The plate tectonics of Cenozoic SE Asia and the distribution of land and sea

Robert Hall
SE Asia Research Group, Department of Geology, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK Email: robert.hall@gl.rhbnc.ac.uk

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Abstract

A plate tectonic model for the development of SE Asia and the SW Pacific during the Cenozoic is based on palaeomagnetic data, spreading histories of marginal basins deduced from ocean floor magnetic anomalies, and interpretation of geological data from the region. There are three important periods in regional development: at about 45 Ma, 25 Ma and 5 Ma. At these times plate boundaries and motions changed, probably as a result of major collision events.

In the Eocene the collision of India with Asia caused an influx of Gondwana plants and animals into Asia. Mountain building resulting from the collision led to major changes in habitats, climate, and drainage systems, and promoted dispersal from Gondwana via India into SE Asia as well as creating barriers between SE Asia and the rest of Asia. Continued indentation of Asia by India further modified Sundaland and created internal barriers affecting biogeographic patterns. From a biogeographic and tectonic viewpoint, the major Cenozoic tectonic event in SE Asia occurred about 25 million years ago, resulting in major changes in the configuration and character of plate boundaries, and caused effects which propagated westwards through the region. This event led to the progressive arrival of Australian microcontinental fragments in Sulawesi, providing possible pathways for migration of faunas and florae between Asia and Australia, but also creating new barriers to dispersal.

Tectonic reconstruction maps of lithospheric fragments cannot be translated simply into maps of land and sea which are of greater value to biogeographers. Determining the palaeogeography of the region is not yet possible, but an attempt is made to outline the main likely features of the geography of the region since the late Oligocene.

Evidence from all fields of biogeography is required to test different tectonic models and identify the origin of present biogeographic patterns but there must be a focus on plants and animals which have difficulty in dispersing, and for which non-geological controls are unimportant. The present distribution of plants and animals in SE Asia may owe much more to the last one million years than the preceding 50 million years.

Introduction

For the geologist, SE Asia is one of the most intriguing areas of the Earth. The mountains of the Alpine-Himalayan belt turn southwards into Indochina and terminate in a region of continental archipelagos, island arcs and small ocean basins. To the south, west and east the region is surrounded by island arcs where lithosphere of the Indian and Pacific oceans is being subducted at high rates, accompanied by intense seismicity and spectacular volcanic activity. Within this region we can observe collision between island arcs, between island arcs and continents, and between continental fragments. At the same time ocean basins are opening within this convergent region. SE Asia includes areas with the highest global rates of plate convergence and separation.

It is clear from the geology of the region that the snapshot we see today is no less complicated than in the past. The region has developed by the interaction of major lithospheric plates, principally those of the Pacific, India-Australia and Eurasia (Fig.1), but at the present day a description only in terms of these three plates is a very great oversimplification. Many minor plates need to be considered, and in some parts of the region the boundaries between these smaller plates are very uncertain. It is also clear that some of the deformation cannot be described in simple plate tectonic terms. Lithosphere has deformed internally, and material has been added by arc volcanic processes, which means that at least one of the axioms of
plate tectonics, of rigid fragments moving on a sphere, cannot be assumed.

The complexity of the present-day tectonics of the region and the observable rates of plate motions (e.g., Hamilton, 1979; McCaffrey, 1996) indicate that major oceans, or multiple small oceans, have closed during the Cenozoic. Several major island arcs have certainly formed during this time and some may have completely disappeared. At some plate boundaries strike-slip faulting has dismembered previously coherent regions, and along these boundaries there can be both major crustal subsidence and uplift due to deformation. During the past 50 million years the configuration of the region has therefore changed significantly in plate tectonic terms. Accompanying these large scale movements have been equally significant vertical movements, recorded in the sedimentary basins of the region, into which large volumes of sediments have been shed, removed from rising mountains. Thus the distribution of land and sea has changed during the Cenozoic, and many parts of the region have seen dramatic vertical movements of several kilometres, with mountains where once there were oceans, and deep marine regions where mountains had existed.

The abrupt division between Asian and Australian floras and faunas in Indonesia, first recognised by Wallace in the nineteenth century, has its origin in the rapid plate movements and reorganisation of land-masses in SE Asia. Wallace realised that the region had changed dramatically in the past without knowing the cause, and since his work there has been a general awareness that the present distribution of land and sea is not the same as that of the past, and that the changes are in some way implicated in bioge-
graphic patterns. We are now confident that the geological changes are the result of plate movements and are not the consequence of an expanding Earth. However, although the very large-scale motions of major plates have been reasonably well known for the last 20 years or so, the detail necessary to reconstruct SE Asia has been lacking. Furthermore, because of the complexity of the geology of the region and because so much of it has been remote and difficult of access, geologists have not been able to clearly describe its long term development and it is only in the last few years that models explaining the development of the region have been produced.

Making tectonic reconstructions of SE Asia becomes more difficult as the age of the reconstruction becomes greater, and examination of the present tectonics of the region shows why this is so. Projecting motions that are known today into the past is very problematical; our observations of the present tectonics indicate that plates, plate boundaries and motions can be geologically ephemeral features. In some parts of the region, for example the Philippines and east Indonesia, it is not even certain that plate tectonics provides a suitable model for a detailed understanding of the development of the region. Despite these difficulties, a plate tectonic model does have value and by working back from the present-day we can, albeit with difficulty, make reconstructions; the known motions of major plates do impose limits on possibilities; and the resulting interpretations do offer a means of identifying important tectonic events and highlighting key problems. This paper explains the background to a plate tectonic model of SE Asia and the SW Pacific and discusses its implications for biogeography.

**Mesozoic to Cenozoic background**

In very general terms, the region owes its origin to the pre-Cenozoic break-up of the Gondwana super-continent (Fig.2), the subsequent movement of Gondwana fragments northwards, and their eventual collision with Eurasia. Metcalfe (1998 this volume) provides an account of present knowledge of the Palaeozoic and Mesozoic development of SE Asia. It is clear that 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 Eurasian continent. By the Mesozoic, a region composed of fragments derived from Gondwana formed a Sundaland core surrounded by subduction zones.

