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Abstract: The Sundaland core of SE Asia is a heterogeneous assemblage of Tethyan sutures and Gondwana fragments. Its complex basement structure was one major influence on Cenozoic tectonics; the rifting history of the north Australian margin was another. Fragments that rifted from Australia in the Jurassic collided with Sundaland in the Cretaceous and terminated subduction. From 90 to 45 Ma Sundaland was largely surrounded by inactive margins with localized strike-slip deformation, extension and subduction. At 45 Ma Australia began to move north, and subduction resumed beneath Sundaland. At 23 Ma the Sula Spur promontory collided with the Sundaland margin. From 15 Ma there was subduction hinge rollback into the Banda oceanic embayment, major extension, and later collision of the Banda volcanic arc with the southern margin of the embayment. However, this plate tectonic framework cannot be reduced to a microplate scale to explain Cenozoic deformation. Sundaland has a weak thin lithosphere, highly responsive to plate boundary forces and a hot weak deep crust has flowed in response to tectonic and topographic forces, and sedimentary loading. Gravity-driven movements of the upper crust, unusually rapid vertical motions, exceptionally high rates of erosion, and massive movements of sediment have characterized this region.

Eastern Indonesia is at the centre of the convergent region between the Eurasian, Australian and Pacific plates (Fig. 1). It is the site of the gateway between the ancient deep Pacific and Indian Oceans which disappeared in the Early Miocene as Australia began to collide with the Sundaland margin of Eurasia. Today it is the passageway for water which continues to move from the Pacific to the Indian Ocean, by complex routes reflecting the evolution of the collision zone since the Early Miocene. This tectonically complex region is known to biologists as Wallacea, with a biota and diversity as complex as the geology. Wallace (1869) recognized in the 19th century that biogeographical patterns in some way reflected geology but we are still very far from understanding the links between geology, palaeogeography, ocean–atmosphere circulation and climate which may have influenced the evolution of life. Unravelling the geology is a first step, but remains a difficult one. Here I discuss this first step: the geological development of the Australia–Asia collision, particularly in eastern Indonesia.

The Cenozoic, particularly Neogene, development was strongly influenced by what was present before collision, so this paper begins with an outline of the Mesozoic and Early Cenozoic history of SE Asia, the Jurassic breakup of the northern Australian part of Gondwana and the assembly of Gondwana fragments in SE Asia in the Cretaceous. Rifting of fragments, now in Indonesia, from Gondwana was the first control on the Australian margin and the character of Sundaland, affecting both the shape of the continental margins and the distribution of different types of crust within them. The nature of the Mesozoic Pacific margin is also touched upon, and the possible contribution of Cathaysian fragments to SE Asia. In contrast to most previous reconstructions of the region, the docking of different fragments is interpreted to have terminated subduction around SE Asia from the mid-Cretaceous until the Eocene, except for a short Paleocene episode of subduction beneath West Sulawesi.

The effects of the assembly of different blocks, with their different internal structures, and separated by sutures, is then considered. The history of subduction resulted in an unusual lithosphere, and a high regional heatflow, and these features, combined with the heterogeneous nature of the basement were a major influence on Cenozoic deformation. It is argued that the Sundaland continent is not a craton or shield, but is a large region of generally weak lithosphere with weak and strong parts responding in a complex way to movement of the rigid plates that surround it. This determined the way in which the Australia–Asia collision proceeded and the deformational response of the upper crust to the movements of major plates, and the collision history is next reviewed, particularly the important subduction rollback into the Banda embayment of the Australian margin.

Finally, I consider if plate tectonics can be reconciled with deformation of the crust and suggest that the region is not behaving as plates or microplates, as illustrated by different parts of eastern Sundaland

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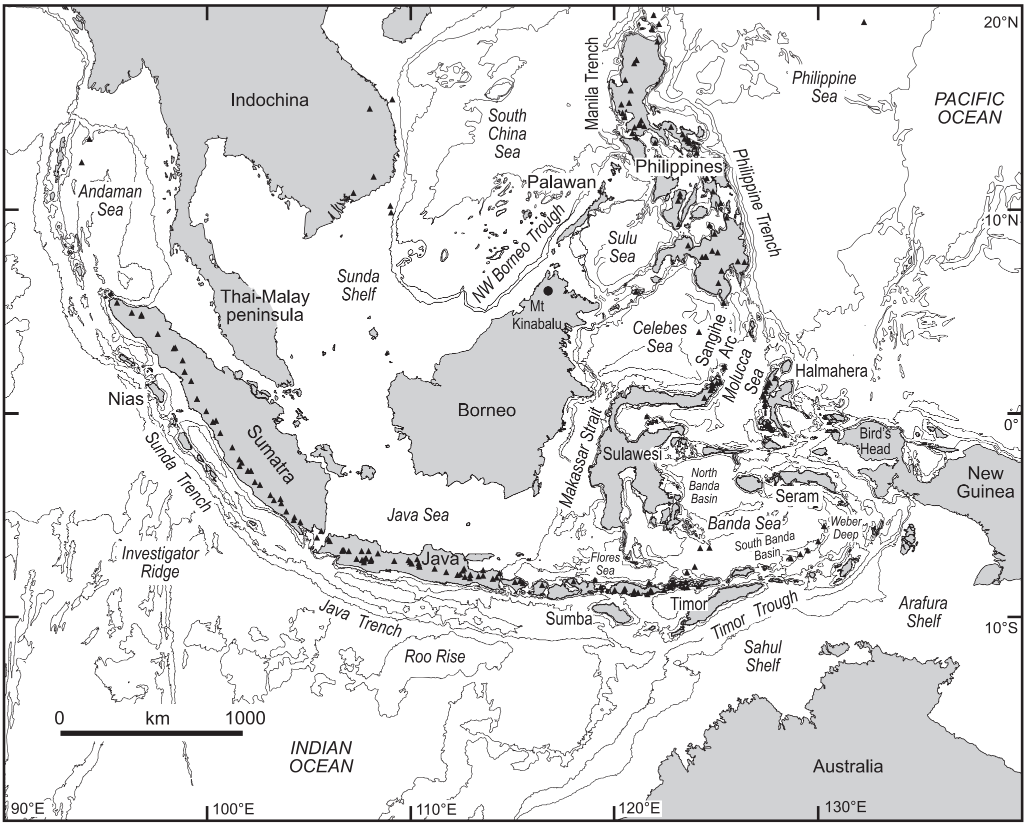


Fig. 1. Geography of SE Asia and surrounding regions. Small black filled triangles are volcanoes from the Smithsonian Institution, Global Volcanism Program (Siebert & Simkin 2002), and bathymetry is simplified from the Gebco (2003) digital atlas. Bathymetric contours are at 200 m, 1000 m, 3000 m and 5000 m.

and Wallacea. I outline an alternative model explaining why the surface topography and bathymetry, and palaeogeography, have changed very rapidly during the late Neogene with important consequences for ocean currents, local climate, and probably global climate.

Assembly of SE Asia

It is now generally accepted that the core of Sundaland (Fig. 2) was assembled from continental blocks that separated from Gondwana in the Palaeozoic and amalgamated with Asian blocks in the Triassic (Metcalfe 2011). The position of the eastern boundary of the Indochina–East Malaya block, the nature of crust to the east of it, and when this crust was added to Sundaland, are not known because much of this area is now submerged or covered with younger rocks. Only in Borneo are there rocks exposed that are older than Mesozoic. Most workers have assumed or implied that the continental core of SW Borneo was attached to Sundaland well before the Cretaceous. Hamilton (1979) drew a NE–SW line from Java to Kalimantan widely accepted as the SE limit of Sundaland continental crust, implying much of Borneo was part of Sundaland by the Cretaceous and considered the region external to this core, from Sarawak to East Java, as Cretaceous and Tertiary subduction complexes. Many workers, including Hamilton (1979), Metcalfe (1988, 1990, 1996), Williams *et al.* (1988) have suggested broadly south-directed subduction beneath north Borneo during the Cretaceous and Early Cenozoic. Cretaceous north-directed subduction beneath south Borneo is indicated by the distribution of ophiolites and HP-LT metamorphic rocks in Java and SE Kalimantan (Parkinson *et al.* 1998). However, it is also possible that SW Borneo was added to Sundaland in the Cretaceous, much later than commonly assumed. Metcalfe (1996) shows most of the area north, east and south of Borneo as accreted crust, including

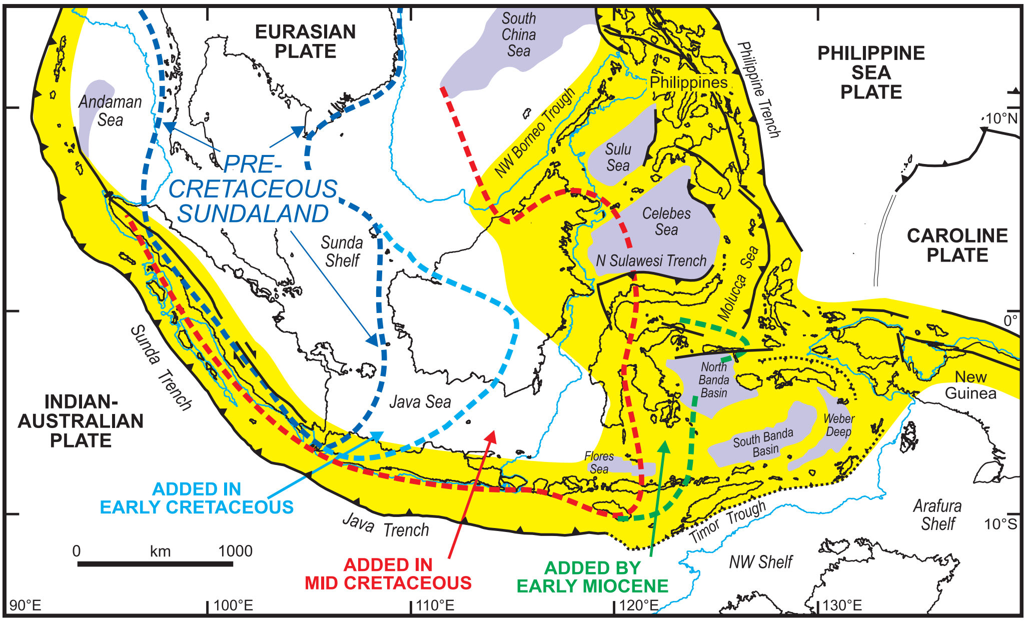


Fig. 2. The Mesozoic and Cenozoic growth of Sundaland. It is suggested here that Sundaland grew in the Cretaceous by the addition of two main fragments: SW Borneo and East Java–West Sulawesi. In the Early Miocene new continental crust was added to Sundaland by collisions in Borneo and East Indonesia. Hamilton's (1979) SE limit of Cretaceous continental crust is the part of the light blue line crossing the Java Sea from Java to Borneo.

several small continental blocks. There have been a number of suggestions for the origin of these continental fragments and Borneo crust, and when they became part of SE Asia.

Ben-Avraham & Emery (1973) suggested a suture west of Borneo along the Billiton Depression interpreted as a transform fault associated with Cretaceous opening of the South China Sea. Metcalfe (1988, 1990, 1996) identified the SW Borneo and Semitau blocks, both with a South China origin, that moved south after rifting in the Late Cretaceous, opening the proto-South China Sea. Although the history of the Asian margin, and the interpreted age of the South China Sea, have changed (cf. Ben-Avraham & Uyeda 1973) an Asian origin for offshore Sarawak and much of Borneo has been supported by obvious Cathaysian characteristics of faunas and floras from the Dangerous Grounds (Kudrass *et al.* 1986), NW Kalimantan (Williams *et al.* 1988) and Sarawak (Hutchison 2005).

Others have suggested an Australian origin for parts of Borneo. Luyendyk (1974) suggested the entire islands of Borneo and Sulawesi separated from Australia during Gondwana breakup in the Jurassic. Johnston (1981) proposed that a fragment rifted from the NW Shelf in the Late Jurassic collided with SE Asia in the mid-Cretaceous and underlies the area from Java to the eastern Banda Arc. Smaller blocks have been interpreted as rifted from NW Australia in the Jurassic (Hamilton 1979; Pigram & Panggabean 1984; Audley-Charles *et al.* 1988; Metcalfe 1988; Powell *et al.* 1988). One major fragment was named Mt Victoria Land (Veevers 1988) or Argoland (Powell *et al.* 1988). Ricou (1994) suggested that Argoland corresponds to the Paternoster 'plateau' which he interpreted to have collided with Borneo in the Paleocene.

However, most authors have interpreted the rifted Australian fragments to be much further away than Indonesia. Audley-Charles (1983, 1988) and Charlton (2001) suggested Argoland is now as far away as south Tibet, but it has most commonly been identified with West Burma. This view has been repeated so often that it has become received wisdom (Fig. 3) despite the fact that Metcalfe (1990, 1996), who first proposed it on the basis of Triassic (quartz-rich) turbidites above a pre-Mesozoic schist basement similar to the NW Shelf, observed it was 'speculative' with 'as yet no convincing evidence for the origin of this [West Burma] block'. Metcalfe (2009) has since abandoned the interpretation. In contrast, for other authors West Burma has been part of SE Asia since the Triassic and is therefore not Argoland. Mitchell (1984, 1992) argued that the Triassic turbidites in Burma were deposited on the southern

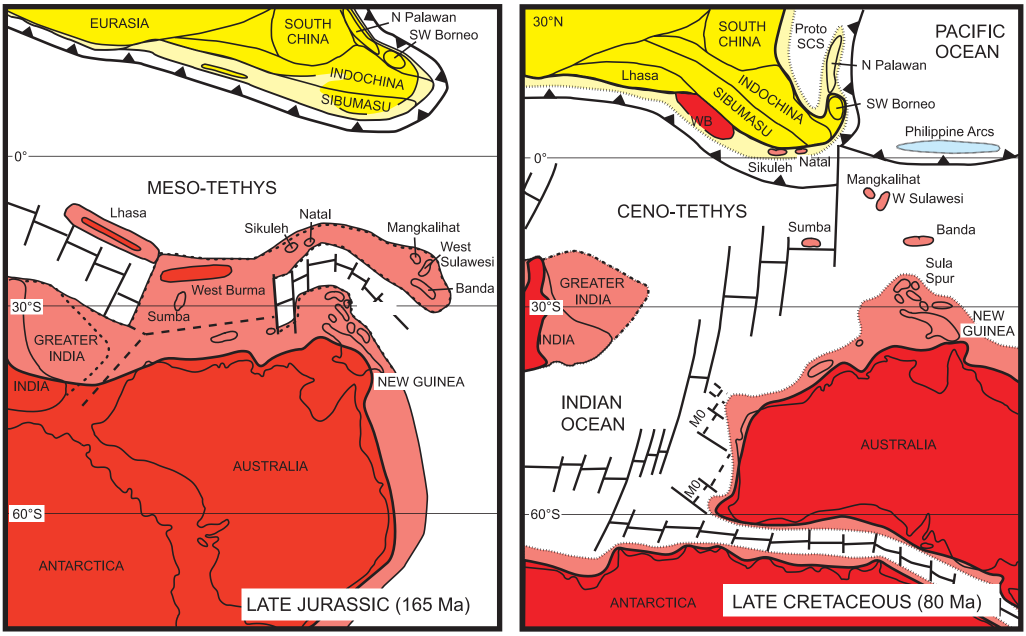


Fig. 3. The most common interpretation of the origin and present position of the rifted blocks from NW Australia shown on reconstructions for 165 and 80 Ma, modified from Wakita & Metcalfe (2005). These interpret the Argo block as rifted from the NW Australian margin in the Late Jurassic and added to Asia as the West Burma (WB) block in the Cretaceous. SW Borneo is interpreted as separated from Asia during the Cretaceous by formation of the Proto-South China Sea (Proto-SCS).

margin of Asia, and Barber & Crow (2009) interpreted West Burma as a continuation of the West Sumatra block, now separated from it by opening of the Andaman Sea, which was part of Sundaland from the Late Palaeozoic.

