

# Reconstructing Cenozoic SE Asia

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**Abstract:** Reconstructions of SE Asia at 5 Ma intervals for the past 50 Ma are presented. They are constrained by new data from the Philippine Sea plate, which forms the eastern boundary of the region, by recent interpretations of the South China Sea and Eurasian continental margin, forming the western boundary, and by the known motions of the Indian-Australian plate to the south. An attempt is made to satisfy geological and palaeomagnetic data from the region. The implications of these reconstructions for the Tertiary evolution of SE Asia are discussed in the light of other new data from the region. There are two regionally important periods of change during the past 50 Ma. Both appear to be the expression of arc-continent collision and resulted in major changes in the configuration of the region and in the character of plate boundaries. At *c.* 25 Ma the collision of the Australian continent with the Philippine Sea plate arc caused major effects which propagated westwards through the region. At *c.* 5 Ma collision of the Philippine arc and the Eurasian continental margin occurred in Taiwan. This appears to be a key to the recent tectonics of the region. Principal features of the model include the following interpretations. Middle Tertiary counter-clockwise rotation of Borneo closed a large proto-South China Sea and led to the development and destruction of marginal basins north of the Celebes Sea. The rotation implies that much of the north Borneo margin was not a subduction, but a strike-slip, boundary for most of this period. It also suggests that the central West Philippine Sea, the Celebes Sea and the Makassar Strait formed part of a single marginal basin which opened between late Eocene and mid Oligocene, and narrowed westwards like the present South China Sea. Luzon is suggested to have formed in an arc on the north side of the Celebes Sea-West Philippine Basin, whereas most of the other Philippine islands probably formed part of an arc at the southern edge of the Philippine Sea Plate before the Early Miocene. Arc-continent collision in the early Miocene caused plate boundaries to change and initiated the clockwise rotation of the Philippine Sea plate. Since then the Philippine fragments have moved in a very narrow zone, mainly as part of the Philippine Sea plate, with significant strike-slip motion of fragments at the plate margin. Most subduction under the Philippines was oblique, mainly at the western edge, and north of Mindanao. The Molucca Sea was a very wide area which formed part of the Philippine Sea plate before *c.* 15 Ma and originated as trapped Indian ocean lithosphere. It has been eliminated by subduction on its east and west sides. The present-day double subduction system never extended north of the present Molucca Sea into the Philippines. The Sulawesi ophiolite has an Indian ocean origin and was emplaced on the west Sulawesi continental margin at the end of the Oligocene. The major change in plate boundaries at the beginning of the Miocene following arc-continent collision of the Australian margin with the Philippine Sea plate arc caused initiation of the Sorong Fault system and led to westward movement of continental fragments which were accreted to Sulawesi during the late Neogene. The Sula platform and Tukang Besi platform formed part of a single large microcontinent with the Bird's Head before *c.* 15 Ma. They moved to their present positions after slicing of fragments from this microcontinent at different times and each was attached to the Philippine Sea plate for a few million years before collision. Most of the Banda Sea is interpreted to have an extensional origin and to have opened during the late Neogene. The reconstructions imply that there has been little convergence at the north Australian margin in Irian Jaya since the early Miocene and most convergence has occurred during the last ~5 Ma. Movement of Philippine Sea arc fragments within the northern New Guinea margin along strike-slip zones probably accounts for the terrane character of this orogenic belt.

Plate tectonic reconstructions of SE Asia have some obvious practical value for the region in helping to understand the development of sedimentary basins, the history of volcanic arc activity, and similar processes which are linked through tectonics to the distribution of natural resources. Reconstructions are also a necessary precursor to

understanding more fundamental processes that have acted. What are the important controls on the tectonic development of the region (e.g. the role of indenter tectonics), what are the critical events (e.g. different types of collision event), and what is the nature of deformation (e.g. rigid plate versus distributed deformation)? How far can plate

tectonics go in describing the development of the region and the behaviour of crust and lithosphere (e.g. what is the role of strike-slip faulting versus contraction in the development of young orogenic belts)? Similar, more general questions have relevance to collision processes and to the understanding of ancient orogenic belts for which parts of SE Asia have often been used as analogues.

During the Cenozoic the region which now forms SE Asia was bounded to the north and west by a Eurasian plate, and to the south by the Indian-Australian plate. The motions of these plates are reasonably well known and their positions provide limits to the zone within which the SE Asian collage of microplates and sub-plate fragments can be moved when attempting plate reconstructions. The boundaries provided by these plate motions have been used as limits in previous reconstructions of Cenozoic SE Asia (e.g. Daly *et al.* 1991; Rangin *et al.* 1990; Lee & Lawver 1994). There have been considerable differences in dealing with the eastern boundary of the region. At present, the eastern edge of SE Asia is bounded by the Philippine Sea plate but the motion of this plate has been difficult to link to the global plate circuit because it is surrounded by subduction zones. Its Tertiary movement history has proved controversial, as illustrated by previous reconstructions, and there are major uncertainties in the position of the eastern edge of the region. Rangin *et al.* (1990) accepted evidence for clock-wise rotation of the plate whereas Daly *et al.* (1991) and Lee & Lawver (1994) did not.

Hall *et al.* (1995b) used palaeomagnetic data from east Indonesia to estimate Tertiary poles of rotation for the Philippine Sea plate and made a new reconstruction of this plate based on these poles, incorporating the effects of marginal basin opening within the plate. Discontinuous clockwise rotation for the entire plate during the last 50 Ma leads to palaeolatitudes predictions which closely fit all palaeomagnetic data and also satisfies constraints on rotation inferred from magnetic anomaly skewness and seamount magnetisation studies from the Philippine Sea plate. This model has been used to define the eastern margin of SE Asia as the basis for reconstructing the region using the ATLAS computer program (Cambridge Paleomap Services 1993) for the last 50 Ma. Fig. 1 shows the present geography of the region and identifies the principal tectonic elements used in the reconstructions. Approximately sixty fragments (the number changes with age) have been used in reconstructing the region. Mercator projections showing reconstructions of the area bounded by latitudes 20°S and 30°N, and longitudes 90°E and 160°E, are presented for 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 Ma as Figs. 2 to 11.

Details of rotation poles, and fragments used, are listed in Tables 1 and 2 which are available as Supplementary Publication No. SUP18101 (5 pp) from the Society Library and the British Library Document Supply Centre, Boston Spa, Wetherby, N Yorks LS23 7BQ, UK as The reconstruction is also available as an animation, on floppy discs, which can be run on either a Windows-based PC or a Mac with adequate hard disc space. Contact the author for details.

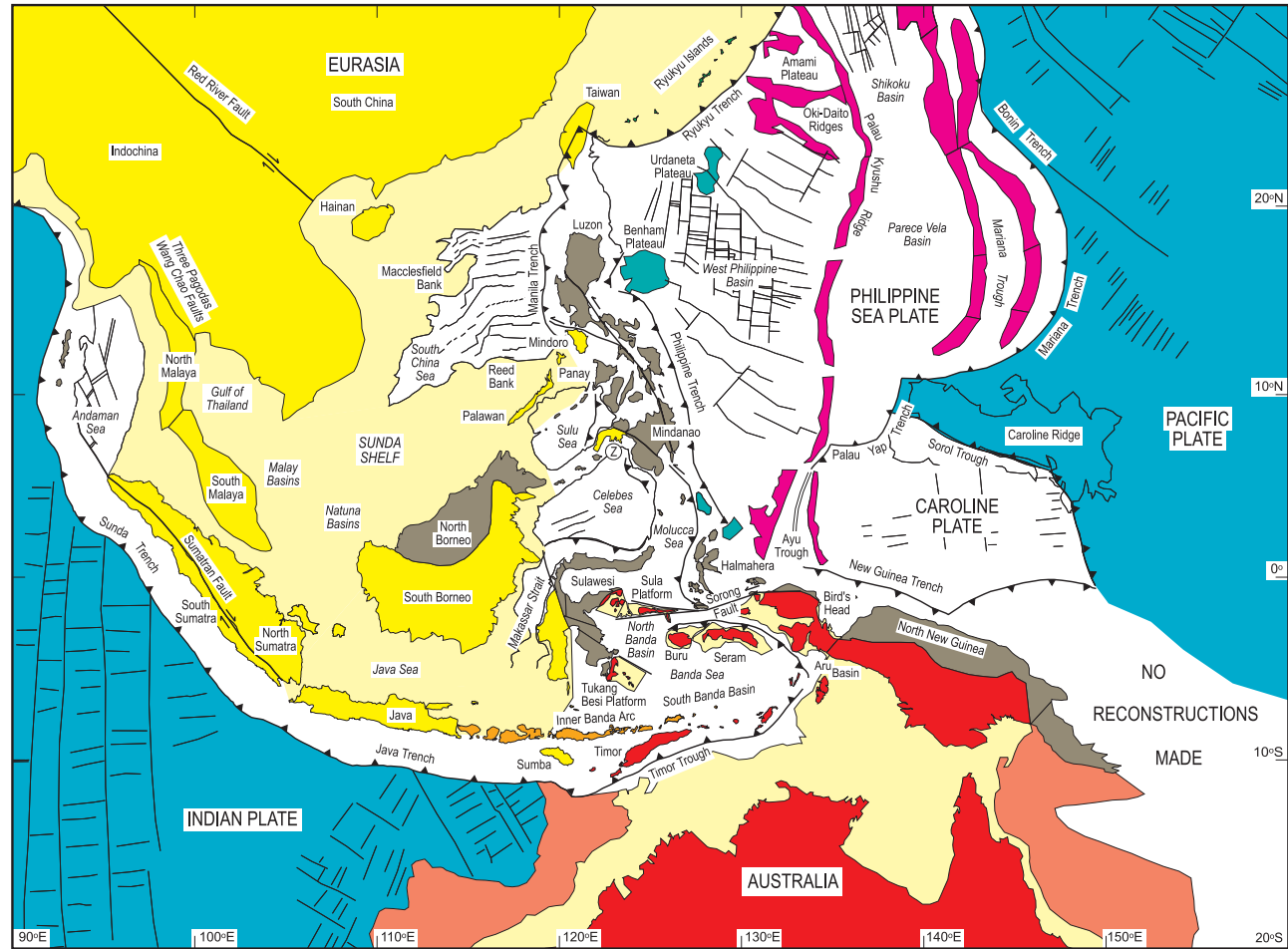
## Methods

### *ATLAS Model*

The ATLAS model uses a palaeomagnetic reference frame with Africa as the reference fragment with its movement defined relative to magnetic north. Movements of other major plates relative to Africa are based on Cande & Leslie (1986), Cochran (1981), Fisher & Sclater (1983), Klitgord & Schouten (1986), Le Pichon & Francheteau (1978), McKenzie *et al.* (1970), Royer & Sandwell (1989), Sclater *et al.* (1981), Ségoufin & Patriat (1980) and Srivastava & Tapscott (1986). In these reconstructions South China is used as a reference and this is fixed to Eurasia for the period 50-0 Ma. There has been little Cenozoic motion of Eurasia whichever reference frame is used (e.g. Livermore *et al.* 1984; Gordon & Jurdy 1986; Besse & Courtillot 1991; Van der Voo 1993) and therefore it remains in a similar position to the present-day in all the reconstructions. In the ATLAS model there are small movements of Eurasia due to the plate circuit used, particularly in the last 5 Ma, and therefore there are minor differences compared to reconstructions which use a fixed Eurasia (Lee & Lawver 1994; Rangin *et al.* 1990).