Subduction meant that the Sundaland margins were complex. Island arcs at the margins may have been underlain by continental and oceanic crust, and there were probably many small ocean basins behind the arcs and above the subduction zones. The widespread ophiolites are fragments of oceanic lithosphere now found on land, and much of this lithosphere was formed in subduction-related settings, such as backarc basins and forearcs. Ophiolites are commonly emplaced at some stage during the convergence of two plates and convergence is ultimately completed by collision between arc and continent, or continent and continent. Throughout the Mesozoic there appear to have been collisions of fragments with the Sundaland margins, and by the beginning of the Cenozoic SE Asia was a composite mosaic of continental crust, island arc material and oceanic crust.

Two major fragments separated from Gondwana in the Cretaceous and moved northwards as parts of different plates: India and Australia. India completed its passage in the early Cenozoic and collided with the Asian continent about 50 million years ago (Fig.3). However, collision did not cause India to become fixed to Asia as
predicted by early plate tectonic models. Instead, India continued to move northwards, albeit at a slower rate than during the Cretaceous. There is considerable disagreement amongst geologists about how the continued northward movement was accommodated during the Cenozoic, and its consequences. According to Tapponnier and colleagues (e.g. Tapponnier et al., 1982, 1986, 1990; Peltzer and Tapponnier, 1988; Briais et al., 1993) the impact of a rigid Indian ‘indentor’ on an Asian margin weakened by subduction-related heating and magmatism caused eastward ‘extrusion’ and rotation of continental fragments, and opening of some of the small oceanic marginal basins of SE Asia. The progressive extrusion of continental fragments to the east and consequent rotation of crustal blocks has been simulated in laboratory experiments using plasticine (Fig.4), and the strike-slip faults which cut across Asia are considered to be zones of major displacements which link to marginal basins, such as the South China Sea, offshore. If correct, this hypothesis implies major changes in SE Asia linked to India’s continued northward movement. In contrast, other workers (e.g. England and Houseman, 1986; Dewey et al. 1989; Houseman and England, 1993) dismiss the extrusion hypothesis, arguing that the displacement on the strike-slip faults has been small and that the continued convergence of India and Asia has been accommodated by crustal thickening with very little eastward movement of crust.

Australia separated from Gondwana, leaving Antarctica as its final remnant, at about the same time as India, but moved less quickly northwards. Instead of a direct collision with another continent Australia is now making a glancing

Fig.3. India and Australia separated from Gondwana in the Cretaceous. The map shows the late Cretaceous and Cenozoic movement of these two major continental fragments north with respect to Asia and SE Asia, both of which are shown in their present day positions for reference.
collision with a composite SE Asia, which includes some of the earlier Gondwana fragments to arrive, and also includes the island arcs formed due to the subduction of oceanic crust north of Australia. In east Indonesia the northward movement of Australia during the Cenozoic has been marked by arc-continent collision and major strike-slip motion within the north Australian margin. Further east, arc-continent collisions have been the result of elimination of marginal basins formed above subduction zones as Australia has moved north, and this system of arcs and marginal basins can be traced east along the margin of the Pacific plate in Melanesia.

During the late Mesozoic and Cenozoic there was subduction of the Pacific ocean to the east of Asia, although the eastern margin of Asia and SE Asia was probably a region of small plates and marginal basins as it is at the present day. At present the Philippine Sea plate and Philippine island arcs separate the east Asian margin from the Pacific plate south of Japan. Unlike the Indian ocean and Pacific oceans, the Philippine Sea plate lacks well defined sea-floor magnetic anomalies which normally provide the basis for reconstructing past plate motions. The Philippine Sea plate is also difficult to link to the movements of the other major plates because it is surrounded by subduction zones. For these reasons the history of movement of plate movements in the west Pacific north of New Guinea has been very uncertain, and consequently the eastern edge of SE Asia has been difficult to reconstruct. Palaeomagnetic data from east Indonesia (Hall et al., 1995) have provided the basis for reconstructing the Philippine Sea plate and its motion since the early Cenozoic, and conse-
Fig. 5. 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. The present extent of the Pacific plate is shown in mid grey. 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. See pages 126-131 for colour plates of Figs.5 to 10. Letters represent marginal basins and tectonic features as follows:

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Combining the Philippine Sea plate history with the known movements of the major plates, India, Australia, Pacific and Eurasia, provides some limits within which reconstructions of SE Asia, and parts of the west Pacific, can be attempted. Within this region there are recent interpretations of the South China Sea opening (Briais et al., 1993) and other marginal basins which limit options still further and provide constraints of variable quality on modelling the tectonic history of the region. The importance of the marginal basins is that only they are likely to contain a clear record, based on ocean floor magnetic anomalies, of the motion history of some of the minor plates. However, many of the marginal basins of SE Asia completely lack magnetic anomalies, many have not been drilled during the ocean drilling campaigns, and their ages and character are still poorly known. Therefore much of the evidence which must be used in a regional tectonic model of SE Asia is based on interpretation of geological data from the small ocean basins, their margins, and from the geologically more complicated land areas around them. The reader should be aware that, as in other areas of science, geologists differ in their interpretations of these data, and much of the information does not lend itself to unambiguous reconstruction. Nonetheless, a complete tectonic history can only be deduced from the geology on land combined with data from the oceans. The account here is therefore my view of the development of Cenozoic SE Asia using plate tectonic reconstructions based on such deductions.

