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Sundaland and Wallacea: geology, plate tectonics and palaeogeography

Robert Hall

3.1 Introduction

The Southeast Asian gateway is the connection from the Pacific to the Indian Ocean, which during the Cenozoic diminished from a wide ocean to a complex narrow passage with deep topographic barriers (Gordon et al. 2003) as plate tectonic movements caused Australia to collide with Southeast Asia (Hamilton 1979, Hall 1996, 2002). It is one of several major Cenozoic ocean passages but has received much less attention than others, such as the Drake Passage, Tasman, Panama or Tethyan Gateways (e.g. von der Heydt and Dijkstra 2006, Lyle et al. 2007, 2008). Unlike others that have closed, the Southeast Asian gateway is still partly open and ocean currents that flow between the Pacific and Indian Oceans have been the subject of much recent work by oceanographers (e.g. Gordon 2005). We now know that the Indonesian Throughflow (Godfrey 1996), the name given to the waters that pass through the Earth’s only low latitude oceanic passage, plays an important role in Indo-Pacific and global thermohaline flow, and it is therefore probable that the gateway is important for global climate (Schneider 1998). It is also known that today the region around the Southeast Asian gateway contains the maximum global diversity for many marine (e.g. Tomascik et al. 1997, Bellwood et al. this volume, Chapter 9) and terrestrial organisms (e.g. Whitten et al. 1999a, b). It is not known precisely when and why this diversity originated, if there is a connection.
between biotic diversity and oceanography, what the role is of the throughflow in the modern climate system, and how the restriction and almost complete closure of the passage between the Pacific and Indian Oceans may be linked to the history of climate change. However, all of these are likely consequences of geological changes related to the closure of the ocean that separated Australia and Southeast Asia at the beginning of the Cenozoic.

This chapter aims to give an overview of the geological history of the region around the gateway for life scientists; more detailed studies are included in a companion *Special Publication of the Geological Society of London* (Hall et al. 2011), which includes papers by predominantly physical science contributors to the meeting. The main intention of this chapter is to explain why the palaeogeography of the region has changed and what were the major causes of the changes. It is hoped that the palaeogeographical maps that accompany the chapter will be useful to life scientists, the explanations given here will suffice for most readers, and that those who seek more complete explanations will find them in the references cited here, Hall (2011), Hall et al. (2011) and other papers in that volume.

There are many locations referred to in the text that cannot be shown on the limited number of figures possible in this chapter. In order to aid the reader, a number of supplementary maps have been placed at http://searg.rhul.ac.uk/FTP/sage_biomaps/, which can be downloaded using any web browser. Also, readers requiring an explanation of some of the geological terminology can refer to the geological section of the glossary in Hall and Holloway (1998: 405–407), available at http://searg.rhul.ac.uk/publications/books/biogeography/biogeog_pdfs/glossary.pdf.

In geological terms, eastern Indonesia separates Asia from Australia. It is a tectonically complex region at the centre of the convergence between the Eurasian, Australian, Philippine Sea and Pacific plates (Fig 3.1). As Australia collided with the Southeast Asian margin in eastern Indonesia the wide and deep oceanic passage between the Pacific and Indian Oceans closed, although a physical oceanic connection remained (Fig 3.2). This is now the passage for water, which moves from the Pacific to the Indian Ocean by complex routes reflecting the development of the collision zone since the Early Miocene. Eastern Indonesia has a biota and diversity as fascinating as the geology and has become known to biologists as Wallacea (Fig 3.3) after Alfred Russel Wallace who contributed so much to our understanding of evolution and our knowledge of the region (van Wyhe this volume, Chapter 2). Wallace (e.g. 1869) recognised very early that distributions of plants and animals reflected changing distributions of land and sea but it was almost another century, following the plate tectonic revolution, before the amount and significance of geological change was fully appreciated.

The plate tectonic development of this region provides the most important framework for interpreting its biogeography, but the explanatory power of this
hypothesis is sometimes exaggerated. Plate tectonics has been the engine, but the consequence has been more than merely movements of pieces across the Earth’s surface. Plates, and possibly microplates, have carried their own biotas, but the land mass of Australia has crossed climatic zones, mountains have risen and disappeared, deep waterways have closed and opened, and islands have provided connections. We are still far from a complete understanding of the geology of this region, still less the links between geology, palaeogeography, ocean–atmosphere circulation and climate which have influenced biological change, biogeographical patterns and biodiversity. It seems more and more likely that the geological history of Wallacea is important not only for understanding the impact on life in this

Figure 3.1 Simplified geography of Wallacea and surrounding regions. Small black filled triangles are volcanoes following the Smithsonian Institution, Global Volcanism Program (Siebert and Simkin 2002), and bathymetry is simplified from the GEBCO (2003) digital atlas. Bathymetric contours are at 200 m and 5000 m. The 200 m bathymetric contour at the edge of the Asian margin, Sunda shelf and the Sahul–Arafura Shelf is shown by a heavy line. The arrows indicate the relative motions between the major plates. The lines with small triangles on them represent subduction zones and the triangles are on the upper plate side and indicate direction of movement of the lower plate.
equatorial region, but also for the planet because of the probable consequences for global climate.

The core of Southeast Asia, Sundaland (Fig 3.3), was initially assembled in the Late Palaeozoic and Early Mesozoic by a process that continued during the Mesozoic – addition of continental fragments carried from Gondwana to Southeast Asia (e.g. Metcalfe 2011). Rifting of fragments, now in Indonesia, from western Australia determined the shape of the Australian margin and influenced its later collision history. Their arrival affected the character of Sundaland, in terms of its strength and elevation, and terminated subduction for a period during the Late Cretaceous and Early Cenozoic. Subduction resumed in the Eocene and continues to the present day. It has been the most important geological process in the development of the region – but unfortunately it has destroyed a good deal of the evidence required to reconstruct the
Figure 3.2 Digital elevation model showing satellite gravity-derived bathymetry combined with SRTM (Shuttle Radar Topography Mission) topography (Sandwell and Smith 2009) of the region shown in Fig 3.1. The image highlights the shallow shelves surrounding Southeast Asia and Australia with the complex geology of eastern Indonesia and the Philippines.

Figure 3.4 Palaeogeography of the region at 80 Ma. The very schematic aspect of this map results from the almost complete absence of rocks of this age from Southeast Asia, because much of the region was emergent. It was probably also significantly elevated judging from the character of sedimentary rocks in Sarawak where there are some of the few rocks of this age that are preserved. They are poorly sorted clastic sediments derived from a granitic source (e.g. Wolfenden 1960) implying deep erosion to expose continental basement rocks from several kilometres depth.
The Cenozoic development was strongly influenced by what was present in Southeast Asia before collision, as well as the form of the Australian margin. The heterogeneous nature of the Sundaland basement, combined with a high regional heatflow due to magmatism and subduction, and subduction-related forces at plate margins, determined the way in which the Australia–Sundaland collision proceeded and the response of the upper crust to the movements of major plates. In Wallacea topography and bathymetry changed very rapidly during the late Neogene.
3.2 Background

The palaeogeographical maps in this chapter (Figs 3.4 to 3.12) are an attempt to display the surface of this region over time and have developed from earlier tectonic reconstructions (Hall 1996, 2002, Hall et al. 2009a) and maps (Hall 1998, 2001, 2009a). The maps cover a large area, have substantial intervals of time between them (10 to 5 Ma) and are inevitably generalised. They differ from earlier maps (e.g. Hall 2001, 2009a) slightly, but possibly significantly for some biogeographers, in showing more small areas of land within Wallacea in the Neogene, as a result of changing ideas discussed in the text below. Drawing them emphasises the difficulties for one person in acquiring and interpreting a vast amount of information and it should not be surprising that they differ considerably from maps that cover larger areas over even greater periods of time with greater intervals between them (e.g. Stampfl i and Borel 2002, Scotese 2010). It is impossible in a short space to identify and explain the differences between the maps here and those of other authors but notable differences are in the orientation and greater southward extent of the Sundaland margin in the Early Cenozoic, the importance of the Banda embayment in the Australian margin and the effective elimination of the wide deep marine gap between Australia and Southeast Asia in the Early Miocene.

Because this chapter is aimed at a reader from the life sciences I have omitted detailed arguments for the geological interpretations and restricted the number of references cited. In many places I have cited recently published papers that include references to primary sources rather than the primary sources themselves, simply to limit the number of references cited. The companion volume (Hall et al. 2011) to this book is concerned with the geology of the region and some of the physical consequences of geological change. The reader is referred to Hall (2011) and several other papers cited below in that volume for geological detail particularly relevant to this chapter. Here, I summarise briefly the region’s geological history, and draw attention to changed and new ideas of its development, especially for Wallacea. In particular, I highlight young and rapid vertical movements of the crust in Wallacea that may have caused greater changes in palaeogeography than previously recognised.

