

# Cenozoic reconstructions of SE Asia and the SW Pacific: changing patterns of land and sea

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**ABSTRACT:** The Cenozoic has seen the major tectonic events which have determined the present configuration of land and sea in SE Asia and the SW Pacific. Subduction throughout this period maintained volcanic arcs which formed discontinuously emergent island chains crossing the region. Early in the Cenozoic the major collision of India with SE Asia enlarged the area of land connected to Eurasia. Later, the continuing collision with Australia led to connections between Australia, Eurasia, and the Pacific. Despite long-term convergence of the major plates there have been important episodes of extension, forming ocean basins and causing subsidence within continental regions, which were probably driven by subduction. It is clear that very rapid changes in topography and distribution of land and sea have occurred. The geological and biogeographic interface of perhaps most interest is that between Sundaland and Australia, extending from Borneo to the Bird's Head of New Guinea. The biogeographic divides of Wallace and later workers have all been drawn through this region. Since the early Miocene the original deep water barrier between Australia and Sundaland has been eliminated but the process of convergence has never produced a simple route for the mixing of Australian and Asian floras and faunas. It is clear from the plate tectonic model summarised here that there have been multiple opportunities for dispersal and vicariance caused by regional tectonic processes. There are also more subtle geologically-related forces which may have modified biogeographic patterns, such as links between tectonics and sea level, the rise of mountains and global/local climate, and closure of seaways and oceanic circulation, which are suggested by the tectonic model. All these changes occurred within a framework of overall long-term cooling. Further, more extreme, changes in climate and sea level occurred during the Quaternary glacial and interglacial periods. A simple picture of convergence in which Australia and Sundaland collided, causing land to emerge, allowing colonisation by animals and plants from east and west is therefore probably too simple. Since the early Miocene Australia and Sundaland have moved closer together but as land emerged and mountains rose in some areas, new deep basins developed. The distribution of Australian and Asian plants and animals should therefore reflect this complexity, with further important modifications imposed by glacially-related sea level and climatic change in the Quaternary. In this picture, the zone of Wallace's Line is partly an ancient deep water barrier, partly a dynamic boundary marking a migration front, but also a relic of Neogene patterns which have been tectonically disrupted and modified by Quaternary climate change.

## 1 INTRODUCTION

Today, the waters of SE Asia contain the highest marine faunal diversity in the world, and the islands of the region contain some of the most diverse collections of plant and animal species found on Earth. The division between Asian and Australian floras and faunas in Indonesia, first recognised by Wallace in the nineteenth century, is now recognised as a biogeographic region of transition, named Wallacea (Figure 1), situated between areas with Asiatic and Australian floras and faunas,

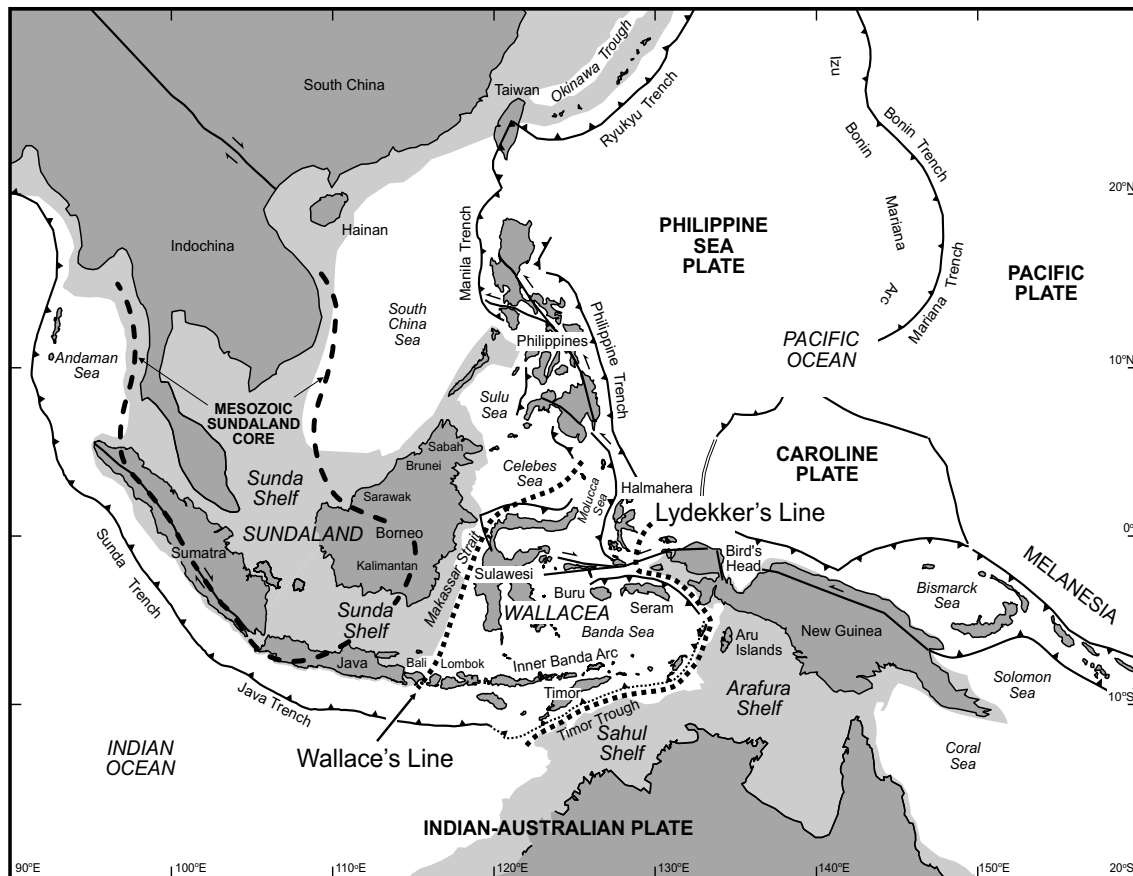


Figure 1. The region of Wallacea. The light shaded areas represent the shallow continental shelves of Sundaland and northern Australia, drawn at the 200 m isobaths. The western boundary of Wallacea is Wallace's Line of 1863. The eastern boundary is Lydekker's Line which is the western limit of strictly Australian faunas.

with elements of both but where organisms show a high degree of endemism. This region extends from east of the Makassar Strait to west of the Bird's Head of New Guinea. It is worth noting that the boundaries of Wallacea are essentially the present edges of the shallow marine shelves of Sundaland and Australia.

Implicit in the concept of Wallacea is the idea that there were originally two principal biogeographic regions, those of Australasia and Asia, which were physically separated and which subsequently became connected. The region has changed as a result of the rapid plate movements during the Cenozoic and geological changes have driven changes in the distribution of land and sea. Wallace (1869) understood that geological processes were important in the development of present biogeographic patterns. However, the geological changes have not been unidirectional, and they have also influenced other factors which are likely to have influenced biogeographic patterns, such as ocean currents and local climatic patterns. In addition, the animals and plants themselves have changed as a result of evolutionary processes. Thus, a geological understanding of the region is likely to be of value to understanding its biogeography, but should be seen more as the essential background to a complex geological, physiographic, climatic and biotic evolution rather than as the explanation of the patterns observed at the present day.

## 2 GONDWANA TO WALLACEA

The SE Asian region owes its origin to the pre-Cenozoic break-up of Gondwana, the subsequent movement of Gondwana fragments northwards, and their eventual collision with Asia (e.g. Metcalfe 1998). Many fragments separated from Gondwana and amalgamated in SE Asia over a considerable period of time. The process of rifting led to formation of new oceans, and the northward motion of

Gondwana fragments required subduction of older oceanic crust at the edges of the growing Asian continent. By the late Mesozoic, fragments derived from Gondwana formed a composite Sundaland core surrounded by subduction zones. Further south and east, the northern Australian margin was a passive continental margin for most of the Mesozoic and it was from this region that many of the Gondwana fragments now found in SE Asia were derived. Between these two regions were wide oceans.

India and Australia separated from Gondwana in the Cretaceous and moved northwards as parts of different plates. India initially collided with the Asian continent about 50 million years ago, but continued to move north accompanied by complex internal deformation within Indochina and mainland SE Asia which continues to the present day. This enlarged the area of land connected to Eurasia. Throughout the entire region subduction processes maintained volcanic arcs which formed discontinuously emergent island chains. During the last 25 million years the collision of Australia with the Sundaland margin led to connections between Australia, Eurasia, and the Pacific. However, despite long-term convergence of the major plates there have been important episodes of extension, forming ocean basins and causing subsidence within continental regions, which were probably driven by subduction. In eastern Indonesia the northward movement of Australia during the Cenozoic has been marked by arc-continent collision, major strike-slip motion within the north Australian margin in northern New Guinea, and accretion of continental fragments derived from Australia. Fragments of arcs have been dispersed in New Guinea, east Indonesia and the Philippines by the movement of the Pacific plate. It is clear that very rapid changes in topography and distribution of land and sea have occurred.

### 3 SOME GEOLOGICAL FUNDAMENTALS

It is now agreed by Earth scientists that the exterior of the earth is formed of lithospheric plates which are more than 100 km thick. The continents are moving on these plates and the size of the globe has not changed in the past 100s of millions of years. The plate tectonic model (e.g. Kearey & Vine 1990) is so strongly supported by a huge range of geological evidence that it really cannot be examined as just another hypothesis. This is in contrast to some ideas that have been current at different times such as earth expansion which really do not pass the tests based on observational data. Explanations that have been put forward in the past for distributions of land masses and links between land masses which rely on such hypotheses as earth expansion or land bridges across the world's major oceans are not realistic.

The plates on the globe have moved in the past and it is possible to tell how they have moved because they have left behind them a pattern of lineations on the ocean floor. The polarity of the earth's magnetic field has changed irregularly through time and as igneous rocks have formed at the plate boundaries at mid-ocean ridges and frozen from melts they have left a trail on the ocean floor of the movement of the major plates in the form of magnetic lineations of alternating reversed and normal polarities. This is important for a number of reasons. It means that the movements of the major plates on the globe can be reconstructed for up to about 150 million years. The oldest crust in the oceans is in the western Pacific and is about 160 Ma old and for areas where there are magnetic lineations, and hence the age of the ocean is known, the history of plate motions can be reconstructed very precisely. In principle, mapping the ocean floors in detail provides the means to work out the motion paths of the plates which can be described in terms of simple mathematical parameters. It is possible to calculate rotation poles and rates of motion and thus build a global model of the history of plate motions.