Pulunggono & Cameron (1984) proposed that north Sumatra includes the Sikuleh and Natal continental fragments, either rifted from Sundaland or accreted to it, and Metcalfe (1996) suggested these had a NW Australian origin. Barber (2000) and Barber & Crow (2005) reviewed these suggestions 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, like Mitchell (1993), as part of the Woyla intra-oceanic arc thrust onto the Sumatran Sundaland margin in the mid-Cretaceous.

If the Australian rifted fragments are not in Tibet, West Burma or Sumatra then where are they? There is increasing evidence that they are in Borneo, West Sulawesi and Java, with some Cathaysian continental crust forming part of NW Borneo and the offshore shelf to the north of Sarawak and east of Vietnam, and that all these fragments arrived in their present positions during the Cretaceous.

Origin of crust of east Sundaland

It is suggested here that the SE Asian promontory east of the Indochina–East Malaya block has grown by the addition of continental crust in two major stages: during the Early to mid-Cretaceous, and during the Neogene (Fig. 2). Some continental fragments have an Asian origin, but most are Australian. I suggest that an Asian fragment collided with east Sundaland, between Vietnam and northern Borneo, in the mid-Cretaceous and that Australian fragments also docked against the East Malaya block in the Early to mid-Cretaceous. A new reconstruction (Hall *et al.* 2009*a*) shows how these fragments moved into SE Asia (Figs 4 & 5).

Offshore Vietnam to Borneo

It is commonly assumed that there was an east-facing Andean margin with subduction of Pacific oceanic crust throughout the Mesozoic (e.g. Taylor & Hayes 1983; Metcalfe 1996) in the west Pacific. For South China and Indochina there is evidence for subduction in the Jurassic and Early Cretaceous but not in most of the Late Cretaceous. In the SE China margin Jahn *et al.* (1976) suggested that a Cretaceous (120–90 Ma) thermal episode was

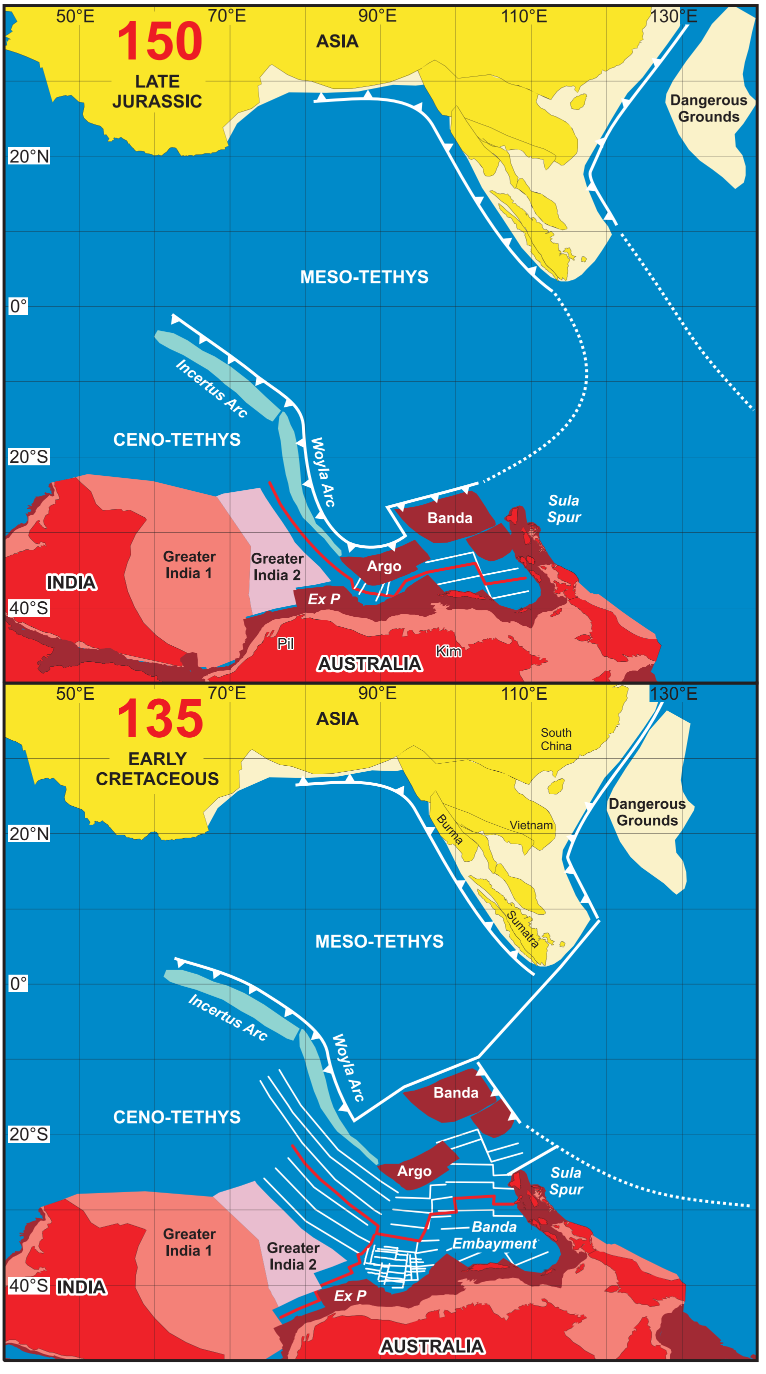


Fig. 4. Reconstructions at 150 and 135 Ma. In the Late Jurassic the Banda blocks had separated forming the Banda embayment and leaving the Sula Spur. The Argo block separated slightly later, accompanied by a reorientation of spreading in the Banda embayment. Spreading propagated west, possibly along the continent–ocean boundary of Greater India to form the Woyla Arc. The arc and continental fragments moved away from the Gondwana margins as the subduction hinge rolled back. At 135 Ma India had begun to separate from Australia. Spreading in the Ceno-Tethys was predominantly oriented NW–SE and the Banda, Argo blocks and the Woyla Arc moved towards Sundaland as the Ceno-Tethys widened. Ex P, Exmouth Plateau.

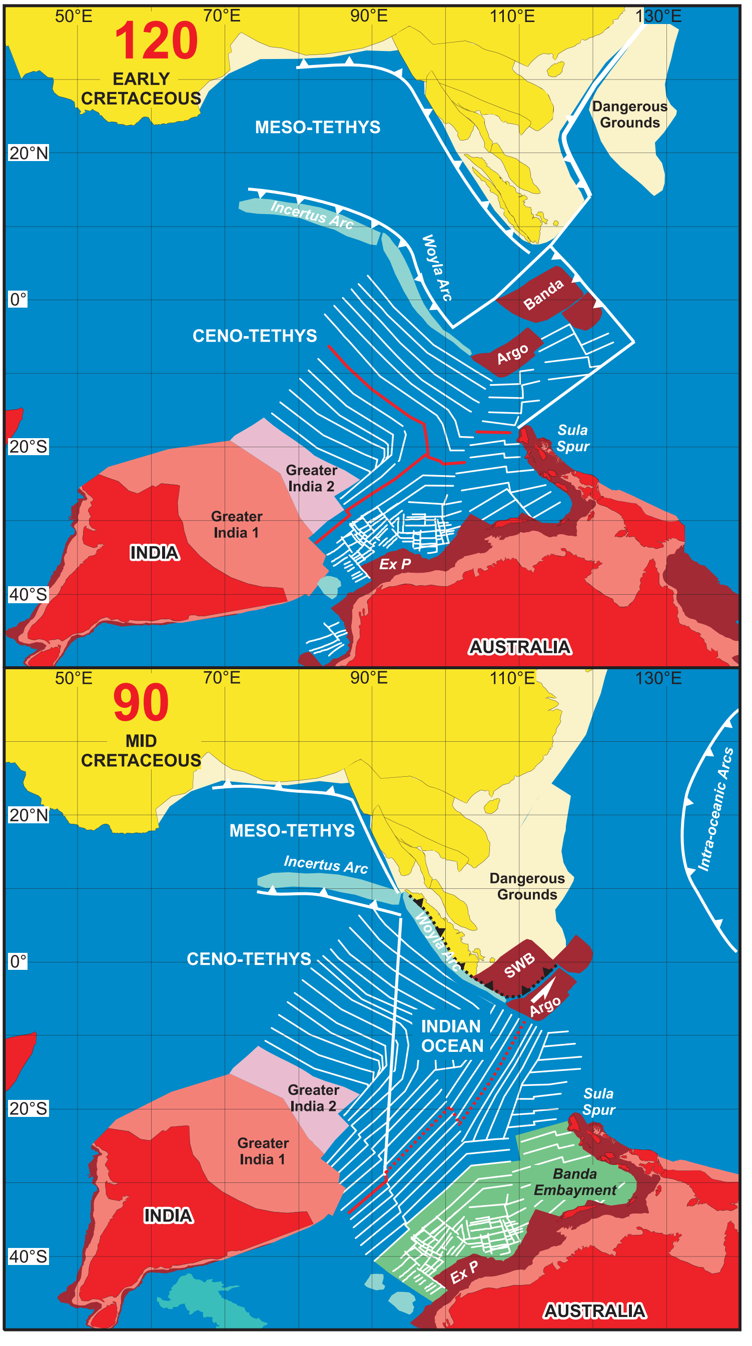


Fig. 5. Reconstructions at 120 and 90 Ma. There were numerous ridge jumps during India–Australia separation. In the Early Cretaceous the Banda block docked with Sundaland along a strike-slip suture at the Billiton Depression to become SW Borneo. Subduction continued beneath the Woyla Arc and probably south of Sumatra. At 90 Ma the Argo block docked with SW Borneo along the strike-slip Meratus suture, forming East Java and West Sulawesi, and the Woyla Arc docked with the Sumatra margin of Sundaland. The collisions terminated subduction. However, India continued to move north by subduction beneath the Incertus Arc (Hall *et al.* 2009*a*) which required formation of a broadly north–south transform boundary between the Indian and Australian plates. At about this time, Australia began to separate from Antarctica but at a very low rate.

related to west-directed Pacific subduction. In South China, around Hong Kong, felsic magmatism ceased in the Early Cretaceous (Sewell *et al.* 2000), but it is not known whether magmatism continued outboard because this area is submerged. Further to the north in South China, there are younger Cretaceous magmatic rocks in a belt further east interpreted as subduction-related but magmatism had ceased by 80 Ma (Li & Li 2007). This suggests that there was a trench associated with west-dipping Pacific subduction, east of the present South China coast, in the Jurassic and Early Cretaceous but not in the Late Cretaceous after 80 Ma, and the subduction zone may have continued south across the South China Sea. Zhou *et al.* (2008) used geophysical data to trace a Jurassic–Early Cretaceous subduction complex south from Taiwan along the present northern margin of the South China Sea which they interpret to have been displaced to Palawan by opening of the South China Sea. This belt probably continued into Vietnam where there are Early Cretaceous granites (Nguyen *et al.* 2004; Thuy *et al.* 2004) with youngest ages of 88 Ma and may have terminated in south Vietnam or, less probably, continued into northern Borneo. From east Vietnam northwards there is no evidence for east-directed subduction after 80 Ma.

There have been many suggestions of west- or south-directed subduction beneath north Borneo in the Late Cretaceous and Early Cenozoic (e.g. Hamilton 1979; Taylor & Hayes 1983; Williams *et al.* 1988; Tate 1991) although Moss (1998) identified problems with the common interpretation of the Rajang Group deepwater clastic sediments as subduction-related. He suggested that subduction had ceased by about 80 Ma after arrival of microcontinental fragments now beneath the Luconia Shoals and Sarawak, leaving a remnant ocean and a foreland basin in northern Borneo in which the Rajang Group was deposited. There is little evidence anywhere of subduction-related magmatism younger than about 80 Ma, and the Late Cretaceous was a period of rifting and extension of the South China margin (e.g. Taylor & Hayes 1983; Zhou *et al.* 2008). Although subduction has been interpreted in Sarawak (Hutchison 1996, 2005) and NW Kalimantan (Williams *et al.* 1988, 1989), Late Cretaceous and Early Cenozoic sequences are fluviatile and marginal marine. Dredged crust (Kudrass *et al.* 1986) from the Dangerous Grounds indicates the presence of a continental sedimentary rocks with Cathaysian affinities and metamorphic rocks with Early Cretaceous ages. In the rest of the region of offshore Malaysia and Vietnam little is known of the basement which is deep below a thick sediment cover. Recent offshore studies suggest a suture could continue towards the SW of Vietnam (Fyhn *et al.* 2010; Pedersen *et al.* 2010). Hall *et al.* (2009*a*) interpreted a Luconia–Dangerous Grounds block of Asian origin, similar to that named Cathaysia by Zhou *et al.* (2008). Collision of this block between 90 and 80 Ma with a suture broadly in the position identified by Zhou *et al.* (2008) can account for Cathaysian continental crust, subduction melanges and magmatism in South China, Vietnam and NW Borneo. It does not require SW Borneo to have been part of Sundaland before this time.

South Borneo and Sulawesi

There have been many suggestions that there was a collision between a Gondwana continental fragment and the Sundaland margin in the mid Cretaceous (e.g. Sikumbang 1986, 1990; Hasan 1990, 1991; Wakita *et al.* 1996; Parkinson *et al.* 1998) with a suture located in the Meratus region. Geochemical evidence (Elburg *et al.* 2003) and zircon dating (van Leeuwen *et al.* 2007) indicate continental crust may lie beneath much of west Sulawesi, and it has an Australian origin (van Leeuwen *et al.* 2007). Recent studies in East Java show that at least the southern part of the island is underlain by continental crust (Smyth 2005; Smyth *et al.* 2007, 2008). The igneous rocks of the Early Cenozoic Southern Mountains volcanic arc contain Archaean to Cambrian zircons and suggest a west Australian origin for the fragment (Smyth *et al.* 2008). Continental crust is also suggested to underlie parts of the southern Makassar Straits (Hall *et al.* 2009*b*) and East Java Sea between Kalimantan and Java, based on basement rocks encountered in exploration wells (Manur & Barraclough 1994).