### *Palaeomagnetic Data*

The model attempts to include the important constraints imposed by palaeomagnetism. Palaeomagnetic data can help to put some limits on interpretation of geological data since in principle they provide indications of palaeolatitudes and rotations. Interpretation is not always simple, and in SE Asia it is particularly difficult to reach unambiguous solutions. Van der Voo (1993) discusses in detail the use and problems of using palaeomagnetic results, and provides a particularly clear summary of problems in SE Asia. Besides the obvious drawbacks of collecting data in predominantly tropical, remote and often harsh terrain, there are additional problems such as error limits, remagnetisation, and equatorial ambiguities. Not least amongst these are the difficulties of deciding



**Fig. 1.** Simplified present-day tectonic configuration of SE Asia. Shaded areas represent mainly ophiolitic, arc and other accreted material added to Eurasian and Australian margins during the Tertiary. Principal marine magnetic anomalies are shown schematically for the Indian ocean, Pacific ocean, South China Sea, Philippine Sea and Caroline Sea. Circled Z identifies Zamboanga peninsula of Mindanao. Double lines represent active spreading centres. Narrow lines represent principal bathymetric features of the Philippine Sea plate and the Caroline Ridge; the margins of the oceanic parts of the South China Sea, the Celebes Sea and the Andaman Sea; and deeper parts of the Sulu Sea and the Makassar Strait. Complexities in the Bismarck-Solomon Sea regions are not shown.

which interpretations of palaeomagnetic results should be accepted.

One major problem with palaeomagnetic data, often not emphasised by the palaeomagnetists, is determining the motion *history* of a region. This is particularly important in areas where, for example, there are results from Mesozoic or older rocks, but few or no results from Tertiary rocks, such as the Malay peninsula and Thailand. Similarities in declinations of similar age rocks may indicate a common regional rotation history but in some cases similar declinations may be the results of different Tertiary motion histories for separate blocks (cf. Celebes Sea counter-clockwise rotation and age, versus Borneo counter-clockwise rotation and age, which are discussed below). Sea-floor magnetic data from the South China Sea, for the Celebes Sea and the West Philippine Sea central basin also provide limits, although in all cases there are uncertainties in anomaly ages and correlation.

The distinction between local and regional rotations is far from clear in SE Asia, particularly because good palaeomagnetic data are sparsely scattered in time and space, and modelling such as that attempted here shows clearly the need for long term, systematic and integrated palaeomagnetic-geological studies of the region. It is possible to avoid many difficulties with palaeomagnetic data by explaining apparently anomalous or controversial evidence of movements as a consequence of local tectonics. This is often sensible, and Surmont *et al.* (1994) provide an excellent SE Asian example of how previously inferred large regional rotations are better interpreted as very local consequences of tectonics. However, at the same time they show that smaller systematic regional rotations can be recognised, and we must accept that much essential evidence for movements, for palaeogeographic reconstructions, and certainly for rotation about vertical axes, can only be acquired from palaeomagnetism and therefore to ignore all palaeomagnetic data is a position of despair. The present author has tried to distinguish regional scale movements from local movements but in several cases, principally Sundaland-Borneo and the Philippines, a choice has to be made between different views on the basis of inadequate data. In these cases decisions were based on regional geological arguments, recognising that other solutions are possible. But once a critical decision has been made, for example in this model that of accepting a large counter-clockwise rotation of Borneo, the reconstructions become both a development, and a partial test, of the decision; can reasonable reconstructions then be made that are consistent with the geological data set for the whole region? Thus, the reconstructions presented here

should be seen as a way of distinguishing local and regionally important data sets, identifying targets for future work, and a possible model of the region which provides a different, albeit sometimes controversial, interpretation of the development of SE Asia.

### *Principles and Tests*

The fragments were left at current size in all reconstructions in order that they remain recognisable. This is broadly satisfactory for Neogene reconstructions, except for some areas of volcanic arcs. The present shape of fragments has been maintained although this may contribute to overlap of blocks if significant new crust has been created, which must be the case in the Sunda, Banda and the Philippine arcs. Before the Neogene many of the fragments may have had quite different sizes and shapes or simply may not have existed. This is true for many areas in which the extent or age of the basements is uncertain, for example, in parts of Philippines, Sangihe arc, Sulu arc, Java, Banda arc. In some cases, this has been incorporated by omitting the fragment before a certain time. For instance, most of the Bonin forearc did not exist at *c.* 50 Ma and probably grew during a period of rapid volcanism in the Eocene (Stern & Bloomer 1992; Taylor 1992). Thus, some fragments may not appear on all reconstructions between Figs. 2 and 11.

In moving fragments Occam's razor has been used in an attempt to find the simplest possible motion histories. Fragments were first attached, or partially coupled to, a major plate with known motion; most minor fragments can be linked in this way to a major plate (Australia, Eurasia, Philippine Sea). If more complex movements were required, experiments were made with transferring fragments from one major plate to another. During the reconstruction process possible solutions were tested by asking (1) are the palaeomagnetic data satisfied? (2) are the geological data satisfied? and (3) is there overlap of fragments during movements? As discussed below, both (1) and (2) require subjective interpretations and judgements; readers will inevitably have their own views of the value of these. The most important sources are cited and the reader may refer to regional compilations and reviews such as Hamilton (1979); Hutchison (1989) and Van der Voo (1993) for overviews of geology and palaeomagnetism. Below, are summarised the main features of the data used and the reconstructions made for principal sub-areas within SE Asia. The implications of the judgements and interpretations made for the development of the region are then discussed.

## Regions considered

### *Indochina and South China Sea*

In the reconstructions South China is fixed to stable Eurasia. The Indochina block south of the Red River fault and north of the Malay peninsula has been moved using the model of Briais *et al.* (1993). They suggest approximately 550 km of movement on the Red River fault system with left lateral motion since the late Miocene. Their average small circle pole (5.3°N, 66.3°E) results in significant overlap of Indochina and South China and this model therefore uses a small circle rotation pole (20.9°S, 61.5°E) further from the Red River fault, as Briais *et al.* (1993) suggest should be the case, which results in a smaller overlap but still provides the history of contraction and extension that they summarise. The movements on the fault estimated by them yield an approximately linear age-displacement relationship and the model assumes regular displacement in the interval 15-32 Ma. The area between the Indochina coast and the present north Borneo coast is underlain by continental crust and the north Borneo margin has been fixed to Indochina to provide an indication of the northern edge of the proto-South China Sea created by removing the extrusion of the Indochina block.

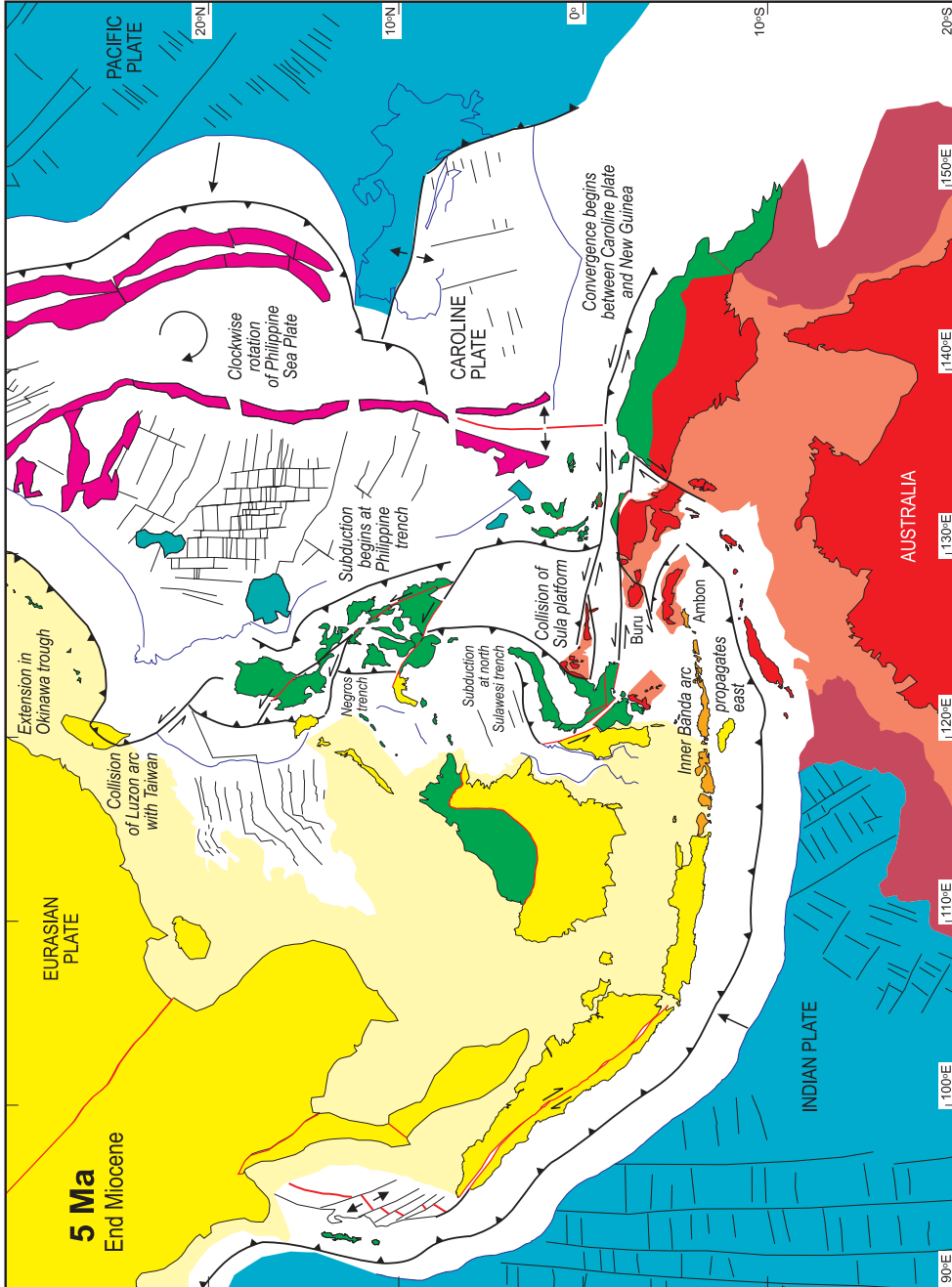
Taylor & Hayes (1980, 1983) identified ocean floor magnetic anomalies and used these to interpret the opening history of the South China Sea. This interpretation has been modified by Briais *et al.* (1993) and their model of opening, using their calculated poles of rotation, has been used in the reconstructions without change except for reassigning anomaly ages to the Harland *et al.* (1990) time scale. Palawan and Mindoro have been moved with Reed Bank in the reconstructions. The islands of Palawan and Mindoro are considered to include continental crust of south China origin and the bathymetric contour marking the north side of the Cagayan ridge is assumed to mark the southern limit of continental crust. The northwest part of the Sulu Sea is thus considered to be underlain by continental crust (Hinz *et al.* 1991).

