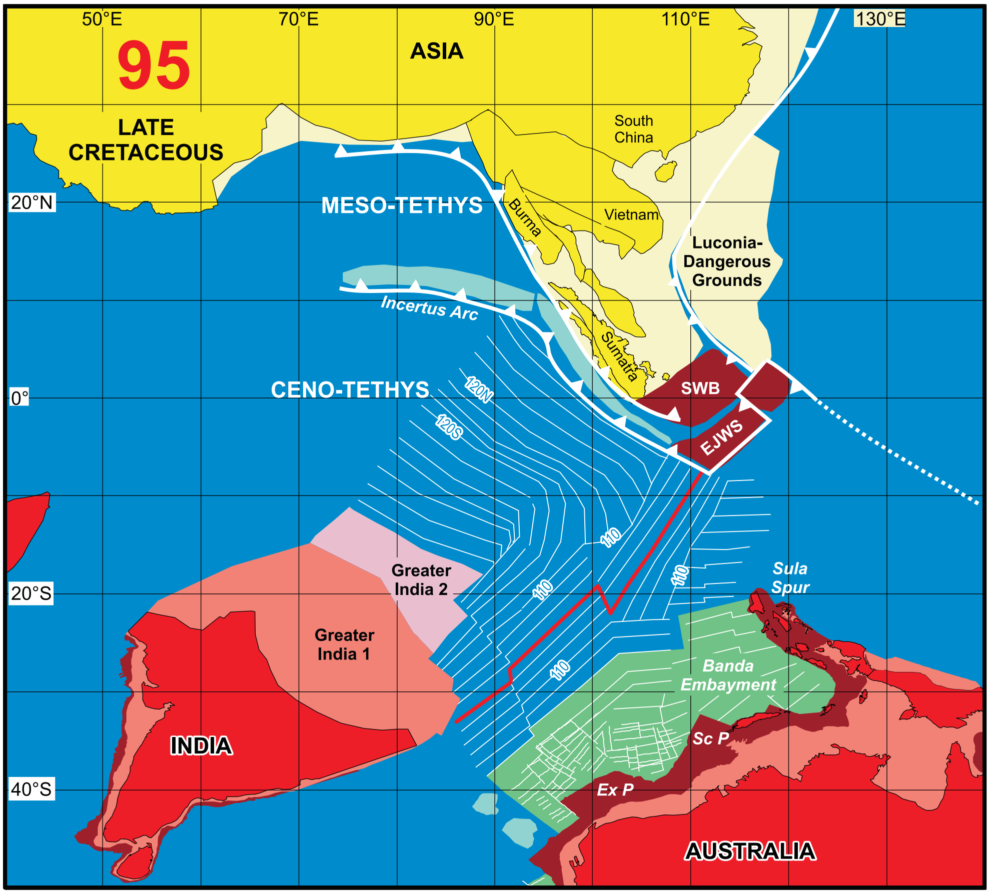

**Fig. 18.** Reconstruction at 95 Ma. The Ceno-Tethys continued to be subducted north of India but widened between India and Australia.

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.

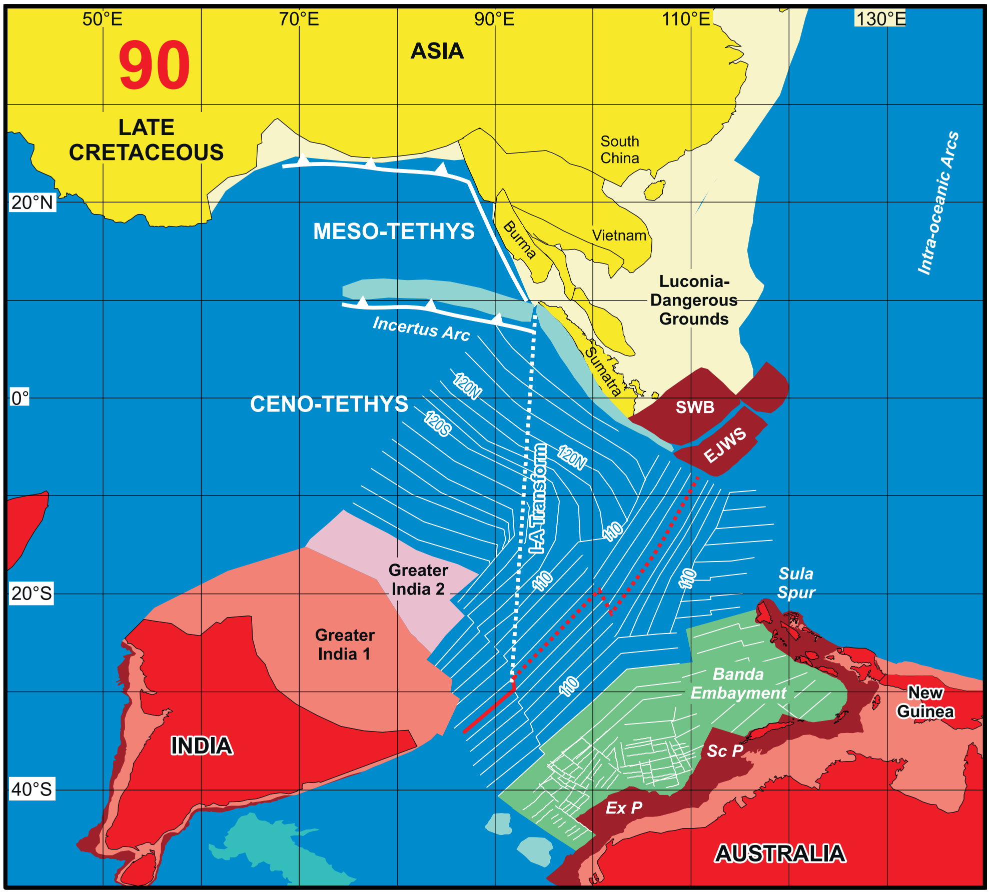

**Fig. 19.** Reconstruction at 90 Ma. There were major changes in the Ceno-Tethys and at its margins. The India-Australia spreading centre died and as India continued to move north a new transform was initiated to form the new India–Australia plate boundary. The Woyla Arc and East Java–West Sulawesi (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 from160 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

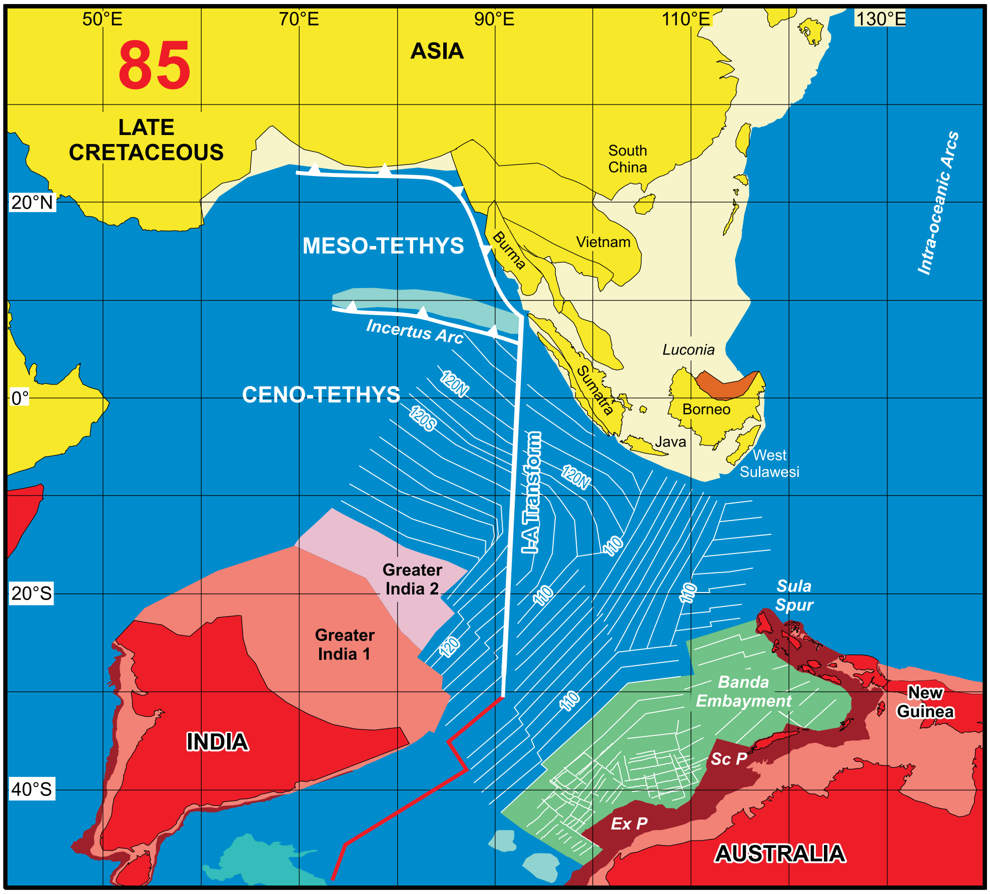

**Fig. 20.** Reconstruction at 85 Ma. Subduction had ceased all round Sundaland. India and Australia continued to separate by spreading on a ridge south of India with strike-slip motion along the I-A Transform.