3.3 Triassic to Cretaceous: assembly of Sundaland

It is now generally accepted that Sundaland (Fig 3.3) was assembled from continental blocks that separated from Gondwana in the Palaeozoic and amalgamated with Asian blocks in the Triassic (Metcalfe 1996, 1998, 2011). The Indochina–East Malaya block separated from Gondwana in the Devonian, and by the Carboniferous
was in warm tropical low latitudes where a distinctive Cathaysian flora developed. In contrast, Carboniferous rocks, including glacio-marine diamictites, indicate the Sibumasu block was at high southern latitudes during the Carboniferous. It collided with Indochina–East Malaya, already amalgamated with the South and North China blocks, in the Triassic. Discussion continues about details of different tectonic models, timing of events and some of the consequences. The major result of subduction and collision was a promontory with a Proterozoic continental basement, intruded by widespread Permian and Triassic granites, which formed an elevated land mass for most of the Mesozoic (Abdullah 2009). This was the area that now includes Sumatra, the Malay peninsula, and the Sunda Shelf east of the peninsula.

Other parts that are commonly included in Sundaland have a less certain origin. Metcalfe (1996, 1998) interpreted a number of smaller continental blocks (or terranes) around the Indochina–East Malaya–Sibumasu core within an area shown as accreted crust. The time when they were accreted is unclear, as is their origin, and some are suggested to have come from Asia and others from Australia. The uncertainties are a result of limited exposure in areas now submerged or covered with younger rocks, or which are under studied. Borneo includes the largest of these blocks with rocks exposed that are older than Mesozoic, and it is often assumed that the Southwest Borneo continental core was attached to Sundaland before the Cretaceous. The surrounding region, from Sarawak, Sabah, East Kalimantan and East Java to South Sumatra has been interpreted as Cretaceous and Tertiary subduction complexes (e.g. Hamilton 1979) including some microcontinental fragments. Different interpretations of the many fragments are reviewed in Hall (2011). Here I summarise my own views, illustrated in Hall et al. (2009a) and Hall (2011), that show where the microcontinental fragments originated and how they moved into Southeast Asia.

Since Metcalfe (1990, 1996) suggested it, on the basis of Triassic (quartz-rich) turbidites above a pre-Mesozoic basement, it has become conventional wisdom that microcontinental fragments rifted from Northwest Australia are now in West Burma, although this was considered by Metcalfe himself as ‘speculative,’ since he observed that there was ‘as yet no convincing evidence for the origin of this [West Burma] block’. I follow Mitchell (1984, 1992) in interpreting West Burma as part of Asia and Barber and Crow (2009) who also interpreted it as part of Asia and as a continuation of the West Sumatra block. These fragments were part of Sundaland from the Late Palaeozoic and were separated by opening of the Andaman Sea. The Sikuleh and Natal blocks in Sumatra are not continental fragments derived from Australia, but were part of the Woyla intra-oceanic arc (Mitchell 1993, Barber 2000, Barber and Crow 2009) thrust onto the Sumatran Sundaland margin in the mid Cretaceous.

I consider that blocks rifted from Northwest Australia in the Jurassic are now part of Sundaland. The Southeast Asian promontory east of the Indochina–East Malaya
block grew by the addition of continental crust during the early to mid-Cretaceous, to form the Early Cenozoic Sundaland continent (Hall 2009c). Some continental fragments have an Asian origin, but most are Australian. An Asian fragment or fragments collided with east Sundaland in the mid Cretaceous, including the area of offshore Vietnam and Sarawak and onshore northern Borneo, within which are the Semitau and Luconia terranes of Metcalfe (1996, 1998). The Dangerous Grounds is in many ways a continuation of this region because it is underlain by stretched continental crust that in the Late Cretaceous was part of the South China continental margin. An Asian origin is supported by obvious Cathaysian characteristics of faunas and floras from the Dangerous Grounds (Kudrass et al. 1986), Northwest Kalimantan (Williams et al. 1988) and Sarawak (Hutchison 2005). The Dangerous Grounds was partly separated from Asia and Sundaland by opening of the South China Sea, subduction of the proto-South China Sea beneath North Borneo, and collision with Borneo.

Fragments rifted from Northwest Australia in the Late Jurassic docked against the East Malaya block in the early to mid Cretaceous (Hall et al. 2009a). Southwest Borneo is the largest and was the first of these to arrive. It separated at about 160 Ma to form the Banda embayment and was added to Sundaland in the Early Cretaceous. A small Inner Banda block is interpreted to have followed the Banda block, but moved relative to it during a later collision event, and may now underlie part of Sabah and northern West Sulawesi. The East Java–West Sulawesi block is interpreted as the Argo block (Mt Victoria Land of Veevers 1988, or Argoland of Powell et al. 1988), which was the offshore continuation of the Canning Basin, whose detrital sediments are the source of Palaeozoic to Archaean zircons now found in East Java (Smyth et al. 2007). The East Java–West Sulawesi block separated from NW Australia at about 155 Ma as rifting propagated west and south (Pigram and Panggabean 1984, Powell et al. 1988, Fullerton et al. 1989, Robb et al. 2005). East Java and West Sulawesi may be 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 intra-oceanic arc with the Sumatran Sundaland margin occurred at the same time as East Java–West Sulawesi docked.

3.4 Mid Cretaceous: collision and termination of subduction

The riftiing of fragments from Australia determined the shape and character of the Australian margin, which were to be a major influence on the Neogene development of Australia–Sundaland collision. The multiple collisions of the continental blocks from Asia and Australia also had a profound effect because they terminated
subduction (Smyth et al. 2007, Hall et al. 2009a) around Sundaland in the mid-Cretaceous for 45 Myr. For the period from about 90 Ma to 45 Ma around most of Sundaland there was no subduction. Australia was not moving north and there was an inactive margin south of Sumatra and Java until 70 Ma, there was also no subduction beneath North Borneo. No significant volcanic activity is recorded during the period 90 to 45 Ma and most granite magmatism also ceased (Hall 2009b, 2009c).

By the mid Cretaceous (c. 90 Ma) there was a large promontory of continental crust that extended from Thailand and Indochina southwards to Sumatra, Java and Borneo, which included West Sulawesi. The palaeogeography of this region is difficult to reconstruct, but it is likely that much of Sundaland was emergent (Fig 3.4) and there were large rivers draining it. Upper Cretaceous and Paleocene rocks

Figure 3.4 Palaeogeography of the region at 80 Ma. The very schematic aspect of this map results from the almost complete absence of rocks of this age from Southeast Asia, because much of the region was emergent. It was probably also significantly elevated judging from the character of sedimentary rocks in Sarawak where there are some of the few rocks of this age that are preserved. They are poorly sorted clastic sediments derived from a granitic source (e.g. Wolfenden 1960) implying deep erosion to expose continental basement rocks from several kilometres depth. See plate section for colour version.
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are almost unknown within Sundaland, although there may be terrestrial conglomerates and sandstones in Sarawak (Muller 1968, Hutchison 2005). Terrestrial deposits from the Malay peninsula, which are Jurassic to Lower Cretaceous, became inverted and were eroded after the Early Cretaceous (Abdullah 2009). Clements et al. (2011) have suggested that a major regional unconformity is a response to the mid-Cretaceous termination of subduction. A prolonged period of emergence and widespread reworking of older rocks is suggested by the character of the oldest sediments in the many Cenozoic sedimentary basins (Hall and Morley 2004, Hall 2009b) throughout Sundaland that formed when sedimentation resumed. Typically sediments are quartz-rich clastics, very mature in terms of grain shape and composition, suggesting multiple episodes of recycling. Although most of Sundaland was emergent in the Paleocene (Fig 3.5) it is likely that at the margins, for example in parts of Borneo, West Sulawesi, Sumba, Central Java and

Figure 3.5 Palaeogeography of the region at 60 Ma. Again, there are few rocks of this age in Southeast Asia, because much of the region was emergent. There was a short-lived volcanic arc at the eastern edge of Sundaland in present-day West Sulawesi and Sumba. Other parts of the Sundaland margins were inactive, although there is some uncertainty about the margin in Sarawak and northwards at this time, because much of the region is offshore and covered by younger sediments. See plate section for colour version.
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Figure 3.6 Palaeogeography of the region at 40 Ma. Subduction resumed around much of Sundaland in the Middle Eocene and many new sedimentary basins began to form, in which terrestrial sediments were deposited, derived from local sources. The Makassar Straits were already a significant marine gap, especially in the northern straits, at the eastern edge of Sundaland.
South Sumatra, deep water sedimentation continued (e.g. Burollet and Salle 1981, Hasan 1990, Wakita et al. 1994, Moss 1998, Wakita and Metcalfe 2005) through the Late Cretaceous into the Early Cenozoic. There was northwest-directed subduction beneath Sumba and West Sulawesi in the Paleocene (63 Ma to 50 Ma) and calc-alkaline volcanism (Hall 2009b, Hall et al. 2009a).