### *Borneo*

The basement of Borneo of western and interior Borneo consists of Palaeozoic and Mesozoic igneous, sedimentary and metamorphic rocks and this area behaved more or less as a craton during the middle and late Tertiary. To the north are younger additions to this continental core which have been interpreted as subduction accretionary complexes (Hamilton 1979) although this view is not universally accepted. In this work north and

south Borneo have been separated at the Lupar line, which is a zone of Mesozoic ophiolites and south Borneo has been treated as a single rigid fragment back to 50 Ma. West Sulawesi separated from east Borneo in the Tertiary, resulting in opening of the Makassar Strait and the development of large sedimentary basins in east Kalimantan. West Sulawesi has a long Tertiary history of igneous activity and the present eastern margin of the Sundaland block appears to have been an active margin for much of the Tertiary.

There are two principal large-scale tectonic views of Borneo: one advocates a large counter-clockwise rotation of the island, the second argues for no rotation of Borneo. Palaeomagnetic results are reported by Haile *et al.* (1977), Haile (1979), Schmidtke *et al.* (1990), Wahyono & Sunata (1987) and Lumadyo *et al.* (1993). These results are reviewed by Fuller *et al.* (1991) and Lee & Lawver (1994); the former favour a counter-clockwise rotation of the island and the latter favour no rotation. It is clear that the existing palaeomagnetic data are inadequate to reach a conclusion and those who reject the rotation of Borneo (Lumadyo *et al.* 1993; Lee & Lawver 1994; Rangin *et al.* 1990) emphasise the problems with the data. However, although not all the evidence points in the same direction there are also regional geological arguments that favour rotation and this model accepts a counter-clockwise rotation of southern Borneo. The major obstacle to incorporating the rotation in a regional tectonic model is determining the position of the rotation pole. The chosen pole is close to the northwest corner of Borneo (1°N, 110°E). This allows Borneo to remain part of a Sunda block while permitting the rotational movement to be absorbed within the north Borneo accretionary complexes by closing a proto-South China Sea. It implies some extension between Borneo and the Malay peninsula and allows the southern boundary of Sundaland to rotate northwards. Because the pole is so close to the northwest corner of Borneo it requires no major deformation of the Sunda shelf to the northwest, although minor deformation would be expected. The earliest inversion event in the West Natuna Basin (Ginger *et al.* 1993) is Early Miocene, which is consistent with the timing chosen for the rotation (see below). The movement requires counter-clockwise motion of west Sulawesi with little latitude change, for which there is some evidence. It fails to account for the similarity of the Thailand and peninsula Malaysia counter-clockwise rotations reported by McElhinny *et al.* (1974) and Schmidtke *et al.* (1990). However, poles further from Borneo which could account for these data result in a much larger proto-South China Sea and also require large latitude changes which are not seen in the palaeomagnetic data.



Data from SW Sulawesi indicate that the SW arm was close to its present latitude in the late Jurassic (Haile 1978) and late Paleogene (Sasajima *et al.* 1980) but has since rotated counter-clockwise by about 45°. Directions recorded by late Miocene volcanic rocks of the SW arm are indistinguishable from those of the present field. The palaeomagnetic results from SW Sulawesi are very similar to those from Cretaceous rocks of the Malay Peninsula (McElhinny *et al.* 1974) and in Borneo (Fuller *et al.* 1991) there are similar counter-clockwise rotations since the late Mesozoic and before the late Miocene. The limited evidence from west Sulawesi and Borneo suggests that counter-clockwise rotation occurred before the late Miocene and sometime during the late Paleogene to middle Miocene. This model therefore uses a rotation of 45° between 20 and 10 Ma.

#### *Thai-Malay Peninsula*

There are a number of faults at the southern boundary of Indochina on which there is likely to have been Tertiary movement although currently the movement histories of these faults are not well known. The Indochina block is separated from Thailand and peninsula Malaysia on a line representing the Three Pagodas and Wang Chao faults. This is undoubtedly an oversimplification and movement of the Malay blocks in the reconstructions cannot account fully for the formation of the sedimentary basins of the western part of the South China Sea. The movement history of the Thai-Malay region is difficult to determine. Offshore, in the western South China Sea, are several large sedimentary basins with complex trans-tensional histories (e.g. Ngah *et al.* 1996; Tjia and Liew 1996). The land area largely lacks Tertiary rocks and palaeomagnetic results do not provide a clear

picture. Post-Cretaceous clockwise rotations are recorded in Thailand and northern Malaysia (Schmidtke *et al.* 1990; Fuller *et al.* 1991) whereas counter-clockwise rotations (McElhinny *et al.* 1974; Haile *et al.* 1983; Schmidtke *et al.* 1990; Fuller *et al.* 1991) are reported from Tertiary and older rocks further south. Therefore a north Malaya block has been separated from a south Malaya block at the Khlong Marui fault. There is no evidence for a major suture separating the Malay peninsula from west Borneo and the counter-clockwise rotations recorded are similar from both regions. However, moving both the Malaya blocks with south Borneo results in major overlap of the peninsula and Indochina. Hutchison (1989) observed, based on the compilation of Haile & Briden (1982), that although the declinations recorded in rocks from peninsula Malaysia and Borneo are similar, there are large differences in inclinations; these differences are also seen in more recent results (Fuller *et al.* 1991). Thus, it is possible that the counter-clockwise rotations of Borneo and Malaysia are of different ages. The model rotates the south Malaya block counter-clockwise about the same pole as that used for south Borneo but reduces its counter-clockwise rotation to 15°. In contrast, clockwise rotations could be explained by extrusion of Indochina. The north Malaya block is rotated clockwise relative to south China using a pole close to the fragment. This keeps the Indochina and north and south Malaya blocks close together and implies late Tertiary trans-tensional faulting in the zone of the Three Pagodas fault where the Indochina and north Malaya fragments overlap before 20 Ma. Rotations are assumed to have occurred between 20 and 10 Ma in order to maintain the separation of the peninsula and south Borneo and to maintain the northern and southern parts of the peninsula as a

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**Fig. 2.** 5 Ma reconstruction of SE Asia. At this stage the Philippine Sea plate was rotating clockwise about a pole close to its north edge (48°N, 157°E; outside the figure) and the Luzon arc collided with the Eurasian margin in Taiwan. On this and the following figures Eurasian blocks and blocks forming part of Sundaland, with areas accreted to its continental core before the early Tertiary, are shown in yellow. The Sunda Shelf and its extensions are shaded in pale yellow. The present areas of the Indian and Pacific plates are coloured blue. Blocks of Australian continental origin are shown in red. Areas shaded in pink are shallow and deep parts of the Australian continental margin. Submarine parts of Sula, Buton-Tukang Besi, and Bird's Head-related fragments are also shaded with pink. Areas shown in green are mainly volcanic arc, ophiolite and accreted material of the Ryukyu islands, the Philippines, north Moluccas, north Borneo, Sulawesi and northern New Guinea. The volcanic islands of the inner Banda arc are shown in orange. Areas within the Philippine Sea plate filled with magenta are remnant arcs. Thin black lines are used to show principal marine magnetic anomalies of the Indian ocean, Pacific ocean, South China Sea, Philippine Sea and Caroline Sea. Thin light blue lines represent marine bathymetry outlining at different stages the present limits of the Philippine Sea plate, Caroline Ridge, Caroline Sea, Sulu Sea, Andaman Sea, margins of the Makassar Strait, and the Java-Sunda, the Izu-Bonin-Mariana-Yap-Palau, Negros and Manila trenches. Complexities in the Bismarck-Solomon regions are not shown. Red lines with short paired arrows represent active spreading centres. Half arrows represent strike-slip motion. Thick black and red lines represent major faults or fragment sutures used in the reconstructions. Long arrows indicate motion directions of major plates. Circular arrows represent rotations.

broadly continuous fragment. Some extension is also predicted by the model from about 32 Ma as a result of Indochina extrusion.