The model

The reconstructions were made using the ATLAS computer program (Cambridge Paleomap Services, 1993) and plate motion model for the major plates. The motion of Africa is defined relative to magnetic north and motions of the major plates are all relative to Africa. Eurasia has been close to its present-day position throughout the Cenozoic. The reconstructions in this paper add to this model for the major plates by including a large number of smaller fragments in SE Asia and the SW Pacific. More than 100 fragments are currently used, and most retain their current size in order that they remain recognisable. During the 50 Ma period fragments represented may have changed size and shape or may not have existed, both for arc and continental terranes. Thus, the plate model can only be an approximation. Some of the elements of the model are deliberately represented in a stylistic manner to convey the processes inferred rather than display exactly what has happened, for example, the motion of the terranes of north New Guinea.

Previous reconstructions which cover all or parts of the region discussed here include those of Katili (1975), Crook and Belbin (1978), Hamilton (1979), Briais et al. (1993), Burrett et al. (1991), Daly et al. (1991), Lee and Lawver (1994), Rangin et al. (1990), and Yan and Kroenke (1993) who also produced an animated reconstruction of the SW Pacific. The reader is referred to the original papers for accounts of the earlier models. Some differences between the model here and other models result from the choice of reference frames; some use the hotspot reference frame, and others use a fixed Eurasia, whereas these reconstructions use a palaeomagnetic reference frame. These choices result in different palaeolatitudes and can cause other differences. There have also been improvements in our knowledge of global plate motions since the earlier regional reconstructions. However, in many cases the principal differences between the different models result from different interpretations of geological data.

This paper gives an account of a plate tectonic model for the Cenozoic development of the region based on my interpretations of a large range of geological data. It summarises the regional tectonic development of SE Asia using a plate model which has been animated using 1 Ma time-slices. Below is a brief account of the model and its major features, which is followed by a discussion of its principal implications for biogeographers relating to the distribution of land and sea during the last 50 million years.

Reconstructions

The model discussed here includes that developed earlier for SE Asia (Hall, 1996) which has been extended to include the SW Pacific (Hall, 1997). Reconstructions of SE Asia and the SW Pacific (Fig.5) shown on a global projection are presented at 10 Ma intervals for the period 50-10 Ma (Figs.6-10). The reader is referred to Hall (1995, 1996) for a more complete account of the assumptions and data used in reconstructions of SE Asia and for maps showing only SE Asia but with more detail.
Fig. 6. Reconstruction of the region at 50 Ma. The possible extent of Greater India and the Eurasian margin north of India are shown schematically. Shortly before 50 Ma collision between the north Australian continental margin and an island arc had emplaced ophiolites on the north New Guinea margin, and in New Caledonia, eliminating ocean crust formed at the former Australian-Indian ocean spreading centre. Double black arrows indicate extension in Sundaland.

Configuration at 50 Ma

At 50 Ma (Fig. 6) India and Australia were separate plates although their motions were not greatly different. Transform faults linked the slow-spreading Australia-Antarctic and the fast-spreading India-Australia spreading centres. Some of the ophiolites of Sulawesi probably formed at the India-Australia mid-ocean ridge.

India collided with Asia in the early Tertiary but there remains considerable controversy about the exact age of collision, and its consequences (Packham, 1996; Rowley, 1996). The position of the Eurasian margin and the extent of Greater India are major problems. The reconstruction shown in Fig. 6 shows a conservative estimate and, since India-Asia collision began at about 50 Ma, this implies that the Asian margin extended...
south to at least 30°N. 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. Despite the great attraction of this hypothesis and the spectacular evidence of displacements on the Red River fault (Tapponnier et al., 1990) the predictions of major rotations, southeastward extrusion of fragments, and the timing of events (Tapponnier et al., 1982), remain poorly supported by geological evidence in SE Asia.

The east Eurasian continental margin was oriented broadly NE-SW. From Japan northwards Asia was bounded by an active margin. Taiwan, Palawan and the now extended crust of the South China Sea margins formed a passive margin, established during Cretaceous times. Sundaland was separated from Eurasia by a wide proto-South China Sea probably floored by Mesozoic ocean crust. The southern edge of this ocean was a passive continental margin north of a continental promontory extending from Borneo to Zamboanga. The Malay peninsula was closer to Indochina and the Malay-Sumatra margin was closer to NNW-SSE. Because rotation of Borneo is part of this model the reconstruction differs from those of Rangin et al. (1990) and Daly et al. (1991) who infer a margin oriented closer to E-W. I see no evidence to support the almost E-W orientation of the Sundaland margin in the region of Sumatra as shown on these and many other reconstructions (e.g. Briais et al., 1993; Hutchison, 1996). Furthermore, such models have major difficulties in explaining the amount, timing and mechanism of rotation required to move Sumatra from an E-W to NW-SE orientation. West Sumatra includes arc and ophiolitic material accreted in the Cretaceous. East Borneo and West Sulawesi appear to be underlain by accreted arc and ophiolitic material as well as continental crust which may be early-rifted Gondwana fragments. This material had been accreted during the Cretaceous and may have resulted in a highly thickened crust in this part of Sundaland, possibly sustained by subduction.

Australia was essentially surrounded by passive margins on all sides. To the west the passive margin was formed in the Late Jurassic, and Fig.6 postulates a failed rift, possibly floored by oceanic crust on the site of the present-day Banda Sea, partially separating the Bird’s Head microcontinent from Australia. Mesozoic oceanic lithosphere was present north of the Bird’s Head, south of the active Indian-Australian spreading centre. Further east in the Pacific, 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 Mesozoic passive margin collided with this intra-oceanic arc causing emplacement of the Sepik and Papuan ophiolites (Davies, 1971). Subsequently, most of the New Guinea margin was a passive margin during the Paleogene but the oceanic crust to the north is inferred to have formed during the Mesozoic in an intra-oceanic marginal basin behind the Sepik-Papuan arc. The position and character of the east Australia-Pacific margin is also uncertain. Tasman and Coral Sea opening had probably been driven by subduction but the site of subduction must have been considerably east of the Australian continent, beyond the Loyalty Rise and New Caledonia Rise. Spreading had ceased in both basins by about 60 Ma (Paleocene). By the Paleocene it appears that subduction east of New Caledonia was to the east not to the west (Aitchison et al., 1995). The history of this region remains poorly known since it is almost entirely submarine, and magnetic anomalies in this area are poorly defined.