North of India between 90 and 45 Ma there was a different tectonic setting. Subduction continued beneath the intra-oceanic Incertus Arc (Hall et al. 2009a) that had been the westward continuation of the Woyla Arc. India moved rapidly north, especially from about 80 Ma, with north-directed subduction within Tethys at this intra-oceanic arc and at the Asian margin. The different movements of the Australian and Indian Plates were accommodated by a transform boundary. There is no evidence from Sundaland that India made contact with Sumatra as it moved northwards, as recently suggested (Ali and Aitchison 2008), but there is increasing evidence for a collision between the Incertus intra-oceanic arc and the northern margin of Greater India (Aitchison et al. 2007a, Hall et al. 2008, 2009a, Khan et al. 2009) at about 55 Ma. The arc was later carried north with India and may be represented in Tibet as the Zedong terrane (Aitchison et al. 2007b) or further west as the Kohistan–Ladakh Arc (Khan et al. 2009). This collision may have biogeographic significance because it could have provided an opportunity for dispersal from India into Sundaland in the Early Eocene; a complete land bridge is improbable but a connection via islands is possible. (In this chapter I use ‘dispersal’ to mean a change in the gross distributional pattern of an organism without implying any particular biological processes which might have caused that change.)

3.5 Eocene to Miocene: resumption of subduction

Until recently, most reconstructions have assumed subduction continued all round Sundaland uninterrupted from the Cretaceous into the Cenozoic (e.g. Haile 1974, Hamilton 1979, Hall 1996, 2002, Hutchison 1996, Metcalfe 1996, Barber et al. 2005, Whittaker et al. 2007). However, as outlined above, there is little direct evidence to support this and almost no subduction-related volcanic record, in contrast to the period before 90 Ma and the period after 45 Ma (Hall 2009b, 2009c). I interpret subduction to have ceased during the Late Cretaceous and Paleocene and to have resumed in the Eocene when global plate models indicate that Australia began to move northwards at a significant rate. The one part of the Sundaland margin in which there is evidence for older subduction-related volcanism is Sumba and parts of west Sulawesi. Here there is evidence for Paleocene and Eocene volcanic activity. Reconstructions suggest northwest-directed subduction of the Australian Plate beneath Sundaland between about 63 Ma and 50 Ma accompanied by slight extension and significant dextral strike-slip motion at the Sumatra and Java margin.
3.5.1 Sundaland palaeogeography

At present the interior of Sundaland, particularly the Sunda Shelf, Java Sea and surrounding emergent, but topographically low, areas of Sumatra and Borneo is largely free of seismicity and volcanism (Hamilton 1979, Engdahl et al. 1998, Hall and Morley 2004, Simons et al. 2007). This region formed an exposed land mass during the Pleistocene and most of the Sunda Shelf is shallow, with water depths less than 200 m and little relief. This has led to a misconception that it is a stable area and it is often described as a shield or craton. Cratons are old continental regions underlain by a thick cold lithosphere stabilised early in the Precambrian and have behaved as strong areas since then. They are typically flat, deformation is largely restricted to their margins, and they may flex on a very long wavelength scale with low amplitude vertical movements. Sundaland is a continent but not a craton (Hall and Morley 2004, Hyndman et al. 2005, Currie and Hyndman 2006). During the Cenozoic, different parts of the continent became substantially elevated and shed sediment to the many sedimentary basins (Hall and Morley 2004) within Sundaland that have subsided substantially and rapidly.

The resumption of subduction was accompanied by widespread extension and basin formation within the Sundaland continent from the Middle Eocene (Fig 3.6). Despite rapid subsidence, most basins were not bathymetrically deep features and contain fluvial and marginal marine deposits. A major exception is to the east of Borneo, where Middle Eocene rifting led to separation of West Sulawesi from East Borneo and formation of the Makassar Straits. It is uncertain whether the straits are underlain by oceanic or continental crust because there is a very thick sequence of sediments, up to 14 km, above the basement in the central parts of the northern straits. From a biogeographic point of view this uncertainty should not be an important issue because extension had formed a significant marine gap (topographic barrier), wider than today, from the Eocene onwards. The South Makassar Straits are probably underlain by thinned continental crust (Hall et al. 2009b), and in the centre may have subsided to depths of up to a kilometre below sea level with shallow marine carbonate platforms to the west and east. At times of low global sea level the marine gap may have been a few tens of kilometres wide. The North Makassar Straits are currently about 2500 m deep and much wider. I consider it likely that they are underlain by highly thinned continental crust as discussed in Hall et al. (2009b). Since the Eocene, the marine gap between land on Borneo and Sulawesia has been at least as great as today.

The palaeogeography changed over time with eustatic sea-level fluctuations, but from the Eocene to Early Miocene (Figs 3.6 to 3.9) most of western Sundaland was terrestrial with deposition in sedimentary basins dominated by fluvial input, with areas of shallow marine seas increasing with time. It is likely that the Malay peninsula was one important elevated region within Sundaland supplying
sediment to Sunda Shelf basins, and the Schwaner Mountains of West Borneo was another. Parts of the present Java Sea may also have been elevated and provided sediment. In the area west of the present Meratus Mountains, known as the Barito Basin, there was a wide river system, where coals and fluvial and estuarine sediments were deposited. This appears to have flowed north during the Eocene from the present Java Sea (D. Witts pers. comm. 2010) towards the Makassar Straits, with limestones deposited during periods of higher sea level. Clastic sediment was also transported into the North Makassar Straits from central or West Borneo.

In the northern Borneo part of the Sundaland land mass there was a narrow shelf and slope at the margin of the deep-water area of the proto-South China Sea (van Hattum 2005). Sediment was carried offshore from rivers flowing from the Malay peninsula and the Schwaner Mountains and deposited on a shelf, in the area of present offshore Sarawak, and carried into a deep-water sediment accumulation, the ‘Crocker Fan’, in Sabah on the south side of the proto-South China Sea.

Figure 3.6 Palaeogeography of the region at 40 Ma. Subduction resumed around much of Sundaland in the Middle Eocene and many new sedimentary basins began to form, in which terrestrial sediments were deposited, derived from local sources. The Makassar Straits were already a significant marine gap, especially in the northern straits, at the eastern edge of Sundaland. See plate section for colour version.
Figure 3.5 Palaeogeography of the region at 60 Ma. Again, there are few rocks of this age in Southeast Asia, because much of the region was emergent. There was a short-lived volcanic arc at the eastern edge of Sundaland in present-day West Sulawesi and Sumba. Other parts of the Sundaland margins were inactive, although there is some uncertainty about the margin in Sarawak and northwards at this time, because much of the region is offshore and covered by younger sediments.

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3.5.2 Sundaland margins

At the southern margin of Sundaland between the Eocene and Early Miocene (Figs 3.6 to 3.8) were volcanic arcs, and within Borneo there was volcanic activity, mainly related to southward subduction of the proto-South China Sea. The volcanoes mainly formed islands rather than continuous and extensive areas of land. It is probable that in West Sulawesi there were no volcanoes.

In Sumatra, volcanic activity became widespread from the Middle Eocene (Crow 2005). The Eocene arc was in a similar position to the Mesozoic arcs (McCourt et al. 1996) and was initially constructed on the edge of the land mass with some volcanic centres in a terrestrial setting and others forming islands on a coastal plain (M. J. Crow pers. comm. 2010). A possible Toba-scale caldera may have spread ash over a major part of Central Sumatra in the Late Eocene (Crow 2005). Later regional subsidence is suggested by Barber et al. (2005) to have led to marine transgression, with deepening and widening of marine basins in both the forearc and backarc leaving the volcanic Barisan Mountains as a chain of large islands south of the elevated Malay peninsula by the Early Miocene. The Sumatran arc remained in essentially the same position during the whole of the Cenozoic.

In Java a volcanic arc ran the length of the island from the Middle Eocene (Smyth et al. 2007, Hall and Smyth 2008) well to the south of the Cretaceous active margin and close to the present south coast of Java. It formed a series of small volcanic islands rather than a large single island and was south of the Sundaland coast and separated from it by a marine gap. The shelf edge ran roughly east-west through northern Java and was locally quite steep. The extensive emergent area of Sundaland to the north of West Java was crossed by large rivers that drained the Malay–Thai peninsula area and West Borneo feeding sediment to the coast, and further east were shallow marine carbonates on a broad flat shelf covering much of the area as far east as Sulawesi.

The Eocene and Oligocene volcanic activity records north by northeast-directed convergence of the Indian–Australian Plate with respect to Sundaland, which meant that in Sulawesi the subduction direction was almost parallel to the continental margin. The volcanic activity that began in the Paleocene ceased in Sumba and West Sulawesi in the Late Eocene (van Leeuwen et al. 2010) or Early Oligocene (Abdullah et al. 2000). There was a transform margin (van Leeuwen et al. 2010) at about the position of the Walanae fault zone in South Sulawesi and an offset in the arc, which continued eastwards into the Pacific via the North Arm of Sulawesi, the East Philippines and Halmahera. South Sulawesi was the site of an extensive carbonate platform for most of the Cenozoic although there may have been some arc activity and possibly a marginal basin along the east side of the transform margin. To the north there must have been some islands in West Sulawesi.
supplying detritus to the Makassar Straits. In the Eocene there appears to have been more land with coal swamps and small marine limestone-capped tilted fault blocks, which became submerged as the Makassar Straits subsided. Small areas of land must have remained until the Pliocene, since clastic shelf sediments are preserved in West Sulawesi and indicate a source east of the Makassar Straits, although where is not known.

