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Australian crust in Indonesia

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It is now generally accepted that the core of Southeast (SE) Asia was assembled from continental blocks that separated from Gondwana in the Paleozoic and amalgamated with Asian blocks in the Triassic. Fragments of these Gondwana/Cathaysia blocks rifted and separated from Asia and later re-amalgamated with the SE Asian continental core. Mesozoic rifting of fragments from the Australian margins followed by Cretaceous collisions, and Cenozoic collision of Australia with the SE Asian margin added more continental crust. There can be no doubt that there is Australian crust in SE Asia, including Indonesia, but where this crust came from, and when it arrived, continues to promote discussion. Argoland has been variously identified in Tibet, West Burma, and Borneo. Other fragments supposed to have rifted from Australia are claimed to be in Sumatra, Java, Sulawesi and Sumba. The Banda region is the site of even more controversy because pieces of Australian crust are found in Sulawesi, the North Moluccas, the Banda Sea, and in numerous islands forming the Inner Banda Arc on both sides of the supposed subduction boundary separating Indonesia from Australia. There is increasing evidence that fragments of Cathaysian/Asian continental crust form parts of northwest Borneo and the offshore shelf to the north of Sarawak and east of Vietnam, and that Australian blocks underlie much of Borneo, West Sulawesi and Java. These fragments rifted from Australia in the Jurassic and arrived in their present positions during the Cretaceous. The rifting led to formation of a continental promontory, the Sula Spur, that extended west from New Guinea on the north side of the Banda embayment. This collided with the SE Asian margin in the Early Miocene and has subsequently been fragmented by subduction-driven extension. The Sula Spur and its fragmentation, and the history of subduction of the Banda embayment, are the causes of many of the controversies about collision ages, and account for the unusual distribution of continental crust in the Banda Arc.

KEY WORDS: Indonesia, continental crust, extension, zircon, Sundaland, Gondwana.

INTRODUCTION

Indonesia is situated in a plate boundary zone where the India–Australia and Pacific–Philippine Sea plates converge on Eurasia. It is part of a composite region (Figure 1) that is underlain largely by fragments of continental crust derived from Gondwana and Australian crust that have been assembled by numerous collisions since the late Paleozoic. At present, Indonesia is surrounded by active subduction zones and there has been subduction beneath SE Asia for over 300 Ma (although not continuously) and this has played a critical role in the geological evolution of the region. Despite the long history of subduction, the region has grown mainly by addition of continental fragments (estimated to be approximately 90% of the total area; Hall 2009b), and additions of material by subduction accretion, arc magmatism and other subduction-related processes have been relatively small. During collisions some arcs ceased activity, shifted their positions or disappeared back into the mantle.

It has been accepted for many years that most of western Indonesia is underlain by continental crust and was at the edge of the Sundaland continent from the end of the Paleozoic. Western Indonesia includes several different blocks or terranes (e.g. Metcalfe 1990, 1996) that are separated by narrow suture zones that include arc and ophiolitic material. Sundaland is often drawn to include much of Borneo, west Java, and sometimes parts of western Sulawesi, but there has been less clarity in when these areas became parts of Sundaland and the nature of the crust beneath them. Hamilton (1979) drew a boundary showing his interpretation of the limit of Cretaceous continental crust that crossed from Java to SE Borneo (Figure 2), and he traced a belt of granites from the Java Sea through Borneo northwards into the Asian margin of Vietnam and South China. He broadly categorised everything to the east and south of this belt as melanges of Cretaceous and Tertiary subduction complexes with some continental fragments, consistent with observations from eastern Indonesia showing the presence of Cenozoic arc and ophiolitic crust and several young ocean basins. Based on the evidence then available this was a reasonable interpretation and has been widely accepted.

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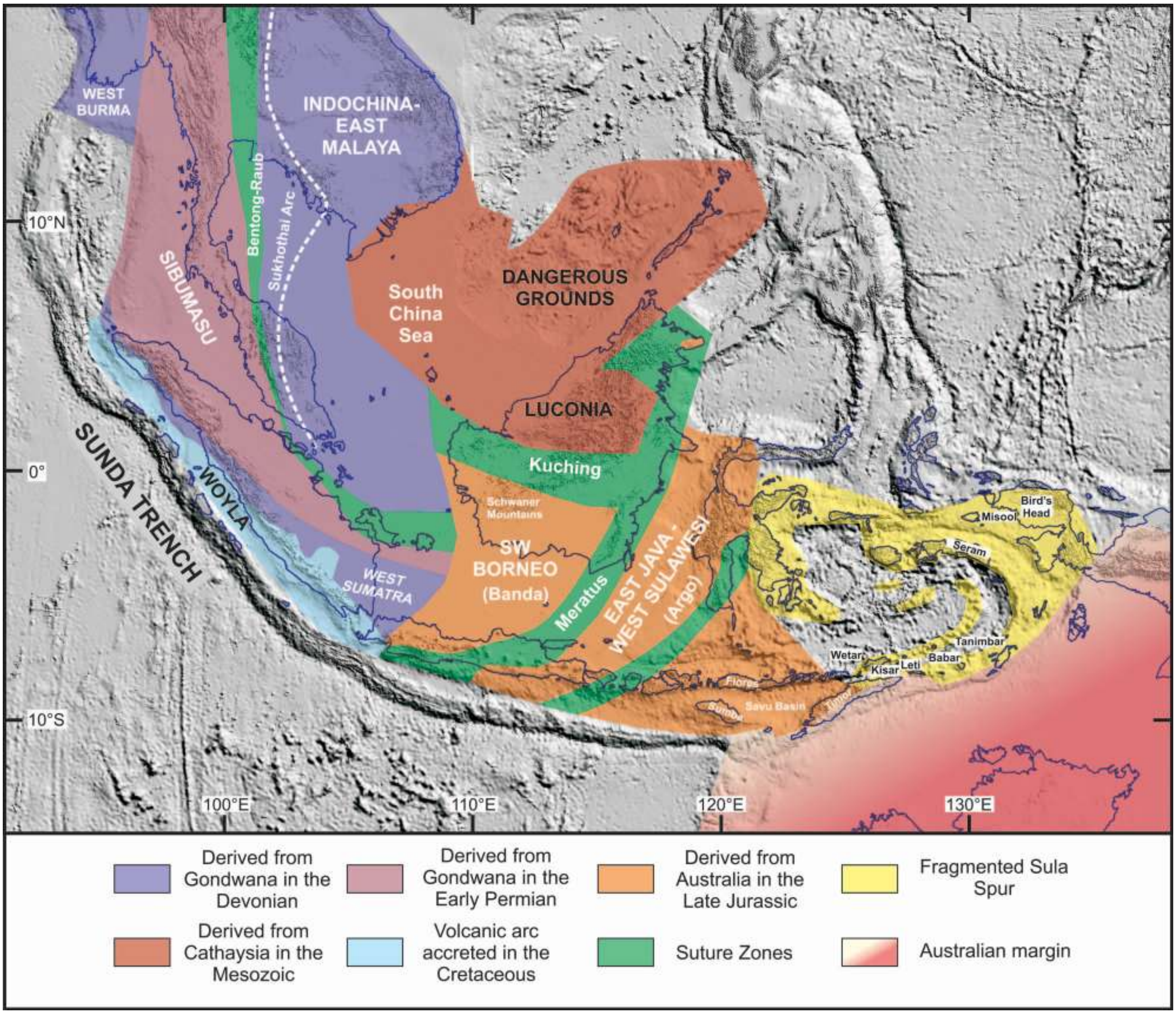

Figure 1 The principal blocks in SE Asia. Ophiolitic/arc sutures are shaded in green. The pre-Cretaceous Sundaland terranes are modified after Metcalfe (1996, 2011a, b) and Barber *et al.* (2005). West Sumatra, West Burma and Indochina–East Malaya formed part of a Cathaysia block added to Eurasia during the Paleozoic. Sibumasu was accreted along the Bentong-Raub suture in the Triassic. West Burma and West Sumatra were part of Sundaland by the Late Triassic although they have moved along the Sundaland margin since then. The Woyla Arc was accreted in the Cretaceous. The Luconia block is interpreted to be a Cathaysia fragment rifted from Asia and added to Sundaland during the Mesozoic. SW Borneo and East Java–West Sulawesi are interpreted to have been rifted from western Australia and added in the Late Cretaceous. In the reconstructions the orange block beneath South Sulawesi, Flores and Sumba is considered part of the East Java–West Sulawesi block. The suture interpreted on the northwest side of this block is based on evidence from South Sulawesi and its extension to the southwest is very speculative.

However, in recent years our views have changed, based largely on studies in Indonesia. Archean to Paleozoic zircons were discovered in East Java (Smyth 2005; Smyth *et al.* 2007) in areas previously thought to be underlain by Cretaceous or younger crust, and subsequently more evidence has accumulated that old continental basement is much more widespread than expected in eastern Indonesia. Attempting to reconstruct the Indonesian region on the basis of this information has led to a new interpretation of its tectonic development.