Ocean crust is also important because it has a history that we know and understand very well. The crust is formed at mid-ocean ridges by the rise of hot magma which is extruded at the surface or frozen at depth. The sea bed is initially at depths of about 2.5 km below sea level and as the crust gets older it follows a very simple pattern of increasing depth with age. It is possible to map the age of the ocean crust around the major oceans very accurately using this simple age-depth relationship which is a function merely of the cooling of the outer earth, the lithosphere, which becomes denser and sinks. Similarly, the rifted passive margins formed during the breakup of continents also have a very predictable history of subsidence which reflects subsidence caused by the rifting followed by a long-term thermal subsidence due to cooling. Thus, for both oceanic regions and passive continental

margins, it is possible to infer with some confidence the depth of sea at a particular age based on the plate tectonic model.

During closure of oceans the oceanic lithosphere is subducted at active margins and is once again predictably associated with given water depths, typically between 7 and 9 km at the deep trenches. The ocean lithosphere sinks deep into the mantle and at distances of about 100 km from trenches water from the subducting slab causes the mantle to melt, forming magmas which rise to the surface and produce island arc volcanoes. The arc volcanoes formed in such intra-oceanic island arc settings or active continental margin settings are not constantly active but over reasonably long periods of time it is likely that they will emerge above sea level. The older the arc, the thicker the crust, and the higher the probability of emergence. Volcanic arcs are ephemeral features, geologically at any rate. Young intra-oceanic arcs, such as those of the Izu-Bonin-Mariana arc, or Melanesian arcs, may never become emergent or be only locally and intermittently emergent at sites of active volcanicity. Such areas of land will disappear quite quickly after the volcanoes cease activity. In contrast, older arcs, and commonly those underlain by older continental or arc crust such as the Japanese islands or the islands of the Sunda arc, may be almost permanently emergent.

As this process proceeds it is possible to build volcanic magmatic mountain belts which are more substantial than those island arcs within oceans. These mountain belts may also grow from time to time by the accretion of objects carried along on oceanic plates, such as a large volcanic islands or microcontinental fragments, often called terranes. The Ontong Java plateau is one such example, and there are numerous other elevated regions of thickened crust throughout the Western Pacific which represent the products of mantle plumes, hotspots, or old arc remnants, and which when accreted will be described geologically as terranes. The idea of terranes is a popular one, and sometimes these are interpreted as the potential carriers of land plants and animals ('arks'), but in many cases these terranes, although very large, have spent their entire history beneath the waves. During the final stages in the plate tectonic or Wilson cycle, arcs and continents, and ultimately continents and continents, collide with one another and the consequence of this stage in the process is huge areas of uplifted land, as seen today north of India in the Himalayas and the Tibetan Plateau, where a very extensive area has been uplifted as a consequence of Asia and India collision.

#### 4 SOME TECTONIC QUALIFICATIONS

Plate tectonics is very good at explaining what happens in the oceans; oceans seem to behave in a relatively rigid and predictable way in which all the deformation is concentrated at the edges of the plates. But continental regions are very different and the deformation is distributed in very odd ways. In the case of India-Asia collision some of the deformation has been taken up along large strike-slip faults within Asia. There is still a great deal of argument about exactly when the Himalayas and the mountain ranges to the north of India rose, exactly how the deformation was distributed, for example, how much of it was in uplift of the continental region and how much of it was taken up in rocks moving aside by strike-slip faulting (e.g. Peltzer & Tapponnier 1988; Houseman & England 1993). It is now accepted that there has been progressive indentation of India into Asia and that as a consequence the Asian continent has been deformed. We do not understand in detail exactly how this has happened. It is also very difficult to incorporate in a purely rigid plate tectonic model. This should be borne in mind in considering the regional reconstructions. The models describe quite well how plates move when they are oceanic but they do not yet describe well what is happening in the continental regions.

The complexity of the present-day tectonics of SE Asia and the SW Pacific means that three major (Pacific, Australia and Eurasia) and numerous smaller plates need to be considered to understand the development of the region. Present plate motions, based for example on GPS measurements and seismicity, appear to have only slight relevance to understanding the long-term kinematic development of the region, and in many areas it is possible to demonstrate significant and young changes in local plate motions. However, the rates of plate motions indicate that vast areas of oceanic crust have been lost, that many major and minor oceans have opened and closed, and the configuration of the region has changed significantly during the Cenozoic. Because so much oceanic lithosphere has been subducted, and because many of the small marginal basins lack well-developed magnetic lineations, there are many difficulties in reconstructing the region. Continental

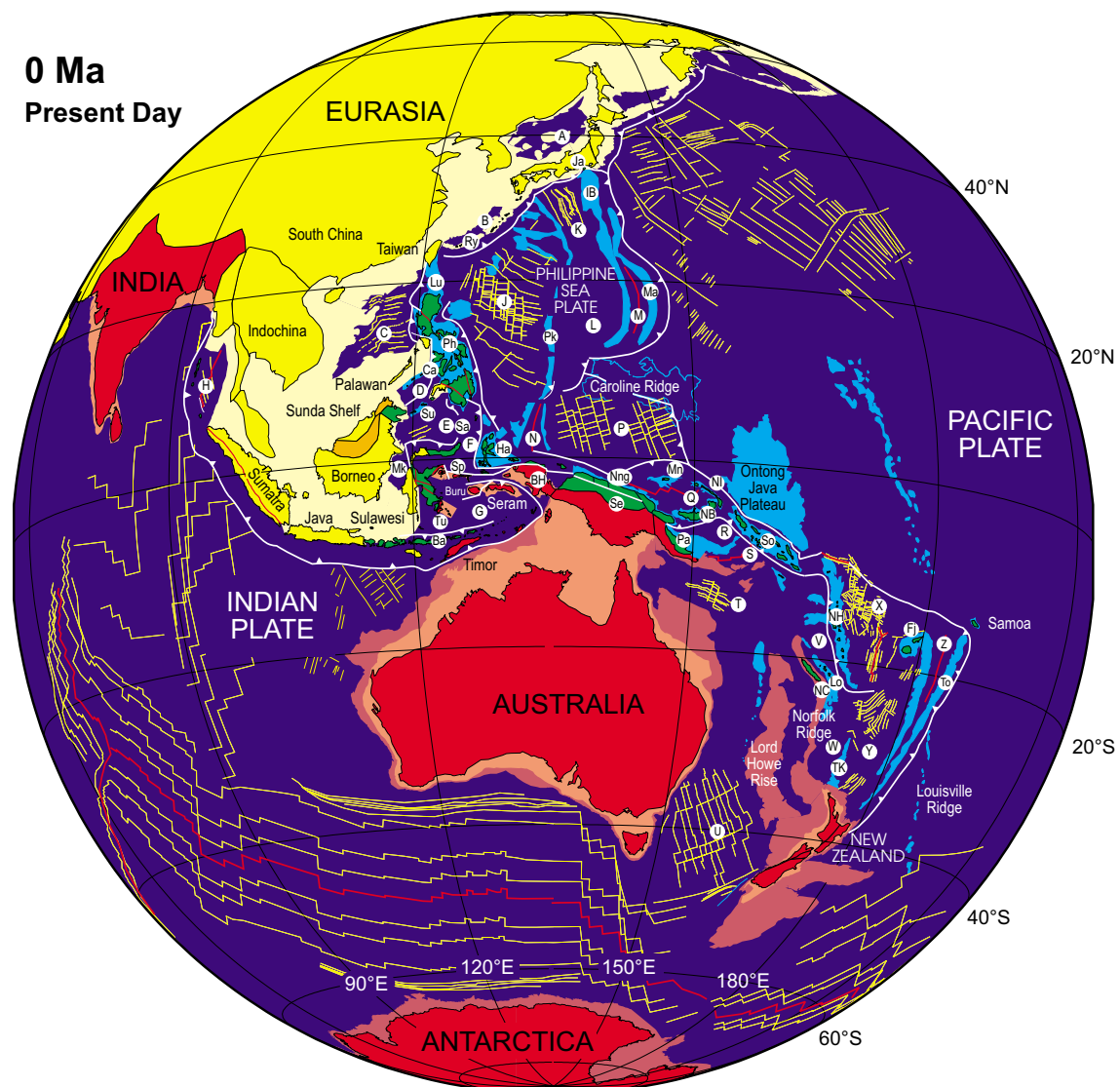
and arc crust has deformed in a non-rigid manner, and there is evidence of significant vertical axis rotations. Furthermore, there are numerous different time-scales, events which may or may not have been synchronous are often vaguely correlated, and the isotopic dating record for the whole region is inadequate. Finally, geological observations in the region where collisions are in progress at the present day show us that important tectonic features can disappear within short periods leaving almost no trace. One example will suffice from an area that I know in particular detail, the Halmahera and the Sangihe Arcs, where the present day Molucca Sea is disappearing by subduction in two directions (Hall et al. 1995a; Hall 2000). The consequence of this collision, which is occurring at the present day, is that the Halmahera arc is being eliminated and without doubt in 2 or 3 million years time only one arc will be preserved. Thus, a plate tectonic model must be regarded as an incomplete approximation which, like any other model, depends on an interpretation of a wide range of geological information from land, and from the basins on and off-shore.

## 5 THE GEOLOGICAL RECORD

Moving from tectonic reconstruction maps to detailed palaeogeographical maps involves further complexities. It is important to recognise when mapping land and sea distributions that the geological record that we deal with is essentially a marine record. Most of Earth history is recorded in rocks deposited below sea-level. Dating of rocks is largely based on fossils, and marine organisms generally provide the fossils of greatest biostratigraphic value which usually also provide some insight into the environment of deposition. Therefore in former marine areas there generally are sedimentary deposits, they have fossils in them, they can be dated and we can often infer a great deal about where those rocks were at different times. Geologists are therefore usually able to reconstruct the history of marine areas quite well.

On the other hand, the geological record as far as land is concerned presents very considerable problems. Uplift, erosion and periods of emergence are mainly recorded by negative evidence, such as unconformities and stratigraphic incompleteness. Even when there is a rock record it will often be difficult to date because sediments deposited on land typically represent restricted types of environments, and usually contain few fossils which have limited biostratigraphic value. It is also much more difficult to interpret continental environments. As one example, Death Valley in the western United States is below sea level but exactly the same sort of stratigraphic sequences could be formed in a continental setting of similar type if that basin were one or two thousand metres or more above sea level. In many ways the features of the rocks would be similar and of course rocks deposited in those sorts of environments cause major problems in dating. This is a major problem throughout Sundaland where we still lack an adequate understanding of the tectonics of basin formation simply because of our inability to date the sequences in the basins. The continuing debate about the timing of the rise of the Himalayas and the Tibetan plateau reflect geologists' uncertainties in dating, deducing topography on land, and interpreting geological evidence.