Java and West Sulawesi were situated above a trench where Indian plate lithosphere was subducting towards the north. The character of this boundary is shown as a simple arc but may have included marginal basins and both strike-slip and convergent segments depending on its local orientation. Extending plate boundaries into the Pacific is very difficult. A very large area of the West Pacific has been eliminated by subduction since 50 Ma which will continue to cause major problems for reconstructions. However, there is clear evidence that this area resembled the present-day West Pacific in containing marginal basins, intra-oceanic arcs and subduction zones. The Java subduction system linked east into Pacific intra-oceanic subduction zones required by the intra-oceanic arc rocks within the Philippine Sea plate; parts of the east Philippines, the West Philippine basin and Halmahera include arc rocks dating back at least to the Cretaceous. North of the Philippine Sea plate there was a south-dipping subduction zone at the southern edge of a Northern New Guinea plate.

50-40 Ma

Whatever the timing of India-Asia collision, a consequence was the slowing of the rate of
plate convergence after anomaly C21 and a major change in spreading systems between anomaly C20 and C19 at about 42 Ma. India and Australia became one plate during this period (Figs. 6 and 7) and the ridge between them became inactive. Northward subduction of Indian-Australian lithosphere continued beneath the Sunda-Java-Sulawesi arcs although the direction of convergence may have changed. 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. They may represent the consequences of oblique convergence or extension due to relaxation in the over-riding plate in response to India-Asia collision, enhanced by slowing of subduction, further influenced by older structural fabrics.

The Java-Sulawesi subduction system continued into the West Pacific beneath the east Philippines and Halmahera arcs. Further east, the direction of subduction was southward towards Australia and this led to the formation of a Melanesian arc system. During the Eocene the extended eastern Australasian passive margin had collided with the intra-oceanic arc already emplaced in New Guinea resulting in emplacement of the New Caledonia ophiolite (Aitchison et al., 1995; Meffre, 1995) followed by subduction polarity reversal. Subduction began beneath Papua New Guinea 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. This model postulates the initial formation of these arcs at the Papuan-east Australian margin as previously suggested by Crook and Belsin (1978) following subduction flip, rather than by initiation of intra-oceanic subduction within the Pacific plate outboard of Australia as suggested by Yan and Kroenke (1993). The evidence for either proposal is limited but this model has the simplicity of a single continuous Melanesian arc.

During this interval there were major changes in the Pacific. The Pacific plate is widely said to have changed its motion direction at 43 Ma, based on the age of the bend in the Hawaiian-Emperor seamount chain, although this view has recently been challenged by Norton (1995) who attributes the bend to a moving hotspot which became fixed only at 43 Ma. Subduction of the Pacific-Northern New Guinea ridge (Fig. 7) led to massive outpouring of intra-oceanic volcanic rocks (Stern and Bloomer, 1992) which formed the Izu-Bonin-Mariana arc system, and the Philippine Sea plate was a recognizable entity by the end of this period. There was significant rotation of the Philippine Sea plate between 50 and 40 Ma and the motion history of this plate (Hall et al., 1995) 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 oceanic basin within the Philippine Sea plate although the reconstructions probably underestimate the width of the Makassar Strait and Celebes Sea, which may have been partially subducted in the Miocene beneath west Sulawesi.

The opening of the West Philippine-Celebes Sea basin required the 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.

40-30 Ma

In this interval (Figs. 7 and 8) the spreading of the marginal basins of the West and SW Pacific continued. 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. This spreading centre may have been linked to backarc spreading of the Caroline Sea which formed from about 40 Ma due to subduction of the Pacific plate. The Caroline Ridge is interpreted in part as a remnant arc resulting from Caroline Sea backarc spreading, and the South Caroline arc ultimately became the north New Guinea arc terranes. 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. 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.

The Philippines-Halmahera arc was stationary, so spreading in the West Philippine-Celebes
Fig. 7. Reconstruction of the region at 40 Ma. India and Australia were now parts of the same plate. An oceanic spreading centre linked the north Makassar Strait, the Celebes Sea and the West Philippine basin. Spreading began at about this time in the Caroline Sea, separating the Caroline Ridge remnant arc from 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.

Sea basin maintained subduction between NE Borneo and north of Luzon. The pull forces of the subducting slab therefore account for stretching of the Eurasian margin north of Palawan, and later development of oceanic crust in the South China Sea which began by 32 Ma. In contrast, the indentor model does not account for stretching at the leading edge of the extruded blocks, such as Indochina, or the normal faulting east of Vietnam often shown as kinematically linked to the Red River fault system. There was approximately 500-600 km left-lateral movement on the Red River fault (Briais et al., 1993) during the extrusion of Indochina (32-15 Ma).

The dextral Three Pagodas and Wang Chao faults are simplified as a single fault at the north end of the Malay peninsula. There are a host of
30 Ma
Mid Oligocene

Fig. 8. Reconstruction of the region at 30 Ma. Indentation of Eurasia by India led to extrusion of the Indochina block by movement on the Red River fault and Wang Chao-Three Pagodas (WC-TP) faults. 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. A wide area of marginal basins separated the Melanesian arc from passive margins of eastern Australasia, shown schematically between the Solomon Sea and the South Fiji basin.

faults through this region, and a plate tectonic model can only oversimplify the tectonics of the continental regions by considering large and simple block movements and broadly predicting regional stress fields. The implication of this simplified model is that basins such as the Malay and Gulf of Thailand basins have a significant component of strike-slip movement on faults controlling their development. However, they may have been initiated in a different tectonic setting, in which a pre-existing structural fabric influenced their development (Hutchison, 1996).