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

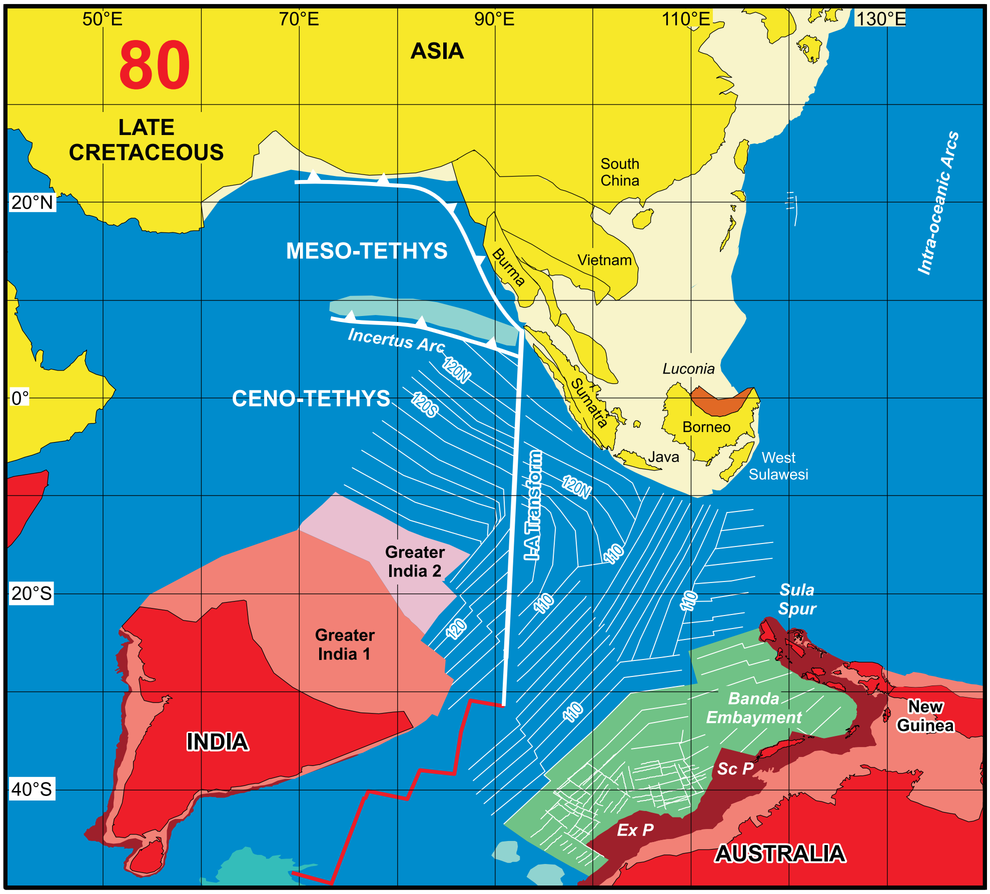

**Fig. 21.** Reconstruction at 80 Ma. India's rate of northward motion increased. Localised magmatic activity is known from the Bird's Head and central New Guinea during the Late Cretaceous. It seems unlikely that this was subduction-related but it may reflect strike-slip movements or extension within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

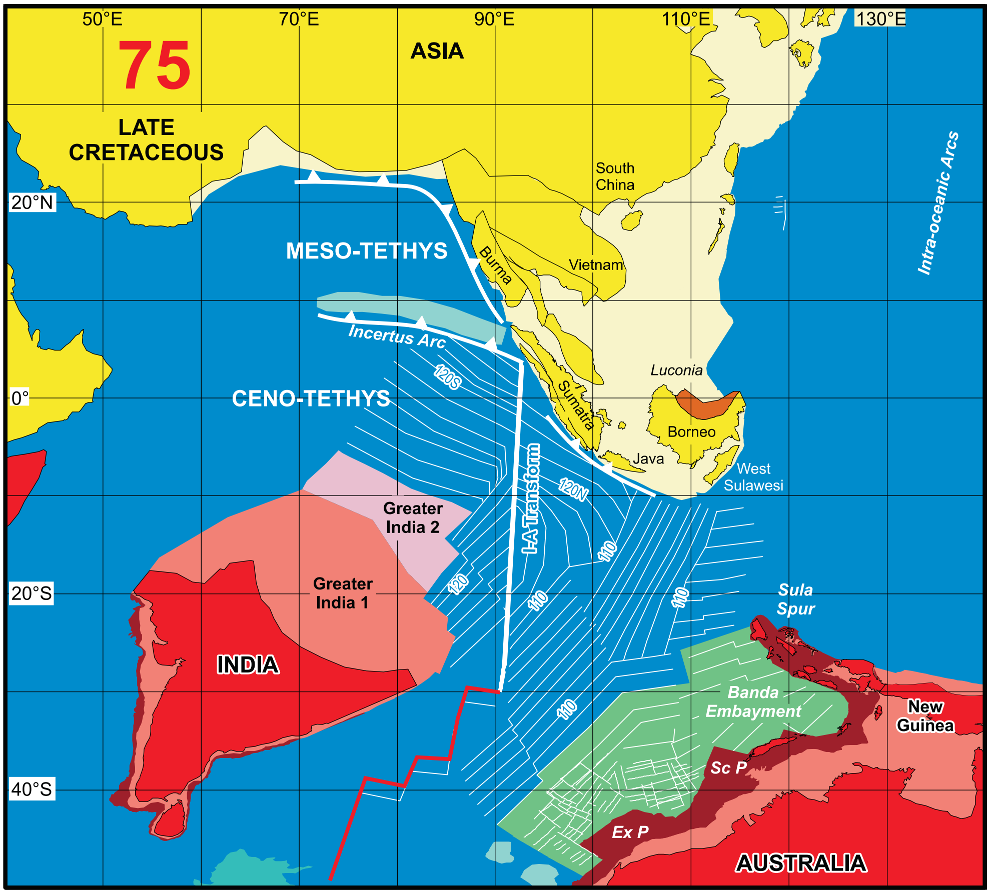

**Fig. 22.** Reconstruction at 75 Ma. India's rapid northward movement continued. During this interval there was no major northward movement of Australia relative to Sundaland but there could have been small amounts of localised subduction at the Sundaland margin between Sumatra and Java due to slow 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. Doutch, 1992; Gower, 1990; Haile, 1974; Williams et al.,