Nonetheless, despite the reservations about applicability of plate tectonics and the deficiencies of the geological record, what the plate tectonic cycle means from the point of view of distributions of plants and animals is that even though there may not be a complete geological record or a perfect model it is possible to say with some confidence something about depths of water and distribution of land. Thus, the mapping of land and sea follows from the mapping of tectonic elements, and this follows from the geological model which is based on a wide range of data. Broadly speaking, the maps of areas of land and sea should be regarded as maps of probability; for example, it may not be possible to know for certain if a particular area was land, but the knowledge that shallow marine clastic sediments are found in the area indicates that material was eroded from nearby land even though the land area cannot be delineated with certainty. By such reasoning it is possible to complete the gaps in maps using geological judgements and therefore, for an area shown as deep marine, the probability of that area being shallow marine is low, and of it being land is very low to zero. For the reasons outlined above, in many areas below sea level, such as passive continental margins and ocean basins, the tectonic history of the region defines the inferred depths quite well. However, for areas close to sea level assignments of depths are less certain. For example, areas of long-lived island arcs develop thickened crust, implying relative shallow water areas and local emergence. When volcanoes are active, magma production, thermal expansion and crustal buoyancy

**Marginal Basins**

A Japan Sea	N Ayu Trough
B Okinawa Trough	P Caroline Sea
C South China Sea	Q Bismarck Sea
D Sulu Sea	R Solomon Sea
E Celebes Sea	S Woodlark Basin
F Molucca Sea	T Coral Sea
G Banda Sea	U Tasman Sea
H Andaman Sea	V Loyalty Basin
J West Philippine Basin	W Norfolk Basin
K Shikoku Basin	X North Fiji Basin
L Parece Vela Basin	Y South Fiji Basin
M Mariana Trough	Z Lau Basin

**Tectonic features**

Ba Banda Arc	Mk Makassar Strait	Ry Ryukyu Arc
BH Bird's Head	Mn Manus Island	Sa Sangihe Arc
Ca Cagayan Arc	NB New Britain Arc	Se Sepik Arc
Fj Fiji	NC New Caledonia	So Solomons Arc
Ha Halmahera Arc	NH New Hebrides Arc	Sp Sula Platform
IB Izu-Bonin Arc	NI New Ireland	Su Sulu Arc
Ja Japan Arc	Nng North New Guinea	TK Three Kings
Lo Loyalty Islands	Terranes	Rise
Lu Luzon Arc	Pa Papuan Ophiolite	To Tonga Arc
Ma Mariana Arc	Pk Palau-Kyushu Ridge	Tu Tukang Besi
		Platform

Figure 2. Present-day tectonic features of SE Asia and the SW Pacific. Light straight lines are selected marine magnetic anomalies and active spreading centres. White lines are subduction zones and strike-slip faults. Labelled filled areas are mainly arc, ophiolitic, and accreted material formed at plate margins during the Cenozoic, and submarine arc regions, hot spot volcanic products, and oceanic plateaus. Pale grey areas represent submarine parts of the Eurasian continental margins. Dark grey areas represent submarine parts of the Australian continental margins.

can lead to emergence but individual volcanoes can be very short-lived on a geological time scale (typically less than one million years) even though an arc may have been a long-lived feature. Within volcanic arc sequences there may be indicators of age and regions of submergence and emergence from such features as weathered horizons, palaeosols, and marine sediment intercalations but it is usually not possible to delineate precisely which areas were emergent, simply that there are likely to have been such areas.

## 6 THE PLATE TECTONIC MODEL

The plate tectonic model outlined here is essentially that described by Hall (1996, 1997, 1998) and the reader is referred to those papers for details and references. Previous reconstructions which cover all or parts of the region discussed here include those of Crook & Belbin (1978), Hamilton (1979), Briais et al. (1993), Burrett et al. (1991), Daly et al. (1991), Lee & Lawver (1995), Rangin et al. (1990), and Yan and Kroenke (1993). Animations and maps relevant to the tectonics and distribution of land and sea in the region are available via the World Wide Web from <http://www.gl.rhul.ac.uk/seasia/welcome.html>. Here I summarise only the key features of the regional tectonic model and various aspects which are relevant to the development of the region of Wallacea. The principal features of the region are shown on Figure 2 and a series of global reconstructions in Figures 3, 4 and 5.

### 6.1 55-45 Ma

Before 50 Ma (Figure 3) the continents of India and Australia were on separate plates. India collided with Asia in the early Tertiary but the exact age of collision and its consequences remain controversial (e.g. Rowley 1996). Many of the tectonic events in SE Asia are commonly attributed to the effects of Indian indentation into Asia and the subsequent extrusion of continental fragments eastwards along major strike-slip faults. However, this hypothesis (Tapponnier et al. 1982, 1990) and its predictions of major clockwise rotations, southeastward extrusion of fragments, and timing of events remain poorly supported by geological evidence in SE Asia.

Taiwan, Palawan and the extended South China Sea margins formed a passive margin, established during the late Cretaceous. Sundaland was separated from Eurasia by a wide proto-South China Sea probably floored by Mesozoic oceanic crust. The Malay peninsula was closer to Indochina and the Malay-Sumatra margin was closer to NNW-SSE. East Borneo and West Sulawesi were part of Sundaland underlain by accreted arc and ophiolitic material as well as small Gondwana fragments which were accreted during the Cretaceous. Java and West Sulawesi were situated above a subduction zone where Indian plate lithosphere was subducting towards the north. The Java subduction system linked east into Pacific intra-oceanic subduction zones which included parts of the east Philippines and Halmahera. There was a north-dipping subduction zone at the southern edge of a Northern New Guinea plate. This area is difficult to reconstruct because so much of the West Pacific has been eliminated by subduction since 50 Ma but there is good evidence that this area resembled the present-day West Pacific in containing marginal basins, intra-oceanic arcs and subduction zones.

Australia was essentially surrounded by passive margins on all sides. To the west the passive margin was formed in the Late Jurassic and there was oceanic crust separating a Bird's Head microcontinent from Australia. Further east, Indian and Australian oceanic lithosphere had been subducting northwards beneath the Sepik-Papuan arc in the early Tertiary. During the Paleocene and early Eocene the New Guinea passive margin collided with this intra-oceanic arc causing emplacement of the Sepik and Papuan ophiolites (Davies 1971). After this event the New Guinea margin remained a passive margin for most of the Paleogene. The Tasman and Coral Seas were both fully open by the beginning of the Tertiary, and the Loyalty Rise and New Caledonia Rise were extended parts of the east Australasian margin.

After India-Asia collision, India moved more slowly northwards and India and Australia became part of a single plate. Northward subduction of Indian-Australian oceanic lithosphere continued beneath the Sunda-Java-Sulawesi arcs. Rift basins formed throughout Sundaland, but the timing of their initial extension is uncertain because they contain continental clastics which are poorly dated, and their cause is therefore also uncertain.

**55 Ma**  
Early  
Eocene

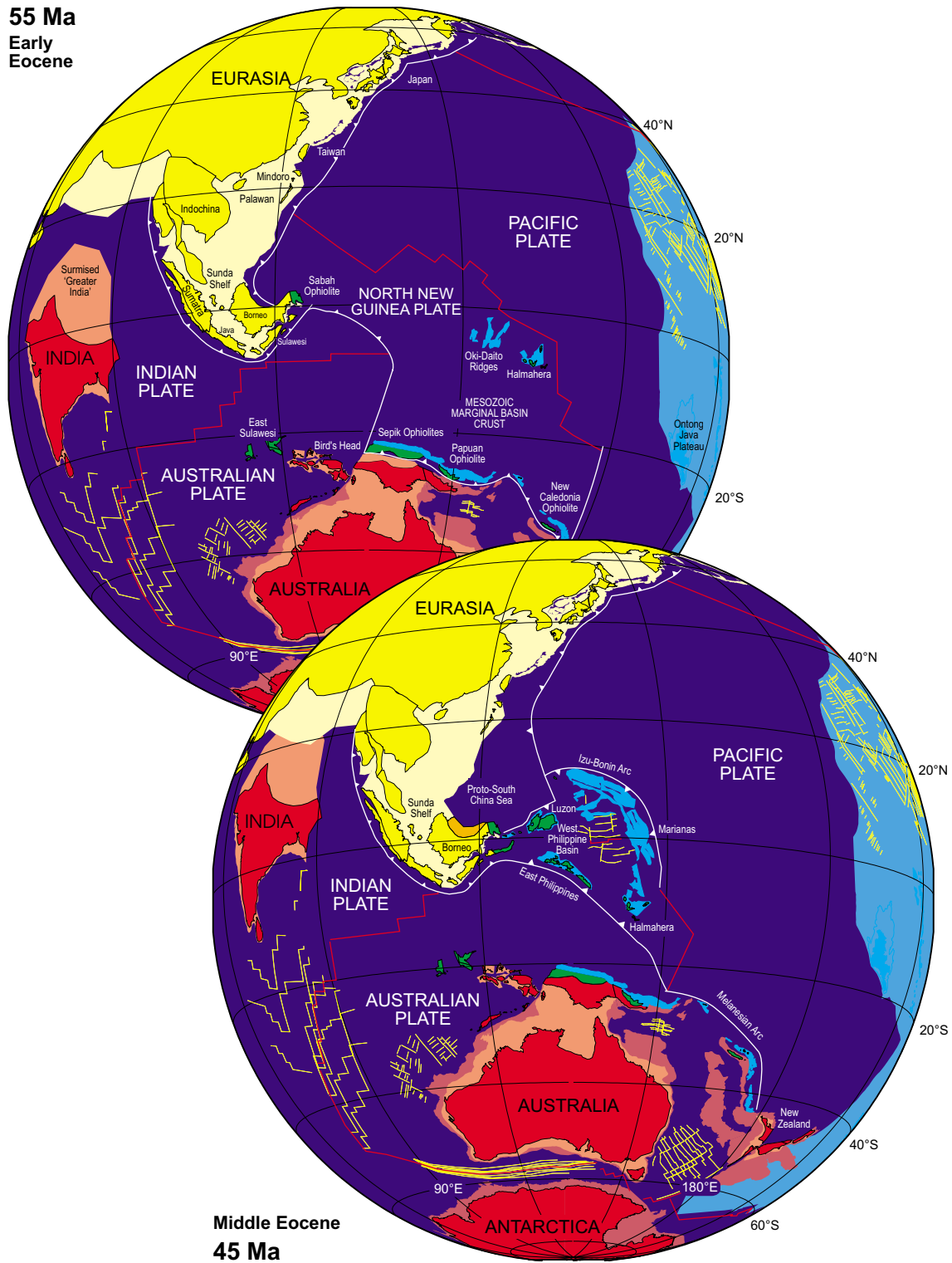


Figure 3. Reconstructions of the region at 55 and 45 Ma. The possible extent of Greater India and the Eurasian margin north of India are shown schematically. This was beginning of the period of collision between India and Asia, and between the north Australian continental margin and Pacific intra-oceanic island arcs which emplaced ophiolites on the north New Guinea margin, and later in New Caledonia. An oceanic spreading centre through the West Philippine basin, the Celebes Sea and the north Makassar Strait developed the deep water rift which became Wallace's Line.