30-20 Ma

This period of time (Figs. 8 and 9) saw the most important Cenozoic plate boundary reorganisa-
Cenozoic plate tectonics of SE Asia

Norfolk basin from a triple junction to the north. Spreading to propagate behind the rise into the east, allowing the rise to advance east and

ated soon after ocean crust was formed to the Kings Rise subduction seems to have been initi-

Sea basin (now mainly subducted). At the Three widening of the South Fiji basin and Solomon

the New Guinea margin.

moved terranes of the South Caroline arc along

the Sorong fault system, which subsequently

the Australian margin became a strike-slip zone,

pines arc ceased and the New Guinea sector of

the Halmahera-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 Sulawesi.

By 30 Ma the Sulawesi margin may have been complex and included ocean crust of different types (mid-ocean ridge, backarc basin). Thus

the Sulawesi ophiolite probably includes mate-

rial formed within the Indian Ocean (Mubroto et al., 1994) as well as ocean basins marginal to Eurasia (Monnier et al., 1995). The arrival of the

Australian margin at the subduction zone caused northward subduction to cease. The ocean crust trapped between Sulawesi and

Halmahera first became part of the Philippine Sea plate and later the Molacc Sea plate. The Philippine Sea plate began to rotate clockwise

and the trapped ocean crust began to subduct beneath Sulawesi in the Sangihe arc.

Soon afterwards the Ontong Java plateau col-

lided with the Melanesian arc. These two major collisions caused a significant change in the character of plate boundaries in the region be-

between about 25 and 20 Ma (Early Miocene). They also linked the island arcs of Melanesia to the New Guinea terranes at the southern margin

of the Caroline plate, and to 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 Pacif-

ic. Both 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, leading first to opening of the Parece Vela basin and later to spreading in the Shikoku basin. The change in plate bounda-

ries led to subduction beneath the Asian margin.

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.

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 initi-

ated 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.

20-10 Ma

The clockwise rotation of the Philippine Sea plate necessitated changes in plate boundaries throughout SE Asia which resulted in the tec-
tonic pattern recognisable today (Figs. 9 and 10). These changes include the re-orientation of spreading in the South China Sea, and the develop-
oment of new subduction zones at the eastern edge of Eurasia and in the SW Pacific. Contin-
ued northward motion of Australia caused the counter-clockwise rotation of Borneo. Northern Borneo is much more complex than shown.

There was volcanic activity and build-out of delta and turbidite systems into the proto-South

China Sea basin. Major problems include the source of sediment in the basins surrounding central Borneo and the location and timing of vol-

canic activity in 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 thickening the crust, resulting in rapid erosion of sediments into the Neogene circum-Borneo
deltas, and ultimately leading to crustal melting.

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, but the simple rigid plate model overestimates the extension in this re-

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.

North Sumatra rotated counter-clockwise with south Malaya, and as the rotation proceeded the orientation of the Sumatran margin changed with respect to the Indian plate motion vector. The consequent increase in the convergent component of motion, taken up by subduction, may have increased magmatic activity in the arc and weakened the upper plate, leading to for-

mation of the dextral Sumatran strike-slip fault system taking up the arc-parallel component of India-Eurasia plate motion.

East of Borneo, the increased rate of subduc-
tion caused arc splitting in the Sulu arc and the
Fig. 9. Reconstruction of the region at 20 Ma. Collision of the north Australian margin in the region between the Bird’s Head microcontinent and eastern New Guinea occurred at about 25 Ma. The Ontong Java plateau arrived at the Melanesian trench at about 20 Ma. These two events caused major reorganisation of plate boundaries. Subduction of the Solomon Sea began at the eastern New Guinea margin. Spreading began in the Parece Vela and Shikoku marginal basins. The north Australian margin became a major left-lateral strike-slip system as the Philippine Sea-Caroline plate began to rotate clockwise. Movement on splays of the Sorong fault system led to the collision of Australian continental fragments in Sulawesi. This in turn led to counterclockwise rotation of Borneo and related Sundaland fragments, eliminating the proto-South China Sea. The Sumatra fault system was initiated.

Sulu Sea opened as a backarc basin (Hinz et al., 1991; Silver and Rangin, 1991) 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. This was a complex zone of opposed subduction zones linked by strike-slip faults. The Philippine islands and Halmahera were carried with the Philippine Sea plate to-
Fig. 10. Reconstruction of the region at 10 Ma. The Solomon Sea was being eliminated by subduction beneath eastern new Guinea and beneath the New Hebrides arc. However, continued subduction led to development of new marginal basins within the period 10-0 Ma, including the Bismarck Sea, Woodlark basin, North Fiji basins, and Lau basin. 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. Further west, motion on strands of the Sorong fault system caused the arrival of the Tukang Besi and Sula fragments in Sulawesi. Collision events at the Eurasian continental margin in the Philippines, and subsequently between the Luzon arc and Taiwan, were accompanied by intra-plate deformation, important strike-slip faulting and complex development of opposed subduction zones. Rotation of Borneo was complete but motion of the Sumatran forearc slivers was associated with new spreading in the Andaman Sea.

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 sub-
duction resulting in local volcanic activity. At the east edge of the Philippine Sea plate spreading terminated in the Shikoku basin.

As a result of the change in plate boundaries, fragments of continental crust were emplaced in Sulawesi on splays at the western end of the Sorong fault system. The earliest fragment to collide is inferred to have been completely underthrust beneath West Sulawesi and contributed to later crustal melting (Polvé et al., 1997). Later, the Tukang Besi platform separated from the Bird’s Head and was carried west on the Philippine Sea plate to collide with Sulawesi. Locking of splays of the Sorong fault caused subduction to initiate at the eastern margin of the Molucca Sea, thus producing the Neogene Halmahera arc. In this way 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 some rotation. In the southern part of the Solomons Sea subduction was in the opposite direction (eastward) and created the New Hebrides arc system. Spreading ceased in the South Fiji basin.

**10-0 Ma**

At the beginning of this period SE Asia was largely recognisable in its present form (Fig.10). 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. This may be the cause of the most recent regional change in plate motions at about 5 Ma. The Philippine Sea plate rotation pole moved north from a position east of the plate; clockwise rotation continued but the change in motion caused re-orientation of existing, and development of new, plate boundaries. 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.