From the Eocene to Early Miocene, the Proto-South China Sea was subducted southwards beneath northern Borneo. As it was subducted, the present South China Sea formed to the north of it between the Oligocene and Middle Miocene (Taylor and Hayes 1983, Briais et al. 1993). The Crocker Fan was deposited in deep water at the active subduction margin (Tan and Lamy 1990, Tongkul 1991, Hazebroek and Tan 1993, Hutchison et al. 2000). Much of the sediment came from the Malay–Thai peninsula and Schwaner Mountains but some has an ophiolitic

**Figure 3.7** Palaeogeography of the region at 30 Ma. Although much of Sundaland was emergent it is likely that topography was significantly lower than earlier in the Cenozoic. Rivers carried recycled clastic sediments to internal basins and the continental margins. On the Sunda Shelf there were large freshwater lakes, not linked to the ocean, which are shown in a different shade from normal salinity seas. See plate section for colour version.
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Figure 3.8 Palaeogeography of the region at 25 Ma. On the Sunda Shelf lakes (shown in a different shade) were intermittently connected to the sea and were brackish. The Sula Spur was about to collide with the volcanic arc of Sulawesi’s North Arm resulting in ophiolite emplacement and uplift, and becoming the first part of the Australian continent to connect Australia and Southeast Asia, although there was no continuous land connection.
provenance indicating some land areas in Sabah (van Hattum 2005, van Hattum et al. 2006).

3.6 Miocene to Recent: Australia collision in Wallacea

At the beginning of the Miocene there was collision between Sundaland and Australia (Figs 3.8, 3.9), and later in the Early Miocene there was collision in north Borneo with the extended passive continental margin of South China (Hutchison et al. 2000, Hall and Wilson 2000). Continental fragments have since been accreted to, or rearranged in, East Indonesia. These collisions led to mountain building in Sulawesi, the Banda Arc, and Borneo. In addition, the arrival of arcs from the Pacific in East Indonesia led to the emergence of islands in east Indonesia.
Figure 3.7 Palaeogeography of the region at 30 Ma. Although much of Sundaland was emergent it is likely that topography was significantly lower than earlier in the Cenozoic. Rivers carried recycled clastic sediments to internal basins and the continental margins. On the Sunda Shelf there were large freshwater lakes, not linked to the ocean, which are shown in a different shade from normal salinity seas.

Figure 3.8 Palaeogeography of the region at 25 Ma. On the Sunda Shelf lakes (shown in a different shade) were intermittently connected to the sea and were brackish. The Sula Spur was about to collide with the volcanic arc of Sulawesi’s North Arm resulting in ophiolite emplacement and uplift, and becoming the first part of the Australian continent to connect Australia and Southeast Asia, although there was no continuous land connection.
3.6.1 Banda: Early Miocene collision

One important influence on the way in which the Australia– Southeast Asia collision developed was the nature of the Australian margin. The Jurassic rifting had 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. Parts of it are now present in East, Central and Southeast Sulawesi, the Banggai-Sula Islands, Buru, Seram but also in submerged ridges of the Banda Sea, small islands of the outer arc, and possibly in Timor. Because of collision-related deformation and subsequent fragmentation it is impossible to know the detailed palaeogeography of the spur, and in particular if there was any land. The limited evidence records a change from terrestrial to marginal marine sedimentation in the Early

Figure 3.9 Palaeogeography of the region at 20 Ma. There was significant marine incursion onto the Sunda Shelf and extensive areas of carbonate build-ups throughout the region on the wide shallow shelves. Borneo became an important source of clastic sediments which began to pour into the deep offshore basins to the north, east and southeast. It is likely that the flow of water from the Pacific to the Indian Ocean was significantly reduced from 20 Ma until after 10 Ma. Much of Wallacea between Sulawesi and the Bird’s Head was the site of shallow marine carbonate deposition and may have been emergent in some areas. See plate section for colour version.
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Figure 3.10 Palaeogeography of the region at 15 Ma. Soon after 15 Ma the Java Trench subduction zone began to propagate east as it tore along to the continent ocean boundary south of the Sula Spur and Bird’s Head. Rollback of the subduction hinge caused major extension in Sulawesi and fragmented the Sula Spur.
to Middle Jurassic and marine transgression later in the Jurassic. Cretaceous rocks from different parts of the spur are marine and suggest quiet deep waters on a continental margin (Cornée et al. 1995) west of the Bird’s Head. The evidence suggests that the Sula Spur was submerged during the late Jurassic and Cretaceous. However, in the Banggai-Sula Islands, Cretaceous–Paleocene rocks are overlain in the west by flat-lying Eocene to Recent shallow marine carbonates with a slight angular unconformity, and further east there are no carbonates but the Mesozoic sequence has been eroded to expose a basement window. Seismic lines offshore show no significant erosional products to indicate that the elevation of the Sula Islands (over 1000 m) occurred during the Late Cenozoic. These observations suggest that parts of the islands, and possibly other parts of the spur, could have become emergent during the Eocene and remained as land until the present (Figs 3.6 to 3.12).

A widely held view of the region is that small fragments of continental crust were sliced from the Bird’s Head during the Neogene, moved along a left-lateral strike-slip zone and have travelled west to collide with Sulawesi. This concept originated with Hamilton (1979) and has become famous as the ‘bacon-slicer’ and is incorporated in many tectonic models and reconstructions. For geologists, the supposed collisions (often vaguely dated) are used to explain all sorts of tectonic events throughout Wallacea and Sundaland, despite the very small size of the blocks. The model has been popular with biogeographers as it may explain dispersal of organisms from Australia as passengers on small ‘arks’ (e.g. McKenna 1973). I now doubt it for many reasons. For example, at the front of the blocks now in Sulawesi there should be a volcanic arc formed above the subducting ocean as the blocks moved west, typically identified with the West Sulawesi plutonic–volcanic arc, or a volcanic arc in the Togian Islands of Tomini Bay for the Banggai-Sula block. It is now known that there was little or no Mio-Pliocene volcanic activity in West Sulawesi, and that which there was in West Sulawesi and the Togian Islands does not have a subduction character (Cottam et al. 2011). There is much other evidence inconsistent with this simple tectonic model, such as the absence of through-going strike-slip faults (Watkinson et al. 2011), timing of slicing and collisions, and the presence of young ocean basins in the collision zone.

Instead, I suggest that soon after 25 Ma the Sula Spur began to collide with the North Sulawesi volcanic arc and this was the first part of the Australian continent to make contact with the Sundaland margin. An animated reconstruction of this collision and its consequences is given by Spakman and Hall (2010). Ophiolites in East Sulawesi (Kündig 1956, Silver et al. 1983) derived from the ocean north of the Sula Spur and probably from the North Sulawesi forearc, were thrust onto the continental crust of the Sula Spur. Ophiolite debris is found in probable Early Miocene terrestrial and marginal marine sediments (Surono 1995) in Southeast Sulawesi. By the Early Miocene there was Australian crust in East and Southeast Sulawesi,
which was connected to Australia via the Bird’s Head, although this does not mean there was an emergent or continuous terrestrial connection (Figs 3.8, 3.9).

Between 25 and 15 Ma the continued northward movement of the Indian–Australian plate was absorbed in several ways: subduction of Indian Ocean crust at the Java Trench; subduction of the Proto-South China Sea; widespread 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. Sulawesi remains something of an enigma during this period. In West Sulawesi there is an incomplete stratigraphic record but there is little indication of mountain building, no sign of a significant sediment input, and no major deformation. In South Sulawesi carbonate deposition continued, although it changed character from an extensive platform to dispersed build-ups. The nature of the boundary between West and East Sulawesi is obscure, and in East and Southeast Sulawesi there is little stratigraphic record.

One key to dating tectonic events in Sulawesi lies in the clastic sediments deposited after collision (Hall and Wilson 2000). Sediments first described by Sarasin and Sarasin (1901) in the Southeast Arm of Sulawesi were named the Celebes Molasse because of their supposed similarity to the molasse of the Swiss Alps. Wanner (1910) correlated similar rocks of the East Arm with the Southeast Arm and van Bemmelen (1949) used the term for clastic sediments of young Neogene age that are found all over Sulawesi. The Celebes Molasse is usually considered to have been deposited in the Early to Late Miocene interval, implying mountains, uplift and erosion, but most of the rocks assigned to it are undated, and the most reliably dated are Late Miocene and Pliocene. The inter-arm bays of Gorontalo and Bone contain thick sediment sequences that could have been eroded during the Early to Late Miocene from a mountainous region in East, Central and Southeast Sulawesi, and in many parts of Central and Southeast Sulawesi there are low grade metamorphic rocks and ophiolites suggesting substantial erosional removal of sedimentary cover rocks, but our present knowledge allows little more than the statement that there was an elevated land mass in Sulawesi during much of the Miocene.