#### *Sumatra and the Andaman Sea*

North Sumatra is fixed to the south Malaya block for all the reconstructions. Because of the rotation of south Malaya discussed above, the Sumatran margin before 20 Ma would have been closer to N-S and sub-parallel to the motion vector for the Indian plate. In this configuration it is possible that the partitioning of convergence into an orthogonal subduction component and a parallel strike-slip component would not occur. South Sumatra is fixed to north Sumatra before 15 Ma. As the counter-clockwise rotation of the Malay peninsula, Sumatra and Java proceeded, the angle between the Sumatran margin and the Indian plate motion vector would have become less oblique leading to formation of the dextral strike-slip system. Dextral motion along the Sumatran Fault zone is incorporated between 15 and 0 Ma. Rotating north Sumatra with the Malay peninsula can also account for extension in the Andaman Sea. The Andaman region has been included in the reconstructions but the model is probably over-simplified. The bathymetry of the Andaman Sea is complex (Curry *et al.* 1979) and very simplified bathymetric contours on the east and west sides of the sea are used as markers, fixed to north and south Sumatra respectively. This suggests that before *c.* 10 Ma there was a small amount of orthogonal extension. After *c.* 10 Ma extension was greater but highly oblique. This is broadly consistent with the age of the oldest oceanic crust in the Andaman Sea (*c.* 11 Ma) and the recent pattern of opening (Curry *et al.* 1979).

#### *Java*

Java is included largely for completion and has been rotated counter-clockwise by 30° between 20 and 10 Ma. This is a compromise between the rotations chosen for Sumatra and south Borneo. There is no evidence for great extension of the Java Sea during this period (e.g. Bishop 1980; Van der Weerd & Armin 1992), but if Java is rotated rigidly with south Borneo there is too much overlap of Java and Sumatra. The difference in the amounts of rotation for south Borneo and Java would permit some extension, and probable strike-slip faulting, of the east Java Sea between 20-10 Ma. Because the pole of rotation is so close to the Borneo, Java and the north Sumatra blocks there is no significant change in their relative positions, although there is some overlap of Java and Sumatra. This could be accounted for by

assuming arc-parallel extension since both Java and Sumatra are likely to have been smaller than their present-day outlines, as indicated by the extensional histories of Neogene sedimentary basins of Sumatra, and the volume of Neogene arc volcanic rocks.

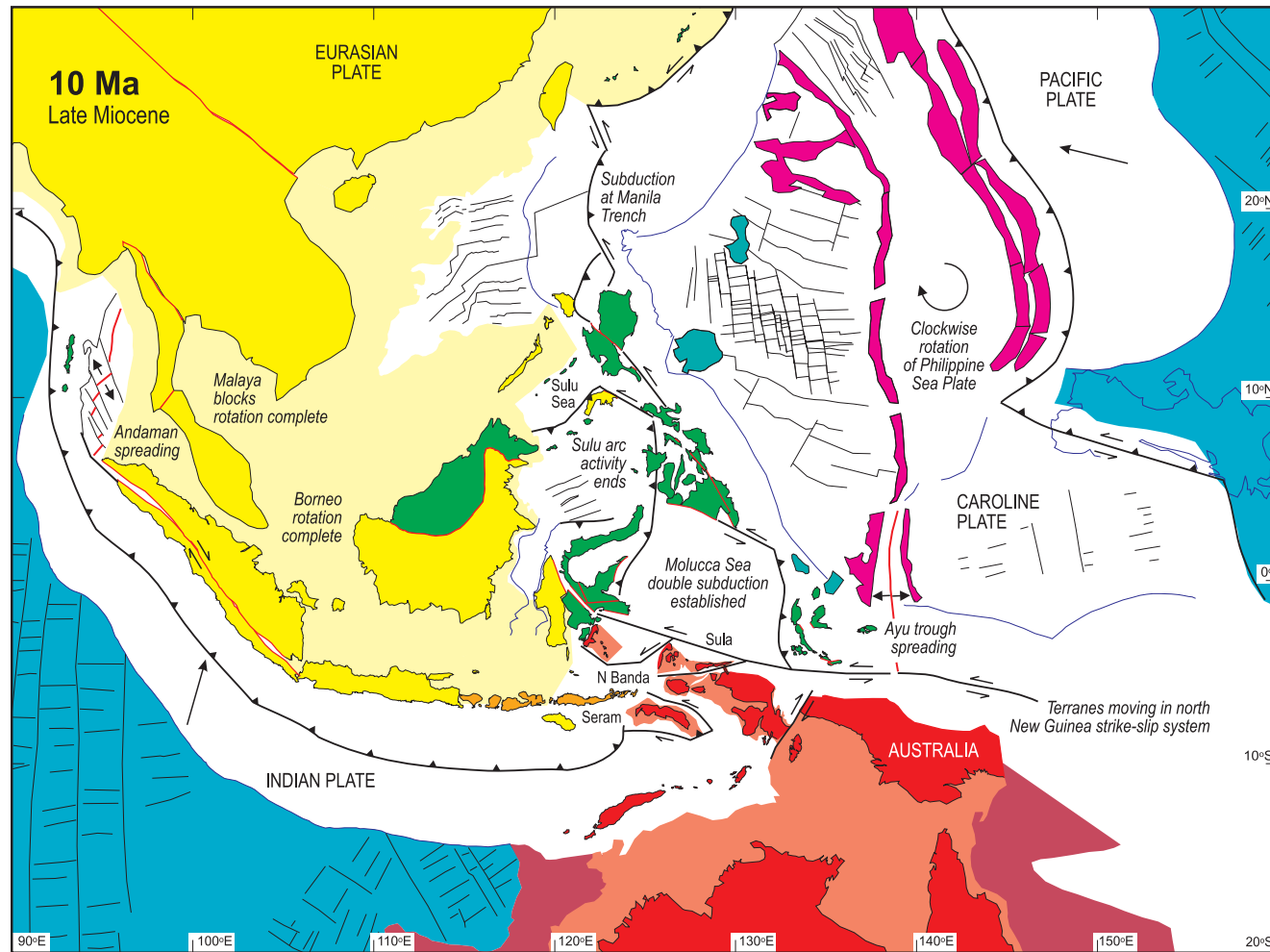
The counter-clockwise rotation gives an assessment of the likely pre-middle Miocene orientation of the subduction zone south of Sumatra and Java which is closer to NW-SE than present-day. The rotation also has implications for the tectonic history of Java (e.g. oblique subduction could have caused strike-slip motion) and for the timing of volcanism. The model predicts important changes in volcanic and tectonic history beginning at about 20 Ma for both Java and Sumatra. The subduction boundary south of Java must have changed eastwards to a more complex link into the Pacific.

#### *Sulawesi*

Sulawesi consists of four principal tectonic belts: the west Sulawesi volcano-plutonic Arc, the central Sulawesi metamorphic belt, the east Sulawesi ophiolite belt, and the continental fragments of Banggai-Sula, Tukang Besi and Buton. This configuration has been widely interpreted in terms of collision between the eastern micro-continental fragments and the western volcanic arc (e.g. Audley-Charles *et al.* 1972; Katili 1978; Hamilton 1979; Silver *et al.* 1983a) resulting in ophiolite emplacement and metamorphism. However, more recent work shows that this apparent simplicity is partly a reflection of incomplete knowledge of the region. There is evidence of several episodes of subduction beneath the west Arm of Sulawesi since at least the late Cretaceous (Hamilton 1979) and this formed part of the east Sunda margin since the early Tertiary. Collision has played a significant part in the Tertiary development of the island but the micro-continental fragments arrived later than initially thought (e.g. Parkinson 1991; Davies 1990; Smith & Silver 1991).

There has been little palaeomagnetic work on Sulawesi. The earliest results by Haile (1978) from the SW and the SE arms indicated that these arms originated in different regions during the late Jurassic-early Cretaceous (Audley-Charles *et al.* 1972; Katili 1978). Data from SW Sulawesi indicate that it was close to its present latitude in the late Jurassic (Haile 1978) and late Paleogene (Sasajima *et al.* 1980) but rotated clockwise by *c.* 45° between the late Paleogene and late Miocene (Mubroto 1988). These results from SW Sulawesi are very similar to those from Cretaceous rocks of the Malay Peninsula (McElhinny *et al.* 1974) and Borneo (Fuller *et al.* 1991). Sasajima *et al.* (1980) reported Eocene-early Miocene clockwise rotation





**Fig. 3.** Reconstruction of the region at 10 Ma. Between 5-25 Ma the Philippine Sea plate rotated about a pole at 15°N, 160°E. Counter-clockwise rotation of Borneo and related rotations of Sundaland were complete.

of the east part of the north arm whereas Otofui *et al.* (1981) suggested no significant latitude change but clockwise rotation of more than 90° by the north arm between the Eocene-early Miocene. There are problems with interpretation of the Otofui *et al.* (1981) data (J. C. Briden, pers. comm. 1994), and Surront *et al.* (1994) show that 20-25° clockwise rotation of the whole north arm has occurred since the Miocene but that larger rotations are related to local shear zones. These rotations are consistent with the late Neogene tectonic history of Sulawesi proposed by Silver *et al.* (1983b) who reconstruct the island by removing the movement on the Palu, Matano, Tolo, Lawanopo and Kolondale faults. I have followed their reconstructions and assumed, as they suggest, that this deformation occurred between 5 and 0 Ma.