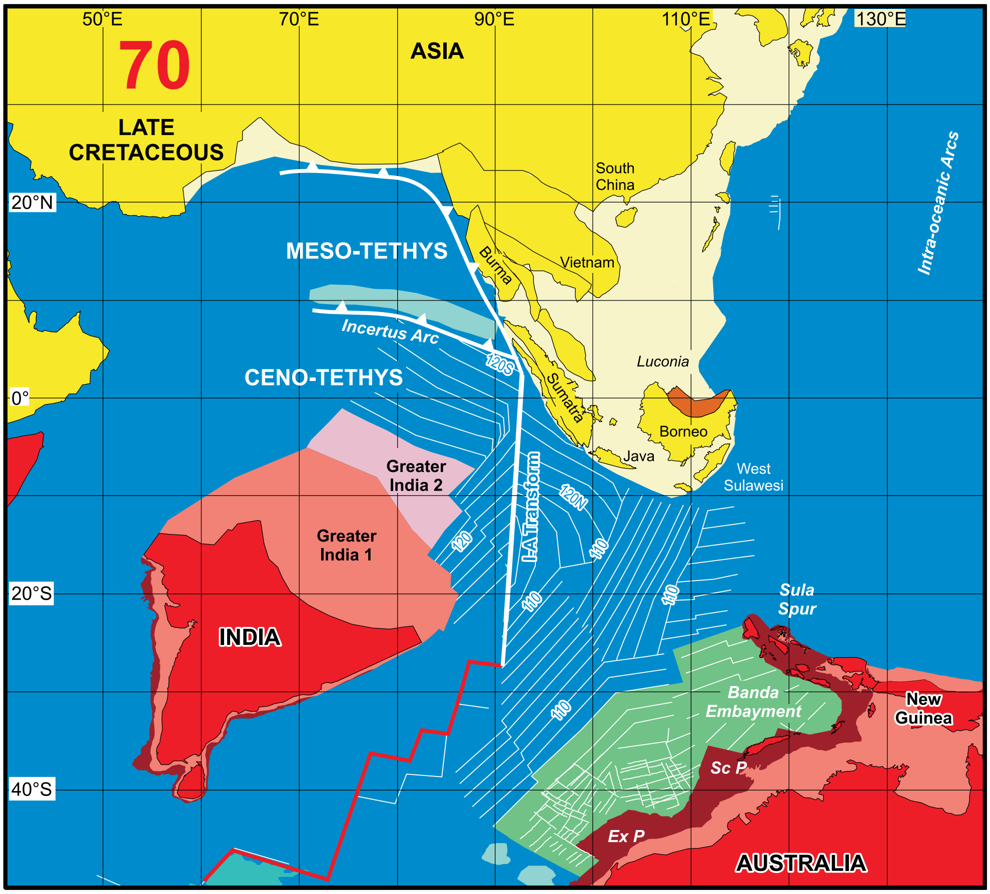

**Fig. 23.** Reconstruction at 70 Ma. The northward trace of the subducted I-A transform was beneath northern Sumatra and the Thai peninsula. Localised magmatism is reported from northern Sumatra and the Ranong and Khlong Marui faults in southern Thailand were active during the Late Cretaceous and Paleocene, 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 than 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

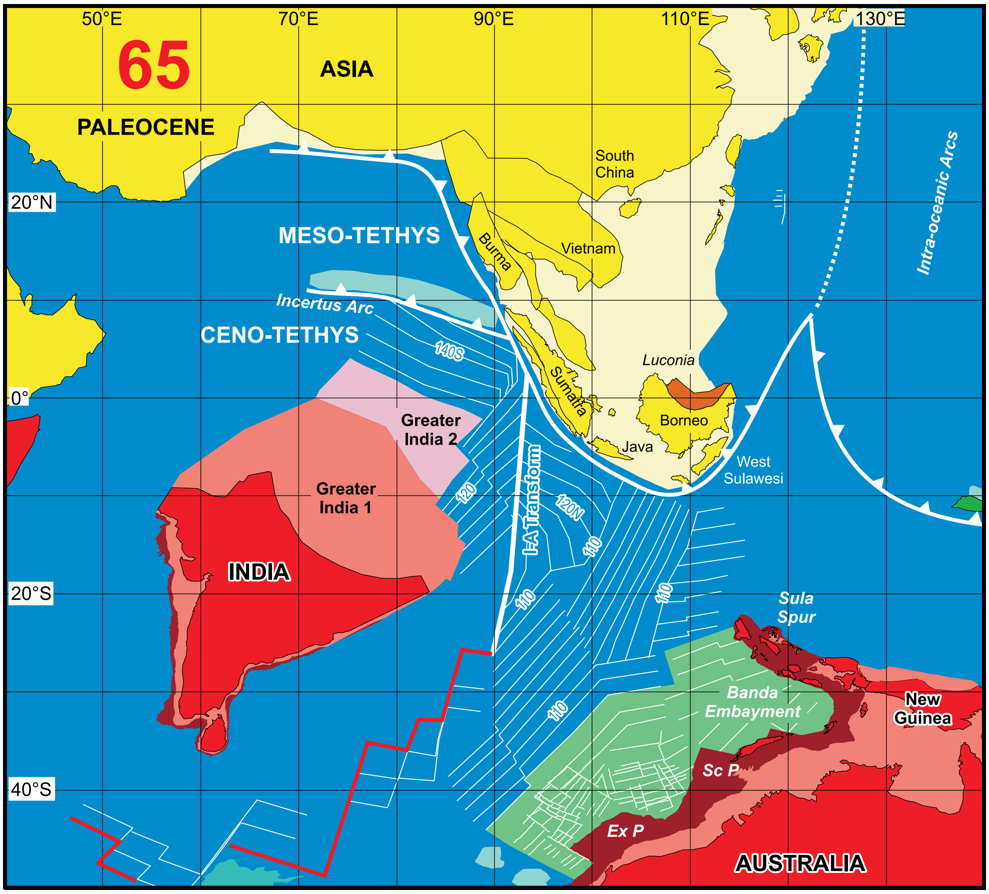

**Fig. 24.** Reconstruction at 65 Ma. There was a brief episode of NW-directed subduction marked by volcanic activity in Sumba and West Sulawesi. There were many intra-oceanic arcs in the Pacific in the Late Cretaceous but their positions are uncertain. Arcs that later collided with New Guinea are speculated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

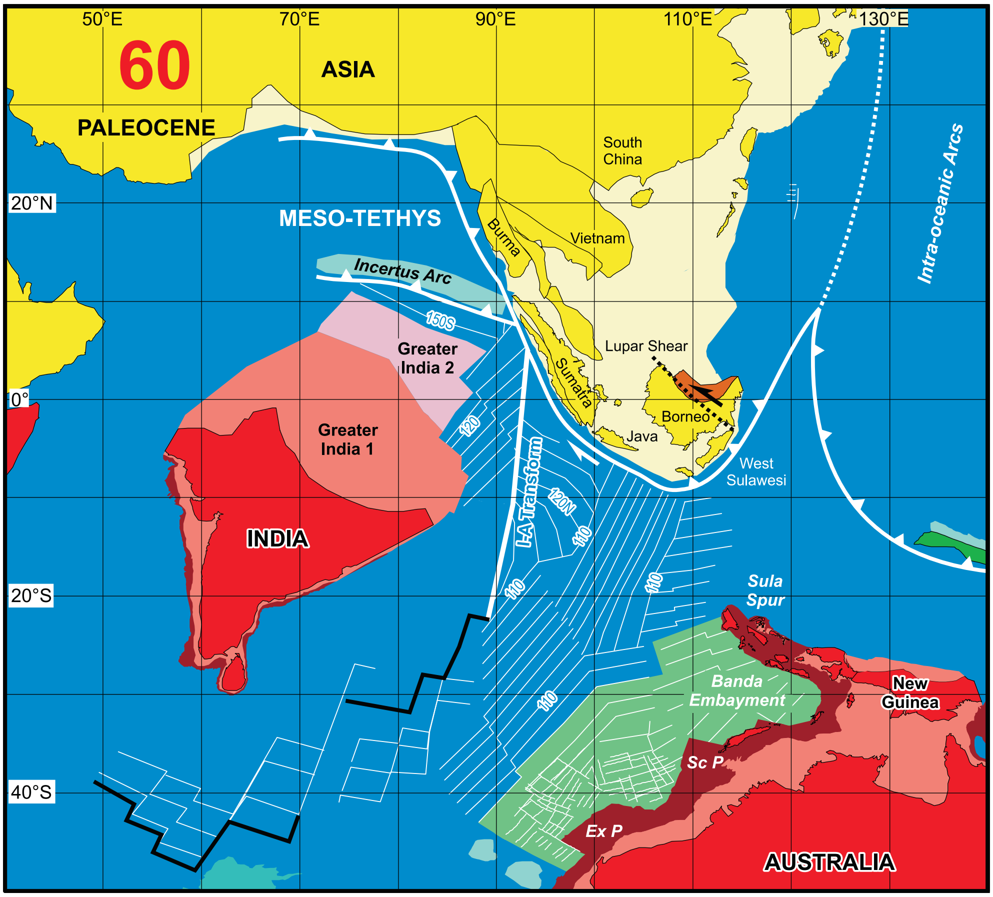

**Fig. 25.** Reconstruction at 60 Ma. The NW-directed subduction beneath Sumba and West Sulawesi was possibly linked to strike-slip motion along the Lupar Line in Sarawak and in Kalimantan along faults parallel to basement structures, contributing to formation of basins such as the Ketungau and Melawi 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