Continental fragments that separated from northern and northwestern Australia during the Jurassic rifting episodes are unequivocally present in SE Asia (Hamilton 1979; Pigram & Panggabean 1984; Audley-Charles *et al.* 1988; Metcalfe 1988; Powell *et al.* 1988; Hall *et al.* 2009). However, their initial positions and arrival ages are still the subject of debate. There are arguments about fragments such as Argoland, named from the block that rifted to leave the Argo abyssal plain off NW Australia, the West Burma Block, and about the crust beneath the Banda Arc. Argoland (Powell *et al.* 1988) or Mt Victoria Land (Mitchell 1986; Veevers 1988) has been variously identified in Tibet (e.g. Audley-Charles 1983, 1988), as the Paternoster 'plateau' (Ricou 1994), and most commonly in West Burma (e.g. Metcalfe 1996). Charlton

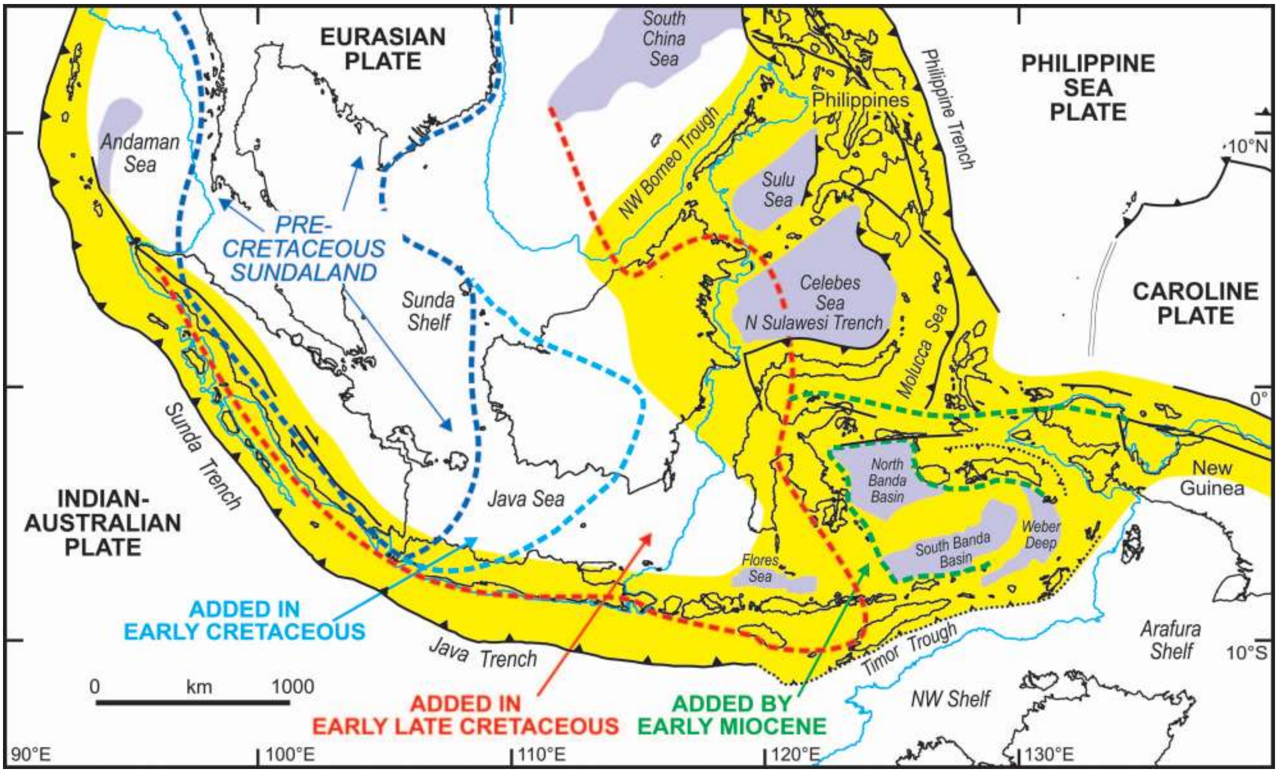

Figure 2 The Mesozoic and Cenozoic growth of Sundaland. Late Triassic Sundaland is outlined in dark blue as pre-Cretaceous Sundaland. The area commonly considered to form the Mesozoic continental core is outlined in light blue with a southern boundary drawn at the limits of Cretaceous continental crust inferred by Hamilton (1979). Sundaland grew in the Cretaceous by the addition of two main fragments: SW Borneo and East Java–West Sulawesi. The area shaded in yellow is the modern plate boundary zone of active orogenic deformation although there are important zones of deformation within Sundaland. In the Early Miocene new continental crust was added by collisions in Borneo and East Indonesia.

(2001) suggested that Argoland was in Tibet and that West Burma is a block that separated to leave the Banda embayment within the north Australian margin. Correlations of West Burma and other blocks with northwestern Australia have been speculative (e.g. Metcalfe 1996) because they are based on little evidence other than similarities of Triassic quartz-rich sandstones of unknown provenance. Other authors (e.g. Mitchell 1984, 1992) argued that West Burma was already part of Asia in the Triassic. Barber & Crow (2009) suggested that before the opening of the Andaman Sea, West Burma was a northwards continuation of the West Sumatra Block and that the two blocks were part of the Asian margin by the latest Permian or Early Triassic.

Interpretations of the Banda Arc and particularly of Timor are even more controversial. Most authors agree that Timor appeared as a result of collision between the Australian continental margin and the Banda volcanic arc (Carter *et al.* 1976; Hamilton 1979; Audley-Charles 2004), but there are numerous tectonic models (e.g. Audley-Charles 1968, 1986, 2011; Fitch & Hamilton 1974; Grady 1975; Charlton *et al.* 1991; Harris 1991, 2006; Spakman & Hall 2010). Bowin *et al.* (1980) pointed out the anomaly of Australian origin continental crust within the Banda Arc that had arrived there before the collision. Different views of the origin of continental basement in Timor (e.g. Charlton 2002; Standley & Harris 2009), the age and significance of metamorphism (e.g. Berry & Grady 1981a, b; Berry & McDougall 1986; Elburg *et al.* 2004; Keep & Haig 2010; Spakman & Hall 2010; Harris 2011) and interpretations of stratigraphy (e.g. Keep & Haig 2010; Audley-Charles 2011) have contributed to the debate about collision ages in the Banda Arc.

This contribution focuses on the character, origin and distribution of continental crust beneath Indonesia and particularly beneath the Banda Arc. It is based on published and unpublished projects, work in progress in Malaysia and Indonesia, including studies of sedimentary provenance and new dating results using zircons, and is intended to be a short assessment of our current views. We first give a chronological overview of SE Asian continental growth from the Paleozoic to recent. The reconstruction discussed here interprets the fragments that separated from northern and NW Australia, leaving the Sula Spur continental promontory, to be in SW Borneo, East Java, West Sulawesi, South Sulawesi, the eastern Sunda Arc, Flores, Sumba and the Savu Sea (e.g. Hall *et al.* 2009; Hall 2011). These continental fragments separated from Australia during the Jurassic rifting episode and arrived in the Cretaceous in two major episodes during the Early and early Late Cretaceous. Numerous fragments of Australian continental crust were present in what became the present Banda region long before the Neogene collision with the Australian margin. The Sula Spur then collided with

SE Asia in the Early Miocene and its crust later became fragmented and dispersed across the Banda Arc during extension driven by the slab rollback during the Neogene. In addition there were a few fragments that were sliced from the Sula Spur and transported west. Most recently, continental crust has been added in the south from the Timor–Australian continental margin and this addition is ongoing in the islands to the east of Timor. All of this continental crust came from Australia but it arrived at different times and has been subsequently fragmented, dispersed and juxtaposed in a complex way so that simply identifying it as 'Australian' is not always helpful. Below we try to unravel this complexity.

THE PALEOZOIC CORE OF SUNDALAND

Multidisciplinary paleontological, stratigraphical, paleomagnetic, geochronological, geochemical, and structural data suggest that the Paleozoic core of Sundaland (Figures 1, 2) includes the Indochina–East Malaya block and Sukhothai Arc (e.g. Sone & Metcalfe 2008; Metcalfe 2011a, b; Sevastjanova *et al.* 2011). There is also convincing evidence that West Burma and West Sumatra Blocks were part of Sundaland before the Mesozoic (Mitchell 1992, 1993; Barber 2000; Barber & Crow 2009; Barber *et al.* 2005). Warm-water Tethyan faunas and Cathaysian floras present on all these blocks suggest that they separated from Gondwana in the Devonian and together formed a composite Cathaysia continent in the Permian (Barber & Crow 2009; Metcalfe 2006, 2009). The Sundaland core also includes Sibumasu with Carboniferous–Permian tillites, which suggest that this block remained attached to Gondwana during the Late Paleozoic glaciation.

Separation of continental fragments from Gondwana opened large Tethyan Oceans (e.g. Metcalfe 1996, 2000, 2009), but almost all oceanic crust has been destroyed by subduction. Abundant Permian–Triassic tin belt granitoids that were produced by subduction of this oceanic crust, and magmatism associated with subsequent collisions between continental fragments, now extend from Thailand, through the Malay Peninsula to the Indonesian Tin Islands (e.g. Cobbing *et al.* 1992).