The Java-Sulawesi subduction system continued into the West Pacific through the east Philippines and Halmahera arcs. During the Eocene the extended eastern Australasian passive margin had collided with an intra-oceanic arc resulting in emplacement of the New Caledonia ophiolite (Aitchison et al. 1995) followed by subduction polarity reversal. This led to the formation of a Melanesian arc system. Soon after 45 Ma south to southwest-directed subduction began beneath the eastern Australian margin, from Papua New Guinea to north of New Zealand, with major arc growth producing the older parts of the New Britain, Solomons and Tonga-Kermadec systems, leading to development of major marginal basins in the SW Pacific whose remnants probably survive only in the Solomon Sea.

Subduction of the Pacific-Northern New Guinea mid-ocean ridge led to massive outpouring of boninitic volcanic rocks (Stern & Bloomer 1992) which formed the Izu-Bonin-Mariana arc system, and the Philippine Sea plate became a recognisable entity. There was significant rotation of the Philippine Sea plate between 50 and 40 Ma and the motion history of this plate (Hall et al. 1995b) provides an important constraint on development of the eastern part of SE Asia. The West Philippine Basin, Celebes Sea, and Makassar Strait opened as single basin within the Philippine Sea plate. The opening of the West Philippine-Celebes Sea basin caused initiation of southward subduction of the proto-South China Sea beneath Luzon and the Sulu arc. It is this subduction which caused renewed extension along the South China margin, driven by slab-pull forces due to subduction between eastern Borneo and Luzon, and later led to sea-floor spreading in the South China Sea, rather than indentor-driven tectonics.

## 6.2 35-25 Ma

From 40-30 Ma (Figure 4) Indian ocean subduction continued at the Sunda-Java trenches, and also beneath the arc extending from Sulawesi through the east Philippines to Halmahera. Sea floor spreading continued in the West Philippine-Celebes Sea basin until about 34 Ma. By 30 Ma the Caroline Sea was widening above a subduction zone at which the newly-formed Solomon Sea was being destroyed as the Melanesian arc system migrated north. To the south of the Caroline Sea the South Caroline arc formed what later became the north New Guinea arc terranes. The backarc basins in the SW Pacific were probably very complex, as indicated by the anomalies in the South Fiji Basin, and will never be completely reconstructed because most of these basins have been subducted.

Within Sundaland deformation was complex and a plate tectonic model can only simplify the tectonics of the region by considering large and simple block movements and broadly predicting regional stress fields. In northern Indochina strike-slip motion was important (Wang and Burchfiel 1997) but deformation was not concentrated at the edge of rigid blocks. The Malay and Gulf of Thailand basins may have a significant component of strike-slip movement on faults controlling their development. However, they may have been initiated in a different tectonic setting, and in a region with an older structural fabric which influenced their development.

The period from 30-20 Ma saw the most important Cenozoic plate boundary reorganisation within SE Asia. At about 25 Ma, the New Guinea passive margin collided with the leading edge of the east Philippines-Halmahera-New Guinea arc system. The Australian margin, in the Bird's Head region, was also close to collision with the Eurasian margin in West Sulawesi and during this interval ophiolite was emplaced in SE Sulawesi. Soon afterwards the Ontong Java plateau collided with the Melanesian arc. These two major collisions caused a significant change in the character of plate boundaries in the region in the early Miocene. They linked the island arcs of Melanesia, the New Guinea terranes at the southern Caroline margin, and the Halmahera-Philippines arcs. This linkage seems to have coupled the Pacific to the marginal basins of the West Pacific, and the Caroline and Philippine Sea plates were subsequently driven by the Pacific.

Advance of the Melanesian arc system led to widening of the South Fiji basin and Solomon Sea basin (now mainly subducted). At the Three Kings Rise subduction seems to have been initiated soon after ocean crust was formed to the east, allowing the rise to advance east and spreading to propagate behind the rise into the Norfolk basin from a triple junction to the north.

The Caroline and Philippine Sea plates began to rotate, almost as a single plate, and the Izu-Bonin-Mariana trench system rolled back into the Pacific. Rifting of the Palau-Kyushu ridge began,

**35 Ma**  
Early  
Oligocene

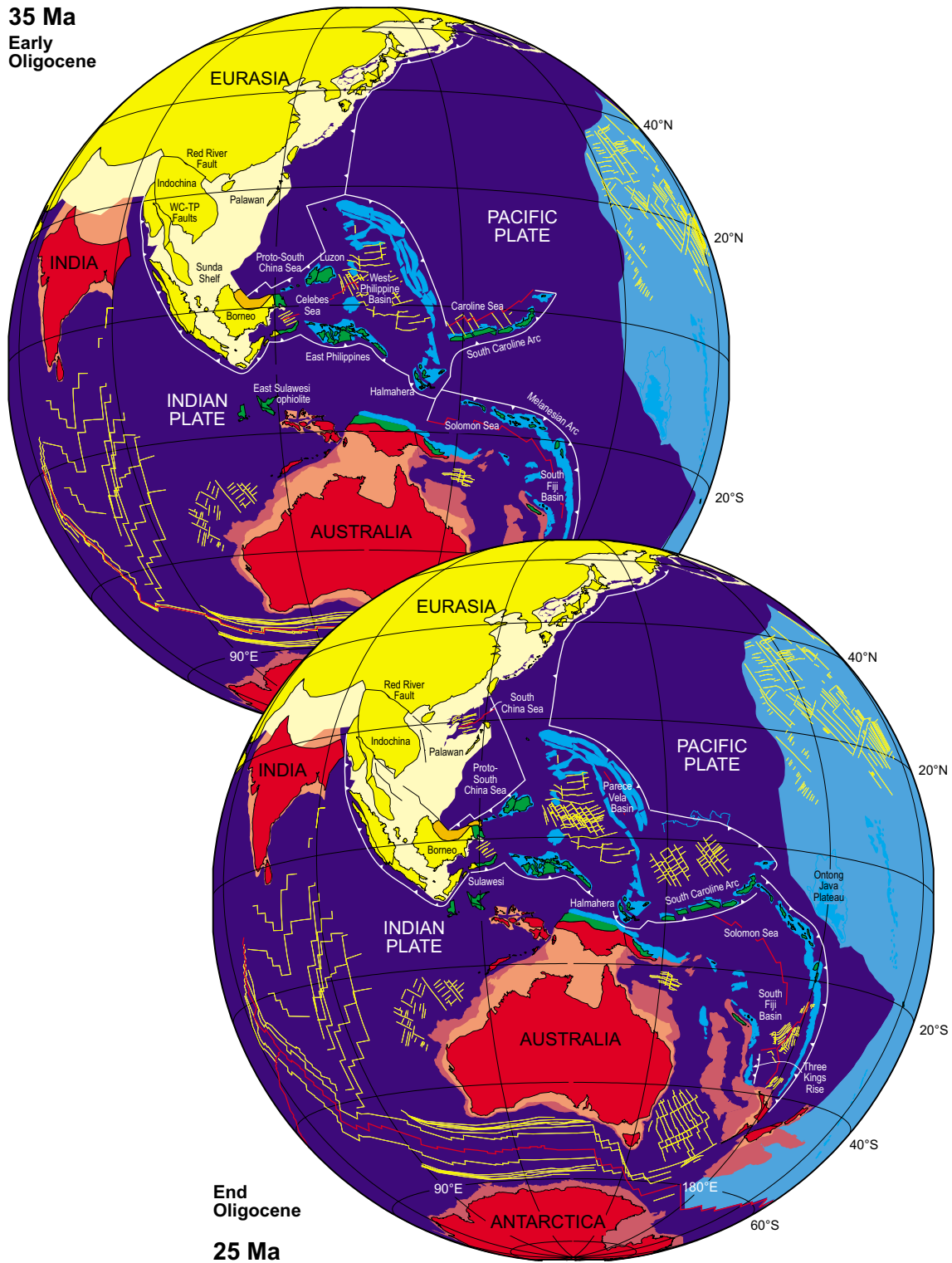


Figure 4. Reconstructions of the region at 35 and 25 Ma. India and Australia were parts of the same plate. Multiple arc systems extended from the Sundaland margin into the west Pacific, including the east Philippines-Halmahera arc, the Izu-Bonin-Mariana arc, and the South Caroline arc. Spreading also began after subduction flip in marginal basins around eastern Australasia producing the Solomon Sea and the island arcs of Melanesia. Slab pull due to southward subduction of the proto-South China Sea caused extension of the South China and Indochina continental margin and the present South China Sea began to open. By 25 Ma the east Philippines-Halmahera-South Caroline arc collided with the Australian margin and the Ontong Java plateau began to collide with the Melanesian arc. These two events caused major reorganisation of plate boundaries.