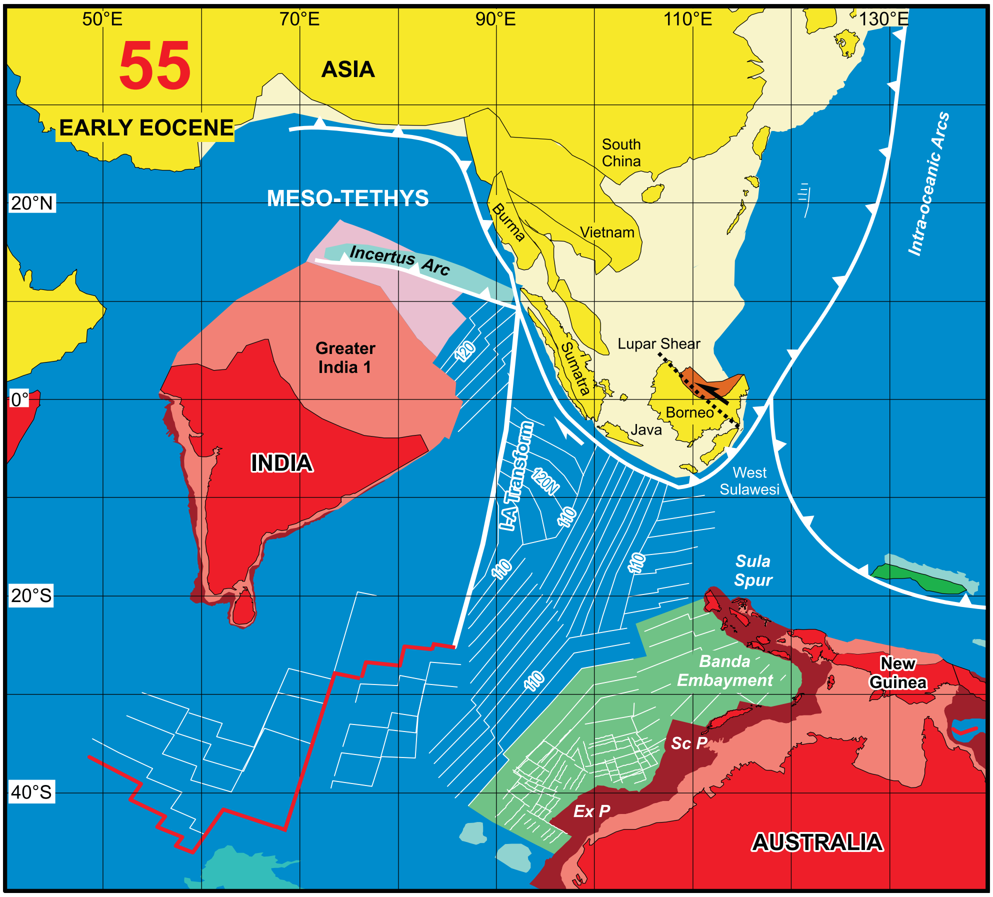

**Fig. 26.** Reconstruction at 55 Ma. India is interpreted to have collided with the Incertus Arc at about this time, which then became accreted to the north India margin. The orientation of the arc is very uncertain and the age of collision is equally compatible with Greater India 1 or 2.

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.

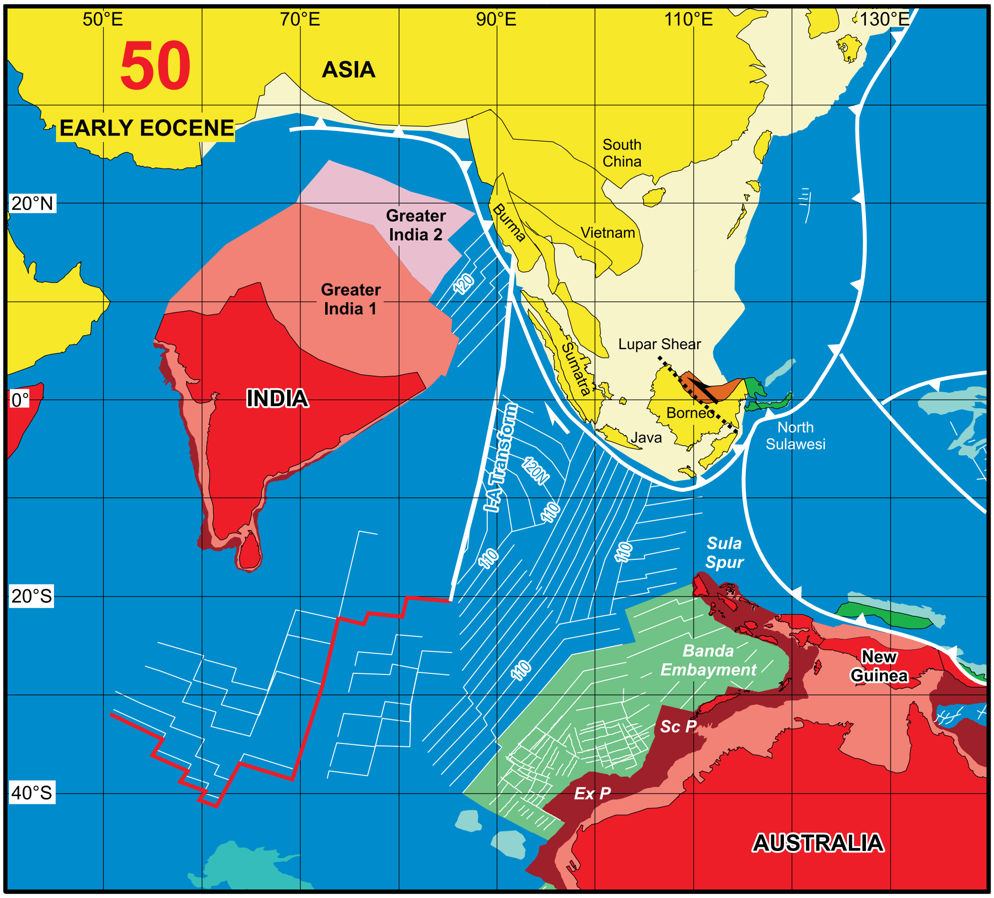

**Fig. 27.** Reconstruction at 50 Ma. The Philippine Sea Plate had begun to form by spreading within Cretaceous arcs and the Sepik terranes arrived at the New Guinea margin.