Different deformation styles of the Carboniferous–Permian and Triassic sedimentary rocks, a Permian–Triassic unconformity observed in limestones, a stratigraphic hiatus at the Permian–Triassic boundary, ages of granitoids, and detrital zircon Hf isotopes indicate that East Malaya–Indochina, the Sukhothai Arc and Sibumasu were assembled into one continent by the Late Permian–Early Triassic (e.g. Metcalfe 1990, 2009; Harbury *et al.* 1990; Barber & Crow 2009; Sevastjanova *et al.* 2011) and it then collided with the North China Block in the Triassic (e.g. Metcalfe 2011a, b).

EARLY TO MID-CRETACEOUS GROWTH OF SUNDALAND

During the Mesozoic SE Asia continued to grow by the addition of Luconia–Dangerous Grounds, SW Borneo (Banda embayment), East Java–West Sulawesi (Argoland), and a number of smaller continental fragments that were accreted to the eastern margin of Sundaland including parts of the Bantimala Complex of South Sulawesi, Sumba, the Savu Basin (e.g. Hall *et al.* 2009; Hall 2011, 2012; Rigg & Hall 2011, 2012) that are simplified in the reconstructions (Figure 3) as the East Java–West Sulawesi block. Details of the reconstructions and methods can be found in Hall (2012). There was also some oceanic crust and arc added to the western margin of Sundaland that formed part of the intra-oceanic Woyla Arc (e.g. Barber 2000; Barber & Crow 2003, 2005).

North Borneo: Asian crust

The area east from the Indochina–East Malaya block is submerged at present and is overlain by Cenozoic rocks, and therefore little is known about the nature of the crust beneath it. Nevertheless, Upper Triassic deltaic sandstones with a *Dictyophyllum-Clathropteris* flora and Cretaceous metamorphic rocks dredged from the Dangerous Grounds in the South China Sea (Kudrass *et al.* 1986) suggest that this area is a continental block of Cathaysian origin (e.g. Hall *et al.* 2009; Hall 2011, 2012). Triassic floras of Cathaysian affinity, similar to those from the Dangerous Grounds, are common in Sarawak (Williams *et al.* 1988; Hutchison 2005) and this suggests that the Dangerous Grounds–Luconia Block continues into northern Borneo.

Subduction around South China and Indochina continued during the Jurassic and Early Cretaceous. Jurassic and Early Cretaceous igneous rocks are abundant in SE China (e.g. Jahn *et al.* 1976; Li 2000; Wu *et al.* 2005), near Hong Kong (Davis *et al.* 1997; Sewell *et al.* 2000), and in the South China Sea (e.g. Li & Li 2007). Jahn *et al.* (1976) interpreted Cretaceous granitoids of SE Asia as products of west-directed Pacific subduction. Other authors argued for an extensional tectonic setting in SE China, because of widely developed metamorphic core complexes, common A-type granitoids, and alkaline rocks in the area (e.g. Li 2000; Wu *et al.* 2005). The Early Cretaceous (Nguyen *et al.* 2004; Thuy *et al.* 2004) granitoids continue southwards into east Vietnam. It is notable that there are no Cretaceous granitoids younger than 80 Ma in the area. Based on geophysical data, Zhou *et al.* (2008) traced a Jurassic–Early Cretaceous subduction complex south from Taiwan along the present northern margin of the South China Sea. They interpret this subduction complex to have been displaced to Palawan by opening of the South China Sea. Hall *et al.* (2009) postulated a trench related to west-dipping Pacific subduction, east of what is now the South China Sea, in the Jurassic and Early Cretaceous but not in the Late Cretaceous. It is possible that the Jurassic–Early Cretaceous subduction zone extended across the South China Sea.

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; Holloway 1982; Taylor & Hayes 1983; Williams *et al.* 1988; Tate 1991). Fyhn *et al.* (2010) argued that the Luconia Block collided with SE Asia in the earliest Paleogene, causing inversion in the Cambodian and

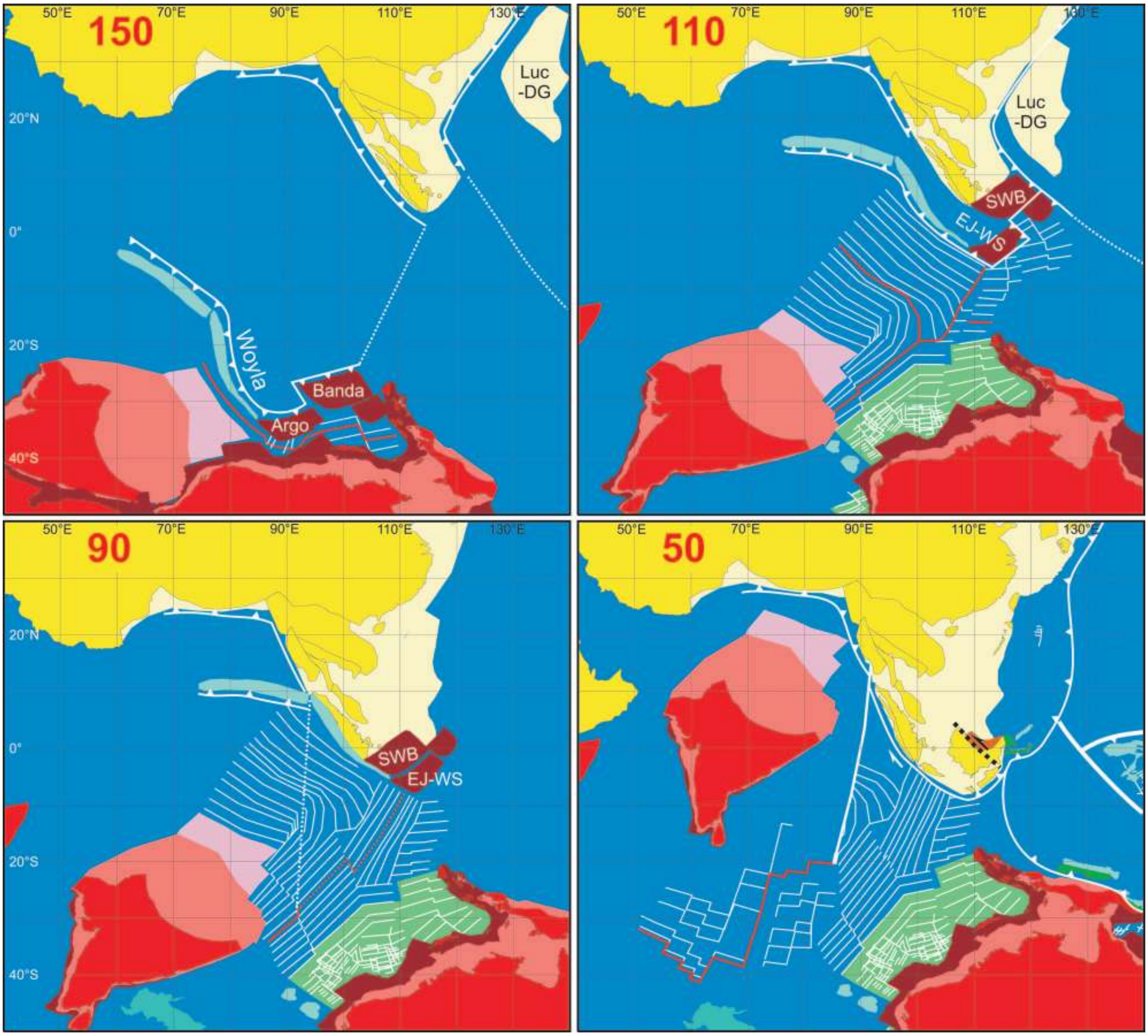

Figure 3 Reconstructions showing Australian break-up and addition of continental blocks to the Sundaland margin during the Mesozoic modified from Hall (2012) in which details of the reconstructions can be found. The Woyla intra-oceanic arc is shown in blue. Collision of the blocks terminated subduction beneath Indonesia for most of the interval between from 90 and 45 Ma, although there was a short period of NW-directed subduction beneath the Sundaland margin from Sumba to West Sulawesi in the Paleocene and Early Eocene. Luc-DG: Luconia-Dangerous Grounds block; SWB: SW Borneo block; EJ-WS: East Java-West Sulawesi block.

Vietnamese Late Jurassic–Early Cretaceous Phuquoc–Kampot Som Basin that developed as a foreland basin in front of the Pacific magmatic arc.

Hutchison (1996) proposed a 'Sarawak Orogeny' had deformed the deep water sediments of the Rajang Group in the Late Eocene at about 45 Ma due to collision of a Balingian–Luconia continental block with SW Borneo following southwards subduction which terminated by *ca* 60 Ma. He suggested that collision, compression and uplift occurred about 15 Ma after the continental promontory (Hutchison 2010) arrived at the trench. In later papers he assigned the orogeny a younger age of about 37 Ma (Hutchison 2004, 2005). However, there are a numbers of reasons to question its age and significance.

Hutchison (1996) dated his orogeny from unconformities described by earlier workers (Wolfenden 1960; Adams & Haak 1962; Haile & Ho 1991) which, where ages are known, show Upper Eocene rocks resting on Upper Cretaceous rocks. All that can be inferred is that the orogeny is older than *ca* 40 Ma. Hutchison (2005) interpreted the unconformities to be synchronous with the collision of India with Asia but his *ca* 37 Ma orogeny age (Hutchison 2004, 2005, 2010) is significantly younger than his own (Paleocene to Early Eocene), and most other, age estimates of India–Asia collision (e.g. Rowley 1996; Leech *et al.* 2005; Green *et al.* 2008; Chen *et al.* 2010; Najman *et al.* 2010), except for the *ca* 34 Ma age of Aitchison *et al.* (2007) which he discounted (Hutchison 2010).