**15 Ma**  
**Middle**  
**Miocene**

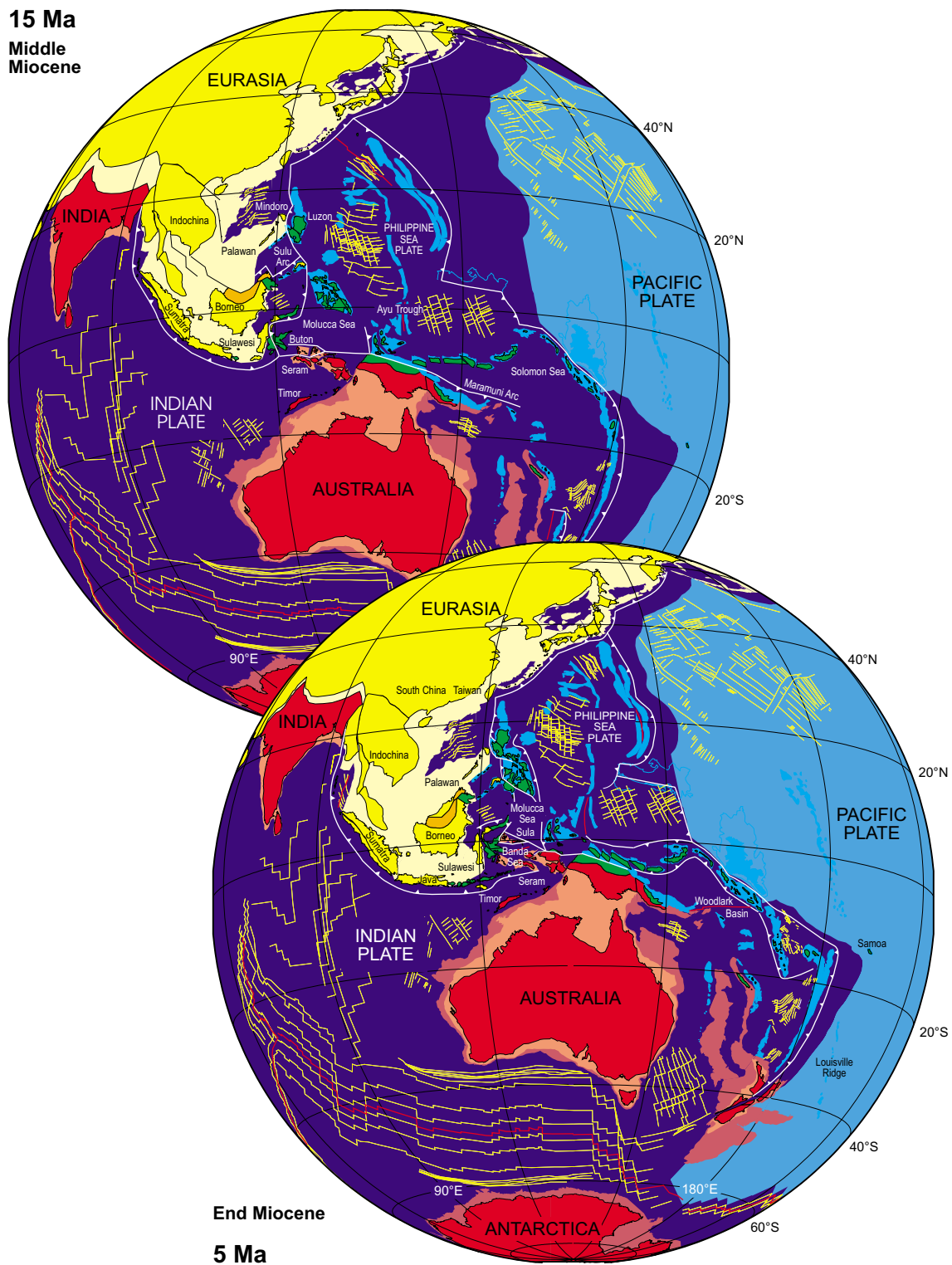


Figure 5. Reconstructions of the region at 15 and 5 Ma. The north Australian margin became a major left-lateral strike-slip system as the Philippine Sea-Caroline plate began to rotate clockwise with the Pacific. Movement on splays of the Sorong fault system led to the collision of Australian continental fragments in Sulawesi. This in turn led to counter-clockwise rotation of Borneo and parts of Sundaland, eliminating the proto-South China Sea. As the old oceanic lithosphere off NW Australia began to subduct extension in the overriding plate led to formation of deep water basins of the Banda Sea. The New Guinea terranes, formed in the South Caroline arc, docked in New Guinea but continued to move in a wide left-lateral strike-slip zone. The Solomon Sea was largely eliminated by subduction beneath eastern new Guinea and the New Hebrides arc but subduction there also led to development of new marginal basins within the last 10 Ma, including the Bismarck Sea, Woodlark basin, North Fiji basins, and Lau basin.

leading first to opening of the Parece Vela basin and later to spreading in the Shikoku basin. The change in plate boundaries led to subduction beneath the Asian margin. The Philippine Sea plate began to rotate clockwise and subduction began beneath north Sulawesi in the Sangihe arc. Subduction beneath the Halmahera-Philippines arc ceased and the New Guinea sector of the Australian margin became a strike-slip zone, the Sorong Fault system, which subsequently moved terranes of the South Caroline arc along the New Guinea margin.

### 6.3 15-5 Ma

After 20 Ma the clockwise rotation of the Philippine Sea plate necessitated changes in plate boundaries throughout SE Asia which resulted in the tectonic pattern recognisable today (Figure 5). These changes include the re-orientation of spreading in the South China Sea, and the development of new subduction zones at the eastern edge of Eurasia and in the SW Pacific. Continued northward motion of Australia caused the counter-clockwise rotation of Borneo. The remaining oceanic crust of the western proto-South China Sea, and thinned continental crust of the passive margin to the north, was thrust beneath Borneo. The rotation of Borneo was accompanied by counter-clockwise motion of west Sulawesi, and smaller counter-clockwise rotations of adjacent Sundaland blocks. In contrast, the north Malay peninsula rotated clockwise, but remained linked to both Indochina and the south Malay peninsula. This allowed widening of basins in the Gulf of Thailand although the simple rigid plate model overestimates extension in this region. This extension was probably more widely distributed throughout Sundaland and Indochina on many different faults. The Burma plate became partly coupled to the northward-moving Indian plate and began to move north on the Sagaing fault leading to stretching of the Sunda continental margin north of Sumatra, and ultimately to ocean crust formation in the Andaman Sea.

East of Borneo, the increased rate of subduction caused arc splitting in the Sulu arc and the Sulu Sea opened as a back-arc basin south of the Cagayan ridge. The Cagayan ridge then moved northwards, eliminating the eastern proto-South China Sea, to collide with the Palawan margin. New subduction had also begun at the west edge of the Philippine Sea plate below the north Sulawesi-Sangihe arc which extended north to south Luzon. The Philippine islands and Halmahera were carried with the Philippine Sea plate towards this subduction zone. North of Luzon, sinistral strike-slip movement linked the subducting west margin of the Philippine Sea plate to subduction at the Ryukyu trench. Collision of Luzon and the Cagayan ridge with the Eurasian continental margin in Mindoro and north Palawan resulted in a jump of subduction to the south side of the Sulu Sea. Southward subduction beneath the Sulu arc continued until 10 Ma. The remainder of the Philippines continued to move with the Philippine Sea plate, possibly with intra-plate strike-slip motion and subduction resulting in local volcanic activity.

As a result of changing plate boundaries fragments of continental crust were emplaced in Sulawesi on splays at the western end of the Sorong Fault system. The first of these to arrive was probably the SE Sulawesi fragment. Later, the Buton-Tukang Besi platform was carried west to collide with Sulawesi. Locking of splays of the Sorong fault caused subduction to initiate at the eastern margin of the Molucca Sea, producing the Neogene Halmahera arc. Thus the Molucca Sea became a separate plate as the double subduction system developed.

After the collision of the Ontong Java plateau with the Melanesian arc the Solomons became attached to the Pacific plate. Westward subduction began on the SW side of Solomon Sea, beneath eastern New Guinea, eliminating most of Solomon Sea and resulting in the formation of Maramuni arc system. As the Solomon Sea was eliminated the South Caroline arc began to converge on the north New Guinea margin and the arc terranes were translated west in the major left-lateral shear zone, probably accompanied by rotation. In the southern part of the Solomons Sea subduction was in the opposite direction (eastward) and created the New Hebrides arc system.

By 10 Ma SE Asia was largely recognisable in its present form. Rotation of Borneo was complete. This, with collision in the central Philippines and Mindoro, and continued northward movement of Australia, resulted in reorganisation of plate boundaries and intra-plate deformation in the Philippines. The Luzon arc came into collision with the Eurasian margin in Taiwan. Subduction continued at the Manila, Sangihe and Halmahera trenches, and new subduction began at the Negros and Philippine trenches. These subduction zones were linked by strike-slip systems active within the Philippines and this intra-plate deformation created many very small fragments which are difficult to describe

using rigid plate tectonics. In west Sundaland, partitioning of convergence in Sumatra into orthogonal subduction and strike-slip motion effectively established one or more Sumatran forearc sliver plates. Extension on the strike-slip system linked to the spreading centre in the Andaman Sea (Curray et al. 1979).

The Molucca Sea continued to close by subduction on both sides. At present the Sangihe forearc has overridden the northern end of the Halmahera arc, and is beginning to over-thrust west Halmahera. In the Sorong fault zone, accretion of Tukang Besi to Sulawesi locked a strand of the fault and initiated a new splay south of the Sula platform. The Sula platform then collided with the east arm of Sulawesi, causing rotation of the east and north arms to their present position, leading to southward subduction of the Celebes Sea at the north Sulawesi trench.

The Eurasia-Philippine Sea plate-Australia triple junction was, and remains, a zone of microplates but within this contractional setting new extension began in the Banda Sea. The Bird's Head moved north relative to Australia along a strike-slip fault at the Aru basin edge. Mesozoic ocean crust north of Timor was eliminated at the eastern end of the Java trench by continued northern motion of Australia which brought the Australian margin into this trench as the volcanic inner Banda arc propagated east. Seram began to move east requiring subduction and strike-slip motion at the edges of this microplate. Since 5 Ma the southern Banda Sea has extended to its present dimensions and continental fragments are now found in the Banda Sea ridges within young volcanic crust.

North of the Bird's Head, and further east in New Guinea, transpressional movements were marked by deformation of arc and ophiolite slivers separated by sedimentary basins. Progressive westward motion of the South Caroline arc within the left-lateral transpressional zone led to docking of the north New Guinea terranes. This caused cessation of southward subduction of the Solomon Sea plate but resulted in its northward subduction beneath New Britain. The New Britain subduction led to rapid spreading in Woodlark basin as a consequence of slab-pull forces and rapid ripping open of continental crust beneath the Papuan peninsula. Elimination of most of the remaining Solomons marginal basin by eastward subduction led to formation of the New Hebrides arc and opening of the North Fiji basins.

## 7 LAND AND SEA IN WALLACEA

The geological and biogeographic interface of interest here is that between Sundaland and Australia, extending from Borneo to the Bird's Head of New Guinea (Figure 6). This area, separating Borneo and New Guinea, and including Sulawesi, the Banda Sea and the Moluccas, encapsulates many of the problems of the region. Figures 7 to 10 compile the general features of land and sea onto maps of the tectonic reconstructions for the region of Wallacea. The maps help to indicate the likely geographical connections and barriers and the periods when these were in existence. The period 30-0 Ma is of most interest to biogeographers since before then the separation between Asia and Australia was greater and for almost all land plants and animals it was probably not possible to cross this barrier. Essentially since 30 Ma (Figure 6) there has been a closure of the marine gap, and collision of the Sula Spur-Bird's Head microcontinental area with the eastern Sundaland margin. However, despite the continued convergence between the principal plates and the movement of fragments of continental crust into Sulawesi, at the same time there has been the opening of new deep ocean basins maintaining a difficult and indirect migration route between Australia and Asia.