Palaeomagnetic work shows that lavas of the east Sulawesi ophiolite have a clear southern hemisphere origin (Mubroto *et al.* 1994) and formed at a latitude of  $17 \pm 4^\circ\text{S}$ . This is in marked contrast to similar Cretaceous and Tertiary rocks in the Halmahera islands where palaeomagnetic results from ophiolitic and associated rocks indicate sub-equatorial latitudes of formation (Hall *et al.* 1995a; Ali & Hall 1995). Palaeolatitudes of Sulawesi rocks are north of Cretaceous and the early Tertiary palaeolatitudes for the northern Australian margin but similar to Cretaceous palaeolatitudes for Sula (Ali & Hall 1995) and Misool (Wensink *et al.* 1989). The age and origin of the east Sulawesi ophiolite is uncertain. Simandjuntak (1986, 1992) interprets the ophiolite as formed at an early Cretaceous spreading centre. K-Ar dates reported by Simandjuntak (1986) include 93-48 Ma gabbros and 54-38 Ma basalts. K-Ar ages on lavas by Mubroto *et al.* (1994) range from 79-16 Ma. Dating and geochemical studies by Girardeau *et al.* (1995) suggest a 44 Ma age and a backarc origin for part of the ophiolite suggesting that the ophiolite could be composite. Since the ophiolite and west arm were juxtaposed by the early Miocene (Parkinson 1991), the ophiolite is fixed to west Sulawesi from 25-0 Ma and before 25 Ma moved with the Indian plate.

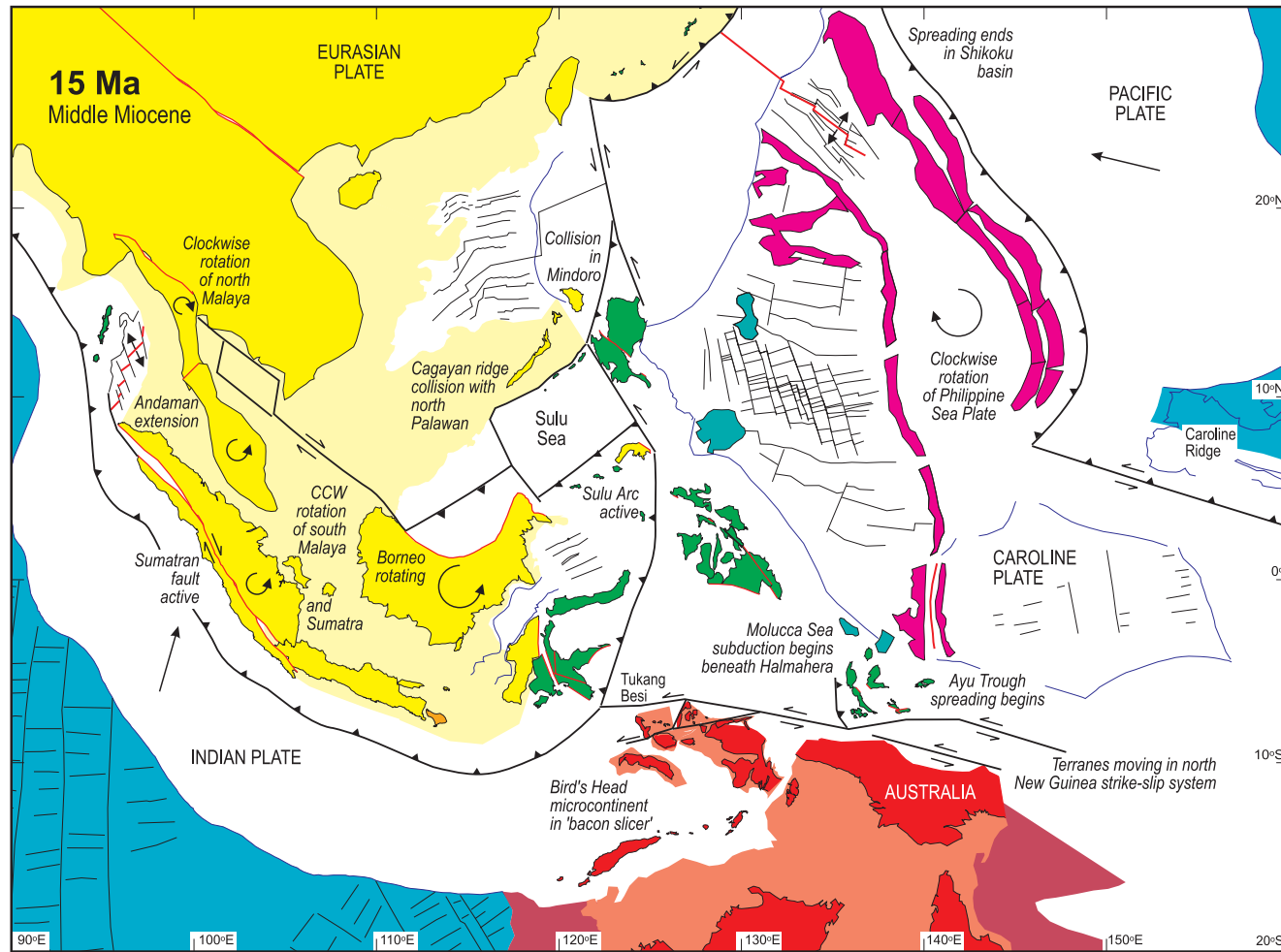
#### *Makassar Strait*

Geological similarities of east Borneo and west Sulawesi suggest that they have moved apart since the middle Paleogene (Hamilton 1979) although the timing is not well constrained. The Makassar Strait is thought to be underlain by attenuated continental crust (Dürbaum & Hinz 1982) and stretching occurred between early Paleogene and Early Miocene (Situmorang 1982). The Makassar Strait was closed by fitting bathymetric contours on the west and east sides of the north and south

Makassar basins although this is only an approximation due to the thick Neogene sediments of the Mahakam delta, and young deformation in west Sulawesi (Bergman *et al.* 1996). The best fit is achieved using a pole NE of the north end of the strait at 6°N, 128°E requiring a rotation of 6°. Because the rotation of Borneo and the Philippine Sea plate results in an alignment of the West Philippine central basin, the Celebes Sea and the Makassar Strait, the author suggests that these basins opened as part of a single basin, probably by spreading which propagated westwards from the West Philippine central basin, as discussed further below. The period of extension is assumed to be the same (44-34 Ma), which is consistent with the stratigraphic interpretation of Situmorang (1982, 1987).

#### *Philippine Sea Plate*

The Philippine Sea Plate provides an eastern boundary for the reconstructions. At present the plate is rotating clockwise about a pole near its northern edge (Seno *et al.* 1993). However, the Philippine Sea Plate is now surrounded by subduction zones which separate it from the oceanic ridge system and consequently its earlier motion with respect to other major plates is difficult to determine. Subduction at the Philippine Trench is young (Cardwell *et al.* 1980) and hence much of the Philippines must have been attached to the plate before the late Neogene. At the southern edge of the plate the Indonesian islands of the north Moluccas still form part of the plate. Reconstruction of the Philippine Sea plate and estimation of its past position is discussed by Hall *et al.* (1995b) with details of the data, the blocks, and the rotation poles used in reconstructing opening of the marginal basins. For the period between 5 and 0 Ma the present Eurasia-Philippine Sea plate pole (Seno *et al.* 1993) has been used. The rotation poles for the plate used for the period 50-5 Ma are based on palaeomagnetic data (Hall *et al.* 1995a) collected from the east Indonesian islands of the Halmahera-Waigeo region which contain a good Mesozoic and Tertiary stratigraphic record and indicate a long arc history. These palaeomagnetic data indicate that the Philippine Sea plate has rotated clockwise in a discontinuous manner since the early Tertiary with *c.* 35° clockwise rotation between 25 and 5 Ma, no rotation between 40 and 25 Ma and *c.* 50° clockwise rotation between 50 and 40 Ma. Reconstructions based on these results, and including opening of marginal basins within the plate, show that other magnetic data from the plate are consistent with this rotation model (Hall *et al.* 1995b).



**Fig. 4.** Reconstruction of the region at 15 Ma. Rotation of Borneo and parts of Malaya, Sumatra and Java were underway. Strike-slip motion at the southern boundary of the Philippine Sea plate fragmented the Bird's Head microcontinent and moved blocks west in the plate boundary zone. Similar motions were occurring in the north Philippines. The backarc Sulu Sea began to close after collision of the Cagayan ridge with the Palawan margin.

### *Celebes Sea*

ODP Leg 124 results indicate that the Celebes Sea formed in the middle Eocene, probably not far from its present latitude (Silver & Rangin 1991). The palaeomagnetic inclinations indicate palaeolatitudes similar to the present-day latitude; no errors are quoted by Shibuya *et al.* (1991) but the data allow movement of up to 19° according to Silver & Rangin (1991) implying relatively large errors. The palaeomagnetic results of Shibuya *et al.* (1991) also indicate a counter-clockwise rotation of *c.* 60° between 42 and 20 Ma. The reconstructions in this paper imply a connection between the Celebes Sea and the West Philippine central basin. The suggestion that these two basins were linked was discussed by Silver & Rangin (1991) who argued against it without excluding it, based on apparent inconsistencies of spreading history, rates and palaeomagnetism between the two basins. In fact, there is no major difference between spreading rates estimated from spacing between anomalies 18 and 20 in the Celebes Sea (Weissel 1980) and the West Philippine central basin (Hilde & Lee 1984), and the small difference is consistent with a basin narrowing westwards. The stratigraphy and sedimentology of the two basins are similar (Nichols & Hall 1995) based on drilling by DSDP Legs 31, 59 and ODP Leg 124. The reconstructions also show that the apparently different rotation histories could lead to a sub-parallel alignment of their magnetic anomalies at the time of basin formation. In this model the Celebes Sea basin is suggested to have originally formed an extension of the West Philippine central basin which opened between 44 and 34 Ma, based on the ages of anomalies identified by Hilde & Lee (1984). The model therefore opens the basin and includes a 45° counter-clockwise rotation between 44 and 34 Ma implying that the rotation occurred during opening. The magnetic anomalies identified by Weissel (1980) indicate the spreading centre was south of the present southern edge of the basin suggesting that part of the ocean has been subducted at the north Sulawesi trench since the late middle Miocene (Rangin & Silver 1991). The model assumes symmetrical spreading and eliminates the southern half of the ocean between 10 and 0 Ma at the north Sulawesi trench. The subduction is interpreted to have resulted largely from rotation of the north arm of Sulawesi (Surmont *et al.* 1994).