Borneo Geological Survey geologists did recognise an episode of folding in the Late Eocene (Kirk 1957; Wolfenden 1960; Haile 1962), but before 37 Ma and as a late event in a long Cretaceous to Eocene history of deformation. In Sarawak, Wolfenden (1960) noted the absence of a marked angular unconformity in some areas and commented that the 'stratigraphic evidence is difficult to reconcile with the concept of an upper Eocene orogeny that caused the entire . . . Rajang Group to be folded' and observed that 'deformation accompanied deposition.'

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

None of these authors provide Cretaceous–Paleocene reconstructions but Hutchison (2010) drew one map that shows an independent block, bounded by faults, that moved southwards during the Late Cretaceous to collide at the Lupar Line in Sarawak. Such a block would not explain the continuation of the Lupar Line eastwards into Kalimantan, nor is there any driving force for its movement, and the volcanic arc to the south that would be expected by the subduction suggested by Hutchison is missing. Williams *et al.* (1988) and Moss (1998) concluded that subduction-related magmatism in the Schwaner Mountains Arc had ceased by about 80 Ma, and Hutchison (1996) also observed that the subduction history, inferred by Tan & Lamy (1990) and Hazebroek & Tan (1993), from Late Cretaceous to Late Eocene, is not marked by subduction-related Eocene volcanic arcs.

Hall (2009a, b) also pointed out that the Late Cretaceous was a period of rifting and extension of the South China margin (e.g. Taylor & Hayes 1983; Zhou *et al.* 2008) and there are no subduction-related granitoids younger than 80 Ma. This suggests that the subduction of the Pacific Plate ceased much earlier than the Paleogene, i.e. in the mid Cretaceous around 90–80 Ma (e.g. Hall *et al.* 2009; Hall 2011, 2012). In the model of Hall *et al.* (2009) and Hall (2012), the Dangerous Grounds–Luconia block became part of Sundaland at about 90 Ma, but there was no southward-directed subduction, because Borneo was moving northwards (see discussion below).

A simple explanation, which can reconcile the facts, is that the Lupar Line was a strike-slip zone separating the emergent area of the Schwaner Mountains, coastal plains and shallow shelf to the south, from a deep-water turbidite basin further north. Syn-depositional deformation in the deep-water basin occurred between the Late Cretaceous and the Late Eocene. The Sarawak Orogeny marks not a collisional event but a regional change in plate boundaries that occurred when Australia began to move north at about 45 Ma, initiating subduction on the north side of Borneo (Hall *et al.* 2008) beneath Sabah and Palawan and south of Java (e.g. Hall *et al.* 2009; Hall 2011, 2012).

SW Borneo, East Java and West Sulawesi: Australian crust

Traditionally, SW Borneo has been interpreted as a fragment of Asian/Cathaysian origin (e.g. Hutchison 1989; Metcalfe 1988, 1990, 1996). The pre-Cretaceous basement of Borneo outcrops in Sarawak and NW Kalimantan where marbles, quartzites, phyllites, and garnet-bearing schists are exposed (Williams *et al.* 1988; Tate 2001) and there is considerable evidence for a Cathaysian origin of the Upper Carboniferous limestones and Mesozoic sedimentary rocks (see Hutchison 2005 for review). A Cathaysian origin has been suggested on the basis of the fauna in the Carboniferous–Permian Terbat limestone near Bau, Sarawak, although Metcalfe (2011b) has discussed other interpretations for this limestone sequence if it is not part of the SW Borneo Block. Hutchison (2005) reviewed the paleontological evidence from the Sadong and Serian formations of Sarawak and concluded that in the Triassic they were probably located in east Vietnam, or close by, supporting a Cathaysian origin for west Sarawak. Some younger rocks in Sarawak and NW Kalimantan may also have Cathaysian affinities. The pre-Carboniferous schists of Sarawak (e.g. Tate 1991; Hutchison 2005) have been correlated with the Pinoh Metamorphics of the Schwaner Mountains of Kalimantan. The Pinoh Metamorphics are intruded by abundant Early Cretaceous granitoids and some authors suggest that these are the continuation of the Vietnamese Cretaceous granitoid belt (e.g. Hamilton 1979; Williams *et al.* 1988; Wakita & Metcalfe 2005; Fyhn *et al.* 2010). However, these correlations into the Schwaner Mountains of SW Borneo are made across the Lupar Line (Tan 1979), which represents a major suture (e.g. Haile 1973; Williams *et al.* 1988), and/or the tectonic melange of the Boyan Zone. The Schwaner Mountains is the area that has been described as the 'Basement Complex', 'Continental Core' or 'Sunda Shield' of West Borneo (van Bemmelen 1949) or the West Borneo Basement (Haile 1974). It completely lacks any unmetamorphosed sedimentary rocks which can be correlated with Sarawak. Furthermore, little is known about the age of the Pinoh Metamorphics, except that they are intruded by the Schwaner granitoids and volcanic rocks and are therefore Cretaceous or older. One Lower Jurassic whole-rock K–Ar age has been reported from a biotite-hornfels of the Pinoh Group (Pieters & Sanyoto 1993). Work in progress (L. Davies, pers. comm., 2012) indicates the Pinoh Metamorphics are much younger than the schists of Sarawak.

The Cathaysian interpretation of SW Borneo *south* of the Boyan Zone is based on little evidence but there are several good arguments for an Australian origin. Luyendyk (1974) was probably the first to suggest that Borneo and Sulawesi had rifted away from Australia in the Late Jurassic, although his suggestion has rarely been considered in subsequent studies, perhaps because it was schematic and simplified and showed the whole of Borneo and Sulawesi rifted from Australia as a single block. Devonian reefal limestones found as float in the Telen River, a tributary of the Mahakam River, in the Kutai basin (Rutten 1940; Sugiaman & Andria 1999) have a coral and stromatoporoid fauna. Hutchison (1989) and

Metcalfe (1990) considered these limestones as a part of a separate Mangkalihat microcontinental block, possibly rifted from New Guinea in the Late Jurassic (Metcalfe 1996), but neither Devonian corals or stromatoporoids have been reported from New Guinea although they are known from the Canning Basin (Playford 1980; Wood 2000). In rivers draining the SW Borneo Block there are detrital diamonds in the Kapuas River of West Kalimantan and the Barito and Meratus areas of SE Kalimantan. The source of the diamonds has not been identified and there are different opinions about their origin. Barron *et al.* (2008) suggested that the Cempaka (SE Kalimantan) diamonds are similar to those from eastern Australia and argued for a subduction origin. Potential source rocks for such subduction-related diamonds could be UHP rocks from the Meratus region (Parkinson *et al.* 1998), although no diamonds have so far been reported from these rocks. However, this would be an improbable source for diamonds in the Kapuas River on the west side of Borneo. Griffin *et al.* (2001) and Metcalfe (2009) suggested that alluvial diamonds of Burma, Thailand and Sumatra were eroded from Permian glacial-marine diamictites of the Sibumasu Block which was rifted from the western Australian part of Gondwanaland. The SW Borneo diamonds could have arrived in a similar way, but on a different Australian block, and have been reworked into river sediments from the basement or its original sedimentary cover. Nitrogen aggregation characteristics reveal similarities between Kalimantan and NW Australian diamonds (Taylor *et al.* 1990). Smith *et al.* (2009) showed that the Borneo diamonds included several groups interpreted to have been reworked from multiple primary sources and argued that external morphology, internal structure, peridotitic and eclogitic inclusions, thermobarometry, and the Archean Re–Os model ages from a sulfide inclusion, indicate that Kalimantan diamonds formed in ancient Gondwana sub-cratonic lithospheric mantle. It is noteworthy that in other parts of SE Asia there are no known diamond occurrences on the Cathaysian blocks.

More continental crust lies outboard of Borneo. Radiogenic isotope data from the Cenozoic volcanic and metamorphic rocks of Western Sulawesi (Elburg *et al.* 2003; van Leeuwen *et al.* 2007), as well as zircon U–Pb ages suggest that it is underlain by continental crust of Australian origin. Jurassic ammonites and bivalves reported from South Sulawesi (Sukamto *et al.* 1990; Sukamto & Westermann 1993) suggest an Australian continental basement.

Continental crust has also been suggested to underlie parts of the southern Makassar Straits and East Java Sea between Kalimantan and Java based on basement rocks encountered in exploration wells (Manur & Barraclough 1994). Zircon U–Pb ages from the early Cenozoic Southern Mountains volcanic arc 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). Offshore seismic data suggest there may be similar crust both to the north beneath the Java Sea (Emmet *et al.* 2009; Granath *et al.* 2011) and south of East Java (Deighton *et al.* 2011). In the Java Sea there is a broadly horizontal regional unconformity at the base of a Cenozoic section and beneath it are synforms containing up to 5–10 km of section which Granath *et al.* (2011) suggest is of Precambrian to Permian–Triassic age. South of Java the Cenozoic section is about 2 seconds TWT thick and there is a broadly flat-lying sequence of more than 4 seconds TWT beneath which Deighton *et al.* (2011) suggest is Mesozoic or older.