In the west, Borneo formed part of Sundaland throughout the Cenozoic. Sundaland was mainly emergent, or intermittently transected by very shallow seas, and would presumably have been biogeographically linked to Asia for the whole of this period. Opening of the South China Sea, Celebes and Sulu Seas from the Eocene onwards had formed deep water barriers to the north and east of Borneo (Figure 6). Thus, from the Eocene, the Makassar Straits was the major barrier to the east because, although west Sulawesi was always close to Borneo it was largely submerged until at least the late Miocene. In the Middle Oligocene, about 30 Ma, there was still a deep oceanic gap between Sundaland and Australia (Figures 6 and 7). There must have been deep trenches along the eastern Sundaland margin extending into the west Pacific. There was certainly a lot of deep water. Virtually the only evidence for any land in the Sula Spur indicates a small emergent area on the island of Buru. In areas of volcanicity there is always the possibility there might have

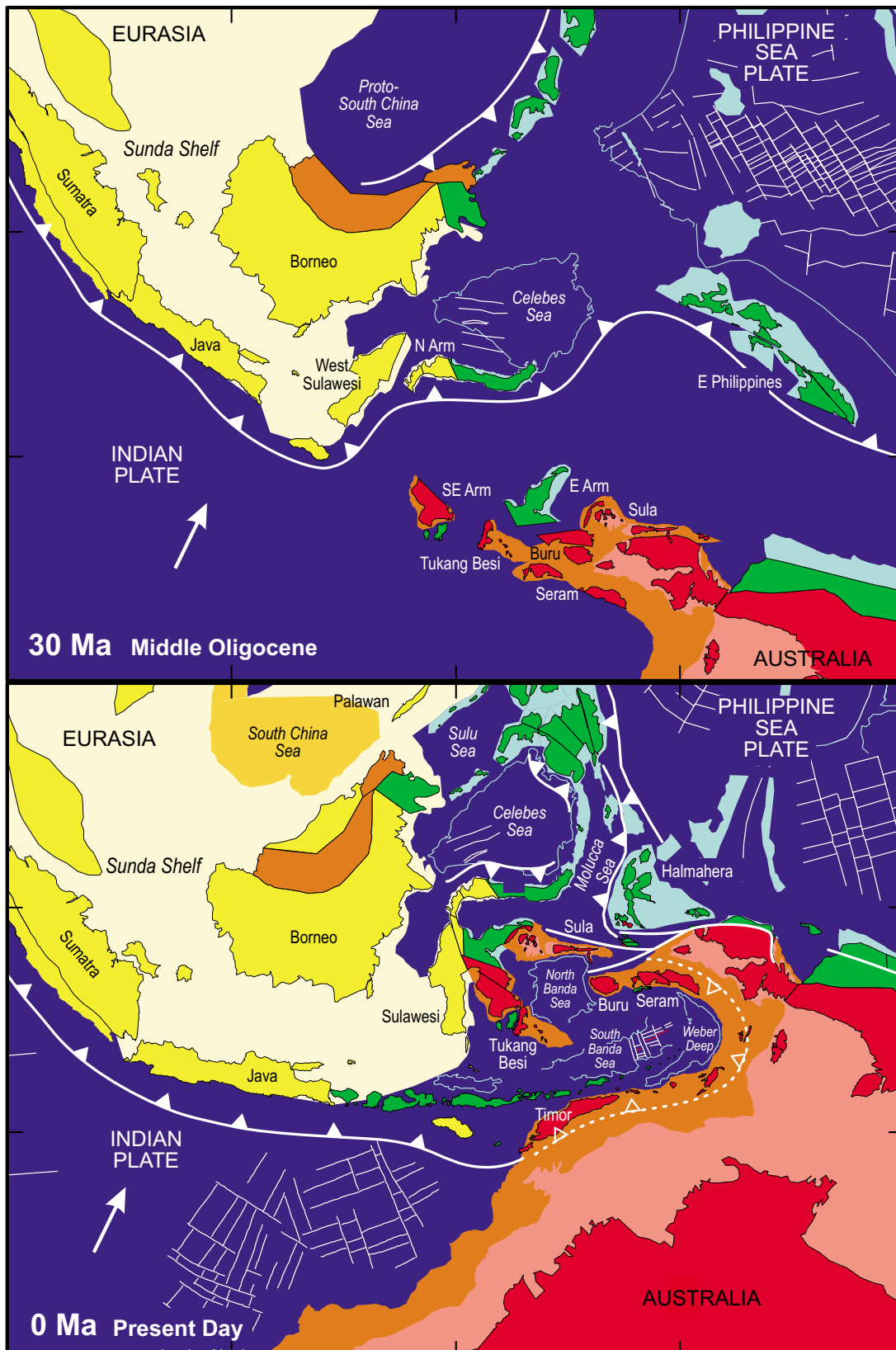


Figure 6. Reconstruction of Wallacea at 30 Ma and the present geological configuration of the area. The past 30 Ma has seen the elimination of oceanic lithosphere between Australia and Sundaland but the creation of the young deep basins of the north and south Banda Sea and the Weber deep. At the same time, Pacific terranes have moved by strike-slip movements along the north New Guinea margin into the Moluccas and Philippines, and deep marine parts of the Australian margin emerged from the sea to form high mountains in the islands of the outer Banda arc.



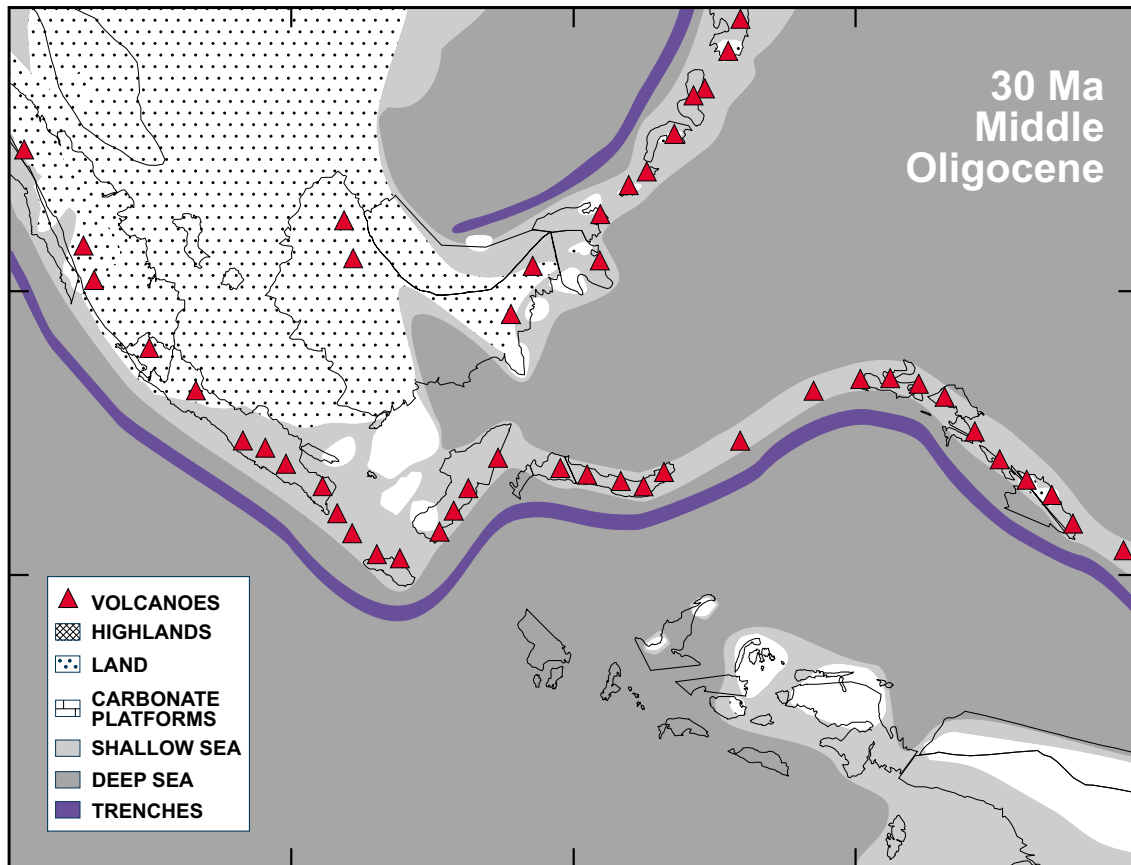


Figure 7. Postulated distribution of land and sea in the region of Wallacea at 30 Ma. Note that on these and subsequent maps modern coastal outlines are used for reference. Some coastal outlines only appear on some maps during the period 30-0 Ma, reflecting crustal growth, for example in the Sunda-Banda arcs. Volcanoes are shown schematically to indicate positions of arcs.

been ephemeral land that could have provided some connection between Sundaland and Australia but the possibility is very low; there is no significant volcanicity in the Sula Spur-Bird's Head area.

From the Early Miocene (Figure 8), mountains rose in Borneo, possibly as high as those now in New Guinea, expanding the area of land, and large deltas built out rapidly into the surrounding deep basins. However, the Makassar Straits remained wider than at present, with a very deep water central area and wide marine shelves, and was therefore the eastern limit of Asian floras and faunas. Recent work in west Sulawesi by the SE Asia Research Group indicates that emergence of land and uplift of mountains was quite recent (late Miocene or later) and rapid. There was no direct way of crossing between Borneo and west Sulawesi. However, the distribution of shallow marine carbonates, and the depths of water of the Sunda shelf, suggest there were always routes from Borneo via Java into Sulawesi, by way of other small islands, although west Sulawesi may itself have been little more than islands until the Pliocene. From the early Miocene there is good evidence for emergence in SE Sulawesi, but in western Sulawesi there is very little evidence of any land, in fact quite the contrary, there is good evidence of continuing marine deposition throughout much of west Sulawesi. So although the tectonic maps indicate that the straight line distances from Borneo to the Bird's Head were not much greater than at present there was probably very little land that might have provided a connection from Borneo to northern Australia. Even at 15 Ma ago the same situation applies. It is important to note that the evidence from the Miocene of Sulawesi particularly, and other parts of the Sula Spur-Bird's Head region, is often relatively poor, because later erosion has removed important parts of the stratigraphic record and because the younger clastic sequences are often difficult to date. However, it is also true that there is very little positive evidence for land throughout most of the area, in particular there is an absence of evidence for the extensive erosional products that would be expected had much of Sulawesi been mountains during