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

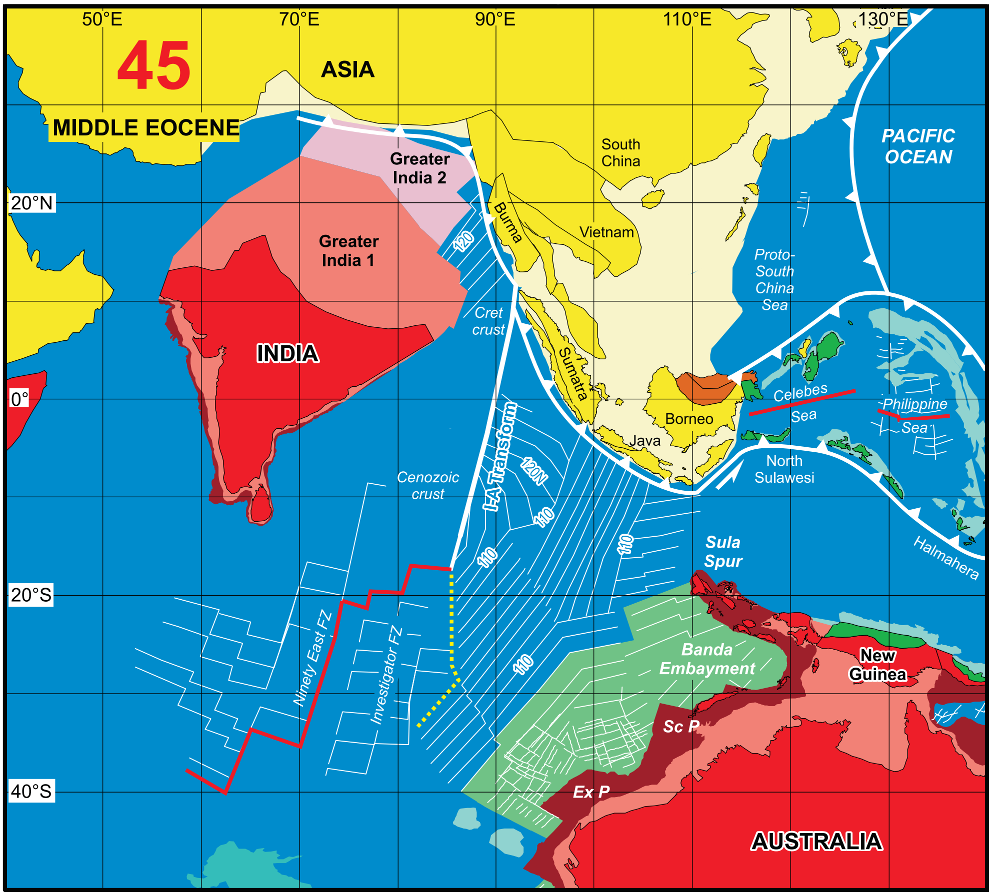

**Fig. 28.** Reconstruction at 45 Ma. Australia began to move northwards and new subduction zones were initiated all round Sundaland. The Proto-South China Sea began to subduct southwards at the Sabah margin. The Celebes and Philippine Sea were spreading in a backarc setting. The Ceno-Tethys was subducted 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 $^{207}Pb/^{204}Pb$ 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 account 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

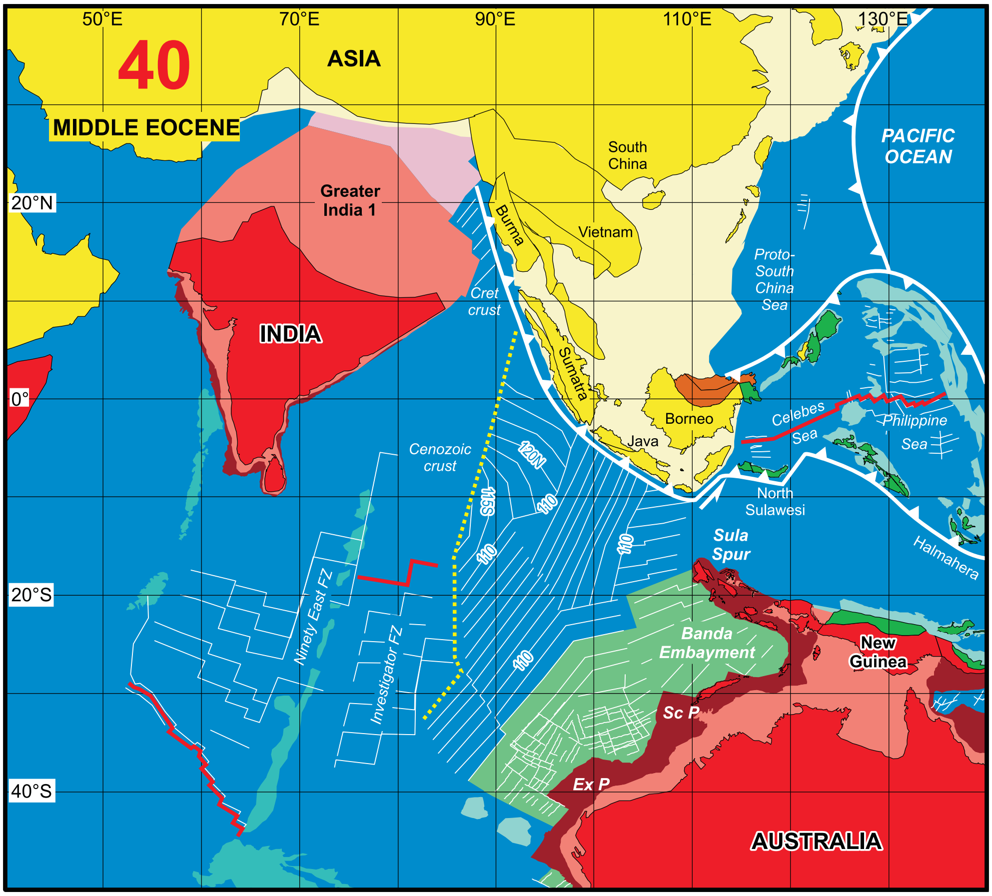

**Fig. 29.** Reconstruction at 40 Ma. India's movement slowed. The yellow dashed line shows the position of the subducting I-A transform. At the north end of the transform the crust was similar in age on each side of the fault. Further south the age difference increased. Close to the spreading centre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

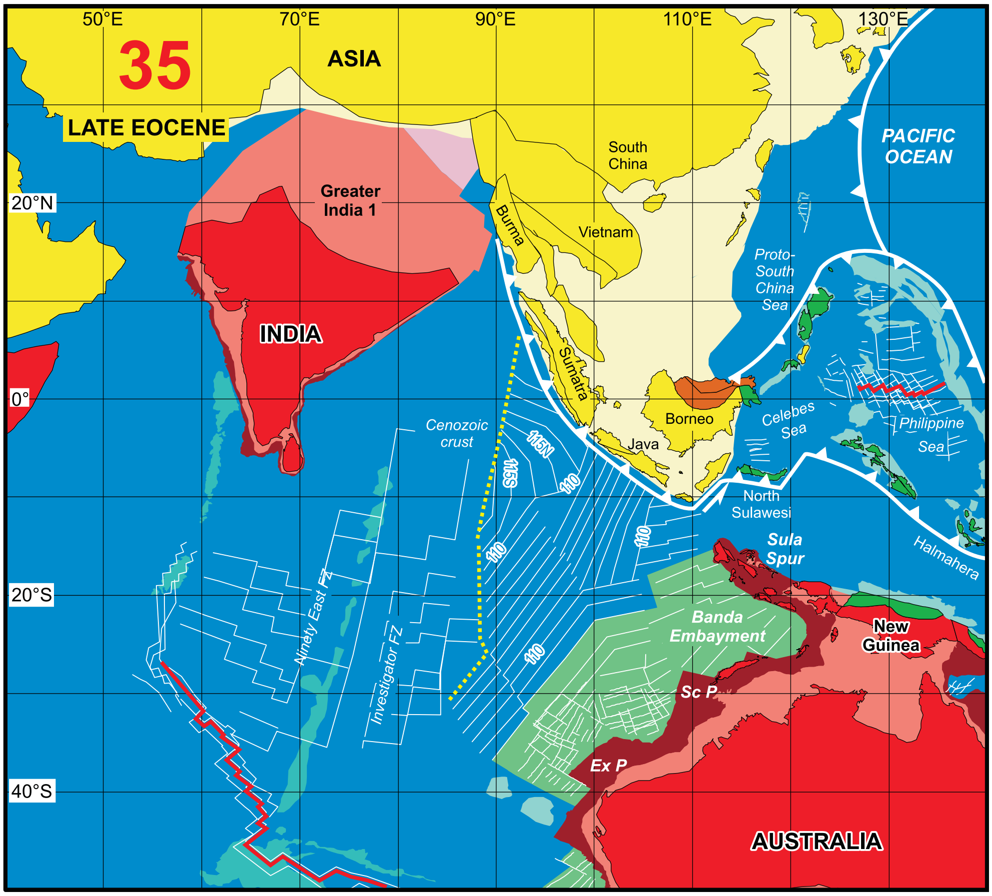

**Fig. 30.** Reconstruction at 35 Ma. The Proto-South China Sea narrowed by south-directed subduction beneath northern Borneo and the Cagayan Arc.