3.6.2 Banda: Miocene extension

There was an important change in the Middle Miocene at about 15 Ma to widespread extension and major subsidence. This change was caused by the second major influence on the Australia–Sundaland collision: the Banda embayment. This was the oceanic area south of the Sula Spur left after the continental fragments now beneath Borneo, West Sulawesi, Sumba and East Java rifted from Northwest Australia in the Late Jurassic. It was part of the Australian plate and contained oceanic crust of Late Jurassic age. Its last remnant is the Argo Abyssal Plain southwest of Timor. From the Late Jurassic to the Neogene the embayment was
surrounded by a passive continental margin that can be traced from the Exmouth plateau, via Timor, Tanimbar and Seram, to Southeast Sulawesi. Subduction of this embayment began, the Sula Spur became fragmented, new ocean basins were created, and continued rollback ultimately led to formation of the Banda Arc as we know it today (Spakman and Hall 2010).

Subduction is often thought of as a consequence of two plates converging, but can be viewed equally well as one plate sinking under the influence of gravity (e.g. Elsasser 1971, Molnar and Atwater 1978, Carlson and Melia 1984). As the lower plate sinks, the subduction hinge moves oceanward, away from the arc, in a process that has been described as subduction rollback, hinge retreat or rollback, trench retreat or rollback, or slab rollback (Hamilton 2007). The rollback induces extension in the upper plate to fill the space created.

As Australia moved north, the Java Trench subduction zone became aligned with the northern margin of the embayment, a tear fault developed from the western edge of the Sula Spur and propagated eastward along the continent–ocean boundary from about 15 Ma. As the tear moved east, the oceanic embayment began to sink rapidly and the subduction hinge began to roll back into the Banda embayment. The effect of rollback was dramatic 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. There was subsidence in the Banda forearc near Sumba (Fortuin et al. 1997, Rigg and Hall 2011), oceanic spreading began in the North Banda Sea (Hinschberger et al. 2000), Banda arc volcanism started, there was extension-related volcanic activity in West Sulawesi (Polvé et al. 1997), and extension formed a core complex in the Sulawesi North Arm (van Leeuwen et al. 2007). Core complexes are metamorphic rocks exhumed rapidly from the middle and lower continental crust by low angle faults that cut through the entire crust. As extension occurs on the faults the lower (footwall) block, with ductile deformed high-grade metamorphic rocks or granites, is exposed at the surface and may be overlain by remnants of much lower grade metamorphic or unmetamorphosed rocks of the upper (hangingwall) block, typically characterised by brittle deformation.

Extension is interpreted to have occurred in three important phases. The earliest phase led to formation of the North Banda Sea between 12.5 and 7 Ma (Hinschberger et al. 2000). Continental crust from the Sula Spur was extended above the subduction hinge and separated from what remains in East and Southeast Sulawesi. Some of this crust remains in the Banda Ridges, and some formed part of the basement of the Banda volcanic arc and its forearc east of Flores. The eastern part of this volcanic arc, from east of Wetar to Seram, was active for a short period (c. 8–5 Ma) 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, the arc and continental crust was further extended to form the Banda forearc and is now
found in Timor and several of the small outer arc islands from Leti to Babar (e.g. Bowin et al. 1980).

3.6.3 Banda: Pliocene collision

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. A remnant of the oceanic embayment remained to the east of Timor after collision and was subducted as rollback continued. This final phase of extension of the upper plate above the retreating hinge formed the Weber Deep, which subsided from forearc depths of about 3 km to its present-day depth of more than 7 km in the last 2 Myr. The very young volcanoes in the eastern part of arc from Damar to Banda (Abbott and Chamalaun 1981, Honthaas et al. 1998, 1999) record the final stage of rollback that accompanied formation of the Weber Deep.

In Timor and Sumba, the arc-continent collision was marked by a cessation of volcanic activity in the inner Banda arc in Wetar and Alor at 3 Ma (Abbott and Chamalaun 1981, Scotney et al. 2005, Herrington et al. 2010) 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). Islands such as Savu and Roti have emerged even more recently and continue to rise.

A number of points are worth reiterating for the Banda region. The term collision is often used in different ways. The first contact between the Australian continent (Sula Spur) and the Sundaland margin was in the Early Miocene in Sulawesi, but collision between the continental margin (Northwest Shelf) and the Banda volcanic arc in Timor did not occur until the Pliocene. This can now be understood as a consequence of the shape of the Australian continental margin and the rollback of the subduction zone into the Banda embayment (Spakman and Hall 2010). Land has emerged at different times since the early Miocene, and many parts of Wallacea have emerged at very high rates. For example, in Timor Audley-Charles (1986) estimated average rates of uplift of 1.5 km/Myr and Quaternary limestones are mapped in West Timor at elevations above 1 km (Suwitodirdjo and Tjokrosapoetro 1975). Other large islands such as Seram, Sumba and parts of Sulawesi have emerged at similar rates. However, at the same time, basins such as the South Banda Sea and Weber Deep have subsided at similar rates. The geography of this critical region has changed dramatically in the last 5 Myr.

3.6.4 Sulawesi

During the Miocene and Pliocene there were significant vertical movements and the palaeogeography of Sulawesi changed significantly (Figs 3.10 to 3.12). This is
true for most of North and East Sulawesi, possibly for Southeast Sulawesi, and certainly for the major enigmatic inter-arm basins of Gorontalo Bay and Bone Bay. West Sulawesi and the North and East Arms are striking in their exceptional elevations (up to 3 km) within short distances of the coast, and the narrow width of these elevated areas. The timing of subsidence, uplift and exhumation is uncertain. In North Sulawesi metamorphic ages may record Early Miocene collision of the Sula Spur. Throughout North and West Sulawesi there is evidence for extension from the Middle Miocene, beginning at about 15 Ma, which I interpret to be driven by subduction rollback in the Banda embayment. The relief and distribution of land are uncertain.

The Makassar Straits was a pre-existing deep-water area into which sediment was transported, but seismic lines across the northern margin of the Paternoster platform indicate at least 1 km of additional subsidence of the North Makassar basin at the end of the Miocene. The subsidence is the same age as the rapid exhumation on land and there is probably a causal link between them. Throughout West,
Figure 3.9 Palaeogeography of the region at 20 Ma. There was significant marine incursion onto the Sunda Shelf and extensive areas of carbonate build-ups throughout the region on the wide shallow shelves. Borneo became an important source of clastic sediments which began to pour into the deep offshore basins to the north, east and southeast. It is likely that the flow of water from the Pacific to the Indian Ocean was significantly reduced from 20 Ma until after 10 Ma. Much of Wallacea between Sulawesi and the Bird’s Head was the site of shallow marine carbonate deposition and may have been emergent in some areas.

Figure 3.10 Palaeogeography of the region at 15 Ma. Soon after 15 Ma the Java Trench subduction zone began to propagate east as it tore along to the continent ocean boundary south of the Sula Spur and Bird’s Head. Rollback of the subduction hinge caused major extension in Sulawesi and fragmented the Sula Spur.
North and East Sulawesi there is evidence for a significant vertical motion on land at about 5 Ma. There was clearly a major increase in output of clastic sediment at this time (e.g. van Bemmelen 1949, Garrard et al. 1988, Davies 1990, Calvert 2000, Calvert and Hall 2007).

In West Sulawesi shallow marine Miocene sedimentary rocks deposited on a shelf on the east side of the Makassar Straits are overlain by Pliocene coarse terrestrial clastics derived from the east (Calvert and Hall 2007). Since 5 Ma there has been a major increase in land area and a significant change in elevation. The deep valleys incised into steep mountains expose deep crustal rocks such as garnet granulites and eclogites, intruded by young granites, in the Palu area (Watkinson 2011), and probably throughout West Sulawesi. Rapid uplift and exhumation, which began about 5 Ma recorded by K-Ar and apatite fission track

**Figure 3.11** Palaeogeography of the region at 10 Ma. Subduction rollback was well under way and extension in Sulawesi led to volcanic activity, subsidence in Bone Gulf and oceanic crust formation in the North Banda Sea. Borneo was now a significantly emergent and elevated area. Wallacea probably had a much more complex palaeogeography than shown as the Sulu Spur was fragmentated. Note that this fragmentation was not the result of slicing of fragments from the Bird’s Head but driven by rollback of the subduction hinge into the Banda embayment. See plate section for colour version.
Figure 3.11 Palaeogeography of the region at 10 Ma. Subduction rollback was well under way and extension in Sulawesi led to volcanic activity, subsidence in Bone Gulf and oceanic crust formation in the North Banda Sea. Borneo was now a significantly emergent and elevated area. Wallacea probably had a much more complex palaeogeography than shown as the Sulu Spur was fragmented. Note that this fragmentation was not the result of slicing of fragments from the Bird’s Head but driven by rollback of the subduction hinge into the Banda embayment.