The evidence for the origin of SW Borneo is admittedly limited. Palaeomagnetism indicates it has been at its present latitude since the Cretaceous (Haile *et al.* 1977; Fuller *et al.* 1999). The Schwaner Mountains are dominated by Cretaceous igneous rocks which intrude a poorly-dated metamorphic basement suggested to be Permo-Triassic (e.g. Williams *et al.* 1988; Hutchison 2005) or older. The interpreted older ages are based on correlation of metamorphic rocks from Sarawak to Kalimantan (e.g. Tate 1991, 2002) across important sutures (Lupar Line and Boyan melange). However, there are convincing links to Australia. Devonian limestones from the Telen River in the Kutai basin (Rutten 1940) have a fauna resembling that of Devonian limestones from the Canning Basin (M. Boudagher Fadel, pers. comm. 2009). Alluvial diamonds from Kalimantan have many similarities to diamonds from NW Australia (Taylor *et al.* 1990). Interpretations of an Asian origin for SW Borneo discussed above were based on Cathaysian faunas and floras found in Sarawak and NW Kalimantan, but all these are within the Kuching zone (Hutchison

2005) or NW Kalimantan Domain (Williams *et al.* 1988) in, or closely associated with, melanges and deformed ophiolites. These rocks are interpreted here as fragments of Asian material accreted during the Cretaceous which are not part of the SW Borneo block.

SW Borneo is interpreted (Hall *et al.* 2009*a*) to be a block separated from the Banda embayment at about 160 Ma and added to Sundaland in the Early Cretaceous. This is consistent with the evidence for its origin discussed above, its size, and the age of rifting on the NW Shelf (Pigram & Panggabean 1984). The northern edge of the block was a south-dipping subduction zone as proposed by many authors (e.g. Hamilton 1979; Williams *et al.* 1988; Tate 1991; Hutchison 1996; Moss 1998) but was not continuous with the South China–Vietnam suture.

A small Inner Banda block is interpreted (Hall *et al.* 2009*a*) to have followed the Banda block but to have moved relative to it during a later collision event, which may now underlie part of Sabah and northern West Sulawesi. SW Borneo accreted to Sundaland in the Early Cretaceous between about 115 and 110 Ma along the Billiton lineament that runs south from the Natuna area (Ben-Avraham 1973; Ben-Avraham & Emery 1973). The East Java–West Sulawesi block is interpreted as the Argo block, including the offshore continuation of the Canning Basin, whose detrital sediments provided the Palaeozoic to Archaean zircons found in East Java. The East Java–West Sulawesi block separated from NW Australia at about 155 Ma as rifting propagated west and south (Pigram & Panggabean 1984; Powell *et al.* 1988; Fullerton *et al.* 1989; Robb *et al.* 2005). East Java and West Sulawesi may include a number of separate fragments, rather than a single block, added to Sundaland at about 90 Ma at a suture running from West Java towards the Meratus Mountains and then northward (Hamilton 1979; Parkinson *et al.* 1998). Collision of the Woyla arc with the Sumatran Sundaland margin occurred at the same time as the East Java–West Sulawesi fragment docked (Hall *et al.* 2009*a*).

Termination of subduction

The rifting of fragments from Australia determined the shape and character of the Australian margin which was to have a major influence on the Neogene development of Australia–SE Asia collision. The arrival of the rifted blocks also had a profound effect because they terminated subduction (Smyth *et al.* 2007; Hall 2009*a*, *b*; Hall *et al.* 2009*a*) around Sundaland in the mid-Cretaceous for 45 million years, and when subduction resumed in the Eocene their deep structure influenced Cenozoic deformation of SE Asia. For the period 90 Ma to 45 Ma around most of Sundaland, except north of Sumatra, there was no subduction. Australia was not moving north, and there was an inactive margin south of Sumatra and Java until 45 Ma. Thus, no significant igneous activity is expected and little is recorded (Hall 2009*a*). The new reconstruction (Hall *et al.* 2009*a*) does, however, predict NW-directed subduction beneath Sumba and West Sulawesi between 63 Ma and 50 Ma where, in the latest Cretaceous and Paleocene, there was calc-alkaline volcanism interpreted as subduction-related (e.g. van Leeuwen 1981; Hasan 1990; Abdullah *et al.* 2000; Elburg *et al.* 2002; see Hall 2009*a*, for review).

Consequences for SE Asian lithosphere

At present the interior of Sundaland, particularly the Sunda Shelf, Java Sea and surrounding emergent, but topographically low, areas of Sumatra and Borneo are largely free of seismicity and volcanism (Hamilton 1979; Hall & Morley 2004; Simons *et al.* 2007). This region formed an exposed landmass during the Pleistocene, and most of the Sunda Shelf is shallow, with water depths less than 200 m and little relief which has led to a misconception that it is a stable area. Sundaland is often described as a shield or craton, but seismic tomography, geological observations and heat flow (Hall & Morley 2004; Currie & Hyndman 2006) show that these terms are not appropriate.

Unlike well-known shields or cratons Sundaland is not underlain by a thick cold lithosphere stabilized early in the Precambrian. P and S wave seismic tomography (Bijwaard *et al.* 1998; Ritsema & van Heijst 2000) show it is an area of low velocities in the lithosphere and underlying asthenosphere, in contrast to Indian and Australian continental lithosphere to the NW and SE (Fig. 6). Such low mantle velocities are commonly interpreted in terms of elevated temperature, and this is consistent with regional high heat flow, but they may also partly reflect the mantle composition or elevated volatile contents.

Also unlike cratons, there has been significant deformation within Sundaland during the Mesozoic and Cenozoic. During the Cenozoic there was widespread faulting, the formation of numerous sedimentary basins, many of which are very deep, and localized but significant elevation of mountains (Hall & Morley 2004). Much of the Sundaland interior has high surface heat flow (Fig. 7), with values typically greater than 80 mW/m^2, much greater than cratons (Artemieva & Mooney 2001). Likely causes are upper crustal heat flow from radiogenic granites and their erosional products,

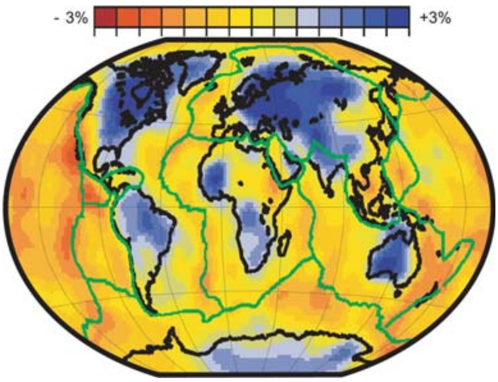


Fig. 6. 150 km depth slice through the S20RTS shear wave tomographic model of Ritsema & van Heijst (2000). High velocities are represented by blue and low velocities by red. Cratons are easily identified; SE Asia is not among them.

the insulation effects of sediments, and a large mantle contribution.

The upper mantle velocities and heat flow observations suggest the region is underlain by a thin and weak lithosphere (Hall & Morley 2004) that extends many hundreds of kilometres from the volcanic margins but is probably a consequence of subduction (Currie & Hyndman 2006) beneath Sundaland throughout much of the Mesozoic until the mid-Cretaceous and from the Eocene to present day. Critically, such 'subduction back-arc' lithosphere (Hyndman *et al.* 2005; Currie & Hyndman 2006) is not only significantly weaker than cratonic lithosphere but is likely to deform internally in response to plate boundary forces (Fig. 8) and to within-plate forces generated by topography (Lynch & Morgan 1987; Whittaker *et al.* 1992; Zoback *et al.* 2002).

Regionally, the entire area north of the Java-Sunda trench and west of the Philippine trench is underlain by weak lithosphere and is very responsive to plate boundary forces, but it is also heterogeneous. The long accretionary history of the region means that it is a composite mosaic of continental fragments (Fig. 9) with varying lithospheric thickness, different internal structures, crossed by sutures with different orientations, and cut by strike-slip faults of different ages (e.g. Allen 1962; Hamilton 1979; Sieh & Natawidjaja 2000; Barber & Crow 2009).

For example, much of East Java, South Borneo, West Sulawesi and possibly parts of Sabah, are underlain by continental crust of Australian origin, and the rifted blocks brought with them the deep structure now observed. Deep structural lineaments, now oriented approximately NW–SE, are often traced across the whole of Borneo and commonly into Sulawesi (e.g. Satyana *et al.* 1999; Fraser *et al.* 2003; Gartrell *et al.* 2005; Puspita *et al.* 2005; Simons *et al.* 2007). Most are not active faults at present, although they are commonly represented in this way. Most of these lineaments show no signs of having been active faults during much of the Cenozoic, although a few have been reactivated. 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 lineament orientations are what would be expected if they are basement structures inherited from Australia (Fig. 10) where there are deep and old structures that can be traced offshore across

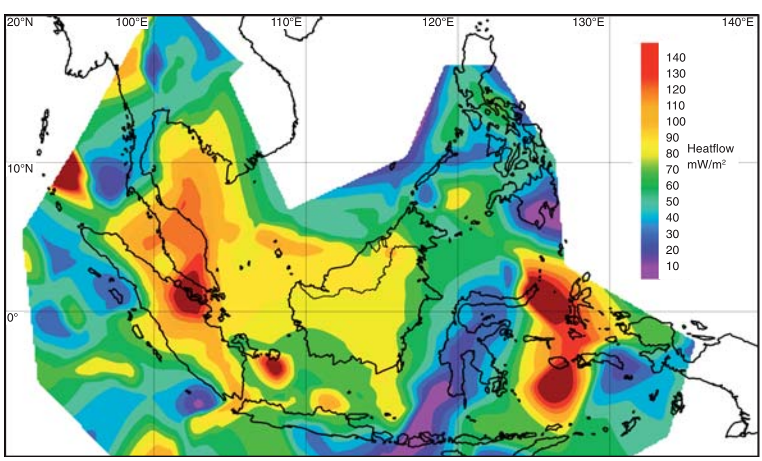


Fig. 7. Contoured heat flow map for SE Asia, modified from Hall & Morley (2004).

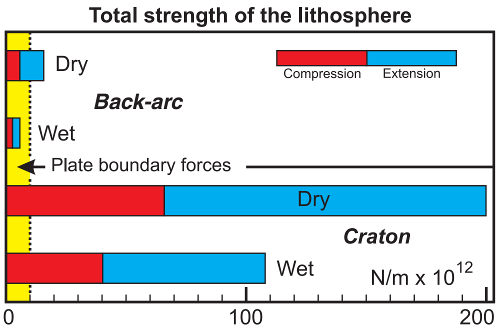


Fig. 8. Relative strengths of cratons and subduction backarc regions from Hyndman *et al.* (2005). Sundaland lithosphere is expected to be very responsive to plate boundary forces, especially when wet.

the NW Shelf and western Australia (e.g. Cadman *et al.* 1993; Goncharov 2004). Furthermore, deep seismic profiles between Borneo and East Java (Emmet *et al.* 2009) show many resemblances to the deep structure of Late Palaeozoic sedimentary basins from offshore western Australia (Fig. 11). This lithosphere was rifted from Australia and was accreted to form East Java, SE Borneo and South Sulawesi and is much thicker, cooler and stronger than other parts of eastern Indonesia. This is reflected in the absence of significant Cenozoic deformation of these parts of Sundaland.

In addition, in the eastern part of the region there are several oceanic basins of different ages. Thus, although overall the region is weak, it includes very strong parts. The complex deformation of the region during the Cenozoic reflects all these features in addition to the changing forces at the plate edges. This is illustrated particularly well by the collision of Australia with SE Asia.

Australia collision

The composite character of the SE Asian lithosphere was a major influence on the way in which Australia–SE Asia collision developed, but also of great importance was the nature of the Australian margin. The Jurassic rifting led to formation of a continental promontory, the Sula Spur (Klompé 1954), that extended west from New Guinea on the north side of the Banda embayment. This embayment was part of the Australian plate and contained oceanic crust of Late Jurassic age. Its last remnant is the Argo Abyssal Plain SW of Timor. From the Late Jurassic to the Neogene the embayment was surrounded by a passive continental

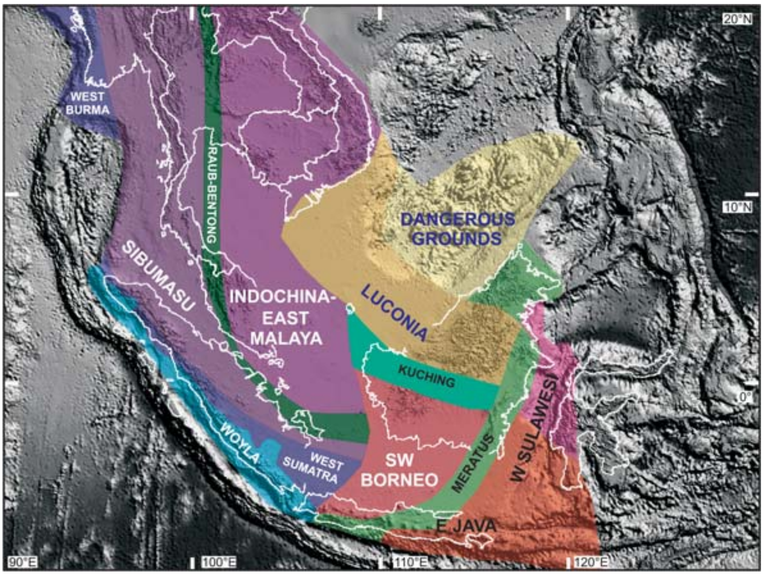


Fig. 9. Sundaland blocks that were part of Sundaland by mid-Cretaceous, modified after Metcalfe (1996) and Barber *et al.* (2005). Ophiolitic sutures are shaded in green. West Sumatra, West Burma and Indochina–East Malaya were Cathaysian blocks added to Eurasia during the Palaeozoic. Sibumasu was accreted along the Raub–Bentong suture in the Triassic. West Burma and West Sumatra were subsequently moved along the Sundaland margin. The Woyla Arc was accreted in the Cretaceous. The Luconia and Dangerous Grounds blocks are interpreted to be Cathaysian fragments rifted from Asia and added to Sundaland in the Cretaceous. SW Borneo and East Java–West Sulawesi were rifted from West Australia and added in the mid-Cretaceous.