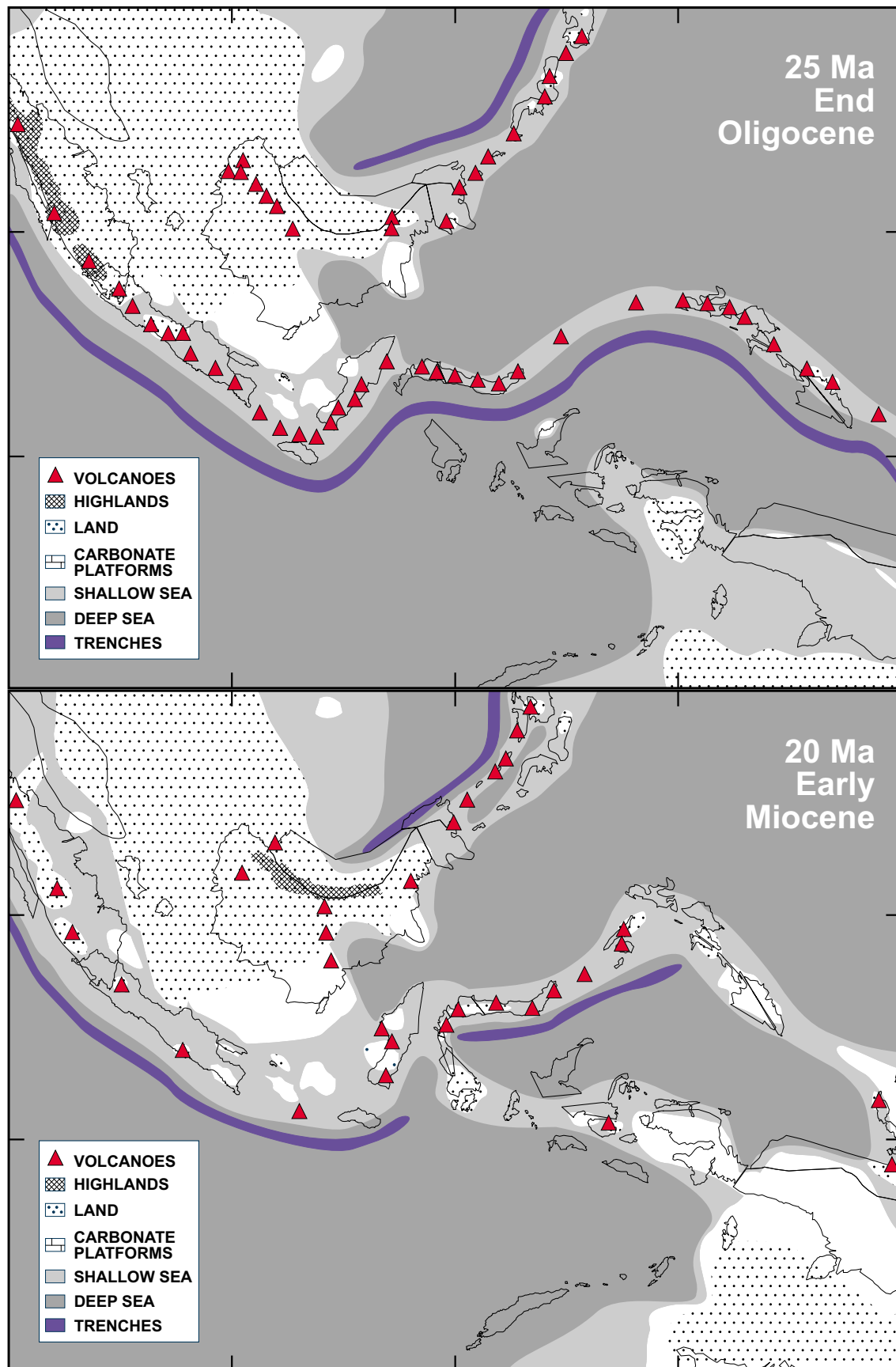


Figure 8. Postulated distribution of land and sea in the region of Wallacea at 25 Ma and 20 Ma.



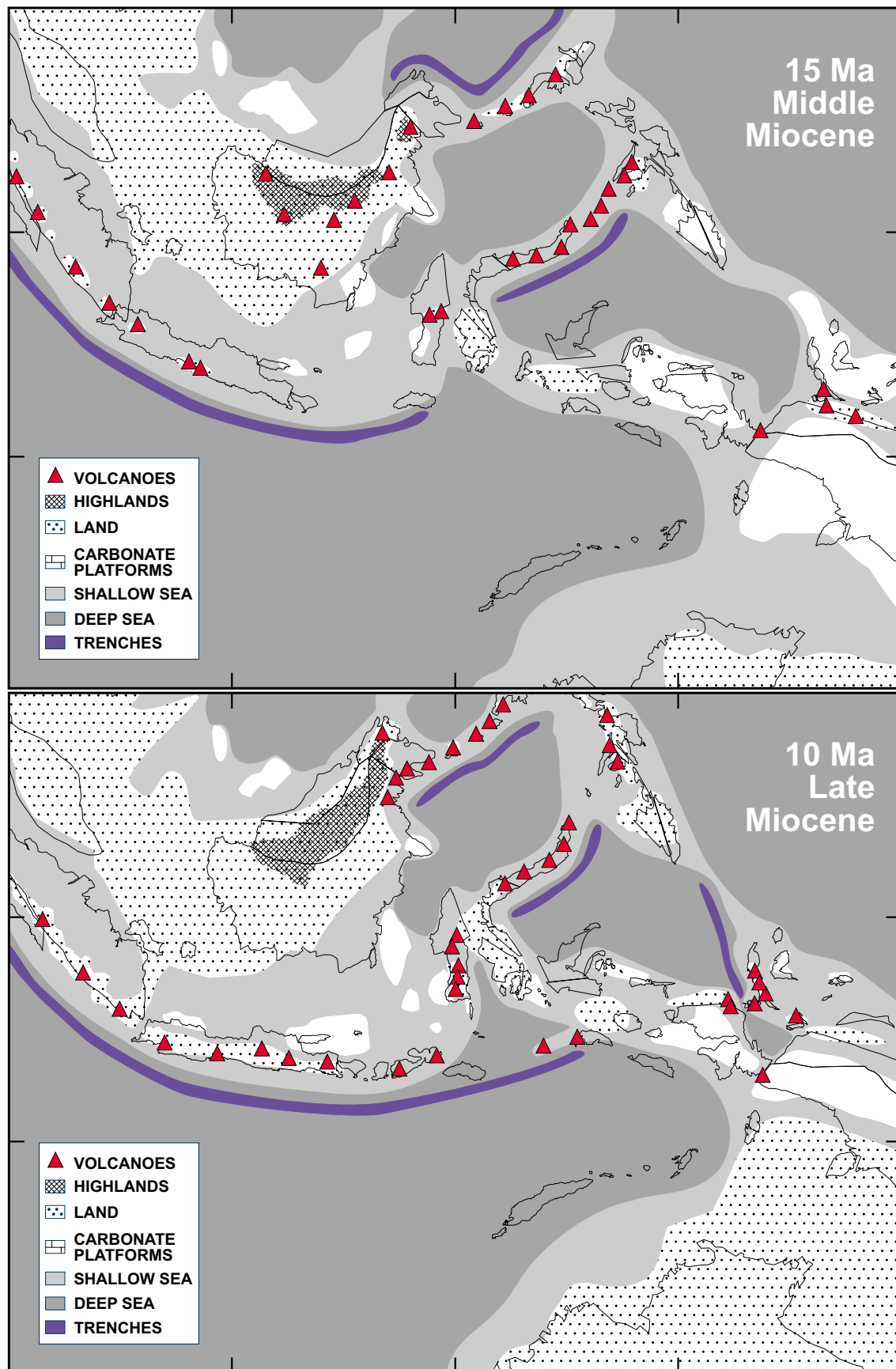


Figure 9. Postulated distribution of land and sea in the region of Wallacea at 15 Ma and 10 Ma.

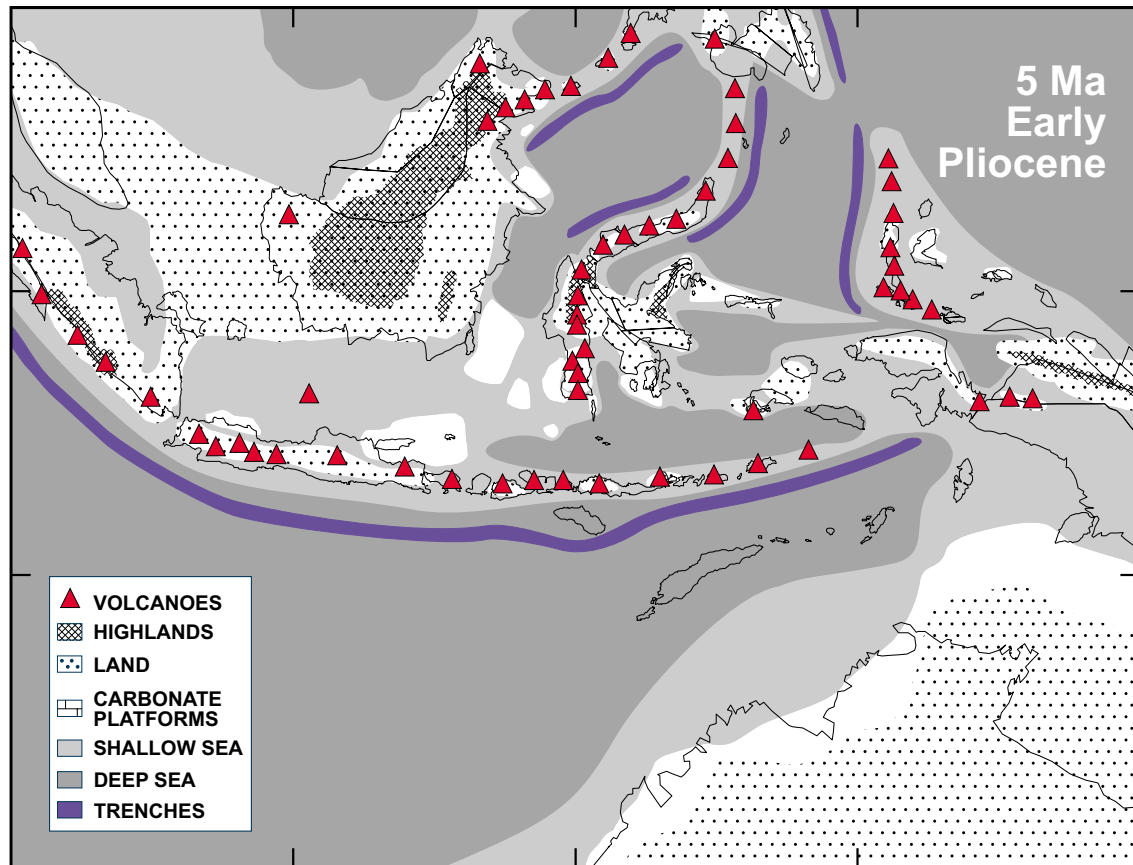


Figure 10. Postulated distribution of land and sea in the region of Wallacea at 5 Ma.

the early and middle Miocene, and there is considerable evidence for marine deposition over much of the region. I believe that the maps of Figures 7 to 10 are generous in assessing areas of possible land and shallow sea.