Figure 3.12 Palaeogeography of the region at 5 Ma. New deep oceanic basins had formed throughout Wallacea. Oceanic spreading in the North Banda Sea had ceased but had begun in the South Banda Sea. Deepening of the Flores Sea is inferred. At the same time substantial and rapid elevation began in Sulawesi, as rollback commenced at the North Sulawesi Trench driving core complex formation in the neck and East Arm, but Goontalo Bay was about to subside to present depths of up to 2 km below sea level. Uplift was about to begin in Timor as the Banda volcanic arc collided with the Australian continental margin in Timor. The last 5 Myr has seen significant changes in palaeogeography and dramatic uplift and subsidence. Seram and Timor are the two largest islands in the Banda region to have emerged in this interval.
Figure 3.12 Palaeogeography of the region at 5 Ma. New deep oceanic basins had formed throughout Wallacea. Oceanic spreading in the North Banda Sea had ceased but had begun in the South Banda Sea. Deepening of the Flores Sea is inferred. At the same time substantial and rapid elevation began in Sulawesi, as rollback commenced at the North Sulawesi Trench driving core complex formation in the neck and East Arm, but Goontalo Bay was about to subside to present depths of up to 2 km below sea level. Uplift was about to begin in Timor as the Banda volcanic arc collided with the Australian continental margin in Timor. The last 5 Myr has seen significant changes in palaeogeography and dramatic uplift and subsidence. Seram and Timor are the two largest islands in the Banda region to have emerged in this interval. See plate section for colour version.

ages (Bellier et al. 2006), provided significant sediment to a young west-vergent offshore fold and thrust belt in the Makassar Straits.

In Gorontalo Bay, spectacular very young and rapid subsidence is recorded by numerous pinnacle reefs now found within a range of water depths between 1–2 km many of which, despite the high rates of sediment supply, are not buried by sediment. Alluvial fan deposits on land in the Togian Islands (Cottam et al. 2011) are separated from their equivalents on the East Arm by water depths up to 1.5 km (Jablonkksi et al. 2007) and 25 km further south elevations on land exceed 2 km. Off shore east of East Arm are probable platform carbonates with no sediment cover at water depths of more than 1 km. They are likely to be Middle and/or
Palaeogeography of the region at 10 Ma. Subduction rollback was well under way and extension in Sulawesi led to volcanic activity, subsidence in Bone Gulf and oceanic crust formation in the North Banda Sea. Borneo was now a significantly emergent and elevated area. Wallacea probably had a much more complex palaeogeography than shown as the Sulu Spur was fragmented. Note that this fragmentation was not the result of slicing of fragments from the Bird’s Head but driven by rollback of the subduction hinge into the Banda embayment.

Palaeogeography of the region at 5 Ma. New deep oceanic basins had formed throughout Wallacea. Oceanic spreading in the North Banda Sea had ceased but had begun in the South Banda Sea. Deepening of the Flores Sea is inferred. At the same time substantial and rapid elevation began in Sulawesi, as rollback commenced at the North Sulawesi Trench driving core complex formation in the neck and East Arm, but Goontalo Bay was about to subside to present depths of up to 2 km below sea level. Uplift was about to begin in Timor as the Banda volcanic arc collided with the Australian continental margin in Timor. The last 5 Myr has seen significant changes in palaeogeography and dramatic uplift and subsidence. Seram and Timor are the two largest islands in the Banda region to have emerged in this interval.
Upper Miocene by comparison with limestones beneath the Celebes Molasse in the Togian Islands, implying subsidence of 1 km or more probably in less than 5 Myr. I interpret the subsidence in Gorontalo Bay, and the extension occurring on land today forming core complexes (Spencer 2010), to be driven by rollback at the North Sulawesi trench as the Celebes Sea is subducted.

Seismic lines across Bone Bay also show thick sediments and a similar subsidence history although this subsidence was driven by Banda rollback. However, west of Bone Bay in South Sulawesi is the Tonasa–Tacipi platform/shelf, where there has been carbonate deposition since the Eocene (e.g. Wilson and Bosence 1996, Ascaria 1997, Ascaria et al. 1997). As with Borneo, there is a difference from north to south from young and spectacular uplift and subsidence to areas that appear to have remained stable and close to sea level during much of the Cenozoic.

3.7 Miocene to Recent: Pacific arcs and northern Australia

At the eastern edge of Wallacea are the Halmahera and Sangihe volcanic arcs, which are the only example of an arc–arc collision in the world. Both of the currently active arcs formed during the Neogene. The Sangihe Arc can be traced from Sulawesi northwards into the Philippines. In biogeographic terms it is within Wallacea but in geological terms is arguably part of Neogene Sundaland. It was constructed on Eocene oceanic crust of the Celebes Sea but in the Neogene formed a continuation of the North Arm of Sulawesi, which had collided with the Sula Spur. The modern Halmahera Arc is relatively recently arrived in Wallacea. It is constructed on older intra-oceanic arcs formed in the Pacific, which were part of the Philippine Sea Plate. Between 45 and 25 Ma the Philippines–Halmahera Arc developed above a north-dipping subduction zone where there was subduction of oceanic lithosphere as Australia moved north (Hall 1996, 2002, Hall and Spakman 2002). After collision of this arc with northern Australia (c. 25 Ma) it moved west along the New Guinea margin north of the left-lateral Sorong fault zone (Hall et al. 1995a, b).

3.7.1 North Moluccas

The history of the Sorong Fault in New Guinea is not well known. It juxtaposes arc and ophiolitic rocks of Pacific/Philippine Sea Plate origin against Australian continental crust in the New Guinea mobile belt (Pieters et al. 1983, Dow and Sukamto 1984). The fault is an irregular wide zone of strands within which there was transpression and transtension, meaning local uplift and subsidence along the fault. Most of the rocks within the fault zone are oceanic and fragments
from the Pacific, although some small slices of continental crust were caught up in fault strands. All these rocks have been carried westwards along the fault zone.

The islands of the North Moluccas are part of the mobile belt and include both arcs and potential arks. The group of islands northwest of the Bird's Head between Halmahera and Waigeo have Middle to Upper Miocene limestones above arc and oceanic basement, a widespread feature of northern New Guinea, indicating that for most of the Miocene this region was close to sea level but mainly submerged (Figs 3.9 to 3.11).

Initiation of east-directed Halmahera subduction probably resulted from locking of strands of the left-lateral Sorong fault zone. The present-day Molucca Sea double subduction system was initiated at about 15 Ma, and the oldest Neogene volcanic rocks in the Halmahera Arc have ages of about 11 Myr (Baker and Malaihollo 1996). Active volcanism would have formed islands similar to the present offshore islands of the Halmahera arc such as Ternate and Tidore. Since 11 Ma the Molucca Sea has since been eliminated by subduction at both its eastern and western sides. The two arcs first came into contact at about 3 Ma and began to build the central Molucca Sea accretionary complex as the two forearcs collided (Hall 2000). Since then, Halmahera has become emergent and the areas of land in the North Moluccas have increased significantly.

3.7.2 New Guinea

New Guinea is not part of Wallacea, but in geological terms the northern part certainly belongs with the North Moluccas, and the Bird's Head has an important connection with the Banda Arc in Seram. In New Guinea there is now a substantial chain of mountains, the New Guinea Highlands, up to 5 km high running from west to east with a coastal plain and tropical swamps to the north and the south. These mountains have risen, and the island has acquired its present form, only in the last 5 Myr (Struckmeyer et al. 1993, Hill and Raza 1999, Hill and Hall 2003, Cloos et al. 2005, van Ufford and Cloos 2005). For most of the Cenozoic the New Guinea Limestones, which now form the high mountains, were part of a wide and long-lived carbonate shelf north of the Australian land mass (Dow 1977, Pieters et al. 1983). Before about 5 Ma, to the north of this shallow marine shelf, it is likely that there were emergent islands in the northern New Guinea mobile belt (Pigram and Davies 1987, Audley-Charles 1991, Crowhurst et al. 1996) as the Philippine Sea Plate moved west, which may have permitted dispersal of faunas and floras. It is likely for most of the Neogene that the palaeogeography resembled the region of small islands currently within splay of the Sorong Fault zone east and west of the Bird's Head but separated from land to the south by a wide, albeit shallow, marine gap. However, the New Guinea Limestone sequences (e.g. Pieters et al. 1983, Carman and Carman 1990, 1993, Brash et al. 1991, Buchanan
1996, Buchanan et al. 2000) include numerous minor unconformities, hard grounds, minor clastic intervals, and signs of karstic alteration suggesting intermittent emergence. It is impossible at present to map the palaeogeography in detail; it seems improbable that the entire shelf was ever completely emergent, but it is likely that the shelf was an area of numerous low islands during most of the Cenozoic.