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

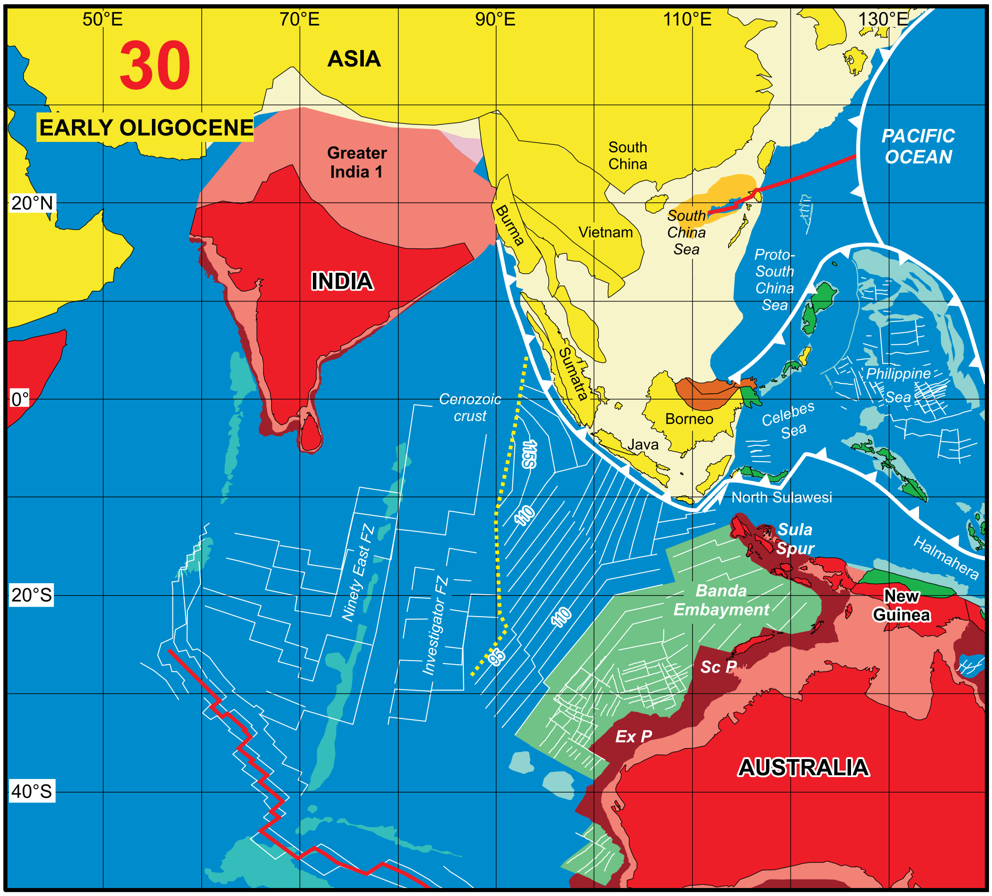

**Fig. 31.** Reconstruction at 30 Ma. South China Sea oceanic crust formation was underway.

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 microplate 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

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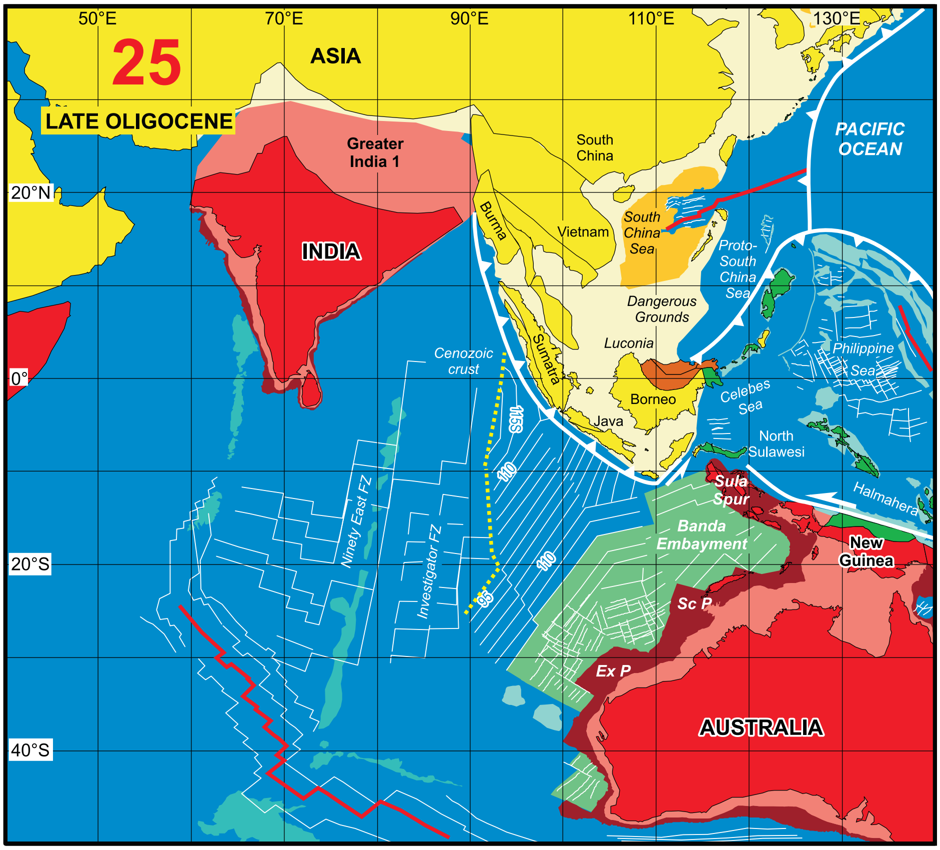

**Fig. 32.** Reconstruction at 25 Ma. The Sula Spur was about to make contact with the Sulawesi North Arm volcanic arc marking the beginning of collision of Australia and SE Asia. The Philippine Sea Plate began to rotate clockwise with strike-slip motion along the northern New Guinea margin following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