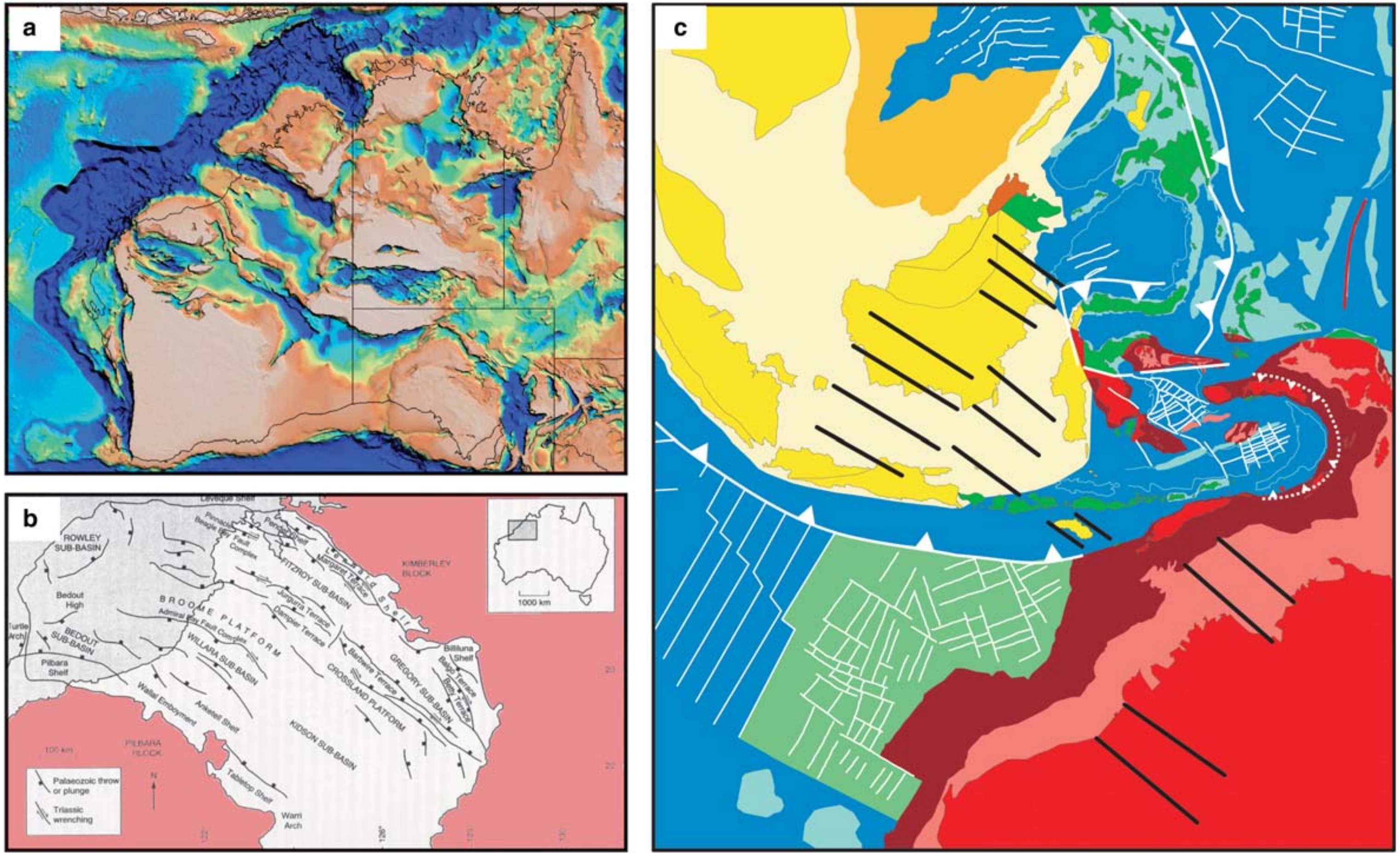


Fig. 10. (**a**) Basement structure of Australia (Oz Seebase^{TM} Study 2005). For the continental crust the image highlights areas of exposed or shallow basement (mainly Archaean or Proterozoic crust) in shades of pink in contrast to areas with thick sedimentary cover in shades of blue. (**b**) Structure of the Canning Basin from Cadman *et al.* (1993). Pink areas are Archaean or Proterozoic basement. (**c**) Black lines show general trends of deep structures in NW Australia and predicted orientation of deep structures in Indonesia at the present-day if these faults were brought with accreted blocks from NW Australia according to the reconstructions of Figures 4 and 5.

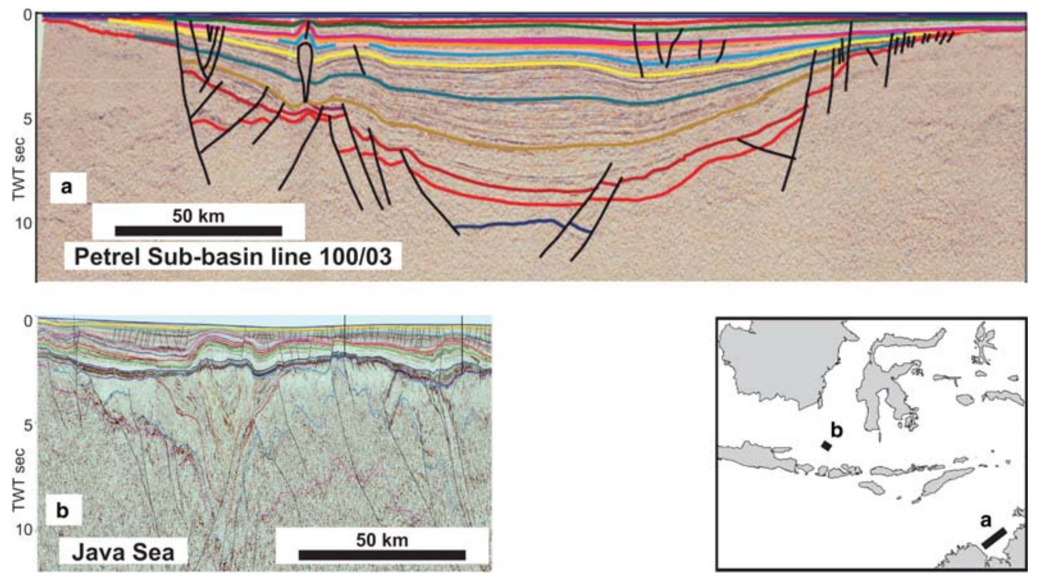


Fig. 11. (**a**) Deep structure of part of the NW Shelf modified from Goncharov (2004). (**b**)-. Deep structure of Java Sea modified from Emmet *et al.* (2009). Seismic lines are approximately the same horizontal and vertical scales and locations are shown on the inset map. TWT sec is two-way travel time in seconds. Both areas are characterized by old deep basement faults and thick sections of relatively undeformed sedimentary rocks of probable Palaeozoic and Mesozoic age.

margin that can be traced from the Exmouth plateau, via Timor, Tanimbar and Seram to SE Sulawesi. The shape of the embayment and great age of the oceanic lithosphere within the Australian plate were major influences on the way the collision developed. The spur, and the way in which it was fragmented during the Neogene (Figs 12 & 13), is the cause of many of the controversies about collision ages, and explains the present unusual distribution of continental crust in the present Banda Arc.

Before 25 Ma there was subduction of oceanic lithosphere at the Java Trench which continued east into the Pacific north of New Guinea, south of the Sulawesi north arm, the Philippines and Halmahera. Soon after 25 Ma the Sula Spur began to collide with the North Sulawesi volcanic arc, and this is the first Australia–SE Asia collision. Ophiolites were thrust onto the continental crust, derived from the ocean north of the Sula Spur and probably from the North Sulawesi fore-arc, and are preserved today in East Sulawesi (Kündig 1956; Silver *et al.* 1983). Ophiolites in South Sulawesi represent other parts of the oceanic crust between the Sula Spur and West Sulawesi; they may have been thrust east during the collision but more likely represent remnants of a Palaeogene transform margin at the eastern edge of Sundaland that have not been thrusted at all. The important points are that by the Early Miocene there was Australian crust in East and SE Sulawesi which continued east to the Bird's Head, and there was no subduction of the embayment.

Between 25 and 15 Ma the convergence between the Australian plate and Eurasia was absorbed in several ways: subduction of Indian ocean crust at the Java Trench; subduction of the Proto-South China Sea; broad non-rigid counter-clockwise rotation of Sundaland (Borneo, West Sulawesi, Java); internal deformation of Sundaland; and contraction, uplift and erosion in East and SE Sulawesi. There has been considerable controversy about reconstruction of the Banda region (see discussions in Hall & Wilson 2000; Hall 2002; Spakman & Hall 2010). Several authors have recognized, implicitly

Fig. 12. Reconstructions of the Banda region at 25 Ma and 15 Ma. Soon after 25 Ma the first stage of Australia–SE Asia collision began as the Sula Spur collided with the Sunda Arc in North Sulawesi. Farther north the Proto-South China Sea was almost eliminated by subduction beneath north Borneo. Green shading shows the extent of oceanic crust older than 120 Ma. By about 15 Ma the Java Trench propagated east along the northern continent–ocean boundary of the Banda embayment and subduction hinge rolled back to the SE.

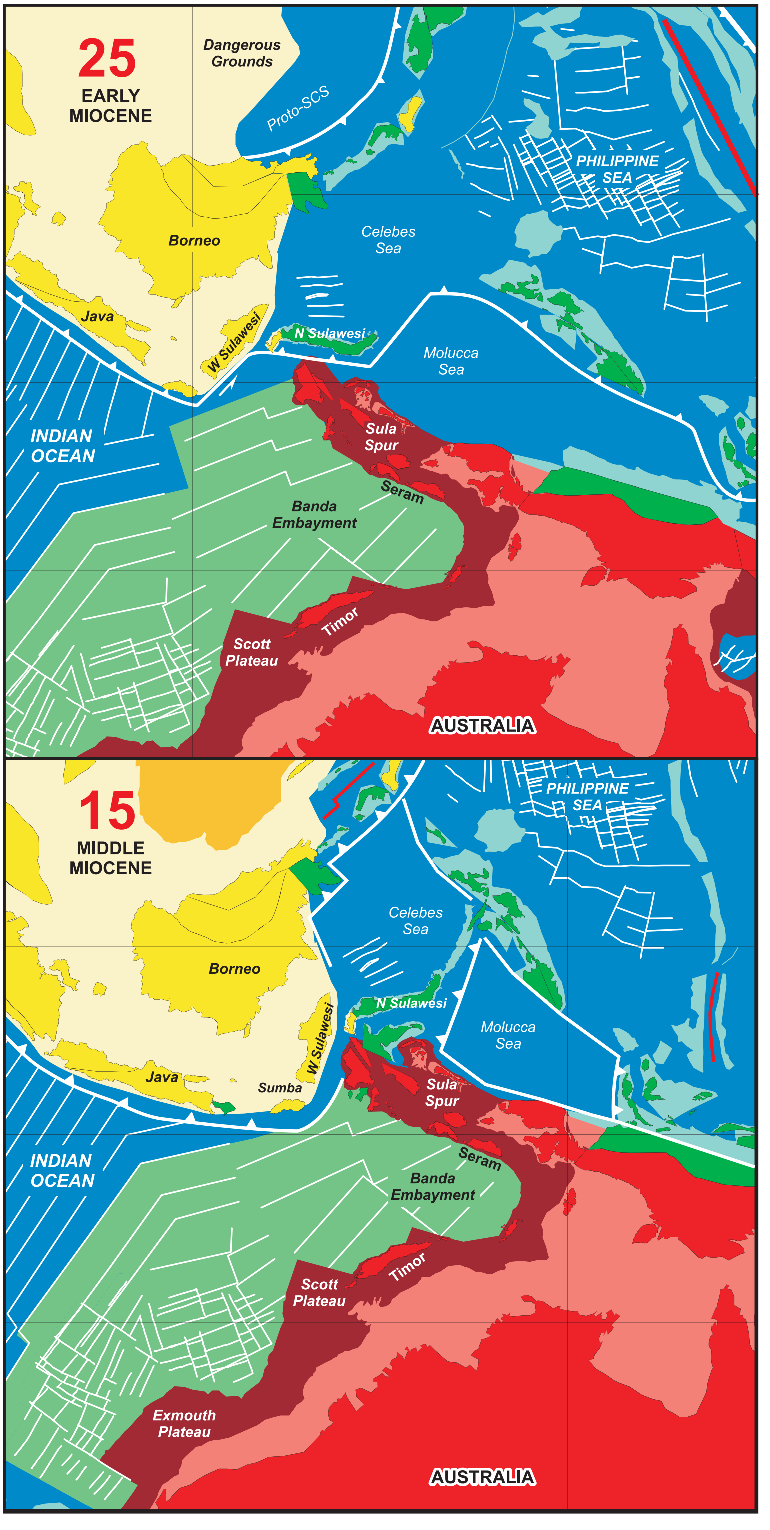
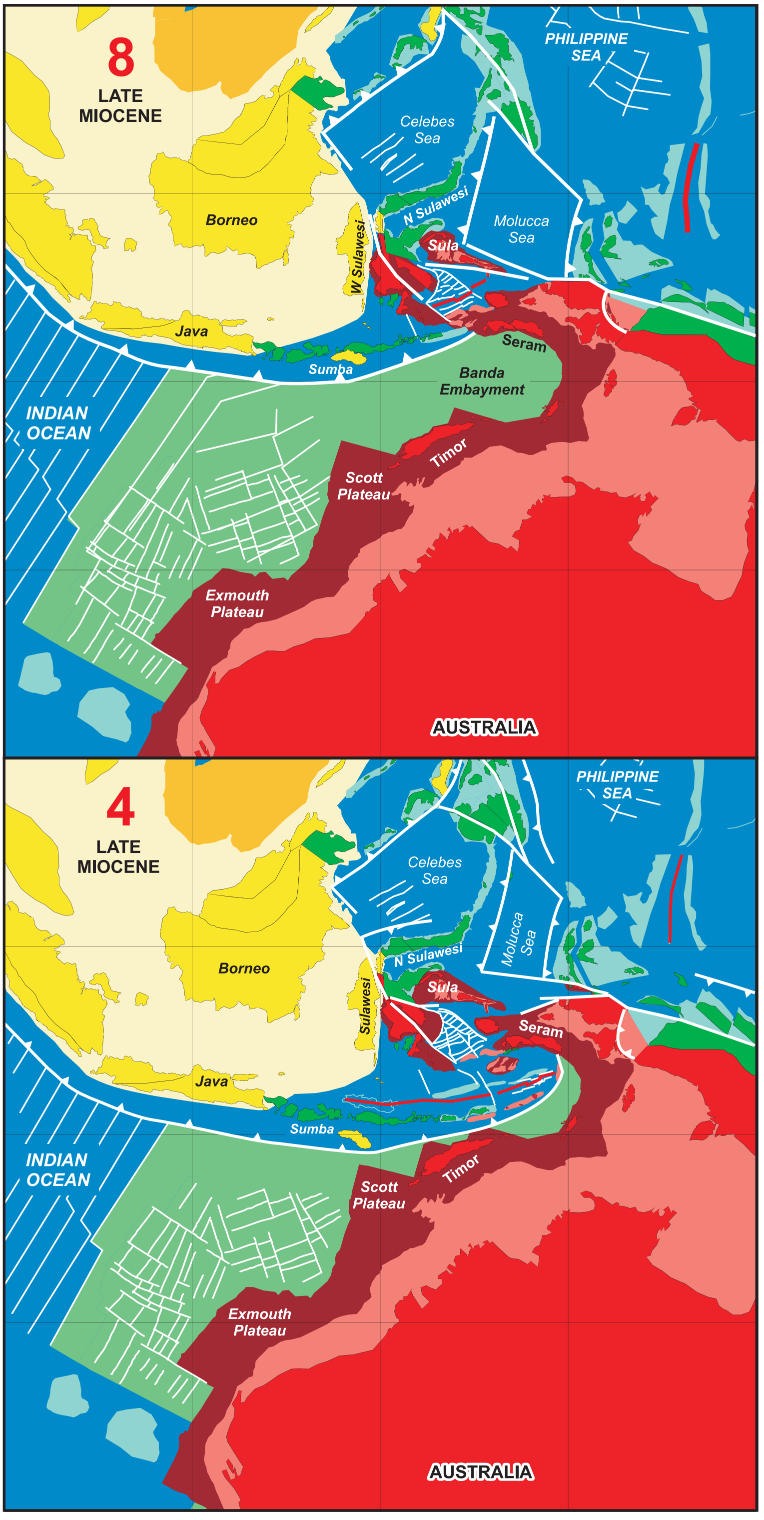

25
EARLY MIOCENE
Dangerous Grounds
Proto-SCS
PHILIPPINE SEA
Celebes Sea
Borneo
Java
W Sulawesi
N Sulawesi
Molucca Sea
INDIAN OCEAN
Sula Spur
Seram
Banda Embayment
Timor
Scott Plateau
AUSTRALIA
15
MIDDLE MIOCENE
PHILIPPINE SEA
Celebes Sea
Borneo
N Sulawesi
W Sulawesi
Molucca Sea
Java
Sumba
Sula Spur
INDIAN OCEAN
Seram
Banda Embayment
Timor
Scott Plateau
Exmouth Plateau
AUSTRALIA

Fig. 12.