Comparison of zircon U–Pb ages from East Java and SW Borneo with those from West Australia support an Australian origin for this deep crust. Compilations of geochronological data for Australia (e.g. Neumann & Fraser 2007; Southgate *et al.* 2011) suggest that source rocks for Archean zircons are common only in Western Australia, in the Pilbara (main population at 3.5–2.9 Ga), and Yilgarn Cratons (main population at 2.7–2.6 Ga). The zircon populations of East Java are similar (Smyth *et al.* 2007). In SW Borneo, Archean zircons are rare and all are younger than 2.7 Ga, but common Paleoproterozoic zircons show populations similar to those of northern and NW Australia.

Hall *et al.* (2009) and Hall (2012) interpreted East Java–West Sulawesi as the Argo block that prior to separation from Australia formed the offshore continuation of the Canning Basin, whose detrital sediments provided Archean and Proterozoic zircons to East Java. SW Borneo is interpreted as Banda, a fragment that was initially adjacent to Argo. A small Inner Banda block, which may now underlie part of Sabah and northern West Sulawesi, is interpreted to have followed Banda (Hall *et al.* 2009). All these fragments separated from Australia in the Jurassic, leaving the continental promontory, the Sula Spur (Klompé 1954) and the Banda oceanic embayment. This interpretation is consistent with the evidence for the Australian origin of these fragments discussed above and the age of rifting on the NW Shelf (Pigram & Panggabean 1984; Powell *et al.* 1988; Fullerton *et al.* 1989; Robb *et al.* 2005). Hall *et al.* (2009) and Hall (2011, 2012) suggested that 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). Continental fragments of the East Java–West Sulawesi block were added to SE Asia at about 90 Ma and the collision occurred along the suture that runs from West Java through the Meratus Mountains northwards (Hamilton 1979; Parkinson *et al.* 1998). At the same time as this collision, the Woyla intra-oceanic arc collided with the Sumatran margin of western Sundaland (Barber *et al.* 2005).

East Sunda Arc, Sumba, and Savu Sea: more Australian crust

Hall *et al.* (2009) considered East Java–West Sulawesi as a single continental block, but recognised that it may be a number of smaller fragments, that separated from Australian margin and were added to Sundaland in the mid Cretaceous along the suture that runs from Central Java to the Meratus Mountains in Borneo (e.g. Hamilton 1979; Parkinson *et al.* 1998). East of the Meratus Suture Zone, in the Central Metamorphic Belt of Sulawesi, there are outcrops of the ophiolitic melange (e.g. Parkinson *et al.* 1998; Watkinson 2011) that may mark another suture zone along which fragments of Australian crust were added to SE Asia in mid to Late Cretaceous. This continental crust now lies beneath South Sulawesi (the Bantimala Complex), Flores, Sumba, the Savu Sea, and Timor (the Lolotoi–Mutis Complex). The Bantimala Complex includes northeast-dipping tectonically stacked slices of the Early Cretaceous high pressure–low temperature metamorphic rocks recording subduction, and Jurassic shallow marine siliciclastic rocks that are interpreted as a remnant of a continental fragment that collided with SE Asia in mid Cretaceous (Wakita *et al.* 1996). Low $^3He/^4He$ ratios suggest that the continental crust continues southwards into the east Sunda Arc and central Flores, Sumbawa, and Bali (Hilton *et al.* 1992; Gasparon *et al.* 1994).

Sumba has long been considered to be underlain by continental crust (e.g. Hamilton 1977; Bowin *et al.* 1980; von der Borch *et al.* 1983; Richardson 1993; van der Werff *et al.* 1994), but it was uncertain whether it is of SE Asian or Australian origin. Paleomagnetic data show that Sumba was part of Sundaland by the Late Cretaceous (Wensink 1994, 1997) and has remained close to its present day position since the Early Miocene (Wensink & van Bergen 1995). Cretaceous siliciclastic rocks on Sumba contain Asian tropical fauna; these rocks are tilted, eroded and unconformably overlain by shallow marine and non-marine Paleogene sediments, while the latter are overlain by Miocene–Pliocene basalts, agglomerates, volcaniclastic sediments, and carbonates (e.g. Richardson 1993). We suggest that the Cretaceous–Paleogene unconformity marks the post-collisional uplift that occurred after the collision with Sundaland and the Paleocene and Miocene volcanics are interpreted as products of subduction beneath Sundaland, when Sumba was already part of it. Rigg & Hall (2011, 2012) suggested that the Savu Basin is also underlain by the continental crust. Crustal thicknesses and densities from this region (Shulgin *et al.* 2009) support this interpretation. The Lolotoi–Mutis and Bebe Susu metamorphic complexes in Timor are usually assigned to the Banda Terrane (e.g. Audley-Charles & Harris 1990; Harris 2006; Standley & Harris 2009; Audley-Charles 2011), although Charlton (2002) has argued that the Lolotoi metamorphic complex is not related to the Mutis complex and is upthrust NW Shelf basement. Zircon U–Pb ages (Harris 2006; Zobell 2007; Standley & Harris 2009) reveal abundant Cretaceous populations that indicate a SE Asian affinity of these rocks, which are considered by us to be fragments of Australian crust that was added to SE Asia in Cretaceous.

LATE CRETACEOUS–PALEOCENE: CESSATION OF SUBDUCTION

No significant continental growth occurred at the Sundaland margin during the Late Cretaceous–Paleocene, and Sundaland was a region of widespread emergence and erosion. Cretaceous collisions resulted in termination of subduction along most of the Sundaland margins and subduction did not resume until the Eocene, when Australia started moving north (e.g. Smyth *et al.* 2007; Hall 2009a, 2011; Hall *et al.* 2009). The collisions were followed by slab break-off that produced dynamic topographic uplift and resulted in a prolonged emergence of Sundaland during the Late Cretaceous–Paleocene (Clements *et al.* 2011). For the period between 90 and 45 Ma subduction continued only north of Sumatra, while south of Sumatra and Java there was an inactive margin. Australia was not moving north and there is no requirement for subduction beneath Indonesia. There is little indication of magmatism during this interval (Hall 2009a) and this is supported by the general absence of detrital zircons of this age range in younger rocks.

However, Late Cretaceous and Paleocene calc-alkaline subduction-related volcanic rocks in Sumba and West Sulawesi (e.g. van Leeuwen 1981; Hasan 1990; Abdullah *et al.* 2000; Elburg *et al.* 2002) suggest that there was a short-lived episode of NW-directed subduction beneath Sumba and West Sulawesi during an interval between 63 Ma and 50 Ma.

NEOGENE: ADDITION OF SULA SPUR CRUST

Subduction of oceanic lithosphere at the Java trench resumed in the Eocene (around 45 Ma), when Australia started to move northwards (e.g. Hall 2002, 2011, 2012; Hall *et al.* 2009). The irregular geometry of the northern Australian margin resulted in a diachronous collision between Australia and SE Asia. The Sula Spur formed a prominent feature on the Australian margin and was the vanguard that started to collide with the North Sulawesi volcanic arc soon after 25 Ma (Figure 4). By the Early Miocene there was a band of Australian crust from East and SE Sulawesi through the Sula Spur into the Bird's Head of New Guinea. Convergence between Australia and Eurasia continued in the Early Miocene, with 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 Southeast Sulawesi (Hall 2011).

The Banda Arc initiated in the middle Miocene (Hall 2002, 2011, 2012; Spakman & Hall 2010). Although interpretations of its evolution vary, many authors have recognised the importance of Neogene rollback (e.g. Hamilton 1976, 1979; Harris 1992, 2003, 2006; Hall 1996, 2002; Charlton 2000; Milsom 2001; Hinschberger *et al.* 2005) although few have shown detailed reconstructions. Spakman & Hall (2010) provided a tectonic reconstruction that links the structure and deformation of subducted lithosphere in the mantle to subduction rollback and crustal deformation, principally extension. This caused extension of Australian continental crust that had been in SE Asia since the Cretaceous and fragmentation of Australian continental crust that arrived in the Early Miocene as part of the Sula Spur.