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. The Banda Sea is here interpreted to be very young as suggested by Hamilton (1979) and others.

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). Within Eurasia reversal of motion on the Red River system may have been one consequence of the regional change in plate motions.

Opening of the Ayu trough separated the Caroline plate and Philippine Sea plate, although the rate of separation at this spreading centre was very low. 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 the 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 ocean crust formation in the North Fiji basins.

**Determining the extents of land and sea**

For the biogeographer, the tectonic development of the region is only a starting point for understanding. In order to understand the distribution of most organisms it is also necessary to know where there was land and sea, where the sea was shallow and deep, and how wide were the seas. For the land, there needs to be some knowledge of topography, particularly where there were mountainous regions. The distribution and character of land and sea will have provided physical pathways and barriers to dispersal, and may well have influenced plant and animal distribution by effects on other controlling factors such as local and global climate, oceanic circulation patterns, and sea-level.

However, moving from tectonic reconstruction maps to detailed palaeogeographical maps involves further complexities. In many ways the geological record is a marine record. Most of Earth history is recorded in rocks deposited at the surface, and the areas where most sediments are deposited are close to or below sea-level, and mainly at continental margins. Dating of rocks is largely based on fossils, and marine or-
ganisms generally provide the fossils of greatest biostratigraphic value which usually provide some insight into the environment of deposition. Geologists are therefore usually able to reconstruct the history of marine areas. In the deep oceans sedimentary rocks may lack fossils but the history of sediments deposited on ocean crust is known because ocean crust subsides with age due to lithospheric cooling and age-depth relationships are well established. Thus, many postulated land-bridges in oceanic regions can be dismissed with some confidence.

In contrast, mapping environments and physiography of former land areas is a great deal more difficult. 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. Unlike marine fossils, fossil assemblages from land rarely yield information about the history of their enclosing sediments relative to sea-level.

However, there are ways to solve some of these problems, and mapping palaeogeography onto the reconstructions is not, in principle, impossible although much of the information required is not yet available. It is possible to identify the positions of former coastlines, interpret the location of former river systems, and indirectly infer areas of mountains. In SE Asia some of the information can be compiled from the literature; an attempt to do this for the region of Wallace’s Line is discussed by Moss and Wilson (1998, this volume). Some data, for example location of former coastlines, could be determined from records of oil companies acquired during
extensive seismic surveys of SE Asia for hydrocarbons. New research could provide further detail and biogeographers themselves could also contribute by, for example, mapping distributions of fossil plants and interpreting their environments.

**Land and sea for 30-0 Ma**

Figs.11 to 16 are an attempt to compile the general features of land and sea onto maps of the tectonic reconstructions showing 5 million year intervals between 30 and 5 Ma for the region of SE Asia. The maps may be useful in indicating the likely geographical connections and barriers and the periods when these were in existence. There are few studies that compile this type of information and all cover limited parts of area for limited times. Thus these maps are based on those few sources, some proprietary information from oil companies, and a wide range of literature and maps. The sources are too numerous to cite and the quality of coverage is very variable. The task is a very large one, given the size of the area, and the results should therefore be regarded as a first order approximation only. I have not attempted to draw palaeogeographical maps for periods before 30 Ma. The period 30-0 Ma is of most interest to biogeographers; before then the separation between Asia and Australia was greater and the tectonic reconstructions are also more uncertain.

The limited ranges of environments and distributions shown are best estimates. Broadly speaking, each area shown should be regarded as a probability. For example, 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. Some of the assignments are educated
guesses. 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 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. It is usually not possible to identify precisely which areas were emergent, simply that there are likely to have been such areas.

The mid Oligocene (Fig.11) was the time of a major fall in global sea-level (Haq et al., 1987). Very large areas of Sundaland and Sunda shelf were exposed and there were probably more emergent areas than at any subsequent time until the end of the Cenozoic. North of Sundaland, Asia was a persistent highland area, and large amounts of sediment moved south from central Asia down major river systems. Much of southern Sundaland was the site of deposition of alluvial, fluvial and deltaic sediments. There were major embayments in the eastern Asian margin formed by the South China Sea, the proto-South China Sea and the Celebes Sea-Makassar Strait. Separating these were elongate bathymetric features which were probably mainly shallow water with intermittent emergent areas, notably where arc volcanoes were active. The southernmost promontory was the Sulawesi-Philippines-Halmahera arc which could have provided a pathway into the Pacific, via volcanic island stepping stones, for organisms that could cross seawater. The other promontories terminated in the deep ocean area of the Pacific.

At about 25 Ma (Fig.12) the north Australian margin came into contact with Sulawesi and the Halmahera arc, and this could have created a discontinuous land connection via the island
arcs of Halmahera and the Philippines into Sulawesi. The arc-continent collision closed the deep water passage between the Pacific and Indian oceans (Kennett et al. 1985) by about 20 Ma (Fig.13) and there must have been major changes of oceanic currents (Fig.17 and 18) with implications for the distribution of many marine organisms, particularly those of shallow marine environments. North-central Borneo was uplifted and shed huge volumes of sediments into the deltas which formed in north and east Borneo.

From about this time there was probably always some land in the area of Sulawesi, and the extensive but poorly dated Celebes molasse (Kündig, 1956) represents the products of subaerial erosion, although there were no permanent land links to Sundaland nor to Australia. However, there were intermittently emergent areas between Australia and Sulawesi, and a broad zone of shallow water within which there could have been numerous islands. Furthermore, strike-slip fault movements led to the arrival of numerous fragments of continental crust in Sulawesi, sliced from the Bird’s Head microcontinent. The northern Makassar Strait remained a deep water area, and presumably formed a barrier to migration for many plant and animals (Moss and Wilson, 1998 this volume).