8
LATE
MIOCENE
PHILIPPINE
SEA
Celebes
Sea
N Sulawesi
Molucca
Sea
Sula
Borneo
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Java
Sumba
Seram
Banda
Embayment
INDIAN
OCEAN
Timor
Scott
Plateau
Exmouth
Plateau
AUSTRALIA
4
LATE
MIOCENE
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Sulawesi
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OCEAN
Timor
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Plateau
Exmouth
Plateau
AUSTRALIA

Fig. 13.

or explicitly, the importance of subduction rollback in the Neogene development of the Banda arc (e.g. Hamilton 1979; Hall 1996, 2002; Charlton 2000; Milsom 2001; Harris 2006). I consider that rollback into the embayment is a key to understanding the development of the region, not only of the Banda arc but also of Wallacea, and the description here is based on a detailed model that links the tectonic reconstruction to the structure of lithosphere in the mantle (Spakman & Hall 2010).

Subduction rollback into the Banda embayment began at about 15 Ma when the Java Trench became aligned with the northern side of the embayment, a tear fault developed from the western edge of the Sula Spur and propagated eastward along the continent–ocean boundary. As the tear moved east, the oceanic embayment began to sink rapidly by its own negative buoyancy and began the rollback of a subduction hinge into the Banda embayment. Australia advanced northward, and the subduction hinge rolled back into the Australian plate forming the west-plunging lithospheric fold defined today by seismicity.

The exact time when rollback began is uncertain, but it was manifested by extension of the region above the Banda slab, which included parts of the pre-collision Sundaland margin in West Sulawesi and the collided Australian crust of the Sula Spur. An age between about 15 and 12 Ma is indicated by extension-related volcanic activity in West Sulawesi (Polvé *et al.* 1997), core complex ages in the Sulawesi north arm (van Leeuwen *et al.* 2007), the beginning of spreading in the North Banda Sea (Hinschberger *et al.* 2000), and subsidence and volcanic activity near Sumba (Fortuin *et al.* 1997). Extension is interpreted to have occurred during three important phases. The earliest phase led to formation of the North Banda Sea between 12.5 and 7 Ma (Hinschberger *et al.* 2000). Extended continental crust from the Sula Spur was separated from that remaining in East and SE Sulawesi and transported into the region of the upper plate above the subduction hinge. Some of this crust remains in the Banda Ridges, and some forms part of the basement of the Banda volcanic arc and its fore-arc east of Flores. The eastern part of this arc, from east of Wetar to Seram, was active only during a short period (*c.* 8–5 Ma) of volcanic arc magmatism before a second major phase of extension led to formation of the South Banda Sea (Hinschberger *et al.* 2001). During opening of the South Banda Sea continental crust was again extended and carried into the Banda fore-arc; this crust is now found in Timor and several of the small outer arc islands from Leti to Babar (e.g. Bowin *et al.* 1980). Volcanic arc activity continued in the Inner Banda Arc from Flores at least as far east as Wetar, but continued rollback of the subduction hinge led to collision between the southern passive margin of the Banda embayment and the volcanic arc which began in East Timor at about 4 Ma (Audley-Charles 1986, 2004) and led to termination of volcanic activity from Alor to Wetar.

The southern passive margin of the Banda embayment had an irregular shape with a number of rectilinear offsets similar to the present-day Exmouth Plateau: one south of Sumba and another in the region of East Timor. Uplift and thrusting of Australian continental crust began earliest in East Timor, whereas in the remnants of the oceanic embayment to the east subduction rollback continued. The most marked final phase of extension of the upper plate above the retreating hinge led to the formation of the Weber Deep which subsided from fore-arc depths of about 3 km to its present-day depth of more than 7 km in the last 2 million years.

Two issues have plagued interpretation of the Banda arc. One is the direction and rate of convergence, and the second is the age of collision. There is no requirement for the two slabs often postulated (e.g. Cardwell & Isacks 1978; McCaffrey 1989; Das 2004; Hinschberger *et al.* 2005; but cf. Hamilton 1979) to account for features such as dip directions of the lithosphere and the apparent rise in the north-dipping subducted slab from depths of several hundred kilometres shown on NNE–SSW sections drawn parallel to Australia–SE Asia convergence direction. It is not Australia–SE Asia convergence, but the rollback of the subduction hinge into the embayment accompanied by deformation of the slab in the mantle, that accounts for the shape of the arc and the subducted lithosphere (Spakman & Hall 2010). During most of the Neogene the rollback direction was broadly to the SE, but after arrival of the Banda volcanic arc at the southern passive margin of the Banda embayment, rollback was east-directed forming the Weber Deep. The size and shape of the embayment

Fig. 13. Reconstructions of the Banda region at 8 and 4 Ma. Rollback of the subduction hinge into the Banda embayment stalled briefly, and spreading ceased in the North Banda basin. By this time the Sula Spur had been fragmented leaving remnants in Sulawesi and the Sula-Banggai Islands. Extended crust on the south side of the embayment was later left as the Banda Ridges in the central Banda Sea as spreading began in the South Banda Basin at about 6 Ma. At about 4 Ma collision between the Banda volcanic arc and the southern continental margin of the embayment began in East Timor. The irregular shape of the margin resulted in a complex collision between Timor and Sumba, while rollback continued to the east forming the Weber Deep.

are similar to the slab dimensions inferred from seismicity, but seismic tomography indicates that part of the continental lithosphere underlying the western Sula Spur must have also been incorporated in the subducted slab (Spakman & Hall 2010).

In the Banda region, notably in Timor but also elsewhere in the Banda arc, a variety of radiometric ages (most are K–Ar ages with a few Ar–Ar ages) has led to much confusion and claims of multiple or pre-Pliocene collisions (e.g. Berry & McDougall 1986; Richardson 1993; Reed *et al.* 1996; Linthout *et al.* 1997; Charlton 2002; Keep *et al.* 2003, 2009; Harris 2006). As discussed by Standley & Harris (2009) for Timor these ages record numerous episodes in the development of the Banda region. Pre-Miocene metamorphic ages represent events predating Australian collision with the SE Asia margin. Collision of the Sula Spur with the Sulawesi north arm occurred soon after 25 Ma and is now recorded by cooling ages of metamorphic rocks in Sulawesi (Parkinson 1998*a*, *b*; van Leeuwen *et al.* 2007), Timor (Berry & McDougall 1986; Standley & Harris 2009), dredged samples from the Banda Ridges (Silver *et al.* 1985), and from Kur in the Banda fore-arc (Honthaas *et al.* 1997). The ages do not record the time of collision at the place the rocks are now found, because they have been moved to their present positions by extension of the upper plate above the retreating subduction hinge (see reconstruction in Spakman & Hall 2010).

Even younger metamorphic and igneous ages, such as those from rocks dredged in the Banda Ridges and from Timor, do not record the age of collision of the southern margin of the Banda embayment with the Asian margin. For example, many authors have followed Berry & Grady (1981) and Berry & McDougall (1986) in interpreting high grade metamorphosed rocks with cooling ages of 8 Ma as marking collision of Australian crust with the Asian margin despite failing to explain why, after collision with the arc, volcanic activity continued until 3–4 Ma. For example, a Late Miocene collision age has been interpreted in Sumba (Keep *et al.* 2003) and even older collision ages suggested for Timor (Keep *et al.* 2009).

The problem cannot be solved by making distinctions between continental crust supposedly of Asian and Australian origin (cf. Charlton 2002; Harris 2006). As explained above, parts of the Cenozoic SE Asian margin were underlain by continental crust of Australian origin that arrived in the Cretaceous. On Timor Standley & Harris (2009) demonstrated an important difference between the Banda Terrane, which has detrital zircons up to mid-Cretaceous age, and Australian continental margin basement which has no detrital zircons younger than Permian–Triassic. The Banda Terrane was part of the Asian margin from the mid-Cretaceous but its basement includes continental rocks with a West Australian provenance (Hall *et al.* 2009*a*) probably similar to those beneath the Australian continental margin that collided in Timor in the Pliocene. More important is the Early Miocene collision of the Australian origin Sula Spur and its subsequent extension and fragmentation during slab rollback (Spakman & Hall 2010). The Banda allochthon in Timor is a complex including continental crust and arc rocks that formed part of the Early Cenozoic Asian margin, their overlying sedimentary rocks, Australian continental crust that collided in the Early Miocene, and Neogene arc rocks formed during the subduction of the embayment.

Elsewhere in the Banda Arc young metamorphic ages have been used to interpret complex tectonic collision-related scenarios. For example, metamorphic and igneous rocks from Seram with ages of 5.5–6 Ma have been used to infer formation of an ophiolite at 15 Ma and obduction at about 9 Ma (Linthout *et al.* 1997). Not only are the rocks completely unlike any other sub-ophiolite metamorphic rocks, it is also difficult to reconcile the proposed two dimensional reconstruction with any reconstructed map of the West Pacific since it requires the Banda volcanic arc to be placed 2000 km north of Timor in the Middle Miocene.

Some confusion results from use of the term collision, but more follows from the assumption that metamorphic ages must mark contractional deformation that accompanied collision – in fact the K–Ar and Ar–Ar ages simply record cooling, which in most cases resulted from extension. Neogene metamorphic ages record extension of this complex upper plate. I interpret all the post-Sula Spur collision metamorphic and igneous ages, mainly between 12 and 4 Ma, to record extension of the upper plate, including Australian-origin continental crust and the Banda fore-arc, and tearing along the northern oceanic–continent boundary of the embayment during rollback.

In eastern Indonesia the first contact of the Australian continent and the Asian margin was soon after 25 Ma. Rollback into the Banda embayment began at between 15 and 12 Ma. 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 & 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 & Chamalaun 1981; Scotney *et al.* 2005) and by the rapid uplift that followed collision which moved sedimentary rocks deposited at depths of several kilometres below

sea level to their present positions of several kilometres above sea level (e.g. Fortuin *et al.* 1997; Audley-Charles 2011). The very young volcanoes in the eastern part of arc from Damar to Banda (Abbott & Chamalaun 1981; Honthaas *et al.* 1998, 1999) record the latest and final stage of rollback into the last remnant of the embayment that accompanied formation of the Weber Deep. However, the extension that accompanied rollback into the embayment formed new oceanic basins in the Banda Sea. It can be argued that Australian–SE Asia collision began about 25 million years ago, continues today, and is likely to continue for many millions of years to come as these small basins are destroyed. The East Indonesian region provides a useful perspective on the debate about India–Asia collision age, variously estimated as between 60 and 35 Ma. For a flavour of this debate see Rowley (1996), Aitchison *et al.* (2007), Garzanti (2008), Khan *et al.* (2009) and Yin (2010). If there has been disagreement about ages in East Indonesia, where collision began more recently, is less advanced, and where continental margins can be reconstructed, it is easy to see why there is controversy surrounding timing of events in the larger and much more deformed Himalayan orogenic belt.

Plate tectonics v. deformation of the crust

Although the plate model used here (Hall 2002; Hall *et al.* 2009*a*) provides a good first order understanding of the history and development of the region it is less clear that plate tectonics provides an adequate basis for understanding the details of the present or Cenozoic deformation of the region. Clearly, plate movements have been a major control and have led to the complex distribution of blocks, sutures, and the character of the lithosphere discussed above. However, it is impossible to draw continuously connected plate boundaries between major plates (Australia, Pacific, Philippine Sea) surrounding SE Asia, for example to join the Java Trench to the Philippine Trench. The problem remains even if smaller plates are postulated, and this is critical for modelling deformation since interpreted regional stresses are critically dependent on the geometry and position of inferred plate boundaries. Furthermore, much of the SE Asian region is continental, and deformation of continents is significantly less well understood than that of the strong oceanic plates; we now know that deformation is, and has been, much more complex than interpreted from models of rigid blocks separated by narrow fault zones that cut the lithosphere (e.g. Thatcher 2009).

An alternative is to consider large parts of the region as a diffuse plate boundary zone (Gordon 1998) or wide suture zone (Hall & Wilson 2000; Hall 2009*b*) within which there is deformation. This type of approach ‘implies that a deforming zone is bounded by two (or more) rigid or nearly rigid plates in motion relative to each other’ (Gordon 1998) but raises the question of identifying the rigid areas. Gordon (1998) represents east Asia and SE Asia (Fig. 14) as a very large deforming region with large rigid parts, such as the Yangtze, Indochina and Borneo ‘plates’ or ‘blocks’, and

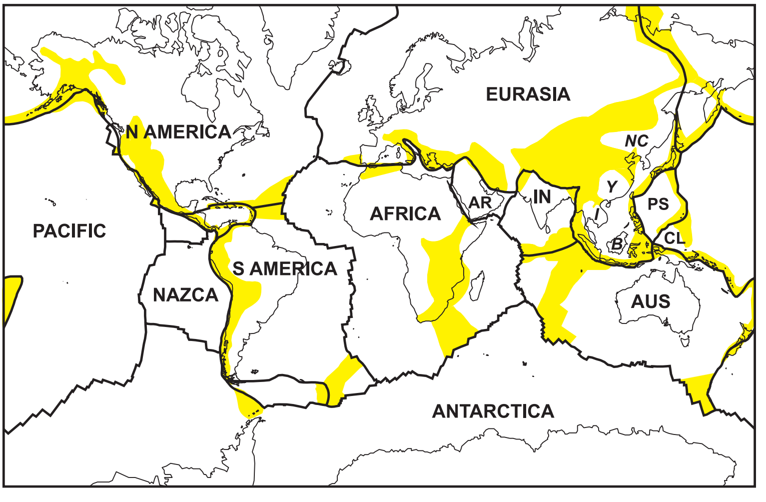

Fig. 14. Diffuse plate boundary zones modified from Gordon (1998). Plate abbreviations are AUS, Australia; CL, Caroline; IN, India; PS, Philippine Sea. East and SE Asia are represented as a very large deforming region with rigid parts, such as the North China (NC), Yangtze (Y), Indochina (I) and Borneo (B) blocks.

shows East Indonesia as a wide deforming zone east of the Makassar Straits. This is consistent with the fact that Sundaland is largely free of seismicity and volcanic activity, which supports proposals of a SE Asian (McCaffrey 1996) or Sundaland (e.g. Simons *et al.* 2007) plate separate from Eurasia. However, I suggest that the identification of this plate does not imply a rigid strong region, but more a contrast with the strong Pacific and Australian plates, from which the Sundaland interior is separated by poorly defined boundary zones that are characterized by intense seismicity and volcanism. On the whole, the entire region of east Asia and SE Asia is better considered as non-rigid with relatively small strong parts within it, and this has been the situation throughout the Cenozoic. The region between the South China Sea and the Bird's Head of New Guinea exemplifies the character of the region and highlights some key features of how it is deforming.