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

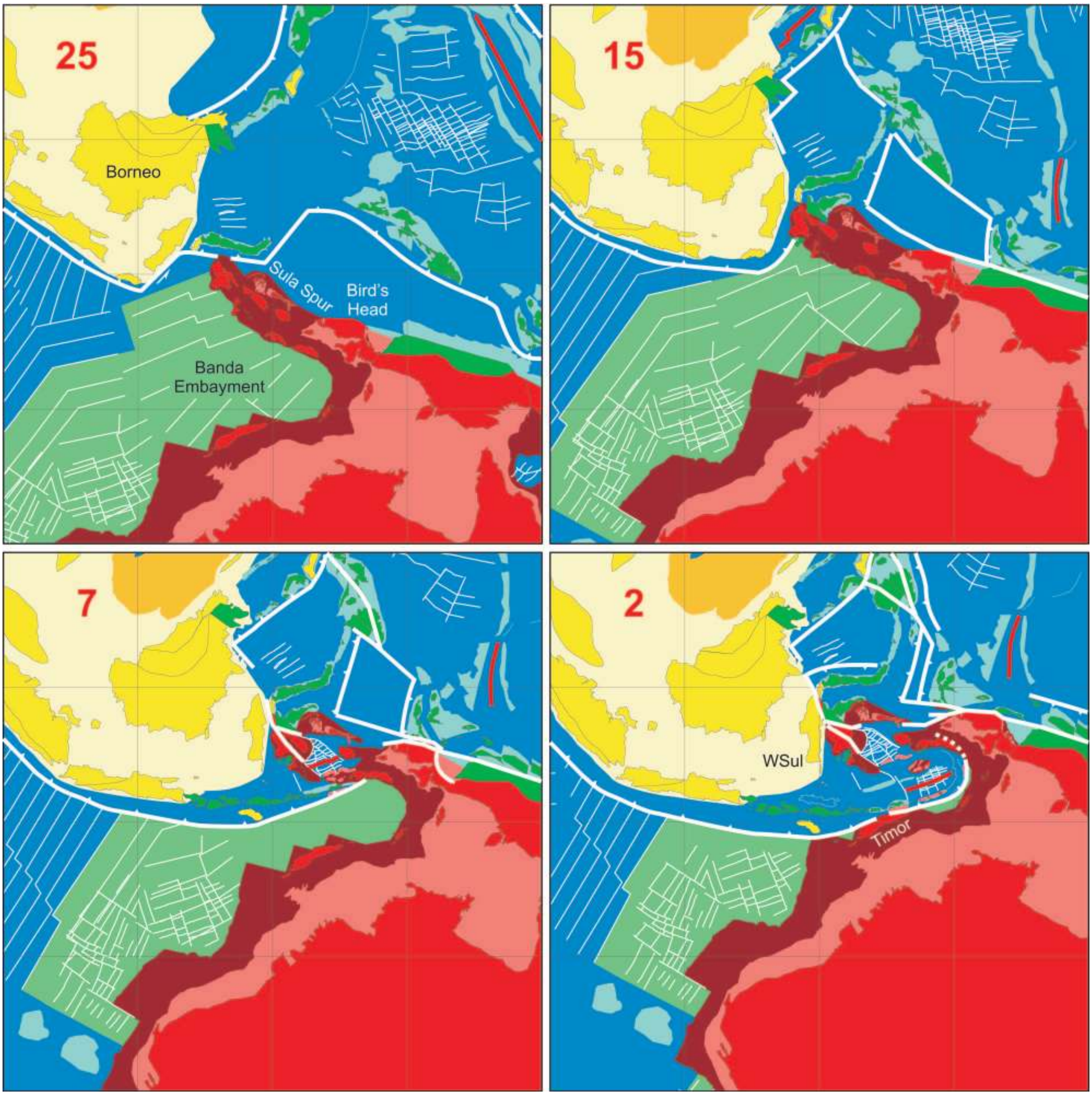

Figure 4 Reconstructions showing Australia–SE Asia collision that began in the Early Miocene when the Sula Spur collided with the North Sulawesi volcanic arc, modified from Spakman & Hall (2010) and Hall (2012). Subduction rollback began at about 15 Ma into the Jurassic Banda embayment causing extension of the Sula Spur. The first stage of extension formed the North Banda Basin between 12 and 7 Ma and remnants of the Sula Spur were carried southeast above the subduction hinge. The Banda volcanic arc is built partly on these fragments, which were further extended as the arc split and the South Banda Basin formed leaving remnants of continental crust and arc rocks in the Banda ridges between the North and South Banda basins. Fragments of continental crust are found today in the Banda forearc in small islands east of Timor and on Timor in the Aileu Complex.

(Fortuin *et al.* 1997) suggest that rollback began around 15–12 Ma (Hall 2002, 2011, 2012; Spakman & Hall 2010). The earliest phase of extension resulted in the opening of the North Banda Sea between 12.5 and 7 Ma (Hinschberger *et al.* 2000) and stretching and fragmentation of crustal fragments from East and Southeast Sulawesi and the Sula Spur. Dredged samples from the Banda Ridges show that they are underlain by Neogene basaltic and andesitic arc volcanic rocks and continental crust similar to that found in Buton, East Sulawesi, Seram, Misool, and Banggai–Sula (e.g. Silver *et al.* 1985; Honthaas *et al.* 1998).

Another significant phase of extension that occurred after *ca* 6 Ma led to formation of the South Banda Sea (Hinschberger *et al.* 2001), and continental crust originally part of the Sula Spur, then the Banda Ridges, was further stretched and carried into the Banda forearc and ultimately Timor when the Australian margin, on the south side of the Banda embayment, began to collide with the Banda forearc. Bowin *et al.* (1980) emphasised

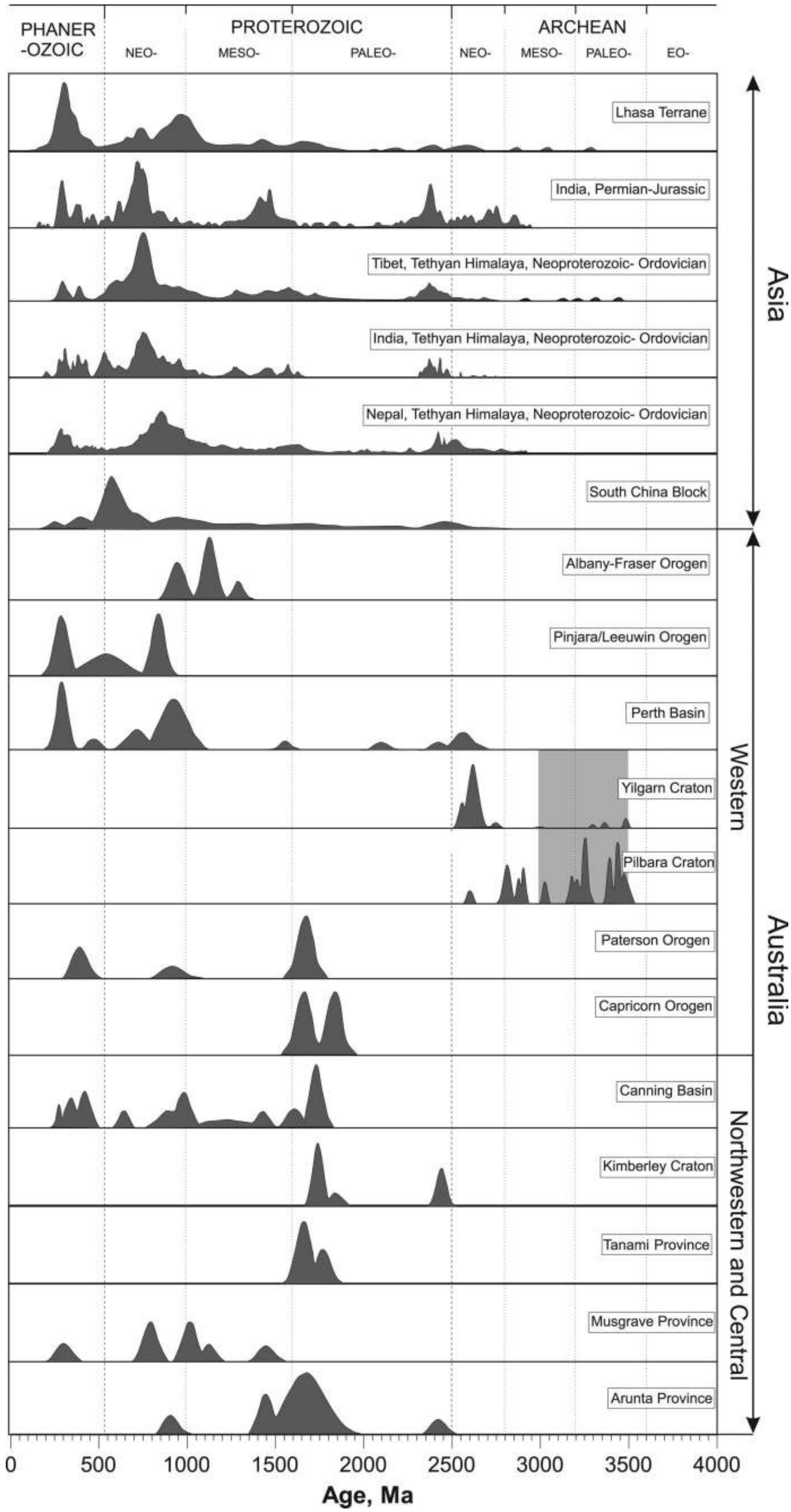

Figure 5 Schematic probability density curves that show zircon populations that are expected to occur in detritus derived from Asia and Australia. Schematic curves drawn based on Chen *et al.* (2011), Southgate *et al.* (2011), Zhu *et al.* (2011), Guynn *et al.* (2012) and references therein.

the presence of Australian continental crust in the Banda forearc such as the small islands between Leti and Babar. Richardson (1993) drew attention to the similarities of these islands with Timor and Tanimbar. Extension due to rollback (Hall 2002, 2011, 2012; Hall *et al.* 2009; Spakman & Hall 2010) explains how this