### *Sulu Sea-Cagayan Ridge*

The Sulu Sea is a marginal basin thought to have opened as a backarc basin during the early Miocene (Holloway 1982; Hinz *et al.* 1991; Rangin & Silver 1991) south of the Cagayan ridge, although the

northern part of the Sulu Sea is underlain by continental crust as noted above. The Cagayan ridge is interpreted as a volcanic arc active for a short period in the early Miocene which collided with the south China margin at the end of the early Miocene (Rangin & Silver 1991). Part of this arc may also be present in Mindoro and Tablas (Marchadier & Rangin 1990). Rangin & Silver (1991) offer two scenarios for the history of this region. Their scenario A has been modelled by southward subduction of a proto-South China Sea beneath the Cagayan ridge between 20 and 15 Ma forming the Sulu Sea. Collision of the Cagayan ridge with Palawan at 15 Ma then resulted in development of a new subduction zone and southward subduction of part of the Sulu Sea beneath the Sulu arc between 15 and 10 Ma.

### *Philippines*

With the exception of Palawan, Mindoro, Zamboanga and nearby parts of the west Philippines, the Philippine archipelago is composed of largely ophiolitic and arc rocks of Cretaceous and Tertiary age. The present Philippine fault is young, <5 Ma, (Aurelio *et al.* 1991; Quebral *et al.* 1994) but there is evidence of older strike-slip faulting in the northern Philippines (e.g. Rutland 1968; Karig 1983; Karig *et al.* 1986; Stephan *et al.* 1986) possibly dating from the early Miocene. There is widespread evidence of volcanic activity throughout the Neogene implying subduction. West Mindanao east of Zamboanga is omitted before 5 Ma since almost all of this block consists of very young arc material, although it may include some basement of Eurasian continental affinities (Ranneft *et al.* 1960; Pubellier *et al.* 1991). It is likely that central Mindanao, although shown on most of the reconstructions, was also much smaller. The Philippines are widely considered to have formed part of an arc system at the edge of the Philippine Sea plate before the Pliocene (e.g. Rangin 1991; Rangin *et al.* 1985, 1991). South of Luzon palaeomagnetic results indicate clockwise rotations consistent with movement as part of the Philippine Sea plate. However, the Philippines are still palaeomagnetically insufficiently known to attempt a detailed plate tectonic model, even assuming this were possible, since so many fragments would be required. However, the general plate tectonic evolution is known (Rangin *et al.* 1990) and indicates that most of the Philippines have moved from the south and have collided with the Eurasian margin during the Neogene, although the relative importance of collision and strike-slip tectonics is uncertain. The tectonic evolution of this complex region has been simplified by localising

all strike-slip movement on the present Philippine Fault and by moving the Philippines south of Luzon with the Philippine Sea plate. On the whole this avoids overlap of fragments, except between 10–5 Ma, and provides some limits on the large scale tectonic setting of the region. The motions for the Philippines south of Luzon in the model are consistent with the palaeomagnetic data which predict clockwise rotations and northward movement (McCabe & Cole 1989; Fuller *et al.* 1991).

The history of Luzon is more controversial. McCabe & Cole (1989), Fuller *et al.* (1991) and Van der Voo (1993) review the different interpretations of the palaeomagnetic data. This model accepts the Fuller *et al.* (1991) preferred interpretation of a largely counter-clockwise rotation history with a small latitudinal change for most of the Tertiary. They interpret relatively young clockwise rotations to indicate late Neogene movement with the Philippine Sea plate. Fuller *et al.* (1983) suggest that the palaeomagnetic results from Luzon indicate tectonic models should involve counter-clockwise rotation of Luzon since mid-Miocene, no important northward motion ( $\pm 500$  km) since then, northward motion of the Zambales complex from equatorial latitudes with counter-clockwise motion since the Eocene, and no significant rotation in the Plio-Pleistocene. If Luzon is moved with the Philippine Sea plate and the rest of the Philippines for the whole of the period 50–0 Ma, most of these conditions are not met and there are major overlaps of Luzon, Sulawesi and the Celebes Sea. However, with the exception of the early counter-clockwise motion of the Zambales complex (which could be incorporated in a more detailed model) all of these constraints are satisfied if Luzon is positioned on the north side of the Celebes Sea before the Neogene. For the Neogene, Luzon was moved using the Philippine Sea plate rotation poles (Hall *et al.* 1995b) but at slightly lower rates, which implies a partial coupling to the plate, between 20–0 Ma, and assumed 40° counter-clockwise rotation between 25–20 Ma. The position of Luzon in the reconstructions is different from that normally assumed (e.g. Rangin *et al.* 1990) but can also satisfy many of the geological data, as explained below.

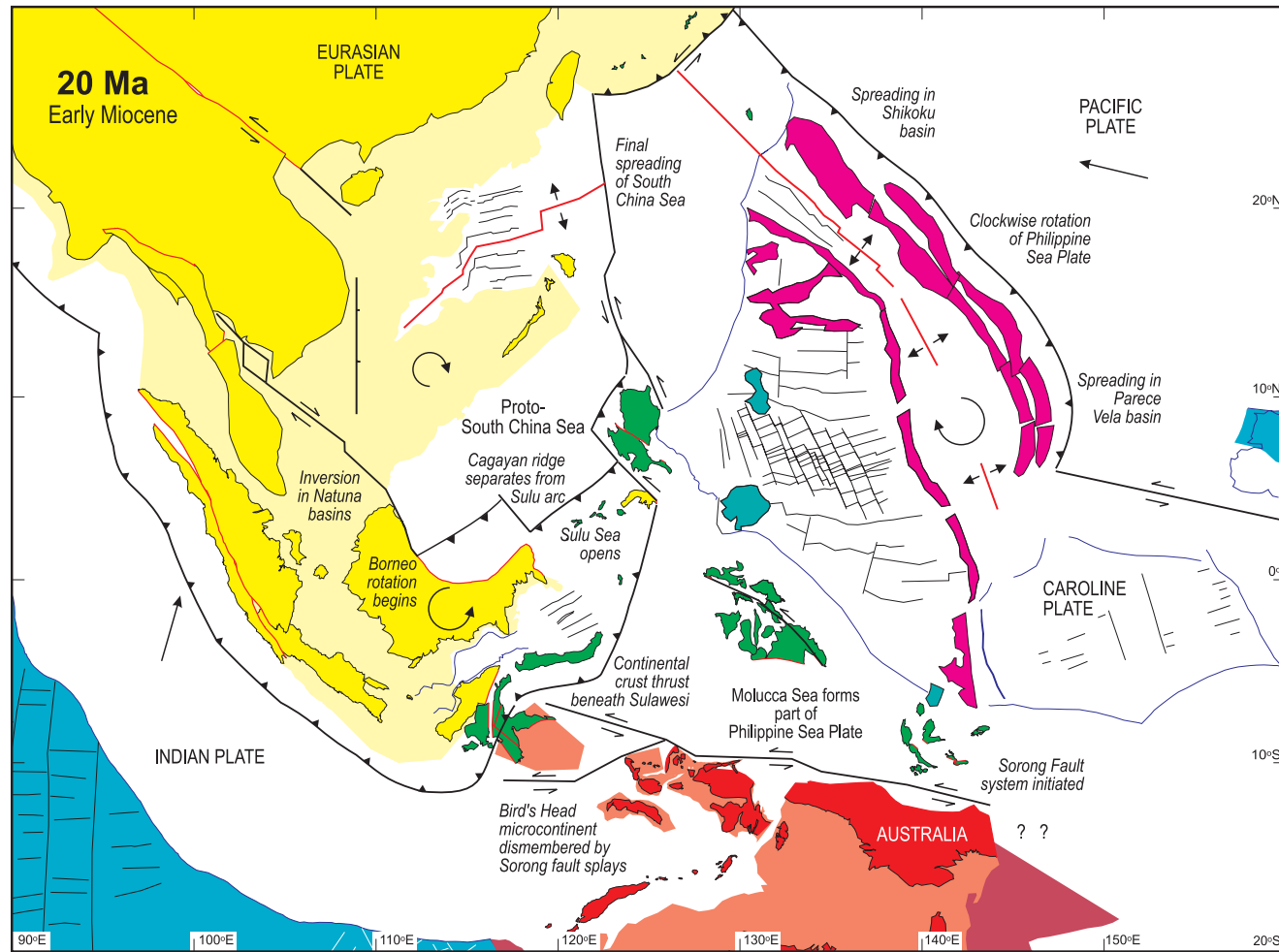
### *Halmahera*

Reconstructions incorporating the rotation of the Philippine Sea plate and removing the effects of subduction at the Philippine Trench can be tested in part against present-day observations in the Molucca Sea region. The Philippine arcs terminate in the south in the Molucca Sea collision zone where the Halmahera and Sangihe arcs are actively

converging. West of Halmahera the Molucca Sea plate has an inverted U-shaped configuration and is dipping east under Halmahera and west under the Sangihe arc. Regional seismicity indicates that there is *c.* 200–300 km of subducted lithosphere beneath Halmahera. On the other side of the Molucca Sea, the Benioff zone associated with the west-dipping slab can be identified to a depth of *c.* 600 km beneath the Celebes Sea. In central Halmahera a fold-thrust belt forms the boundary between the ophiolitic eastern basement and arc volcanic western basement. Balanced cross-sections indicate at least 60 km east-west shortening between east and west Halmahera in the fold-thrust belt and within the east arms (Hall & Nichols 1990). The age of thrusting is between 3 and 1 Ma. This movement is incorporated in the model and probably reflects intra-plate deformation associated with the change in motion of the plate. The western arms of Halmahera are covered by late Neogene to Recent volcanic products related to eastward subduction of the Molucca Sea Plate. The volcanic arc was initiated at *c.* 12 Ma and subduction probably began at *c.* 15 Ma. An older phase of arc volcanic activity commenced in the late Eocene and terminated in the early Miocene. Stratigraphic similarities and the relative position of the Halmahera islands and the east Philippines suggest that they formed part of the same arc system before 5 Ma. The Halmahera islands were moved with the southern Philippine Sea plate in all the reconstructions.