By about 10 Ma (Figure 9) the Australia-Sundaland gap seems to have been at its narrowest and the areas of possible land were relatively extensive. The Makassar Strait was still fairly wide but there is at that time the first good evidence for the emergence of land in much of Sulawesi. This is rather later than most previous workers suggest. This interpretation is partly a consequence of going carefully through the existing literature and also research in progress (S. J. Calvert, personal communication 1999) on the eastern side of the Makassar Straits in western Sulawesi which is dating sequences that are definitely continental and which are much younger than expected. It was not until 5 Ma (Figure 10) that there was substantial land in Sulawesi but by that time one of the pathways that may have existed previously which may have offered a Sundaland link into Sulawesi, started to be broken up because of the formation of the deep water basins in the Banda Sea region. The Banda basins probably opened in the last 10 million years by very rapid extension during convergence of Australia and Sundaland induced by roll-back of the subducting Indian ocean slab as the Java trench propagated east since the late Miocene. During the last few million years there have been significant movements of continental fragments into and around the Banda Sea on splays of the left-lateral Sorong fault system and local collisions and uplift as a result. However, the uplift has been accompanied by extension, partly driven by strike-slip faulting and partly driven by subduction forces and therefore deep water barriers have appeared as older ones disappeared. As these areas became deeper due to extension, mountains rose in Seram and Timor elevating former deep water deposits of the Australian margin. With the possible exception of small overthrust fragments of the Sundaland margin now found on Timor, the islands of the outer Banda arc must have been entirely populated by plants and animals since their emergence within the last 5 million years. During the same period the north Moluccan islands arrived from the east with Pacific island

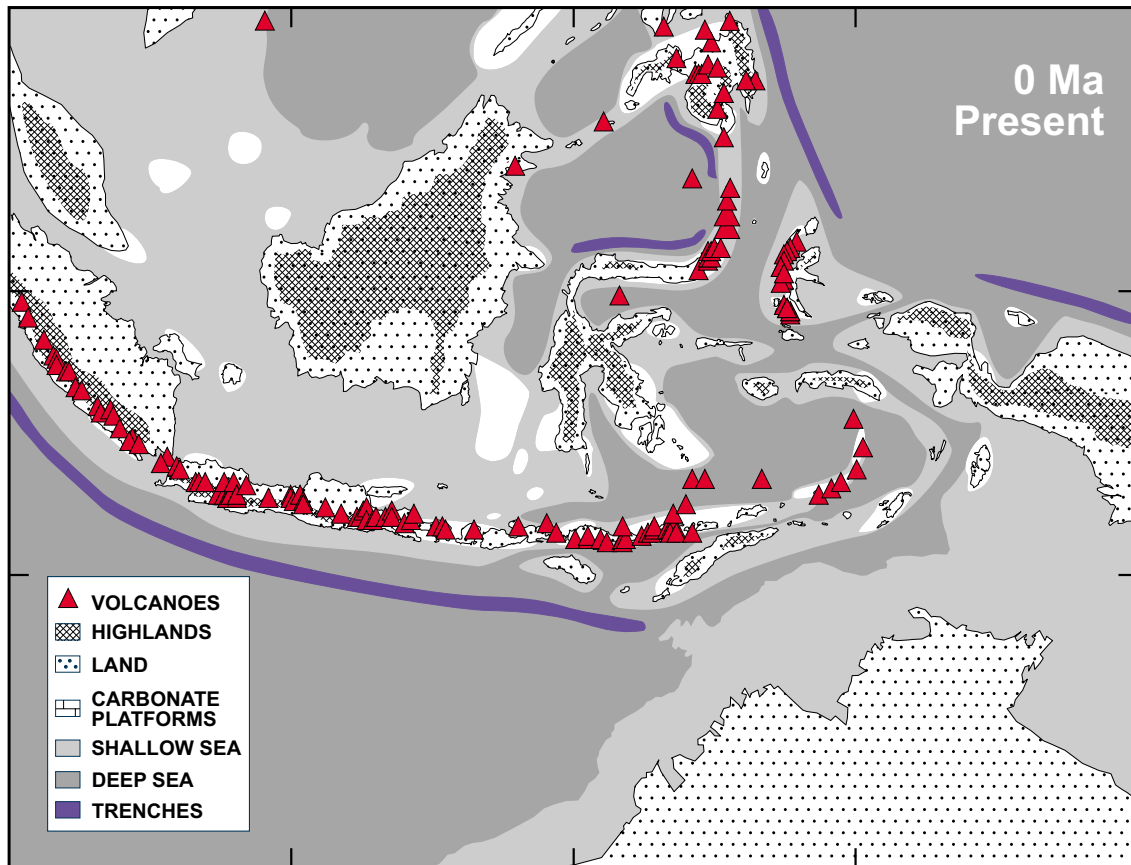


Figure 11. Simplified present day distribution of land and sea in the region of Wallacea for comparison with the palaeogeographic maps of earlier periods. Even a sea level fall of about 200m, the maximum probable fall during the Quaternary due to polar ice cap growth, would not provide a complete continuous link between the Australian and Sundaland continental margins.

arc fragments. They moved along the north New Guinea margin, remaining close to it at all times, and providing possible pathways for migration of Australian faunas and floras onto volcanic islands of the Halmahera arc. Thus by a strange irony, despite the convergence of Australia and Sundaland, geological processes have maintained the barriers to the mixing of Asian and Australian floras and faunas (Figure 11). There seems to have been no time when land plants and animals would have been able to avoid crossing water gaps in order to move between the two continents.

## 8 EFFECTS OF SEA LEVEL CHANGE

According to long term global sea level curves we currently live in a period of relatively low sea level but sea level has been much lower and higher during the very recent past due to melting and freezing of ice caps. Although there is now broad agreement on trends of Cenozoic changes in sea level there is still disagreement about the magnitude of eustatic (global sea level) changes (e.g. Haq et al. 1987; Kominz et al. 1998). It is currently not possible to be very precise about water depths on the maps presented here, and consequently assessing the effects of global sea level change is very difficult. Distinguishing the effects of global and tectonic contributions to sea level change is particularly problematical in tectonically active regions like SE Asia and the SW Pacific. However, as noted above, I believe that I have been generous in assessing the extents of land and shallow seas in these regions. I consider the boundary between shallow and deep water areas on the maps to approximate the 500 m isobath. If sea level did fall by 200 m, the maximum relative fall advocated for a single event in the Cenozoic with the exception of the Quaternary (Haq et al. 1987), it might have been possible to establish a short-lived land connection between Sundaland and Australia,

although this seems unlikely. At other times before the Quaternary no such continuous connection seems possible. During the Quaternary, known sea level changes would at times have exposed most of the Sunda and Sahul-Arafura Shelves, as well as inducing significant biogeographic side-effects such as reduction in the areas of rain forest, but would never have allowed a continuous land link between Sundaland and Australia. I therefore consider this to have been the most likely situation during the earlier period of the Cenozoic, i.e. there were never continuous land links between Sundaland and Australia.

## 9 IMPLICATIONS

Sulawesi is an area of obvious interest because of its special fauna and flora. There is some evidence that at 20 Ma the SE parts of the island were emergent. There is a possibility that parts of the north arm of Sulawesi, where there were volcanoes, could have been emergent by then, but most of Sulawesi, certainly western Sulawesi, was not emergent at that time. There may have been the occasional island there but there could not have been much land. There is a good marine record during that period and it was not until much more recently that western Sulawesi emerged from the sea. By about 10–5 Ma there was probably a significant area of land in Sulawesi bearing in mind all the qualifications made earlier about negative evidence and uncertainties. It does not seem that there has ever been a continuous land link to northern Australia although it there may have been areas of ephemeral land which may have allowed island hopping. The period at about 10 Ma seems to be the time when there may have been the best chance of crossing Wallacea for land animals or plants that were able to traverse relatively narrow marine areas, before new deep ocean basins started to open. As far as the other smaller islands of Wallacea are concerned, many of them may have maintained areas of land, albeit ephemeral and changing in distribution, but most have emerged from the sea in the last 5 million years at most and many have emerged from great depths. Most of Wallacea has been populated by plants and animals since 5 Ma.

At the eastern end of this interface, northern New Guinea includes many fault-bounded terranes which accreted to the Australian margin during the late Cenozoic. Its mountains also emerged from the sea rapidly and very recently. New Guinea therefore provided wonderful opportunities for newly arrived plants and animals, in a climatic setting in which high diversity was encouraged. The rise of mountains probably provided a large range of new niches, at the same time forming new physical barriers, while their rapid rise may well have modified atmospheric circulation patterns contributing to drier climates in the Australian continent, and consequently forming climatic barriers to plant and animal movements. Geological processes contributed to biogeographic patterns by forming land and influencing climate but probably not by rafting unique biotas.

I summarised above some reservations about simplistic interpretations of geological data to explain biogeographic patterns. New Caledonia serves to remind us all of some fundamental geological and biogeographic problems in the region (Keast 1996). In New Caledonia there is apparently an ancient Gondwana flora, and other strange features of the flora and fauna seem to imply some land there since the late Cretaceous. On the other hand it is difficult to find any geological evidence that New Caledonia was above sea level until the late Eocene. How do we resolve this dilemma? I suggest that it indicates that we should remain cautious about apparently simple and definitive answers to our geological and biogeographic problems and we should all remain critical of our data and beliefs. The biogeographic patterns we observe today are the product of many factors, and geology, although fundamental, is only one of many important controls. It is clear from the geology of the region that the snapshot we see today is no less complicated than in the past. It is also clear that our geological data set is still not adequate to deal with the many questions we wish to answer. On the other hand, geology does have a historical record in the forms of fossils and rocks whereas many biogeographic patterns, and often those most enthusiastically interpreted, are nothing but present-day distributions which can be interpreted in numerous different ways. Molecular studies may in future provide a better historical record.

Since the early Miocene Australia and Sundaland have moved closer together but as land emerged and mountains rose in some areas, new deep marine basins developed. As these geologically-controlled changes occurred, oceanic and atmospheric circulation patterns changed, partly as the result of the closure of the Indo-Pacific seaway, and a host of new habitats were created. The

distribution of Australian and Asian plants and animals should therefore reflect this complexity, with further important modifications imposed by glacially-related sea level and climatic change in the Quaternary. The zone of Wallacea is partly an ancient deep water barrier, partly a dynamic boundary marking a migration front, but also a relic of Neogene patterns which have been tectonically disrupted and modified by Quaternary climate change. Like the geology, the present biogeographic patterns need to be viewed as one image in a rapidly-changing scene which is still very far from achieving equilibrium.

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