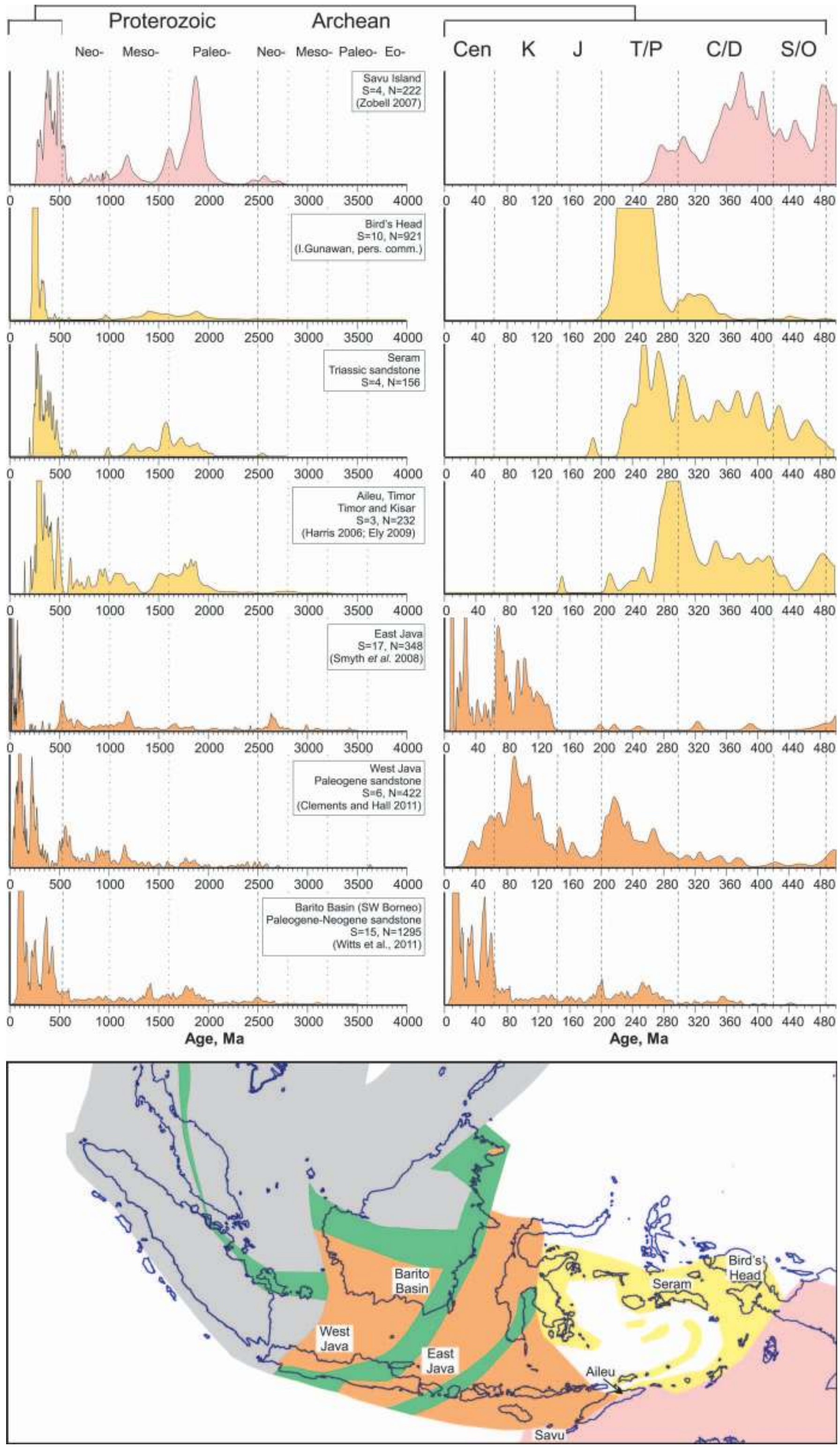

Figure 6 Schematic probability density curves that show zircon populations common in the fragments of the Australian margin (pink), Sula Spur (yellow), and Australian crust that was added to SE Asia in the Cretaceous (orange). Map at the bottom shows the location of these crustal fragments. Schematic population curves are based on U–Pb zircon ages in samples from Harris (2006), Zobell (2007), Smyth *et al.* (2008), Ely (2009), Clements & Hall (2011), Witts *et al.* (2011), and unpublished data from the SE Asia Research Group. S indicates number of samples and N shows number of zircon analyses from each area. Only 90–100% concordant data were included in the diagrams.

continental crust from the northern part of the Sula Spur (Eastern and Southeast Sulawesi) arrived in the southern Banda Arc.

AGE OF AUSTRALIA–SE ASIA COLLISION

There have been many attempts to resolve the geological history of the Banda Arc by differentiating between fragments of continental crust derived from Australia and Asia (e.g. Charlton 2002; Harris 2006). The stratigraphic succession of Timor has been divided into para-autochthon, autochthon, and allochthon (e.g. Audley-Charles 1968, 2011; Carter *et al.* 1976). The para-autochthon is subdivided by Audley-Charles (2011) into (i) a Gondwana Sequence of Permian–Upper Jurassic strata that were deposited on the Australian crust before Jurassic break-up and (ii) an Australian Continental

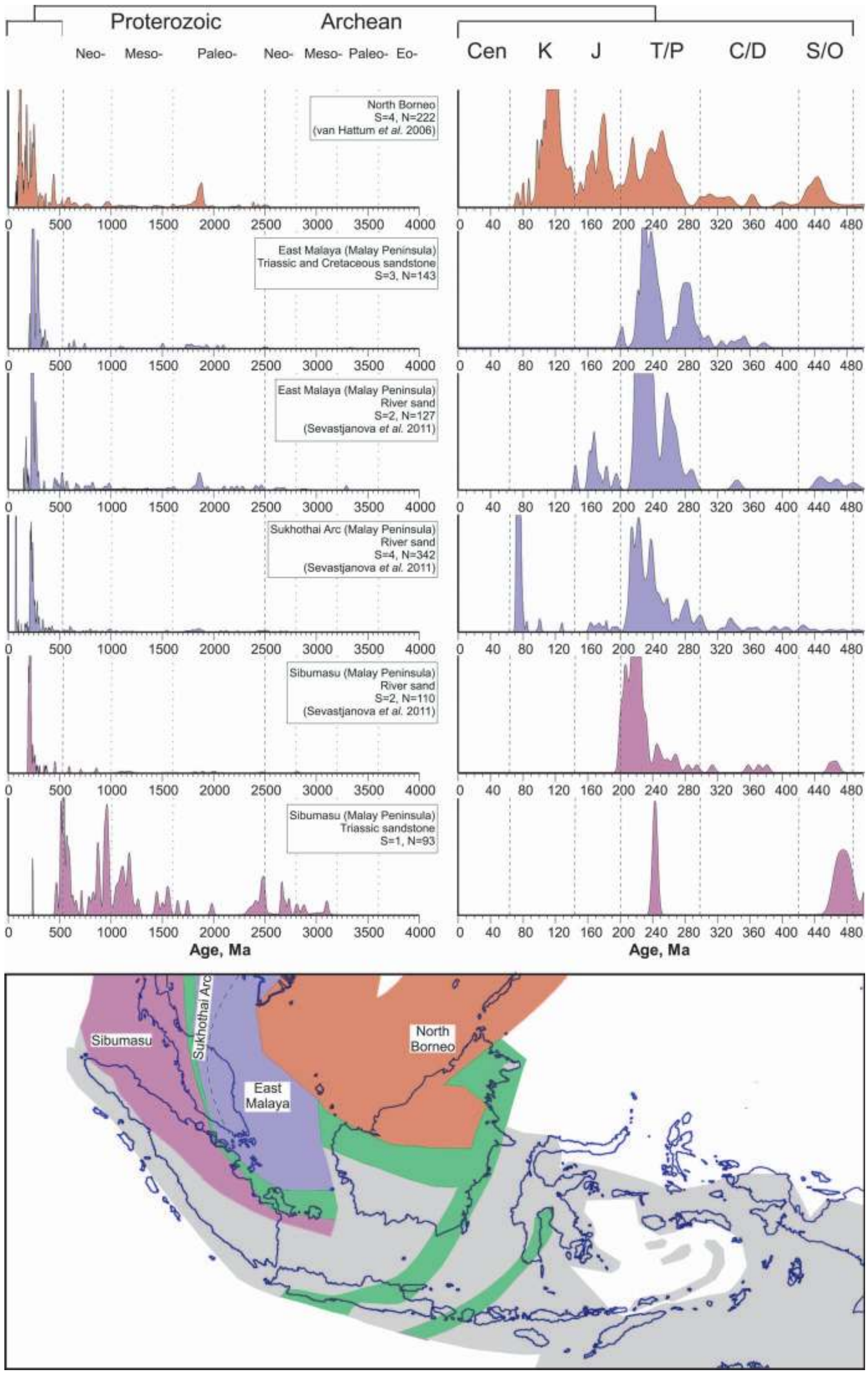

Figure 7 Schematic probability density curves that show zircon populations that sample North Borneo (brown), Indochina–East Malaya (blue), and Sibumasu (purple). Map at the bottom shows the location of these crustal fragments. Schematic population curves are based on U–Pb zircon ages in samples from van Hattum *et al.* (2006), Sevastjanova *et al.* (2011) and unpublished data from the SE Asia Research Group. S indicates number of samples and N shows number of zircon analyses from each area. Only 90–100% concordant data were included in the diagrams.