From 15 Ma to 5 Ma (Figs.14, 15, 16) was a period in which emergent Sundaland reduced in area, while the deep marginal basins in the east were eliminated (proto-South China Sea) or reduced in size (Sulu, Celebes and Molucca Sea). Local collision and volcanic arc activity led to intermittent emergence in many of the arc regions but these probably always resembled the present Philippine and North Molucca arcs, with land separated by sea, which could locally have been quite deep. More of Borneo became emer-
gent and the central mountains on the Sarawak-Kalimantan border extending into Sabah became wider and higher with time. It is important to be aware that within this convergent setting deep basins also formed (e.g., Sulu Sea, Banda Sea) which must have represented new barriers to dispersal which formed at the same time as new land pathways were established.

Conclusions

There are three important periods in regional development. At about 45 Ma plate boundaries changed, probably as a result of India-Asia collision. From a biogeographical viewpoint the arrival of India would have led to a movement of Gondwana plants and animals into Asia. Mountain building resulting from the collision led to major changes in habitats, and climate, accompanied by changes in land area and drainage systems. Huge volumes of sediment began to move south from central Asia into the sedimentary basins of the Sunda shelf. Ultimately all this would have driven dispersal from Gondwana via India into SE Asia (e.g. Harley and Morley, 1995), and later speciation centred in Sundaland which for many organisms became separated from Asia by climate and topography, and which remained separated from Australia by marine barriers. Continued indentation of Asia by India modified the Eurasian continent but much more knowledge is required of the timing of fault movements and the amounts of displacements before Sundaland can be adequately understood. The deformation within Asia and Sundaland is likely to have led to the formation of geographical barriers, principally mountains, some of which were associated with strike-slip faults and geologically short-lived.

Fig. 16. Postulated distribution of land and sea in SE Asia at 5 Ma.
Fig. 17. Circulation patterns of surface and near-surface waters in the Pacific ocean inferred by Kennett et al. (1985) at three stages during the Neogene as the Indonesian sea-way closed. Black arrows indicate cold currents and unfilled arrows indicate warm currents.

Fig. 18. Possible circulation patterns of surface and near-surface waters in eastern Indonesia shown on the tectonic reconstructions of this paper. The currents postulated are based on Kennett et al. (1985) and present-day circulation patterns (Fine et al., 1994).
The second major period is around 25 Ma when plate boundaries and motions changed again, partly due to collision between the north Australian margin and arcs to the north. This, together with collision of the Melanesian arcs and the Ontong Java plateau, changed the tectonics of the oceanic-arc region east of Asia (Philippines, Celebes Sea, Sulu Sea, Philippine Sea, Caroline Sea, north New Guinea, New Britain, Solomons, Tonga). The 25 Ma event was probably the most important tectonic event from the biogeographical point of view as it led to new, albeit discontinuous, links between Australia via Sulawesi into SE Asia across areas which were mainly shallow marine and locally included land. It also resulted in a very long discontinuous island arc link between Asia and Melanesia. However, as the pathways between Australia and Sundaland came into existence, new barriers also formed. The central Borneo mountains began to rise in the early Miocene and became a regional drainage divide sending sediment north into the Sarawak basins and Baram delta, and southeast into the Tarakan and Mahakam deltas. North of Borneo, as the proto-South China Sea closed, the Oligo-Miocene South China Sea widened and the Sulu Sea opened. As the distance between Australia and Sulawesi closed, the deep Banda Sea opened. Thus, movement of plants and animals between Australia and Sundaland would have remained difficult. Perhaps it was this zone of barriers, close to a region of deep and former deep ocean barriers separating Borneo and Australia, which is the origin of Wallace’s line. The narrow Makassar Strait, which at its south end terminates in a long-lived discontinuous carbonate platform, could not alone have been a major barrier to dispersal.

Plate motions and boundaries changed again at about 5 Ma, possibly as a consequence of arc-continent collision in Taiwan, and in the last 5 Ma there has been renewed tectonic activity and a significant increase in land and highlands all round the margins of SE Asia. A number of new dispersal pathways developed across the region, for example those linking Taiwan and New Guinea through the Philippines and North Moluccas, and connecting New Guinea to Thailand via the Banda and Sunda arcs. It is also probable that there was an increase in the range of habitats along these routes, due to elevation of mountains, and likely associated variations in rainfall.

Disentangling the contribution of geology to biogeographic patterns is not simple. Geology and tectonics could be a controlling factor in some cases. Cicada distributions in New Guinea suggest a geological control (Boer and Duffels, 1996), and slicing of crustal fragments from the Bird’s Head could have caused influxes of faunas and floras into Sulawesi from Australia at intervals in the last 20 Ma. However, geology and tectonics also influence other variables which are more subtle controls on biogeographic patterns. Sea-level, elevation of land areas, soil, wind and water movements, and climate are all examples of factors upon which there is some geological influence. Climatic controls are too difficult to model at present, but at some time in the future it will be possible to use the tectonic models as the basis for simulation of ancient climates in SE Asia. It is notable that at present there are more highland areas, and a greater area of land than at any time during the last 30 million years. This is consistent with rather restricted areas of modern carbonate platforms which are limited in part by clastic sediment influx. The present distribution and size of shallow water carbonate areas may in part reflect a period of relatively low sea-level, but also record the recent rise of mountains due to tectonic forces as the area is compressed between Asia and Australia.

Some of the biogeographic patterns in SE Asia at present are difficult to relate simply to geology, for example, the distance between Borneo and Sulawesi (Wallace’s line and equivalents) should have been as easy to cross as the barriers between Australia and Sulawesi. This raises the question of the longevity of biogeographic patterns, about which we currently lack adequate information. During the last million years there have been periods of low sea-level associated with glacial intervals when far greater areas of land were emergent than at present, and the present areas are significantly greater than those during the Neogene. Much of the Sunda shelf would have been emergent although in eastern Indonesia there are many narrow deep water areas (such as the Makassar Strait) which would have remained physical barriers. However, elsewhere large sea-level falls would have separated some formerly connected ocean basins as shallow water areas became emergent, changing oceanic circulation patterns and modifying weather and climate (e.g. Huang et al., 1997). Fluctuations in temperatures and rainfall are likely to have been more extreme at intervals in the last million years than in the preceding 30 million years. Therefore, the last period of geological history, perhaps one million years or
even much less, may have had a far greater influence on biogeographic patterns than the much longer period before.