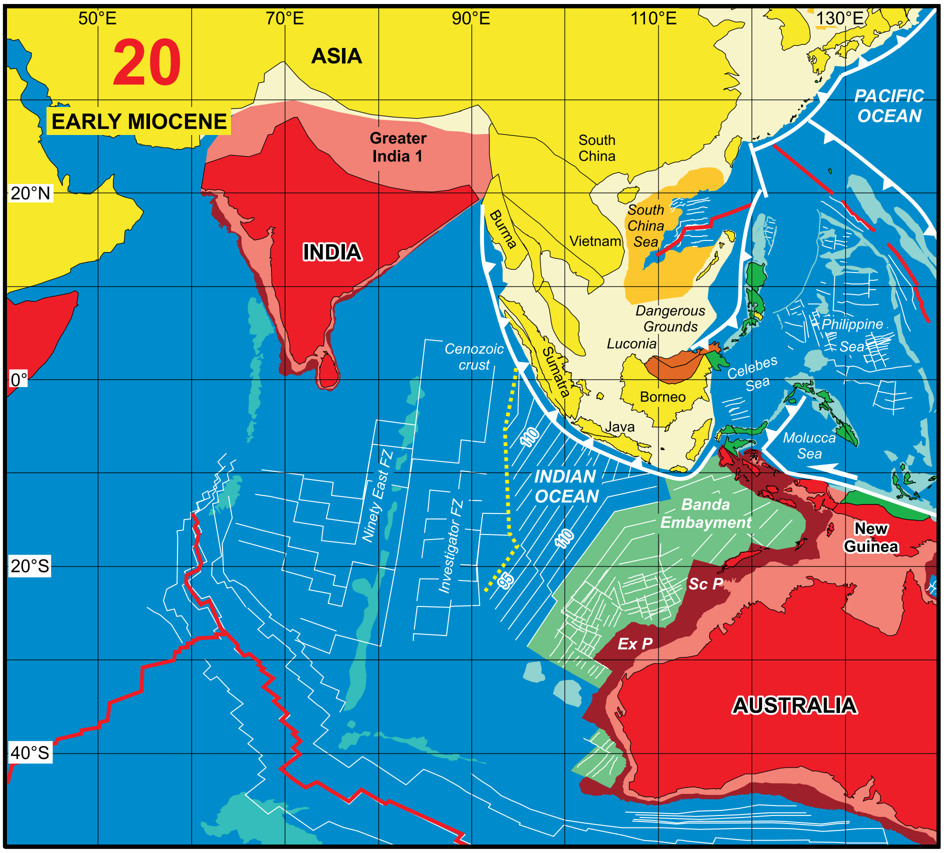

**Fig. 33.** Reconstruction at 20 Ma. Proto-South China Sea subduction beneath Sabah terminated and South China Sea spreading was about to end.

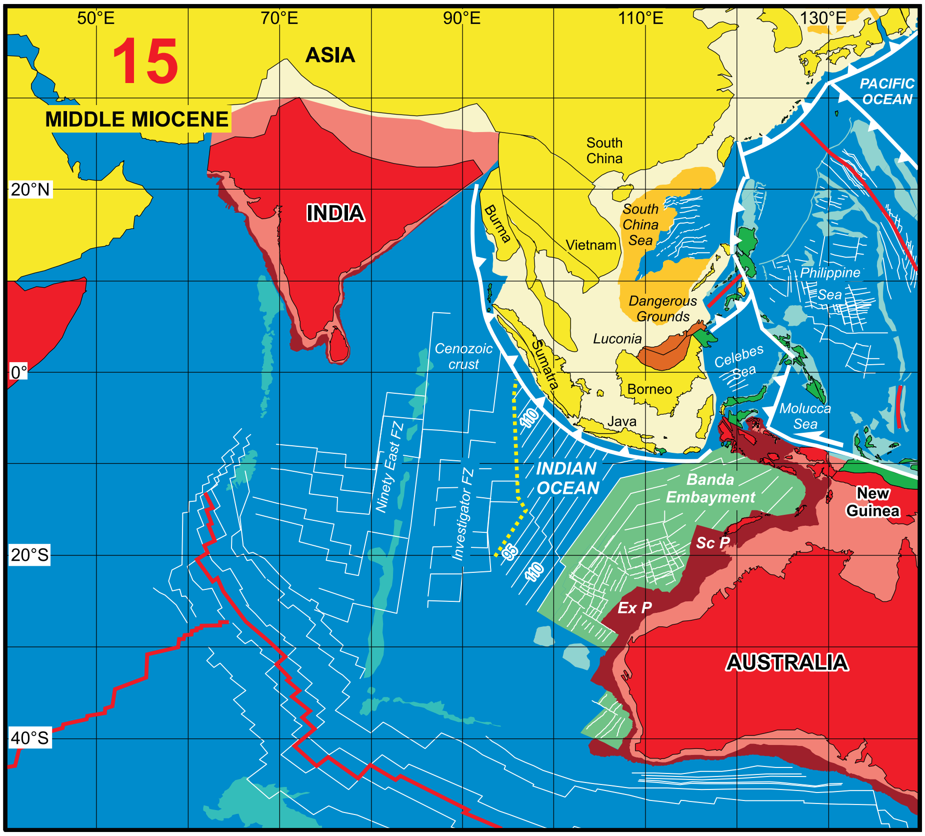

**Fig. 34.** Reconstruction at 15 Ma. Collision of the Cagayan Arc and the Palawan microcontinent was complete. Subduction rollback of the Celebes Sea caused spreading of the Sulu Sea in a backarc setting. The Java Trench subduction zone began to roll back into the Banda Embayment beginning extension 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.

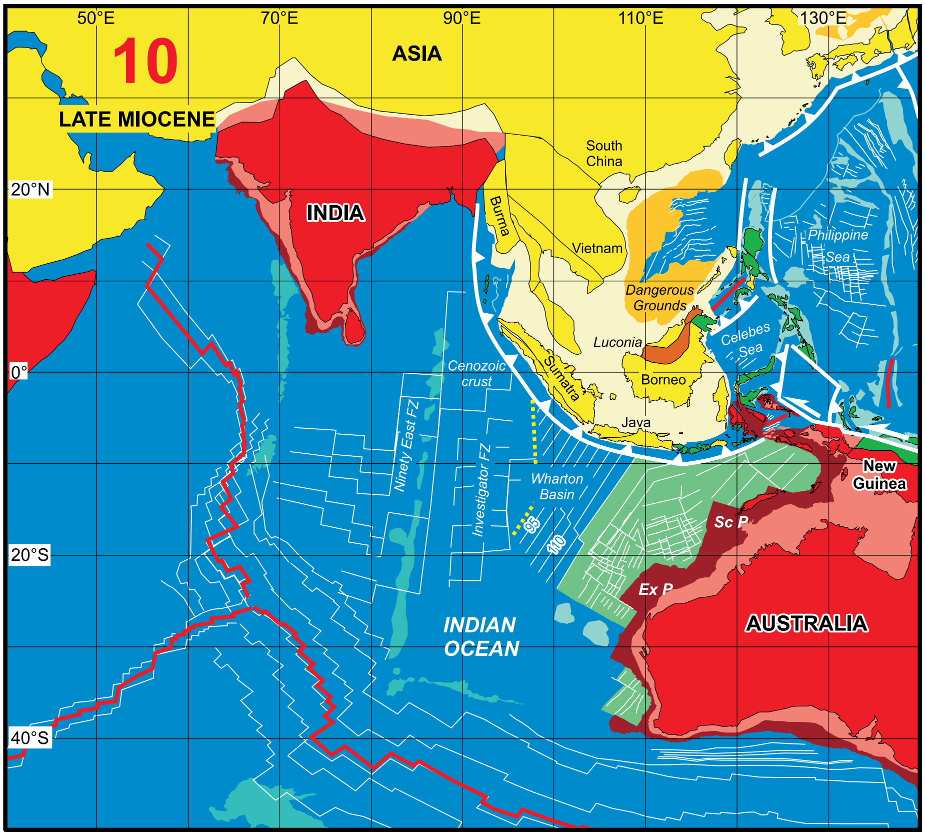

**Fig. 35.** Reconstruction at 10 Ma. Rollback into the Banda Embayment caused extension of the Sula Spur to form the North Banda Sea. Andaman Sea spreading was underway.

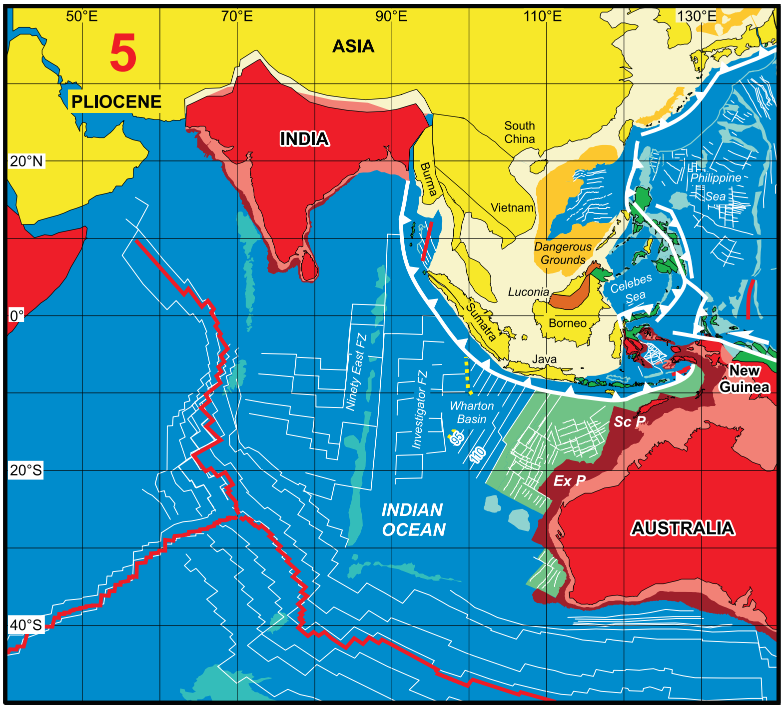

**Fig. 36.** Reconstruction at 5 Ma. Rollback into the Banda Embayment caused extension to form the South Banda Sea. Molucca Sea subduction was almost complete and the Halmahera and Sangihe Arcs were about to collide.