Northern Borneo

Hall & Morley (2004) drew attention to the weakness of Sundaland during the Cenozoic, recorded by the presence of numerous sedimentary basins, many very deep, and elevated areas. During the Cenozoic most of Borneo north of the Paternoster–Lupar lineaments was a weak deforming region, but southern Borneo and South Sulawesi was a stronger block, or possibly blocks. To the north of the these lineaments are the Rajang–Crocker fold belts, including thick Upper Cretaceous to Eocene, and Eocene to Lower Miocene, deepwater sediments, thick sediments of the Kutei basin, and the deep North Makassar Basin. Most of emergent north Borneo has a Neogene history of contraction and has been the source of the large volumes of sediment filling Neogene basins onshore and offshore, with clear evidence of significant vertical motions relative to sea level, of the order of kilometres, in the last 10 to 15 million years. In contrast, in southern Borneo west of the Meratus Mountains is a broad downwarp, the Barito Basin, filled by Eocene to Miocene terrestrial to marginal marine clastic sediments and shallow marine limestones, whereas to the east is the long-lived Eocene to Miocene Paternoster–Tonasa carbonate platform. With the exception of a narrow zone of deformation in the Meratus Mountains, which may be a reactivated strike-slip suture in the basement, both areas are still largely undeformed. Seismic lines across the Paternoster Platform, and field studies on land, show that Eocene to Recent largely shallow marine carbonates are of the order of 1–2 km in thickness and record vertical movements relative to sea level of much smaller amounts over 40 million years.

Northern Borneo is the site of important and misunderstood deformation. Haile (1973) first recognized the role of subduction in the history of northern Borneo, and Hamilton (1979) identified the deep NW Borneo–Palawan trough as an extinct subduction trench. Hinz and co-workers (e.g. Hinz & Schlüter 1985; Hinz *et al.* 1989) disputed this interpretation and argued that the trough was the site of northward thrusting but not subduction, and these alternative views continue to create confusion (e.g. Hutchison 2010).

The history of northern Borneo is reviewed and discussed elsewhere (e.g. Hall & Wilson 2000; Hutchison *et al.* 2000; Hutchison 2005; Hall *et al.* 2008). Subduction of the proto-South China Sea beneath northern Borneo terminated in the Early Miocene after collision of the extended South China continental margin crust. However, the subduction zone was approximately 150 km south of the present NW Borneo Trough and is now beneath Sabah. The collision resulted in uplift and erosion in the interior of Borneo which provided sediment to the north, east and south.

After collision there was a brief period of erosion which formed the Top Crocker Unconformity (van Hattum *et al.* 2006; Hall *et al.* 2008) on land and offshore. However, soon after the emergence of much of Sabah, the situation changed again. Although a narrow band of mountains probably remained along the present spine of the Crocker Ranges, the areas to the north and south subsided below sea level and sedimentation resumed. In southern Sabah there was a wide basin SE of the Crocker Ranges (Noad 1998; Balaguru *et al.* 2003; Balaguru & Nichols 2004). Most of the sediment fed into this basin and carried to the Sulu Sea came from the Borneo interior. River and shallow marine sediments are now preserved in a number of structures described as circular basins, which are remnants of the much larger basin supplied by a large river system, flowing NE, which deposited sand and mud in a delta and coastal plain complex. NW of the Crocker Ranges there was deposition of thick sediments in deltas and coastal plains of north Sabah and Brunei by rivers flowing to the north or NW. In Brunei and offshore Sabah, the position of the shelf edge at different times can be identified (Hazebroek & Tan 1993; Sandal 1996) showing that it moved seaward during the last 15 million years. This indicates that the Crocker Ranges were narrow about 15 million years ago, and have widened gradually with time.

In offshore Brunei and NW Sabah Morley *et al.* (2008) noted that inversion, thrusting and uplift of the present-day onshore area and inner shelf occurred during the Middle Miocene to Pliocene, while a deepwater fold and thrust belt developed during the latest Miocene to Holocene. There was

a seaward shift of deformation with time (C. K. Morley, pers. comm. 2010) consistent with the movement of the shelf edge. Although some of the deformation can be attributed to shallow gravitational processes in a delta, in places there is more shortening in the deepwater fold and thrust belt than there is extension within the Neogene sedimentary section. On the shelf thick-skinned contractional deformation has episodically affected the Sabah margin from the Middle Miocene to the Pliocene (C. K. Morley, pers. comm. 2010). Therefore a number of authors (e.g. Ingram *et al.* 2004; Morley *et al.* 2008; Hesse *et al.* 2009, 2010; King *et al.* 2010) interpret deformation, shortening magnitudes, stress orientations, GPS observations (Simons *et al.* 2007) and recent seismicity to indicate a role for tectonic stresses which they attribute to ongoing convergence of blocks or plates, subduction or inheritance from former subduction.

It is noteworthy that almost all the data on which these interpretations are based, with the exception of GPS observations and seismicity (Simons *et al.* 2007), are from offshore NW Sabah and nearby land areas such as Brunei. Little is published or available for the Sulu Sea side of Sabah, yet on land the structural grain is completely different from west Sabah, changing from the NNE-trending Crocker to the ESE-trending Sulu direction (e.g. Hamilton 1979; Hazebroek & Tan 1993; Tongkul 1991, 1994) and offshore fold axes and thrusts are apparently broadly parallel to the Sulu trend. This is inconsistent with suggested microplates (e.g. Simons *et al.* 2007) based on GPS observations, and the deformation history and structural trends in southern Sabah (Balaguru 2001; Balaguru *et al.* 2003; Tongkul & Chang 2003) are equally incompatible. I suggest there is no plate convergence in the NW Borneo region and that deformation is largely a result of topographically-induced stresses and mobility of the deeper crust. NW of the Crocker mountains is a very thick Neogene sediment wedge, including the offshore fold and thrust belt (Fig. 15). Recent studies show thin crust beneath this sediment wedge (Franke *et al.* 2008; C. Foss, pers. comm. 2008), which requires thinning of crust previously thickened during the Early Miocene collision of the Dangerous Grounds microcontinental block and the Sabah active continental margin. Seismic lines from oil companies (Hutchison 2010) and new data acquired during Malaysian Law of the Sea investigations (V. R. Vijayan, pers. comm. 2008) show elevated features within the NW Borneo Trough at water depths close to 3 km which are capped by carbonates and pinnacle reefs, indicating major subsidence. There is almost no seismicity associated with the trough, no volcanic activity on land, and nothing to indicate southward subduction; nor is there evidence for converging plates to produce the fold and thrust belt. On the other hand there is evidence for repeated failures of the shelf edge and slumping into deepwater (e.g. McGilvery & Cook 2003). To the south, on land, there are >2 km high mountains formed of deformed Eocene to Lower Miocene Crocker deep marine sediments, intruded by the 7–8 Ma Kinabalu granite (Cottam *et al.* 2010) forming a 4 km mountain, and I suggest these observations indicate a link between significant rapid and young uplift on land, evidenced by exhumation of a 7–8 Ma granite now exposed at 4 km above sea level, and significant rapid and young subsidence offshore. The trough is thus a flexural depression due to sediment loading and is associated with a flexural bulge in the Dangerous Grounds. In this interpretation the offshore fold and thrust belt, and major shelf failures producing huge deepwater mass transport complexes observed on the sea floor and in the Neogene sequences beneath, are the result of landward normal faulting producing deepwater thrusting. However, although this is not quite the toe-thrust model of the Shell geologists (e.g. Hazebroek & Tan 1993) developed from Niger delta studies, there are important similarities in area and scale (Corredor *et al.* 2005).

In contrast, several authors have argued that the NW Borneo margin is significantly different from the Niger Delta (e.g. Morley *et al.* 2008; Hesse *et al.* 2009, 2010; King *et al.* 2010) based on differences in modern stress patterns, and the observation that in parts of the deepwater fold and thrust belt there is more contraction than extension in the Neogene sedimentary section. I suggest this simply reflects the absence in west Africa of the several kilometres of elevation on land in Sabah, and the balance between contraction v. extension would be found if the section on land were included. In other words, there is no requirement for regional convergence to account for deformation which in any case can explain only deformation of offshore NW Borneo (if that, e.g. Hesse *et al.* 2009 show that fold orientations are inconsistent with GPS observations) and not that observed in other parts of northern Borneo and offshore. The subsidence and crustal thinning offshore and uplift onshore can be explained by movement of the deeper crust, and this is a phenomenon observed in other parts of the region.

West Sulawesi

West Sulawesi has many of the features of northern Borneo except on a larger scale (Fig. 16) but there is even less information in the public domain. On land in the Lariang and Karama areas shallow marine Miocene rocks are overlain by Pliocene coarse clastic sediments derived from an orogenic belt to

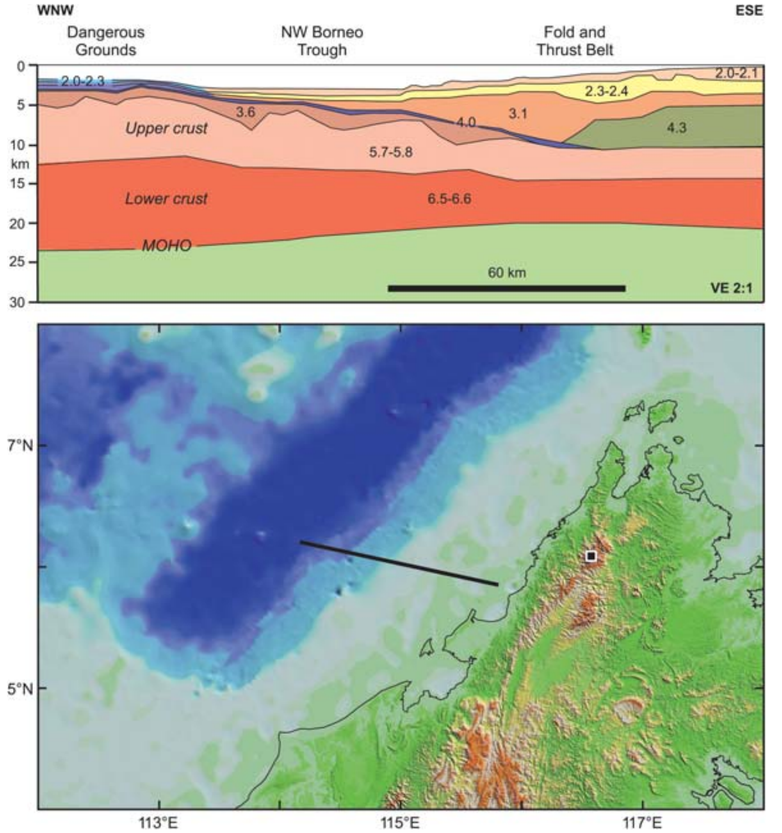

Fig. 15. Profile across the Sabah margin with crustal P wave velocities (m/s) modified from Franke *et al.* (2008). The section shows the Dangerous Grounds continental crust that was thrust beneath the NW Sabah margin in the Early Miocene and loaded by a thick wedge of sediments that has built out from Sabah during the Neogene; the wedge of sediment now forms an actively deforming fold and thrust belt. A critical point is thinning of the upper and lower crust beneath the thickest part of the wedge. The location of the line is shown on the DEM of satellite gravity-derived bathymetry combined with SRTM topography (Sandwell & Smith 2009). The deepest part of the trough is immediately NW of the 4000 m granite peak of Mt Kinabalu, marked by the black square.

the east (Calvert & Hall 2007). There are mountains up to 3 km above sea level which expose deep crustal rocks such as garnet granulites and eclogites, intruded by young granites, in the Palu area, and probably extensively throughout West Sulawesi (T. van Leeuwen & I. Watkinson, pers. comm. 2009). Rapid uplift and exhumation provided sediment to the broadly west-vergent offshore fold and thrust belt. From north to south the character and orientation of the fold belt changes. The trend of fold axes indicates a radial transport of material away from the mountains which terminate relatively abruptly to the south at the northern edge of the South Sulawesi Tonasa–Tacipi platform where there has been carbonate deposition since the Eocene (e.g. Wilson & Bosence 1996; Ascaria 1997; Ascaria *et al.* 1997). Like northern Borneo there was a pre-existing deepwater area into which the fold belt could grow, the Makassar Straits (Hall *et al.* 2009*b*), but seismic lines across the northern margin of the Paternoster platform indicate at least 1 km of subsidence of the North Makassar basin on reactivated faults close to Sulawesi at the end of the Miocene. The subsidence is the same age as the rapid exhumation on land. Like north Borneo there is a temporal link, and I suggest a causal link, between subsidence and deformation offshore and uplift and exhumation on land.

North and East Sulawesi

West Sulawesi is not the only part of Sulawesi that records rapid subsidence and uplift. This is true for most of North and East Sulawesi, possibly for

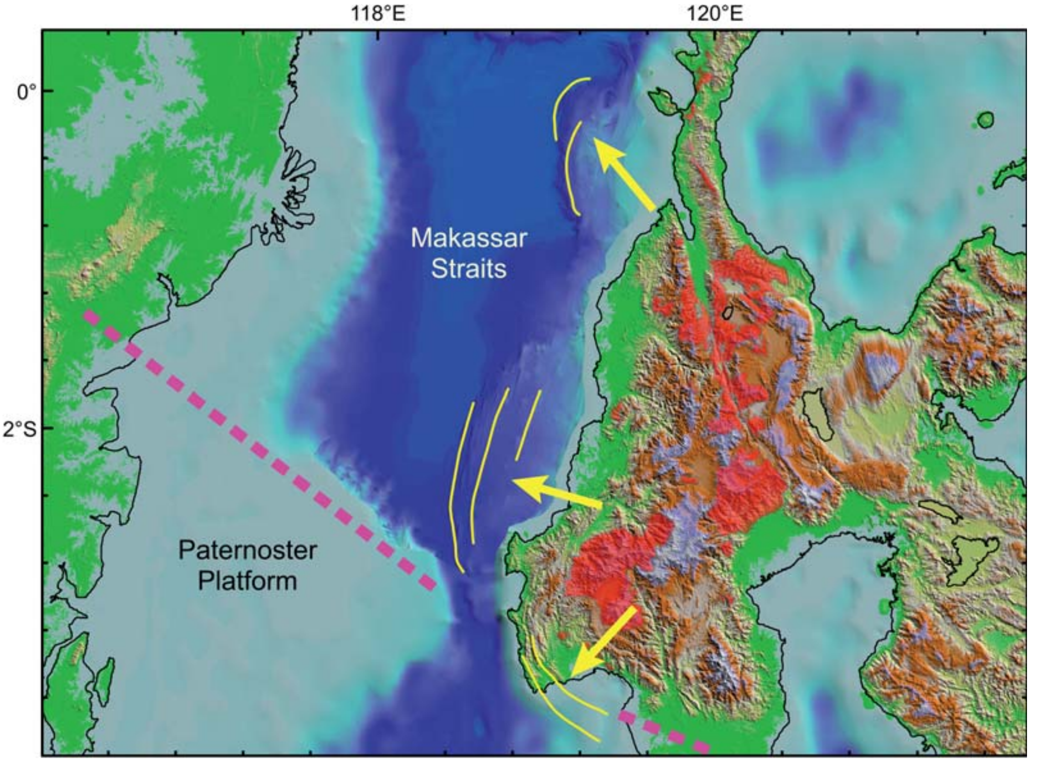

Fig. 16. DEM of the West Sulawesi region with satellite gravity-derived bathymetry combined with SRTM topography (Sandwell & Smith 2009) merged with bathymetry from Puspita *et al.* (2005). Fold trends in the offshore fold belt are highlighted in yellow and suggest westwards radial vergence. On land areas of (mainly) Late Miocene and younger granites are shown in red. The area north of the NW–SE lineament is suggested to be a weak area with significant deformation whereas south of the lineament the Paternoster Platform and its equivalent in South Sulawesi is a strong area that is almost undeformed.