3.7.3 Bird’s Head

The Bird’s Head of New Guinea is in a critical position between Australia and Wallacea. At present it is largely aseismic but surrounded by shallow seismicity (hypocentres shallower than 70 km). GPS studies indicate it is moving southwest towards Seram relative to Australia. The Bird’s Head has been relatively little studied since regional mapping by Australian–Indonesian teams in the early 1980s (Pieters et al. 1983, Dow and Sukamto 1984, Dow et al. 1986). The northern Bird’s Head is crossed by strands of the Sorong Fault system. To the north is the mobile belt and to the south is Australian continental crust. East of the Bird’s Head is a triangular embayment, Cenderawasih Bay, with a thick sediment cover above a basement of unknown type (Dow and Hartono 1982). On the east side is a zone of young deformation on the seafloor adjacent to the Bird’s ‘body’, and to the east is the Wandaman peninsula, which includes high grade metamorphic rocks with very young metamorphic ages, and west of that the west-directed Lengguru fold and thrust belt of Late Miocene–Pliocene age (Dow et al. 1985, Bailly et al. 2009, Sapin et al. 2009).

The northeast part of the Bird’s Head includes mountains, which supplied sediment to the southwest from at least the Late Miocene. On its southwest side is a topographic ridge, the Misool–Onin–Kumawa Ridge (Fraser et al. 1993, Pairault et al. 2003, Sapin et al. 2009), which is a broad anticline. This was an emergent feature in the Early Pliocene and a widespread unconformity suggests much of the Bird’s Head was emergent at times during and since the Late Miocene. In the offshore region near to Misool, the importance of this unconformity was recognised from seismic data only a few years ago (Pairault et al. 2003). New seismic and detailed bathymetric information, as yet unpublished, from the offshore areas including Cenderawasih Bay to the east, the Seram Trough and the Misool–Onin–Kumawa Ridge to the south, and the Sorong fault zone to the west is now adding to our knowledge and changing our picture of the Bird’s Head development, which is still not well understood. It is too early to be certain but recent work is highlighting important palaeogeographic changes including more, and more persistent, areas of land during the late Neogene. It is possible that emergent terrestrial dispersal routes from Australia, via the Bird’s Head and Sula Spur into Wallacea, were more important and more enduring than previously suggested.
3.8 Miocene to Recent: Sundaland collision, uplift and subsidence

While the most important geological changes were in Wallacea and northern New Guinea as Australia moved north, there were also significant events in Sundaland, notably, but not only, in Borneo.

3.8.1 Borneo collision

Subduction ceased in the Early Miocene when the thinned passive margin of the Dangerous Grounds underthrust northern Borneo causing deformation, uplift and crustal thickening (Hutchison et al. 2000, Hall and Wilson 2000). Deep marine sedimentation stopped and the sediments of the Crocker Fan were exposed on land. In parts of central Borneo there was some Miocene magmatism, but volcanic activity largely ceased following arc-continent collision after complete subduction of the proto-South China Sea. The collision resulted in uplift of much of the interior of Borneo. Most of the deep Cenozoic basins around Borneo are filled by sediments (van Hattum et al. 2006) carried from Borneo by large rivers as the island emerged and land area increased through the Neogene. However, there are differences between the areas north and south of the Paternoster–Lupar lineaments.

3.8.2 Southern Borneo

The area south of the Paternoster–Lupar lineaments has a continental basement rifted from the Australian margin in the Late Jurassic inferred to have a thick strong and cold lithosphere. With the exception of the Meratus Mountains this area has remained close to sea level since the Middle Eocene.

In east Kalimantan, gold mineralisation is associated with Early Miocene magmatism and hydrothermal alteration in volcanic settings similar to those of the present-day North Island of New Zealand (Davies et al. 2008). The gold belt appears never to have been deeply buried (T. van Leeuwen pers. comm. 2008) and was exhumed in the Pleistocene.

Southeast of the gold belt, the Meratus Mountains are a narrow zone of deformation, which may be a reactivated strike-slip suture in the basement, probably elevated between the Late Miocene to Pleistocene. 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 Asem-Asem Basin and the long-lived Eocene to Miocene Paternoster–Tonasa carbonate platform. Both areas are still largely undeformed. The Asem-Asem Basin was the eastern part of the Barito Basin until uplift of the Meratus Mountains. 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 Myr. Apart from the Meratus Mountains, southern Borneo has subsided to allow sediment to accumulate, but the surface has always been close to sea level so expansion of the area of shallow marine carbonates, notably during the Oligocene, records eustatic sea-level rises.

3.8.3 Northern Borneo

In contrast, the rest of Borneo has supplied large amounts of sediment to basins on land and offshore. Early Miocene rise of the Central Borneo Mountains shed sediment first into deltas of the Kutai and Sandakan Basins and later into the Tarakan and Baram Basins. In the Kutai Basin sediment was derived from erosion of the Borneo highlands and inversion of older parts of the basin. Inversion, emergence and erosion migrated from west to east during the Early and Middle Miocene. A similar progressive outward movement of coastline is typical of most of Borneo north of the Paternoster–Lupar lineaments.

In Sabah the history is more complicated than a simple and continuous rise of mountains. At the end of the Early Miocene, Sabah was emergent but soon afterwards most of west and east Sabah subsided below sea level (Balaguru et al. 2003) probably leaving a narrow band of highlands along the present Crocker Ranges. Subsidence may be related to break-off of the subducted Proto-South China Sea slab, the load of a lithospheric root formed during the collision, or could be connected to Middle Miocene (Rangin and Silver 1991) opening of the Sulu Sea.

It is possible that this may have been driven by subduction rollback. In south Sabah there was a Middle and Late Miocene volcanic arc in the Dent and Semporna peninsulas (Kirk 1968) formed by north-directed subduction of the Celebes Sea (Chiang 2002). Plio-Pleistocene volcanism can be traced offshore into the Sulu arc but is basaltic and has an ocean island character (Macpherson et al. 2010) suggesting an important tectonic change in the Late Miocene.

During the Middle and Late Miocene in east Sabah, a large river system, flowing northeast, in a similar position to the present Kinabatangan River, deposited sediment in a delta and coastal plain complex extending across most of the area as far as Sandakan. Subsidence broadly kept pace with sediment supply and several kilometres of sediment accumulated. Northwest of the Crocker Ranges there was also deposition of thick sediments in deltas and coastal plains of north Sabah and Brunei by rivers flowing to the north or northwest. The Crocker Ranges were narrow at 15 Ma and the shelf edge moved northwards since then.

At the northern end of the Crocker Ranges is Mount Kinabalu, which is a granite pluton that crystallised several kilometres beneath the surface at about 7–8 Ma (Cottam et al. 2010), and is now exposed at the summit 4 km above sea level. Kinabalu has since been exhumed at an average rate of about 0.5 km/Myr. As Kinabalu and the Crocker Ranges grew, most of east Sabah emerged above sea
level, and the former large sedimentary basin to the east was reduced in area by erosion leaving only circular remnants. In northern Sabah and Brunei, the shelf edge continued to move north. Although much of Sabah is topographically relatively low, it has risen from below sea level, the area of emergent land has increased and several kilometres of cover rocks have been removed by erosion. Kinabalu is one of the few mountains between New Guinea and the Himalayas that was capped by ice during the Pleistocene. It is likely that the summit was ice-covered and ice-free several times in the last 2 Myr. Carbon dating of wood in glacial tills shows that ice was present at about 1500 m at 35 ka, whereas dating of plant material in cores from small lakes shows the summit was free of ice by about 9.2 ka.

3.8.4 Dangerous Grounds

Northwest of Sabah between the coast and the Dangerous Grounds is the linear northeast-southwest-trending Northwest Borneo Trough with water depths of up to 3 km. It has been interpreted as an extinct subduction trench, an active trench and the site of thrusting but not subduction. The Dangerous Grounds are a rifted microcontinental fragment from the South China margin capped by locally emergent carbonate reefs, shoals and atolls that give the area its name. Between the Sabah coast and the trough is a thick Neogene sediment wedge in an offshore northward-directed fold and thrust belt.

Offshore hydrocarbon exploration studies have shown that there have been repeated gravitational failures near the shelf edge that are effectively huge submarine landslides. Steep fault scarps can be mapped, and there are large debris fields on the deep sea floor north of Brunei and Sabah that cover hundreds of square kilometres and include blocks up to 1 km across and 150 m high. Debris flows of similar size and character can be recognised in the subsurface, showing that these failures have been repeated numerous times during the last few millions of years. Furthermore, the sequences of debris flows and interbedded deep-water sediments, probably mainly turbidites, are folded and thrust northwards away from Sabah. New exploration work in the Sulu Sea indicates similar structures suggesting transport of material away from land to the northeast.

Seismic lines (Hutchison 2010) show elevated features within the Northwest Borneo Trough, now at water depths close to 3 km, capped by carbonates and pinnacle reefs that must have formed at sea level, 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. Recent studies show thin crust beneath the offshore Neogene sediment wedge (Franke et al. 2008), implying thinning of crust previously thickened during the Early Miocene North Borneo collision.