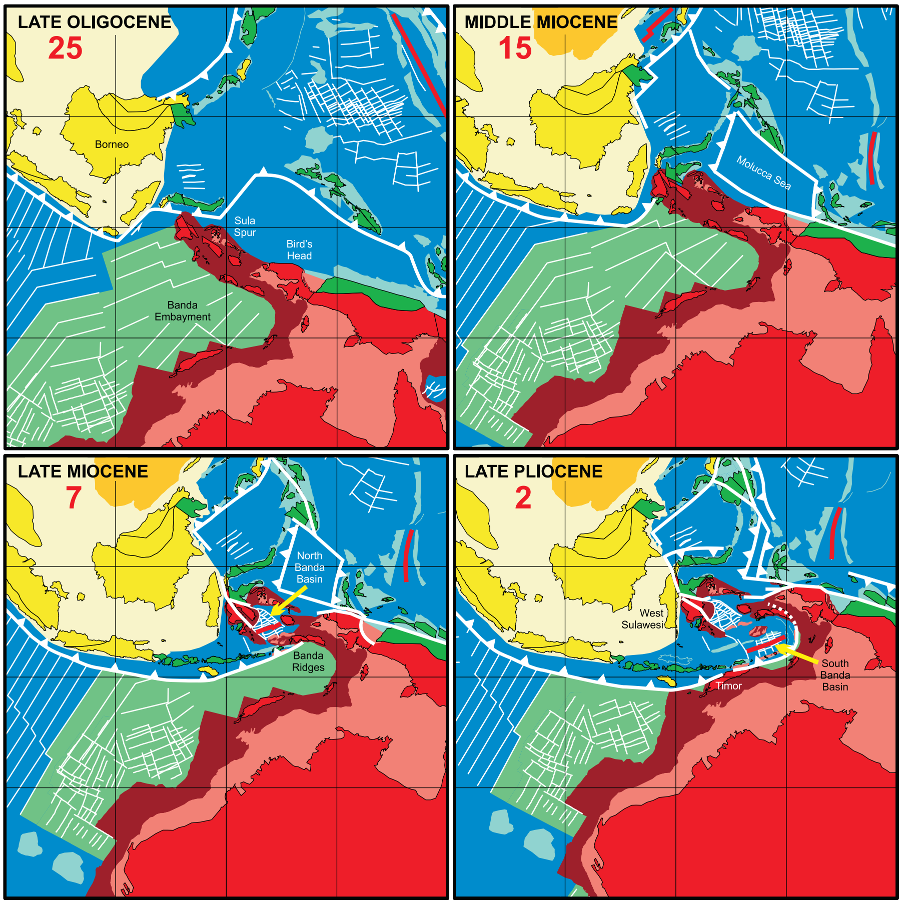

**Fig. 37.** Details of Banda reconstruction showing Australia–SE Asia collision began in the Early Miocene when the Sula Spur collided with the North Sulawesi volcanic arc. Subduction rollback began at about 15 Ma into the Jurassic Banda Embayment causing extension of the Sula Spur. The first stage 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.

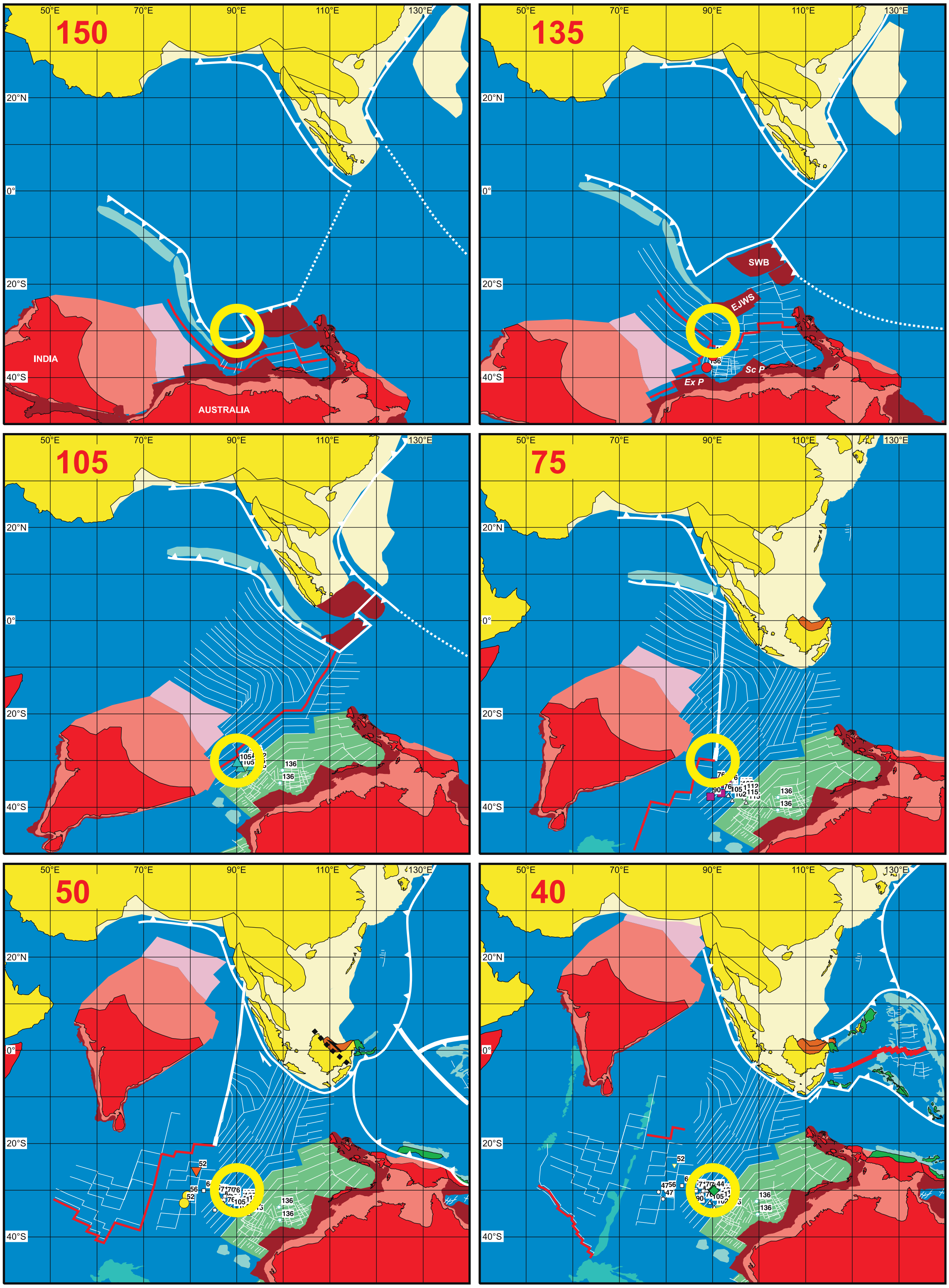

**Fig. 38.** Reconstructions of the Christmas Island Volcanic Province plotting location and ages of volcanic rocks dated by Hoernle et al. (2011) on the reconstructions of this paper. Larger coloured symbols indicate active magmatism and smaller white symbols show the location of samples after magmatism 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.

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## 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.

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