### *Bird's Head*

The Neogene movement of the Bird's Head has been estimated from constraints imposed by reconstruction of the Molucca Sea. Progressively restoring the oceanic crust subducted at the Sangihe and Halmahera Trenches requires a wide ocean and the Bird's Head needs to be moved further south than the northern Australian margin in order that the Bird's Head is south of this ocean. McCaffrey (1996) suggests the Bird's Head is currently moving south relative to Australia and this is incorporated by a small movement in the past 0.5 Ma. Before this time the movement of the Bird's Head has been modelled by assuming left-lateral strike-slip motion along a boundary parallel to the Aru Basin edge between 0.5 and 2 Ma. A small counter-clockwise rotation of the Bird's Head has been incorporated between 4 and 8 Ma based on palaeomagnetic results of Giddings *et al.* (1993). A further small strike-slip motion is incorporated between 8 and 12 Ma, again constrained by reconstruction of the Molucca Sea. Before 12 Ma the Bird's Head is fixed to Australia.



**Fig. 5.** Reconstruction of the region at 20 Ma. Rotation of Borneo and parts of Malaya, Sumatra and Java began. Subduction of the Proto-South China Sea caused arc splitting in the Sulu arc and the separation of the active arc of the Cagayan ridge. South China Sea opening propagated SW into the Sunda shelf.

### *Sula*

The Sula platform is a fragment of continental crust widely considered to have been transported west by the Sorong Fault. Its origin is uncertain. Many authors consider it to be a piece of New Guinea that was detached from western Irian Jaya in late Cenozoic time (e.g. Visser & Hermes 1962; Audley-Charles *et al.* 1972; Hamilton 1979; Silver & Smith 1983). In contrast, Pigram *et al.* (1985) have proposed that it originated *c.* 1000 km further east, and was detached to form an independent micro-continent from central Papua New Guinea before the early Cretaceous. All these suggestions are based on stratigraphic features discussed by Pigram *et al.* (1985). The Sula platform is now attached to east Sulawesi and has a thrust contact with the east Sulawesi ophiolite. It was originally suggested that the collision of the west Sulawesi island arc and the Sula platform resulted in ophiolite emplacement in the east arm (Kündig 1956; Hamilton 1979; Silver *et al.* 1983a). However, recent evidence indicates that this suggestion is incorrect. The ophiolite was obducted westward onto west Sulawesi at the end of the Oligocene (Parkinson 1991), whereas thrusting of the ophiolite onto the western edge of the Sula platform occurred in the latest Miocene (Davies 1990) indicating collision of the Sula platform with east Sulawesi must have occurred at *c.* 5 Ma. Sula is therefore moved with east Sulawesi from 0-5 Ma. Hamilton (1979) shows the Sula platform as a fragment moving along the north side of the Sorong Fault, implying it was attached to the Molucca Sea or Philippine Sea plates. By moving the Sula fragment with the Philippine Sea plate before 5 Ma it fits closely to the Bird's Head at *c.* 10-11 Ma. Charlton (1996) shows that the Tomori and Salawati basins, both of which are sharply truncated, would have formed the northern and southern parts of a single large basin if the Sula platform were moved back to this position. This need not preclude a Mesozoic separation of a Bird's Head microcontinent from further east on the north Australian margin.

### *Buton-Tukang Besi*

The Tukang Besi platform is a micro-continental fragment that collided with Sulawesi during the Miocene, although the timing of the collision is interpreted differently by different authors. Davidson (1991) suggested Buton to be a micro-continental fragment which collided in the early Miocene with SE Sulawesi, before the Tukang Besi platform. Here, both have been treated as parts of a single block, following Smith & Silver (1991), who consider Buton as part of the Tukang Besi platform.

This difference may be explicable if both formed part of an extended Bird's Head microcontinent, as discussed later. Smith & Silver (1991) argue that collision of the Tukang Besi platform with Sulawesi was complete before the late Middle Miocene, since ophiolitic conglomerates and sandstones of this age (N13-N14) overlie deformed basement rocks. They interpret Lower Miocene conglomerates (N7-N9) that lack ophiolitic debris to indicate uplift associated with initial detachment of the platform from the northern New Guinea margin. If this interpretation is correct, initial uplift associated with detachment from New Guinea occurred between *c.* 15 and 17 Ma and collision of Tukang Besi with Sulawesi must have been complete by *c.* 11 Ma.

To model this history Tukang Besi was fixed to west and central Sulawesi between 0 and 11 Ma. By attaching the platform to the southern edge of the Philippine Sea plate before that time Tukang Besi returns to a position, west of, and adjacent to the Sula fragment and the Bird's Head by 14 Ma. To obtain the best fit requires rotation of the Tukang Besi block, and this is incorporated by a clockwise rotation of 40°. The author therefore interprets the sequence of events to be: at *c.* 15 Ma a strand of the Sorong fault propagates west, south of Tukang Besi; by 14 Ma Tukang Besi is fully attached to Philippine Sea plate; at 11 Ma Tukang Besi collides with Sulawesi, locking this strand of the Sorong fault and requiring a development of a new fault strand which caused the detachment of Sula. It is interesting to note that the development of Molucca Sea subduction beneath Halmahera begins at *c.* 13-15 Ma, indicated by K-Ar ages of volcanic rocks and reset ages (Baker & Malaihollo 1996), as well as biostratigraphic ages. Thus, a locking of subduction at the west side of the Molucca Sea, requiring initiation of a new subduction system on its east side is temporally linked to development of the Sorong fault splay.

### *Seram and Buru*

Hamilton (1979) suggested there is only shallow seismicity associated with the Seram Trough whereas Cardwell & Isacks (1978) argued that a deep slab was bent round the entire Banda arc. McCaffrey (1989) attempted to reconcile these differences on the basis of an increased number of better located seismic events, and concluded that there are two slabs, one subducted at the Timor trough, and a second subducted at the Seram trough. The Seram slab extends to no more than 300 km whereas the Indian ocean slab is continuous to over 600 km indicating that they record different histories of subduction. The bend in the Indian ocean slab implies that Seram has moved

eastwards while Australia has moved north. During the late Neogene the Banda arc has migrated east since the volcanoes become younger and the length of the subducted slab decreases eastwards. This configuration was modelled by moving Seram northwards to its present position relative to the Bird's Head between 4 and 0 Ma and moving Seram eastwards relative to the Bird's Head from 12-4 Ma. This is consistent with, although simplified from, the present tectonic configuration in the Banda Sea inferred by McCaffrey (1989).

Buru is currently situated between strands of the Sorong Fault system and Hamilton (1979) suggests it may have moved westward from New Guinea. The present author has allowed a small amount of westward movement between 4 and 0 Ma which fits Seram, Buru and the Bird's Head closer together but this is merely a guess.

#### *Caroline Plate*

The Ayu Trough opened during the middle and late Miocene (Weissel & Anderson 1978) and spreading may be continuing at the present day. There has been no subduction at the Caroline-Philippine Sea plate boundary and little convergence at the Caroline-Pacific boundary since *c.* 25 Ma. The model uses the Caroline-Philippine Sea plate rotation pole and rate of Seno *et al.* (1993) for the period 5-0 Ma and then moves the Caroline Plate with the east side of Ayu Trough before this. The Caroline plate is omitted from the reconstructions before 25 Ma.

### **Implications**

#### *Timing of Major Changes*

The animated reconstructions show clearly that, during the interval 50-0 Ma, although there are important changes in movements and locally there are significant manifestations of these changes, there are two truly regionally important periods of change. Both of these appear to be the expression of arc-continent collision and resulted in major changes in the configuration of the region and in the character of plate boundaries. At  $\sim 25$  Ma the collision of the Australian continent with the Philippine Sea plate arc in New Guinea (Fig. 6) caused major effects which propagated westwards through the region. The Philippine Sea plate began to rotate clockwise requiring development of new subduction systems at its western edge. This led to the assembly of the Philippines archipelago, initiated new arc systems from north Sulawesi through to the Philippines, and led to the growth and partial destruction of marginal basins such as the Sulu Sea. The continued rotation of the Philippine Sea plate ultimately resulted in elimina-

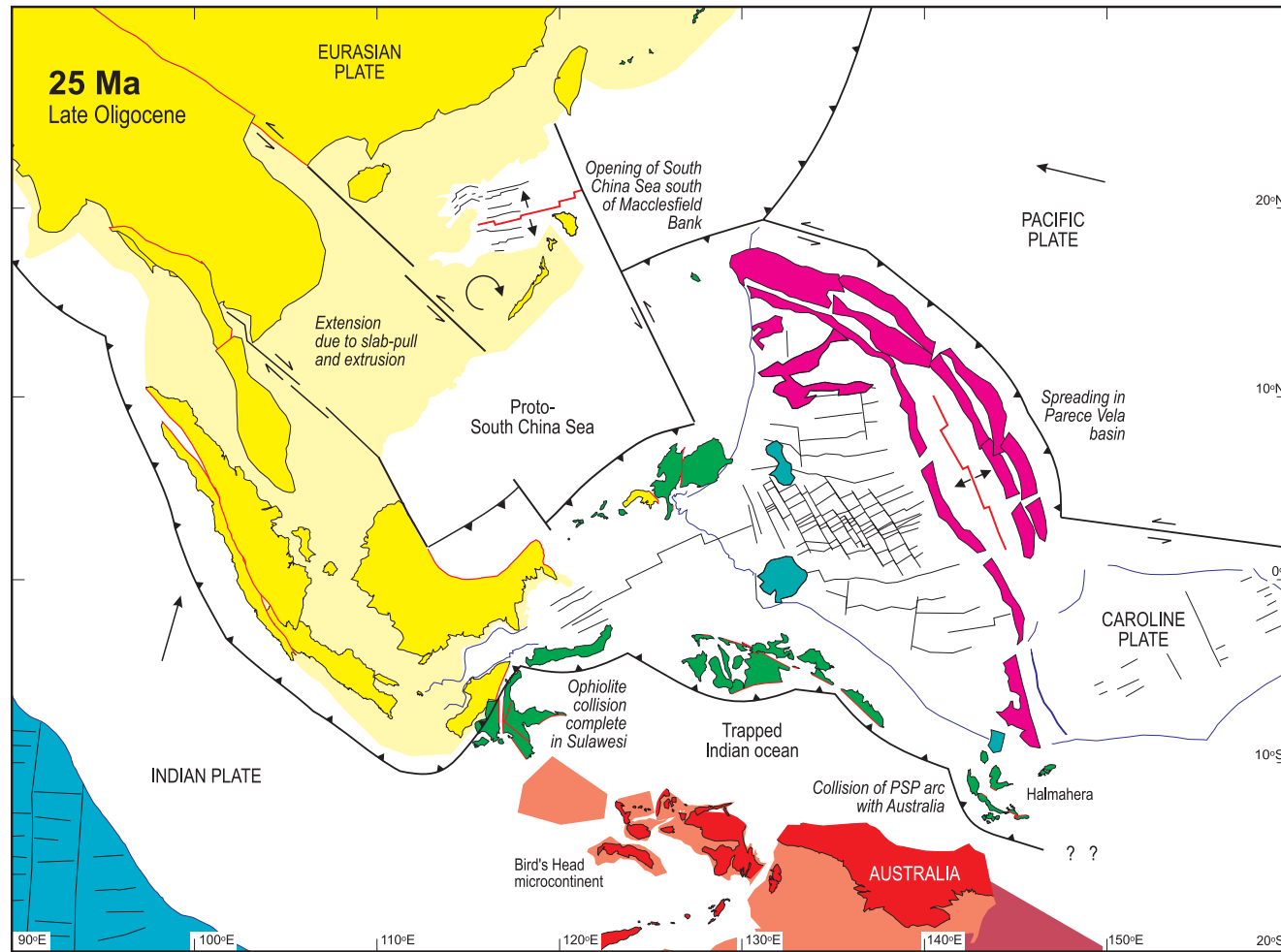
tion of the Molucca Sea plate and accretion of fragments from the northern Australian margin into the SE Asian margin, notably in Sulawesi. At *c.* 5 Ma collision of the Philippine arc and the Eurasian continental margin occurred in Taiwan (Fig. 2). This appears the key to the recent tectonics of the region. Once again, the Philippine Sea plate motion changed, and new subduction systems were initiated, such as those currently active on the east and west sides of the Philippines. Most deformation now seems to be concentrated in the region between the Banda Sea and Taiwan. Summarised below are the major implications of the reconstructions for different parts of SE Asia.