Margin Sequence that includes the Early Cretaceous–Pliocene post-rift strata. The para-autochthon is generally considered to be of Australian affinity (e.g. Harris 2006; Audley-Charles 2011). The allochthon includes metamorphic rocks of non-Australian affinity, i.e. 'the Banda Terrane' (of Asian affinity according to Harris 2006) and the Aileu Metamorphic Complex (e.g. Berry & McDougall 1986; Audley-Charles 2011).

Reconstructions used here (Hall *et al.* 2009; Spakman & Hall 2010; Hall 2011, 2012) suggest that Australian crust was added to Sundaland in the Cretaceous and in the Early Miocene. Consequently the term 'Australian' is not specific enough and it is necessary to distinguish between fragments of Australian crust added to Sundaland in the Cretaceous, parts of the fragmented Sula Spur, and the present day northern Australian margin.

In the Banda region K–Ar and Ar–Ar ages (Berry & Grady 1981 a, b; Silver *et al.* 1985; Berry & McDougall 1986; Honthaas *et al.* 1999; Parkinson 1998a, b; van Leeuwen *et al.* 2007; Ely 2009; Standley & Harris 2009) have led to 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; Harris 2006). Harris

(2006) suggested that Sulawesi collided with continental fragments sheared from northern Australia as early as the Late Eocene to Early Oligocene and several authors (e.g. Charlton 2002; Keep *et al.* 2003) have suggested that collision between Australia and the Banda Arc commenced around 8 Ma in Sumba (e.g. Keep *et al.* 2003) and in Timor initial collision was 'immediately post 9.8 Ma' or 'between 9.8 Ma and 5.5 Ma' according to Keep & Haig (2010). Berry & McDougall (1986) interpreted *ca* 8 Ma Ar–Ar ages from Timor as due to collision but additional Ar–Ar cooling ages from the same rocks imply that metamorphism of the Aileu Complex must have commenced by at least 12 Ma (Ely 2009). We interpret these ages not to record collision but extension. There are numerous arguments (see Audley-Charles 2011) to support a Pliocene collision age in the Timor region. Volcanic arc activity is known to have continued well after supposed 8 Ma arc–continent collision until about 3–2 Ma (Abbott & Chamalaun 1981; Scotney *et al.* 2005; Ely *et al.* 2011; Herrington *et al.* 2011) and remains active in the eastern part of arc from Damar to Banda (Abbott & Chamalaun 1981; Honthaas *et al.* 1998, 1999). In Sumba there is a continuous deep marine stratigraphic record from the Middle Miocene to Pliocene (Roep & Fortuin 1996; Fortuin *et al.* 1997) that conflicts with the proposed >8 Ma collision age.

In the Banda region there has been collision between Australian continental crust of the southern Banda embayment margin, Australian continental crust that had arrived in the Cretaceous (e.g. Sumba–Flores region), and Australian continental crust that arrived in the Early Miocene as part of the Sula Spur then fragmented and carried south into the Banda forearc. There is no evidence for a Late Eocene to Early Oligocene collision with Australian continental crust in Sulawesi, nor for emplacement of the East Sulawesi ophiolite as suggested by Harris (2006). The pre-Neogene metamorphic ages must reflect other events within the SE Asian margin, possibly deformation at a transform margin in South Sulawesi (van Leeuwen *et al.* 2010; Hall 2011, 2012). None of the metamorphic ages 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 (Spakman & Hall 2010). They record events predating Australian collision with the SE Asia margin, collision in Sulawesi in the Early Miocene of the Sula Spur, extension and associated rapid cooling from the Middle Miocene, and Pliocene exhumation due to extension (e.g. Seram) and collision (e.g. Timor).

DETRITAL ZIRCON U–PB AGES

The number of detrital zircon studies in SE Asia has grown in recent years (e.g. Carter & Moss 1999; Bodet & Schärer 2000; Carter & Bristow 2003; Smyth 2005; van Hattum 2005; Harris 2006; van Hattum *et al.* 2006; Standley & Harris 2009; Smyth *et al.* 2007, 2008; Ely 2009; Clements & Hall 2011; Sevastjanova *et al.* 2011; Witts *et al.* 2011), but the number is still very small for the size of the region. It is difficult to characterise the region and different areas within it because the U–Pb zircon age dataset is limited. However, some features can be identified (Figures 5–7) that have significant implications for paleogeographic and plate tectonic reconstructions of SE Asia.

Paleo- and Mesoarchean zircon populations (>2.8 Ga) are common only in East Java (Figure 6). Inherited zircons of this age are also known from igneous and metamorphic rocks in NW Sulawesi (van Leeuwen *et al.* 2007). The most probable source for zircons of this age is western Australia, from the Pilbara and Yilgarn Cratons (Figure 5). Proterozoic zircons occur throughout SE Asia, however ages in the interval 1.9–1.3 Ga are uncommon on Cathaysian blocks. We suggest that these zircon populations indicate crustal fragments that separated from northern and NW Australia in the Mesozoic.

Permian–Triassic zircons in many areas of Sundaland (Figures 6, 7) indicate derivation from the Tin Belt granitoids that extend from the Thai–Malay Peninsula to Sumatra. In Paleogene sedimentary rocks from northern Borneo, the abundances of Permian–Triassic zircon grains and Proterozoic grains are well correlated suggesting a common source. The Proterozoic and Permian–Triassic ages are very similar to those typical of the Malay Peninsula, and cassiterite is present, although rare, in heavy mineral assemblages of North Borneo Paleogene sandstones (van Hattum 2005) supporting a Tin Belt provenance (van Hattum *et al.* 2006). However, recent provenance studies show that Permian–Triassic zircons are also common in Eocene samples from the Barito Basin of SE Borneo (Witts *et al.* 2011), and Mesozoic sandstones from Seram (our unpublished results) and the Bird's Head (I. Gunawan, pers. comm., 2011). This suggests that there is another Permian–Triassic source. Acid magmatism of Permian–Triassic age is known from the Bird's Head (Pieters *et al.* 1983), and the Banggai-Sula Islands (Pigram *et al.* 1985; Garrard *et al.* 1988). Transport of Permian–Triassic zircons from the Tin Belt to SE Borneo is unlikely (Witts *et al.* 2011) but their presence can be explained if they were eroded from the SW Borneo block itself. The new reconstruction interprets the SW Borneo block to have been rifted from the Banda embayment, which before the Late Jurassic would have been south of the Sula Spur, and therefore zircons of similar age in these two areas, now widely separated, is plausible. If detrital material were carried still further west (in present coordinates) the same source area would account for Triassic zircons reported from the NW Shelf (Southgate *et al.* 2011).

Jurassic zircons are uncommon in most Indonesian and Malaysian sandstones but are locally more abundant in northern Borneo samples. Jurassic magmatism is reported from Sumatra (McCourt *et al.* 1996) but is very significant in South China and zircons of this age probably indicate a Cathaysian provenance. Cretaceous zircons older than about 90 Ma are common in Indonesia and mainly represent magmatism in the area between Borneo and the Sunda margins, particularly the Schwaner Mountains, which is associated with fragments that separated from Australia in the Jurassic and collided with SE Asia in the mid Cretaceous. Cretaceous zircons found in some parts of the Thai–Malay Peninsula presumably reflect magmatic activity along the western margin of Sundaland. In contrast we would not expect Cretaceous ages from zircons derived from the fragments that were part of Australia until the Neogene, such as the southern Banda embayment margins.

CONCLUSIONS

Most of Indonesia is underlain by continental crust. Apart from the Cenozoic oceanic basins of the Celebes Sea, North Banda and South Banda basins, the only area likely to have no continental crust at depth are the Sangihe and Halmahera arcs. Western Indonesia formed part of SE Asia from the Late Triassic and is underlain by continental blocks derived from the Gondwana margins. This core has been added to in several stages. During the Cretaceous there were two principal collisions, the first during the Early Cretaceous which added SW Borneo, and the second during the early Late Cretaceous when East Java and West Sulawesi were added. These blocks came from different parts of the Australian margin. SW Borneo corresponds to the Banda embayment and East Java–West Sulawesi formed Argoland. West Burma is not a block rifted from Australia in the Mesozoic.

The development of the collision of SE Asia and Australia has been strongly influenced by the Australian inheritance. Two features are of particular importance in the Banda region; first, the Sula Spur promontory which made the initial contact with the Sundaland margin in the Early Miocene, and second, the shape, position and age of the Banda embayment, which influenced the history of subduction rollback. Rollback drove extension of the Sula Spur, which was fragmented across the Banda Arc, with parts remaining in Sulawesi, Seram and Buru, the Banda Ridges, and the Banda volcanic arc and forearc. Remnants of the Sula Spur in the Banda forearc began to collide with the southern margin of the Banda embayment in the Pliocene.

It is possible to distinguish different pieces of Australian crust and decipher their provenance and zircon studies are a key methodology. It will be vital to identify the different fragments and label them carefully. There is already enough confusion that has resulted from using the label 'Australian', assuming that metamorphic ages mark collision, failing to understand that continental crust has arrived in the region in multiple episodes, and has been fragmented and juxtaposed by subduction-related processes, and an over-simple concept of collision.

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