I suggest all these observations indicate a link between young and rapid uplift on land, evidenced by exhumation of the 7–8 Ma Kinabalu granite now exposed
at 4 km above sea level, and young and rapid subsidence offshore. Their importance from a biogeographic perspective is the demonstration of significant vertical movements within a few million years, and within the largely seismically and volcanically inactive interior of Sundaland. We do not yet understand their causes. This does not justify a return to mythical land bridges, which were discredited by the plate tectonic revolution (Tarling 1982), but it should alert geologists and biologists to the possibilities of faster palaeogeographical changes than previously expected, possibly driven by subduction rollback or deep crustal movements. Evidence from the biota, particularly freshwater organisms, and molecular techniques, could contribute in some areas to a better mapping of the past distribution of land where the geological record is silent for reasons explained in Hall (2001).

3.8.5 Sumatra and Java

From the Middle Miocene, Sumatra gradually and steadily became the large island of today as the Barisan Mountains rose and widened. A number of factors have contributed and Barber et al. (2005) attribute most of the changes in palaeogeography to regional processes. Sumatra is underlain by continental crust and the processes that led to basin formation never caused substantial and widespread subsidence below sea level. Global sea level has fallen since the Early Miocene. Volcanic activity and strike-slip faulting have contributed to the elevation of the Barisan Mountains. Inversion and uplift may also be due to region-wide Sundaland deformation following Australian collision in east Indonesia. Features on the subducting Indian Plate may have contributed to elevation of Sumatra and its forearc. Thick sediments to the west of the Investigator Fracture which were part of the huge Bengal–Nicobar fan have been subducted beneath northern Sumatra, and the Investigator Ridge itself is likely to have played a role, as suggested by the coincidence in the inferred position of the subducted ridge and the Toba volcanic centre. There are several elevated linear features broadly parallel to the Investigator Ridge on the downgoing plate, and it is plausible that they too are implicated in the elevation of the forearc islands, certainly from Simeulue to the Mentawai Islands. From Nias and Siberut the forearc south of the Sumatran coast is extremely shallow and there is almost no deep basin between the forearc high and the coast, as there is to the northwest and southeast. Several of the large islands, such as Nias and Siberut, were probably connected at times to the Sumatran mainland although this is less likely for the islands further southeast, and improbable for the small island of Enggano at the south end of the forearc high.

In contrast to Sumatra, Java became the large island of today more abruptly and more recently. The Paleogene Southern Mountains volcanic arc ceased activity at about 20 Ma, possibly with a Toba-scale explosive eruption not far from present-day Merapi. Northern Java and the Java Sea was a shallow shelf that was
close to sea level and intermittently emergent, whereas further south there was widespread carbonate deposition on the eroded Paleogene arc. Volcanic activity resumed in the Late Miocene at about 10 Ma in a chain of volcanic islands. The position of the volcanic arc moved abruptly northwards at about 7 Ma, and this movement was associated with a widespread episode of thrusting throughout Java, with the most displacement in the west leading to the emergence of most of West Java. The deformation and shift in the arc position is interpreted as a result of the arrival of a buoyant basaltic plateau, similar to the Roo Rise, at the subduction trench, which caused volcanic activity to cease for an interval. Unusual K-rich volcanoes erupted near the edge of the Sunda Shelf during this interval and normal arc volcanism resumed only in the last 1–2 Myr and broadly coincides with the emergence of East Java, which has made Java the elongate large island of today. This picture of the late Neogene emergence of the large island of Java is consistent with palaeogeographic inferences from mammals (van den Bergh et al. 2001).

3.9 Pleistocene change

There were major changes in sea level during the Pleistocene but it was primarily the shelf areas of Sunda and Australia that changed. Simply using a modern bathymetric map and changing sea level is a good guide to what happened (Voris 2000). The present islands around the Sunda Shelf were connected at times and the entire shelf was emergent. The same was true for the Sahul Shelf. However, at the edge of Sundaland the Makassar Straits remained an important topographic barrier although it was narrower, which, because it is the main passageway for Pacific waters, could have made it more difficult for biota to cross because currents could have been much faster.

Glacially driven sea-level change would have had little effect on Wallacea where shelves surrounding islands are narrow, and shelf edges very steep. Modelling the consequences of sea-level change using modern bathymetry is problematical because tectonic change has been substantial on geologically short time scales. In Wallacea, and possibly in north Borneo, average rates of vertical movements of the order of 1.5 km/Myr have been recorded in areas such as Timor (Audley-Charles 1986), Sumba (Fortuin et al. 1997), Savu and Roti (Roosmawati and Harris 2009), with locally higher rates for some intervals. Such movements indicate the possibility of substantial palaeogeographical change on the scale of 1 Myr. The geography of Wallacea has changed very substantially in the last 5 Myr, and the overall trend has been a significant increase in areas of land, and an increase in elevation (3 km above sea level is not unusual). However, recent work in and around Sulawesi suggests surprisingly rapid subsidence of inter-arm bays such as Gorontalo Bay. It
still seems unlikely that there were continuous connections between most east Indonesian islands, and most of the islands of the Banda Arc have emerged in the last few million years, but it is probable that there were substantial areas of land between the Bird’s Head and Sulawesi since the first collision in the Early Miocene. The palaeogeographical maps (Figs 3.8 to 3.12) may underestimate the extent of land.

3.10 Conclusions

Southeast Asia is an unusual region. Plate tectonics provide a first order description of the region’s history, and a microplate model does help explain how the region has grown by the addition of large and small fragments that include rifted continental crust and island arcs. However, Sundaland has a complex internal structure, with strong areas of old continental fragments and oceanic crust within a much weaker crust. It is not a craton or shield. The term Sunda Shield has been inherited from the period before the plate tectonic revolution and is less commonly used today, but the term craton continues to be misused by geologists. Except for an extensive flat area of the Sunda Shelf, Sundaland has nothing in common with the cratons and shields of South and North America, the Baltic, Africa, India and Australia, which are ancient and strong parts of the continents.

Sundaland was not a rigid plate and Wallacea is part of the complex plate boundary zone between this overall weak continental region and the strong surrounding plates of the Pacific, Philippine Sea, Australia and India. The shape of the Australian margin, in particular the Banda embayment, has been an important influence on the development of the region and subduction rollback into the embayment led to formation of young ocean basins at the heart of the collision zone. The heterogeneous character of the Sundaland continent has influenced the way in which different parts of the region have responded to plate tectonic forces. In the weaker areas, the upper crust appears to be deforming almost independently of the deeper lithosphere, and in eastern Indonesia there have been exceptionally high rates of vertical movements, both up and down.

We need to look at the region in new ways to understand its palaeogeography and the consequences for biogeography. The microplate or terrane approach, when applied to smaller and smaller areas, is less and less useful and biologists need to exercise caution in applying such models to explain their patterns. The concept of slicing fragments from New Guinea followed by multiple collisions is increasingly implausible, and new models (Spakman and Hall 2010) interpret the microcontinental fragments to be the result of a larger coherent continental spur that has been fragmented by extension driven by subduction rollback. Different parts of Borneo and East Indonesia have risen and subsided since the Early
Miocene following Australia's initial contact with Southeast Asia. Very substantial change in relief began at about 8 Ma in northern Borneo, and at about 5 Ma in West, North and East Sulawesi. In Timor, the Halmahera Islands, and probably in Seram, significant relief changes are even younger. Subduction rollback has caused some of this rapid subsidence and uplift, but some of the causes of vertical movements appear to be related to movements within the crust not easily linked to specific tectonic mechanisms, and rates of changes are greater than would be expected from conventional geological models. An important conclusion is that the palaeogeography has changed more quickly in and around Wallacea, particularly in the last 15 Myr, than would be expected from geological models developed in other tectonic settings elsewhere in the world. Biogeographically, although terranes may not have behaved as arks, dispersal may have been possible by other means. Rapid vertical movements may mean there was more land than previously expected and perhaps more short-lived stepping stones for terrestrial dispersal and biogeographical convergence. Conversely, for other organisms, or at other times, such rapid changes could have disrupted populations, habitats and biogeographical continuity, resulting perhaps in local extinctions and biogeographical divergence by vicariance. In their discussion of different biogeographical models of Southeast Asia, Bellwood et al. (this volume, Chapter 9) consider that one possible cause of the region's high biodiversity was an ongoing combination of such frequent convergences and divergences in different organisms at different times (their ‘dynamic mosaic’).

The collision of Australia with the Southeast Asia margin has closed an important major marine passage but water still passes through from the Pacific to the Indian Ocean through a complex gateway that reflects the geological history of Wallacea. The Indonesian Throughflow is now a major topic of research because of its importance in the global oceanographic system and its likely contribution to global climate. The present distribution of plants and animals in the region is the result of many factors. Geology is at the base of pyramid, something Wallace recognised many years ago, and can explain some of the most obvious biogeographic patterns, but to understand the diversity and complexity of Wallacea we need to unravel the interplay and feedbacks between tectonics, palaeogeography, ocean and atmospheric circulation, and the record of life – something that has only just begun (e.g. Renema et al. 2008, Bellwood et al. this volume, Chapter 9).

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