SE Sulawesi, and certainly for the major enigmatic inter-arm basins of Gorontalo Bay and Bone Gulf. The north and east arms of Sulawesi are striking in their exceptional elevations (up to 3 km) within short distances of the coast, and the narrow width of these emergent areas. Dating uplift and exhumation is only just beginning. K–Ar and Ar–Ar cooling ages of 23–11 Ma from micas and hornblende are reported by van Leeuwen *et al.* (2007) from the Malino Complex at the west end of the north arm, which they interpret as a core complex. The ages appear to fall into two groups and although there is only a small number (23 ages from 6 samples). I speculate that the older ages record Early Miocene collision of the Sula Spur, and the cluster of ages from 14–11 Ma record rollback-induced extension. Throughout West, North and East Sulawesi there is evidence for significant vertical motions on land at about 5 Ma, recorded by K–Ar and apatite fission track ages from granites (e.g. Bergman *et al.* 1996; Elburg *et al.* 2003; Bellier *et al.* 2006), and by widespread and thick Celebes Molasse deposits which indicate rapid exhumation from about 5 Ma (e.g. Calvert 2000; van Leeuwen & Muhardjo 2005). The term Celebes Molasse is used for a variety of Neogene terrestrial or shallow marine deposits found throughout Sulawesi, but although it may include Lower Miocene post-ophiolite detrital sediments (e.g. Surono 1995; Surono & Sukarna 1996) there was clearly a major increase in output of clastic sediment in the Latest Miocene and/or Early Pliocene in West and East Sulawesi (e.g. van Bemmelen 1949; Garrard *et al.* 1988; Davies 1990; Calvert 2000; Calvert & Hall 2007).

Offshore, recently acquired seismic and multibeam data in Gorontalo Bay show spectacular subsidence recorded by numerous pinnacle reefs now found within a range of water depths between 1 and 2 km many of which, despite the high rates of sediment supply, are not buried by sediment. They indicate very young and rapid subsidence. For

example, between the north coast of the east arm and the Togian Islands there is a 50 × 20 km lobe of sediment with a thickness of up to 2 s TWT (two-way travel time) (Jablonski *et al.* 2007), that links alluvial fan deposits on land at north and south ends of the lobe. The water depths in the area between the east arm and the Togian Islands are now up to 1.5 km; 25 km to the south of the east arm coast elevations exceed 2 km. East of Poh Head at the end of the east arm are probable platform carbonates with no sediment cover at water depths of 1 km, and possible carbonates still deeper beneath bedded sediments (Ferdian *et al.* 2010; Watkinson *et al.* 2011). The platform carbonates are likely to be Middle and/or Upper Miocene by comparison with limestones beneath the Celebes Molasse in the Togian Islands, implying subsidence of 1 km or more in probably less than 5 Ma.

North Moluccas

A striking feature of East Indonesia is that, although there are undoubtedly some small plates, when plate boundaries are revealed by seismicity (Engdahl *et al.* 1998) they terminate abruptly and cannot be traced into other boundaries, implying relatively rapid changes from subduction to distributed deformation of the same plate (Fig. 17). Much of the deformation recorded by the upper crust seems to be almost independent of the deeper lithosphere. The Philippine Trench terminates at about 3°N; to the north the slab has been subducted to at least 100 km, dips steeply and becomes almost vertical, and there is a deep trench. This plate boundary neither continues southeastwards as often shown, nor does it connect via obvious faults to the Molucca Sea. The abrupt termination of the trench implies considerable distributed deformation in the north Halmahera area.

In the Molucca Sea seismicity shows the well-known double subduction system (Silver & Moore 1978) clearly indicated by seismicity, tomography and volcanic activity. There is no trench associated with either the west or east-dipping slabs, and it appears that the ‘melange wedge’ of the central Molucca Sea (McCaffrey *et al.* 1980) is deforming independently of the subducted Molucca Sea plate beneath. The southern edge of the west-dipping Molucca Sea slab terminates abruptly beneath Gorontalo Bay and runs almost due east–west. There is no surface expression, although this is not to be expected in Gorontalo Bay which forms the upper plate. However, surprisingly the lineament that would be expected to mark the former southern boundary of the Molucca Sea Plate, named the North Sula Sorong Fault (Hamilton 1979), which should be a major left-lateral strike-slip fault, has no expression on the sea bed, and has no seismicity

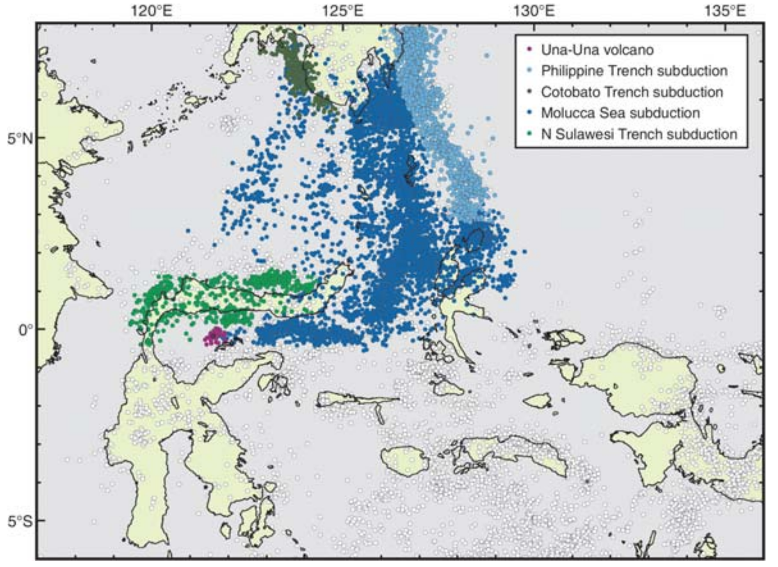

Fig. 17. Earthquake hypocentres in East Indonesian from Engdahl *et al.* (1998) and the Global CMT database (CMT Project 2009). Hypocentres that can be identified with different plate boundaries are shown in colour chosen to match Figure 19. At the mantle scale these imply a number of sharply demarcated and distinct plates, but at the surface many of the plate boundaries are not connected, and the Molucca Sea Plate is completely subducted with no surface expression, being overridden by the two converging fore-arcs which are deformed into the central Molucca Sea wedge.

in the crust. There are a very small number of hypocentres below 30 km, a few of which could indicate left-lateral displacement on a broadly-east–west fault system, but at the sea bed the most obvious structures in the plate boundary region are southward-directed thrusts. Even these do not have the displacement expected. Silver *et al.* (1983) suggested that thrusting was related to southward gravity-driven movement of the Molucca Sea wedge, and this is plausible north of the Sula Islands. However, close to Poh Head the thrusting occurs at the southern termination of strands in a right-lateral fault system which can be traced east from land (Simandjuntak 1986; Ferdian *et al.* 2010; Watkinson *et al.* 2011). The existence and displacement on this right-lateral fault system casts doubt on the connection between the fold belt in the east arm south of Poh Head (an Early Miocene structure), the interpreted Batui Thrust crossing Poh Head on land, and the Sangihe subduction offshore.

Some of the faults shown on maps of the region do exist but are old structures (Fig. 18) that no longer have surface expression (e.g. the Molucca Sea Trenches). Some plate boundaries do not connect to others and require distributed deformation of the lithosphere to maintain an internally consistent plate model (e.g. the Philippine Trench). Some of the faults probably do not exist or are not connected in the ways shown on most maps, for example, the NW–SE Greyhound Fault does not cross the seabed at all, and its existence is doubtful. The improvement in the quality of remotely sensed data (notably SRTM and Aster imagery for the rain forest areas of eastern Indonesia), and new seismic and multibeam data, means that structures can be mapped with more confidence, but there are still many areas of uncertainty. Nonetheless, it is certain that if the crust in the Sulawesi–North Moluccas region is broken into a series of blocks the boundaries do not correspond to those of the known plates. In fact, it is very unlikely that the upper crust is deforming as a series of rigid blocks, and some of the relative movements of the upper crust are not those predicted by our current plate models (Fig. 19).

Deformation

If the region is not deforming as plates or microplates, nor reflecting microplate movements, how is it responding to movements of the large plates? The common features of the region between offshore northern Borneo and the North Moluccas are rapid uplift of land to elevations of up to 3 km (and locally higher in the case of Mt Kinabalu at 4 km), and rapid subsidence offshore with water

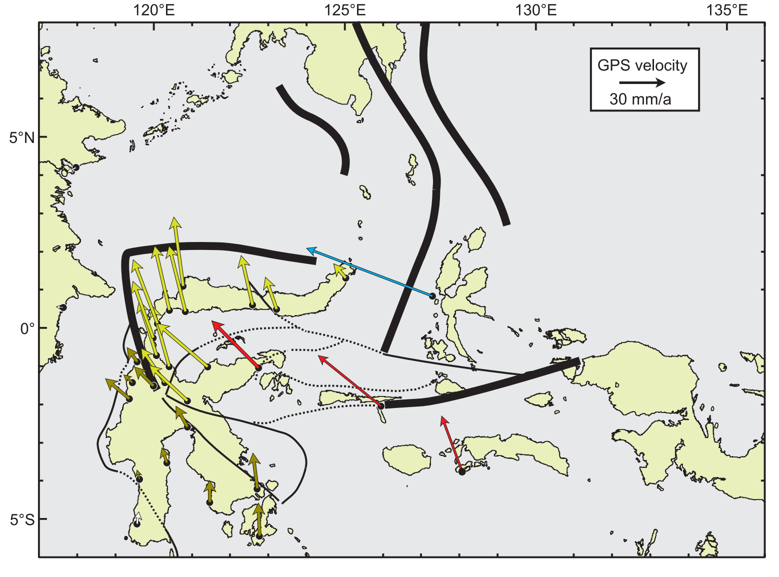

Fig. 18. GPS velocities and interpreted blocks in East Indonesia modified from Socquet *et al.* (2006). Different colours of GPS vectors show the different blocks outlined by the faults shown in black lines and are coloured to match Figure 19. Faults that penetrate the lithosphere are shown with heavy black lines. Many of the interpreted block boundaries are upper crustal faults of uncertain character and age; dashed lines are inactive, non-existent or very doubtful. The upper crust is clearly deforming in a complex way not directly related to plates that can be identified from seismicity (compare with Fig. 17).

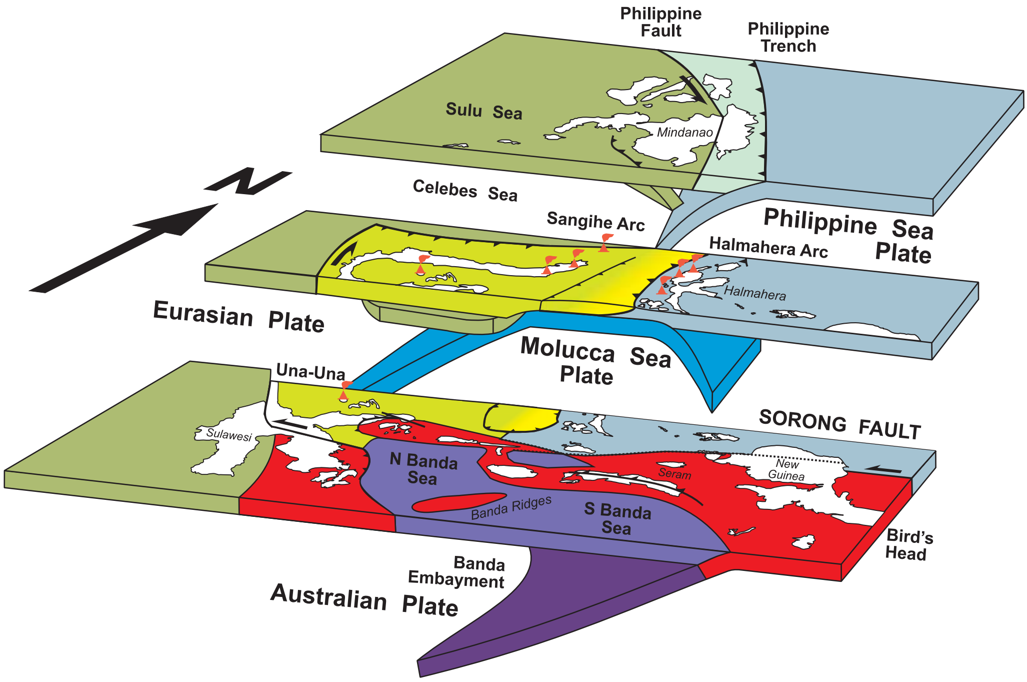

Fig. 19. 3D cartoon of plate boundaries in the Molucca Sea region modified from Hall *et al.* (1995). Although seismicity identifies a number of plates there are no continuous boundaries, and the Cotobato, North Sulawesi and Philippine Trenches are all intraplate features. The apparent distinction between different crust types, such as Australian continental crust and oceanic crust of the Philippine and Molucca Sea, is partly a boundary inactive since the Early Miocene (east Sulawesi) and partly a younger but now probably inactive boundary of the Sorong Fault. The upper crust of this entire region is deforming in a much more continuous way than suggested by this cartoon.

depths of more than 2 km and several kilometres of sediment below the seabed. The term uplift is now used with reluctance because it is imprecise in specifying what has moved, and it is difficult to quantify amounts and rates (England & Molnar 1990). However, it is very probable that what is now the land surface in this region was very close to sea level only a few million years ago and that slopes were less steep. Areas now offshore also had less relief and were close to sea level, demonstrated for example, by the distribution of carbonates. Material that was at the top of the crust on land several million years ago was eroded, transported offshore and deposited in sediment layers, above carbonates deposited close to sea level, which are in many places now at depths of several kilometres below sea level. What is now at the surface on land at elevations of up to 3 km in Sulawesi was, a few million years ago, more than 3 km below the land surface and has been exhumed by high rates of erosion. On land we generally lack the means to be precise about the amounts of uplift of the land surface or uplift of rocks within the crust, whereas in offshore regions hydrocarbon exploration drilling can provide accurate dating, but at present in the frontier regions of eastern Indonesia ages are generally lacking.

Different parts of Borneo and east Indonesia have risen and subsided since the Early Miocene following Australia's initial contact with SE Asia. I make the assumption, based on the best but limited evidence currently available, that very significant change in relief began at about 8 Ma in northern Borneo, and at about 5 Ma in West, North and East Sulawesi. In the Halmahera islands, and probably in Seram, significant relief changes are even younger.

From the area of West, North and East Sulawesi around Gorontalo Bay it is possible to identify a number of features that are typical of the much larger region of eastern Indonesia. Uplift and subsidence are intimately interlinked in time. Uplift has been maintained despite high rates of erosion, implying that the forces causing the uplift continue to act. Sometimes high erosion rates are explained away by suggesting very weak rocks at surface – this is a possible explanation in Sabah, although many of the rocks now exposed do not seem to be

unusually weak, but the Celebes Molasse contains abundant fragments derived from igneous rocks of the East Sulawesi ophiolite implying erosion of strong rocks. The rates of subsidence are greater than would be expected from purely thermal processes but are similar to those driven by extension in some parts of the world. However, most tectonic models suggest this region is being deformed by converging plates where contraction would be expected.