To go further, detailed maps of land and sea, and palaeo-topography must be compiled from published maps and papers, and unpublished coastline, shelf edge, age and litho-facies information, much in oil company files. In particular the display of uplift and subsidence, and timing of magmatic events, on tectonic reconstructions would help in identifying underlying processes and give more confidence in mapping land and sea into areas where there is little direct evidence. Biogeographers must contribute, for example, distributions of fossil plants can provide information on palaeo-temperatures and environments. There is a need to focus on biogeographic patterns which are most likely to reveal the links to geology using plants and animals which have difficulty in dispersing, and for which non-geological controls are unimportant. It is for the biogeographers to identify such critical floral and faunal indicators. We still know little about rates of speciation and dispersal, and for most animals and plants the fossil record is poor or non-existent. DNA studies offer one way of determining a time-scale for biological development which could contribute to an explanation of biogeographic patterns. Another way forward is mathematical simulation of the biological variables, testing biogeographic patterns against predictions. It is certain that no single factor will account for the distribution of plants and animals in SE Asia; tectonic movements may be a control but their importance is still far from clear.

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Colour plates for:

The plate tectonics of Cenozoic SE Asia and the distribution of land and sea

Robert Hall
SE Asia Research Group, Department of Geology, Royal Holloway University of London

Captions

Fig. 5. Present-day tectonic features of SE Asia and the SW Pacific. Yellow lines are selected marine magnetic anomalies. Cyan lines outline bathymetric features. Red lines are active spreading centres. White lines are subduction zones and strike-slip faults. The present extent of the Pacific plate is shown in pale blue. Areas filled with green are mainly arc, ophiolitic, and accreted material formed at plate margins during the Cenozoic. Areas filled in cyan are submarine arc regions, hot spot volcanic products, and oceanic plateaus. Pale yellow areas represent submarine parts of the Eurasian continental margins. Pale and deep pink areas represent submarine parts of the Australian continental margins. Letters represent marginal basins and tectonic features as follows:

Marginal Basins

A Japan Sea  B Okinawa Trough  C South China Sea  D Sulu Sea  E Celebes Sea  F Molucca Sea  G Banda Sea  H Andaman Sea  I West Philippine Basin  J Shikoku Basin  K Parece Vela Basin  L Mariana Trough

Tectonic features

Ba Bandar Arc  BH Bird's Head  Ca Cagayan Arc  Fj Fiji  Ha Halmahera Arc  Ib Izu-Bonin Arc  Ja Japan Arc  Lo Loyalty Islands  Lu Luzon Arc  M Mariana Trough  N Nth China Sea  P Paracel Islands  R Rennell Rise  S Solomon Islands  Tu Tuvalu  V Viti Levu  W Wake Island  X Xiamen Island  Y Yamanashi

Fig. 6. Reconstruction of the region at 50 Ma. The possible extent of Greater India and the Eurasian margin north of India are shown schematically. Shortly before 50 Ma collision between the north Australian continental margin and an island arc had emplaced ophiolites on the north new Guinean margin, and in New Caledonia, eliminating ocean crust formed at the former Australian-Indian ocean spreading centre. Double black arrows indicate extension in Sundaland.

Fig. 7. Reconstruction of the region at 40 Ma. India and Australia were now parts of the same plate. An oceanic spreading centre linked the north Makassar Strait, the Celebes Sea and the West Philippine basin. Spreading began at about this time in the Caroline Sea, separating the Caroline Ridge remnant arc from the South Caroline arc. Spreading also began after subduction flip in marginal basins around eastern Australia producing the Solomon Sea and the island arcs of Melanesia.

Fig. 8. Reconstruction of the region at 30 Ma. Indentation of Eurasia by India led to extrusion of the Indochina block by movement on the Red River Fault and Wang Chao-Three Pagodas (WC-TP) Faults. 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. A wide area of marginal basins separated the Melanesian arc from passive margins of eastern Australia, shown schematically between the Solomon Sea and the South Fiji basin.

Fig. 9. Reconstruction of the region at 20 Ma. Collision of the north Australian margin in the region between the Bird's Head microcontinent and eastern New Guinea occurred at about 25 Ma. The Ontong Java plate arrived at the Melanesian trench at about 20 Ma. These two events caused major reorganisation of plate boundaries. Subduction of the Solomon Sea began at the eastern new Guinean margin. Spreading began in the Parece Vela and Shikoku marginal basins. The north Australian margin became a major left-lateral strike-slip system as the Philippine Sea-Caroline plate began to rotate clockwise. Movement on spays 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 related Sundaland fragments, eliminating the proto-South China Sea. The Sumatra Fault system was initiated.

Fig. 10. Reconstruction of the region at 10 Ma. The Solomon Sea was being eliminated by subduction beneath eastern new Guinea and beneath the New Hebrides arc. However, continued subduction led to development of new marginal basins within the period 10-0 Ma, including the Bismarck Sea, Woodlark basin, North Fiji basins, and Lau basin. 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. Further west, motion on strands of the Sorong Fault system caused the arrival of the Tukang Besi and Sula fragments in Sulawesi. Collision events at the Eurasian continental margin in the Philippines, and subsequently between the Luzon arc and Taiwan, were accompanied by intra-plate deformation, important strike-slip faulting and complex development of opposed subduction zones. Rotation of Borneo was complete but motion of the Sumatran forearc slivers was associated with new spreading in the Andaman Sea.
50 Ma
End Early Eocene
40 Ma
Middle Eocene
20 Ma
Early Miocene
10 Ma
Late Miocene