There are faults, but seismicity indicates that few if any are lithosphere-scale structures. As mentioned above, several lithospheric faults have no surface expression, and of those that do only the North Sulawesi subduction zone and the Palu-Koro Fault may cut the entire crust. It is not surprising that there are faults in the upper crust, but there are no obvious fault-bounded blocks, and even if there were this would imply that they were merely upper crust features, disconnected from the deeper lithosphere. The deformation appears largely independent of plate boundaries, and the distribution, amounts and rates of vertical movements appear to be far greater than expected from conventional models of stretching or from other mechanisms such as strike-slip faulting.

The region of Sulawesi around Gorontalo Bay has been deformed into elevated north and east arms and subsided central bay, and there is also a lower elevated ridge running roughly east–west through the Togian Islands. Considering a north–south section across Gorontalo Bay the scale of the deformed region can be approximated as a curve with wavelength of 200 km and amplitude 5 km. These amounts are small for deformed plates, where wavelengths are much larger and amplitudes smaller, and also appear unusual for deformed continental crust, based on comparison with other parts of the world, whether in extension or contraction, although features on this scale could be produced under certain conditions by compression (D. A. Waltham, pers. comm. 2009).

GPS studies show that there are very high rates of movements (e.g. Walpersdorf *et al.* 1998; Vigny *et al.* 2002; Socquet *et al.* 2006; Simons *et al.* 2007), comparable to estimates of plate movements in the region (Fig. 18), and they also show what is recorded by geological observations: relatively abrupt changes from strongly deformed to little deformed areas, although it is not clear if the boundaries between these areas are narrow or wide. Since GPS measurements cover a period of only a few years, stations are very scattered, and some may be poorly sited, it is not clear what these results mean. Attempts have been made to outline fault-bounded blocks that may explain GPS measurements, but the blocks demarcated are bounded by structures of different ages, some without surface expression, and some are simply required by a block model but are surmised with no evidence.

An alternative model

I suggest all these observations indicate that the region (Fig. 20) bounded by the strong parts of the Australian and Pacific–Philippine Sea Plates is not a plate, in the sense of a large rigid entity of the plate tectonic paradigm, but rather is a large region of generally weak lithosphere responding to movement of the rigid plates that surround it. The region is thousands of kilometres across. It deforms internally as the forces acting at the boundaries change in direction and magnitude. Its response to the external forces is modified by the distribution of strong areas within it which are more or less rigid. Some of these subduct, such as the Celebes Sea, and the Banda embayment, inducing deformation, and others do not, such as the strong old continental fragment(s) that form East Java, SE Borneo and South Sulawesi. These latter transmit, refract, and focus deformation.

Australia collision with North Sulawesi in the Early Miocene caused some contraction, with emplacement of ophiolites in Sulawesi, and broader consequences throughout Sundaland, such as local inversion, which probably reflect the changing balance of forces on the entire region. Several new subduction zones were initiated in the Neogene, such as those at the NW, NE and southern edges of the Celebes Sea, and the Java Trench propagated into the Banda embayment (Spakman & Hall 2010). It is not clear how subduction was initiated, and whether there was a period of compression before the plate broke, although in the Banda embayment it is likely that a pre-existing lithospheric fracture simply broke along an older boundary when the opportunity became available.

The deformation induced by subduction was predominantly extensional, was concentrated in the upper plate as the Banda subduction hinge rolled back, and was modified by several factors including the heterogeneous nature of the upper plate, magmatism caused by decompressional melting, and melting induced by fluid movements into the mantle wedge above the subducted slab. Subduction rollback at the North Sulawesi Trench has caused additional extension and contributed to subsidence in Gorontalo Bay and exhumation of metamorphic core complexes on land in Sulawesi (Spencer 2010). The response to rollback was predominantly subsidence in the weaker parts of the region, but stronger areas, such as SE Borneo–South Sulawesi, were almost unaffected by nearby deformation and have remained at a similar elevation relative to sea level. The stronger areas have also acted to transmit

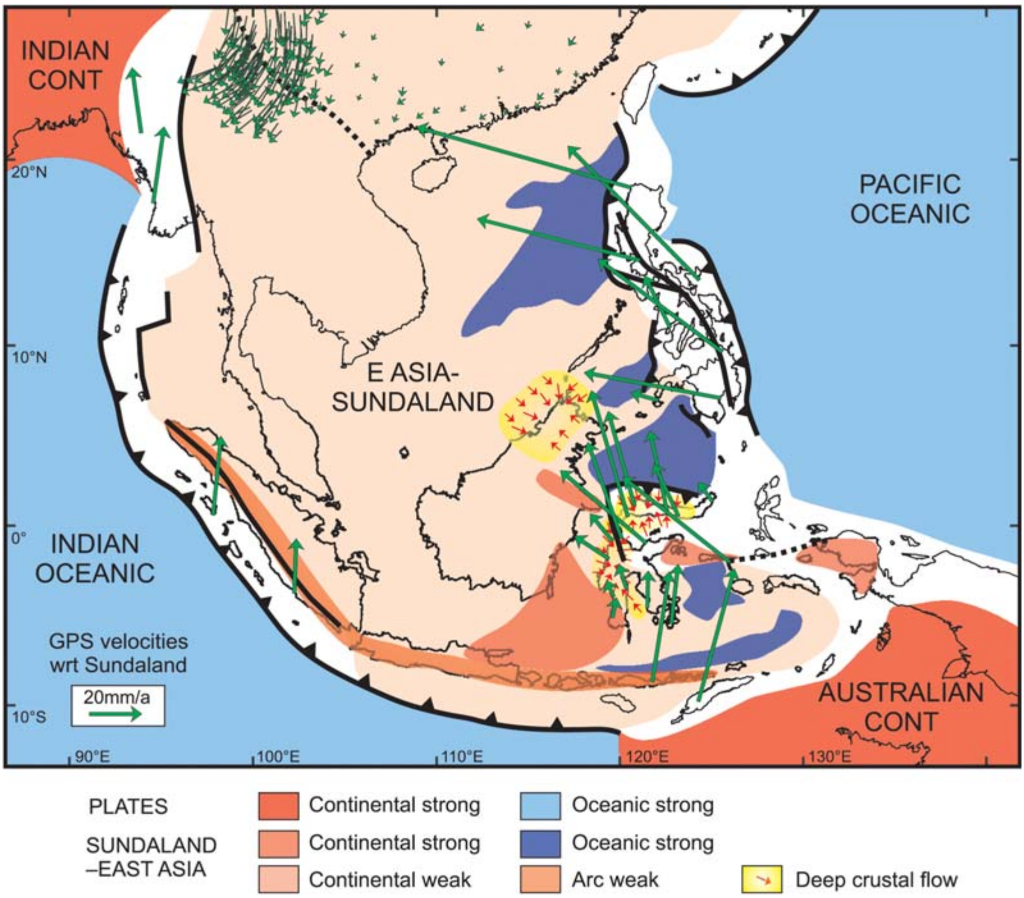

Fig. 20. Deformation of East and SE Asia. The region is surrounded by plates that include strong continental and oceanic lithosphere but without completely connected boundaries shown as solid black lines. The white area is a deforming region that cannot be easily assigned to particular plates. GPS vectors from Shen *et al.* (2005) and Simons *et al.* (2007) with green arrows show the upper crust is deforming in a complex way not directly connected to plate movements. SE Asia is a largely weak area with strong oceanic and continental parts.

compressional forces from the plate boundaries, and this has caused uplift in adjacent weak areas such as the Central Borneo Mountain Ranges, West Sulawesi Mountains, and North and East Sulawesi.

Subsidence and uplift in weak areas were temporally linked. Morley & Westaway (2006) have shown that unusually rapid and large amounts of subsidence in basins of SE Asia can be explained by deep crustal flow with thinning of the crust beneath the basins; they argued that in these settings sediment loading can cause, or contribute significantly to, subsidence. They suggested that the deep crust moved away from the depocentre, thinning the crust, and flowed towards the sediment source regions where the crust was thickened. They focused their attention on the role of crustal flow in producing deep sedimentary basins and not on the regions towards which lower crust was flowing, except as a source for sediment. The basins they studied were formed and largely filled since the Eocene and are now observed at a relatively late stage in their development. However, the Morley & Westaway (2006) model offers an explanation for the link between subsidence and uplift from northern Borneo eastwards at a much earlier stage in basin evolution. I suggest that deep crustal movements not only enhanced subsidence and provided sediment sources, but flowed laterally into areas already elevated and drove significant further uplift. This flow maintained relief, erosion, and provided sediment that drove further subsidence in adjacent basins. In particular, it has contributed to the formation of very high mountains in the last 5 Ma. The high short-term sediment yields in SE Asia are commonly attributed to extreme local relief plus high rainfall, with exceptionally large

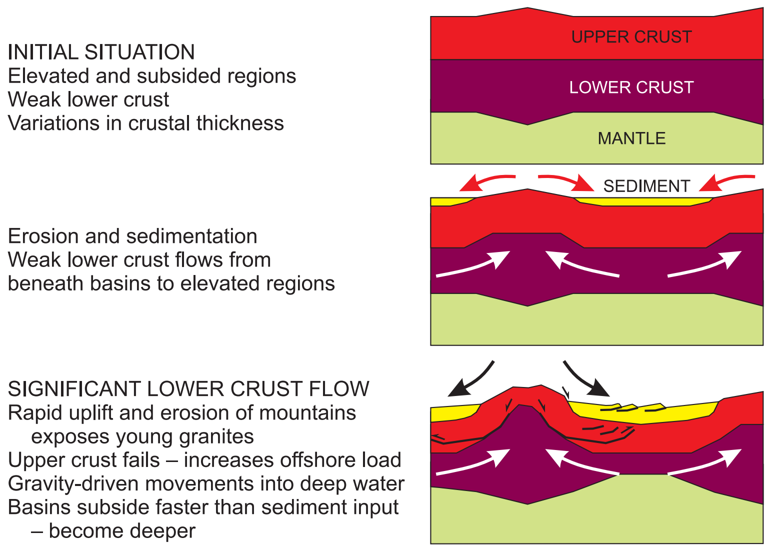

Fig. 21. Cartoon illustrating the concept of deep crustal flow linking basin subsidence and mountain elevation. Deformation of an originally irregular crust is assumed to be initiated by stresses transmitted from stronger rigid plates outside the area, and the weaker areas are most responsive. Flow of the deep crust in weaker areas then drives subsidence of basins and elevation of mountains to lead to formation of deepwater fold and thrust belts such as those of northern Borneo and West Sulawesi. Crustal flow may also enhance extension driven by other processes such as subduction rollback, or uplift resulting from delamination, both of which could be contributing to deformation in Borneo and Sulawesi.

sediment volumes carried by short mountainous rivers (e.g. Milliman & Syvitski 1992; Milliman *et al.* 1999). However, in many parts of SE Asia these high sediment yields have been maintained for tens of millions of years (Hall & Nichols 2002; Hall & Morley 2004) which requires a tectonic mechanism to provide relief. Deep crustal flow is a solution to this problem. Once there is movement of the deep crust a feedback process begins. Furthermore, the erosional supply may be enhanced by gravitational movement of the upper crust with detachments at depths up to several kilometres. Figure 21 shows in a cartoon form the process envisaged. Major uplift and high exhumation rates on land will promote shelf failures and produce offshore fold and thrust belts such as those documented from offshore northern Borneo and offshore West Sulawesi, similar in style and dimensions to the Niger delta, but differing in their position adjacent to significantly elevated mountains. These fold and thrust belts are largely aseismic as they are not the result of converging plates. One implication of the model is that structures in many SE Asian mountain belts previously interpreted as thrusts are actually major extensional detachments, a now relatively uncontroversial view in more accessible regions without thick rainforest vegetation cover (e.g. Coney 1980; Coney & Harms 1984; Lister *et al.* 1984; Lister & Davis 1989).

This model leaves unanswered the questions of why deep crustal flow starts, and why in some areas rather than others. Ultimately, it could be initiated by changes such as regional plate reorganizations, initiation of subduction and rollback, or even climate change. Areas unaffected are strong, and include relatively old oceanic lithosphere (e.g. the Celebes Sea) or areas underlain by thick old continental lithosphere (e.g. East Java–West Sulawesi). Areas that are affected are weak, which may be the result of processes such as heating associated with long term subduction, magmatism, or loss of deeper lithosphere by delamination.

Conclusions

SE Asia is an unusual region. In eastern Indonesia there have been exceptionally high rates of vertical movements and rapid but varied horizontal movements that are not explicable as movements of small rigid micro-blocks, nor easily described in terms of plate tectonics. Plate tectonics provides the first order description of the region's history, but to understand it more completely we must view it as an extensive region of very weak lithosphere, probably most of East and SE Asia, with a heterogeneous basement structure, within which are strong areas of old continental lithosphere and

oceanic crust, all deforming in response to the changing balance of forces at boundaries with the strong surrounding plates of the Pacific, Philippine Sea, Australia and India.

Seismicity shows a relatively simple plate tectonic setting with convergence of the Pacific, Philippine Sea, Australia and India plates towards SE Asia, but GPS motions record a much more complex pattern of deformation. On the whole this should not be viewed as reflecting small block movements but as a continuum of deformation in the upper crust which is partly or completely decoupled from the deeper lithosphere and the response of the upper crust to local stresses, such as those induced by topography. The location of uplift and subsidence are largely independent of plate boundaries. Hall & Morley (2004) suggested that a continuum model may offer a better description than a rigid block model and that deformation might be understood by finite element modelling of stresses originating from all the plate boundaries surrounding Sundaland combined with those from topography. However, even this approach is likely to be unsuccessful because of the heterogeneity of the 'plate' and because of the decoupling of upper crust and lithosphere.

For most of the Cenozoic the strong areas of old continental lithosphere have remained little deformed, and several areas (SE Borneo, South Sulawesi, Banggai-Sula) contain broadly flat lying sediments deposited close to sea level. In the weaker areas are thick sedimentary successions in deep basins, commonly adjacent to deeply exhumed elevated areas, which have subsided at high rates as the adjacent mountains have risen, been deeply exhumed and supplied sediments to the basins. Rates are greater than those predicted by conventional stretching models and isostatic responses. Several features suggest that there is a connection between subsidence and uplift caused by crustal flow at depth, away from the sedimentary basins, thus causing or contributing to subsidence, and towards the mountains, promoting further uplift and maintaining sedimentation. This is different from the India collision zone where deep crust is flowing away from the thickened area (e.g. Royden *et al.* 1997; Clark & Royden 2000; Shen *et al.* 2005). In East Indonesia positive feedback has maintained subsidence, uplift, and fold and thrust deformation for more than ten million years. It explains the paradox of the high sediment yields from small land masses in SE Asia that are maintained for long periods.

The magnitude and rates of vertical motions raise many questions for tectonic studies, hydrocarbon and mineral exploration, and changes in palaeogeography and their implications for life sciences, which remain to be explored. Is eastern Indonesia an analogue for earlier Cenozoic deformation of Sundaland west of the Makassar Straits? Is this region an analogue for other orogenic belts? What initiated the most recent changes in the last 10 Ma?

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