#### *Borneo*

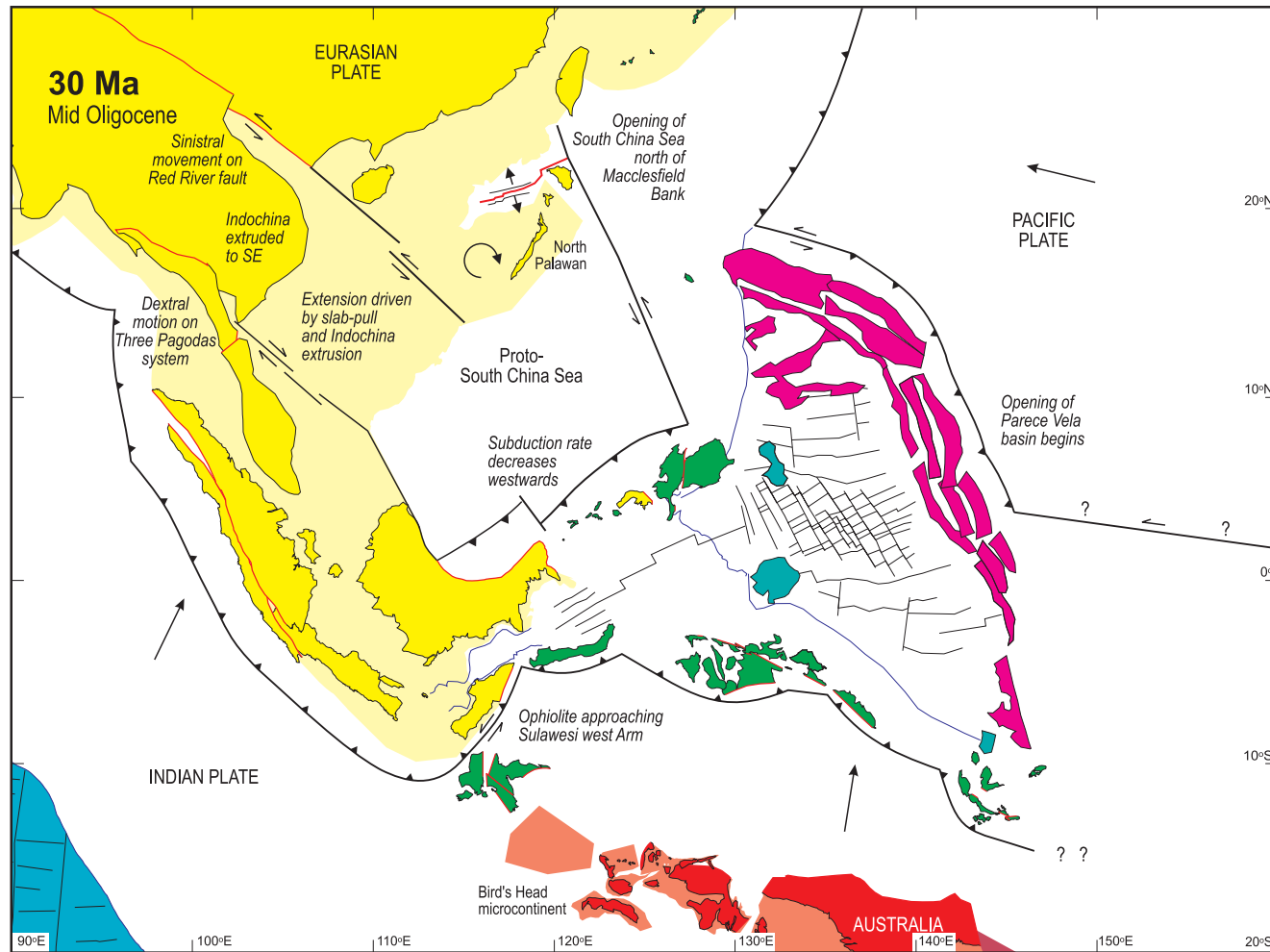
Accepting rotation of Borneo has some important consequences for the reconstruction of the region, although the amount of rotation could be reduced to about  $30^\circ$  without seriously affecting the model. It means that there was initially a very wide proto-South China Sea (Fig. 11) which began to close from *c.* 44 Ma (Fig. 10). Alternative reconstructions (e.g. Rangin *et al.* 1990; Lee & Lawver 1994) which do not incorporate this counter-clockwise rotation, appear to lack the space required for the opening and closing of ocean basins such as that north of the Cagayan ridge and the Sulu Sea. Although the closure of the proto-South China Sea may have been partly driven by extrusion of the Indochina block the reconstructions suggest it was achieved by subduction either at the southeast side of the ocean or within the ocean (Figs. 8 and 9). Once subduction was established slab-pull force would have caused extension of the Indochina-South China margin leading to formation of oceanic crust and extension of Eurasian continental crust (Fig. 7). Thus, extension in this region may not have been driven by strike-slip-related extrusion. In fact, the model suggests that subduction may have been underway before South China Sea opening began. Opening of the Celebes Sea required northward motion of Luzon because of its position north of the spreading centre, thus implying a subduction zone on the south side of the proto-South China Sea (Fig. 9). The Oligocene reconstructions are thus very similar to those of Taylor & Hayes (1983) except that south Borneo is rotated further.

Many of the differences between this model and that of Rangin *et al.* (1990), which otherwise have many resemblances, result from the new constraints imposed by reconstruction of the Philippine Sea plate. If Borneo is not rotated there are problems in accounting for the evidence of continental crust in west Sulawesi in the early Miocene (see below, Bergman *et al.* 1996). The extended Bird's Head





**Fig. 6.** Reconstruction of the region at 25 Ma. Collision of the Australian continental margin in New Guinea, and the Bird's Head microcontinental block in Sulawesi with the arc from north Sulawesi to Halmahera caused major reorganisation of plate boundaries. The active ridge jumped south in the South China Sea.



**Fig. 7.** Reconstruction of the region at 30 Ma. South China Sea opening was driven by pull of the subducted Proto-South China Sea slab, and possibly by extrusion caused as India indented Eurasia. Arc splitting began in the eastern margin of the Philippine Sea plate with spreading in the Parece Vela basin.

microcontinent would have been much further north than shown in the reconstructions and hence would have occupied the site of the Molucca Sea.

For most of the Oligocene and early Miocene (Figs. 6 and 7) the Sundaland margin in Borneo would have been oriented NW-SE and would have been a strike-slip dominated region and therefore the sedimentary basins of northwest Borneo should record an important component of this strike-slip history. This configuration also suggests that much of the sediment now found in north Borneo may have been fed southwards across the Sunda shelf from Indochina. This resolves a problem of the sediments now found in north Borneo which could not have a south Borneo provenance because of their volume and because most of south Borneo was below sea level during much of this period. The timing of subduction suggested by the model is similar to that deduced from the north Borneo stratigraphic record by oil company geologists (e.g. Tan & Lamy 1990) and the present author suggests that their 'Deep Regional Unconformity' is one manifestation of Australia-Philippine Sea plate collision, and consequent reorganisation of plate boundaries. Subduction became increasingly important in NE Borneo between *c.* 20 and 10 Ma (Figs. 3-5) and the proto-South China Sea was entirely eliminated before 10 Ma.

For Malay blocks west of Borneo, the reconstructions (Figs. 4 and 5) can be regarded only as an approximation. The model suggests greater extension than that recorded in the Malay basins, and the timing of the rotations in the model needs to be improved. The similarities in rotations recorded through this part of Sundaland may be no more than coincidental, but if Borneo and Java have rotated, there must have been some movement of Sumatra and the Malay peninsula, otherwise there is major overlap of fragments. The implications of rotations of blocks for the wider region are a problem which the palaeomagnetists often neglect, and therefore the model has some value, even if wrong, in attempting to face up to these implications, which in turn emphasises the need for more data to identify timing and to separate local and regional rotations. There can be no doubt that at present the palaeomagnetic data from Sundaland do not on their own convincingly demonstrate regional rotations.

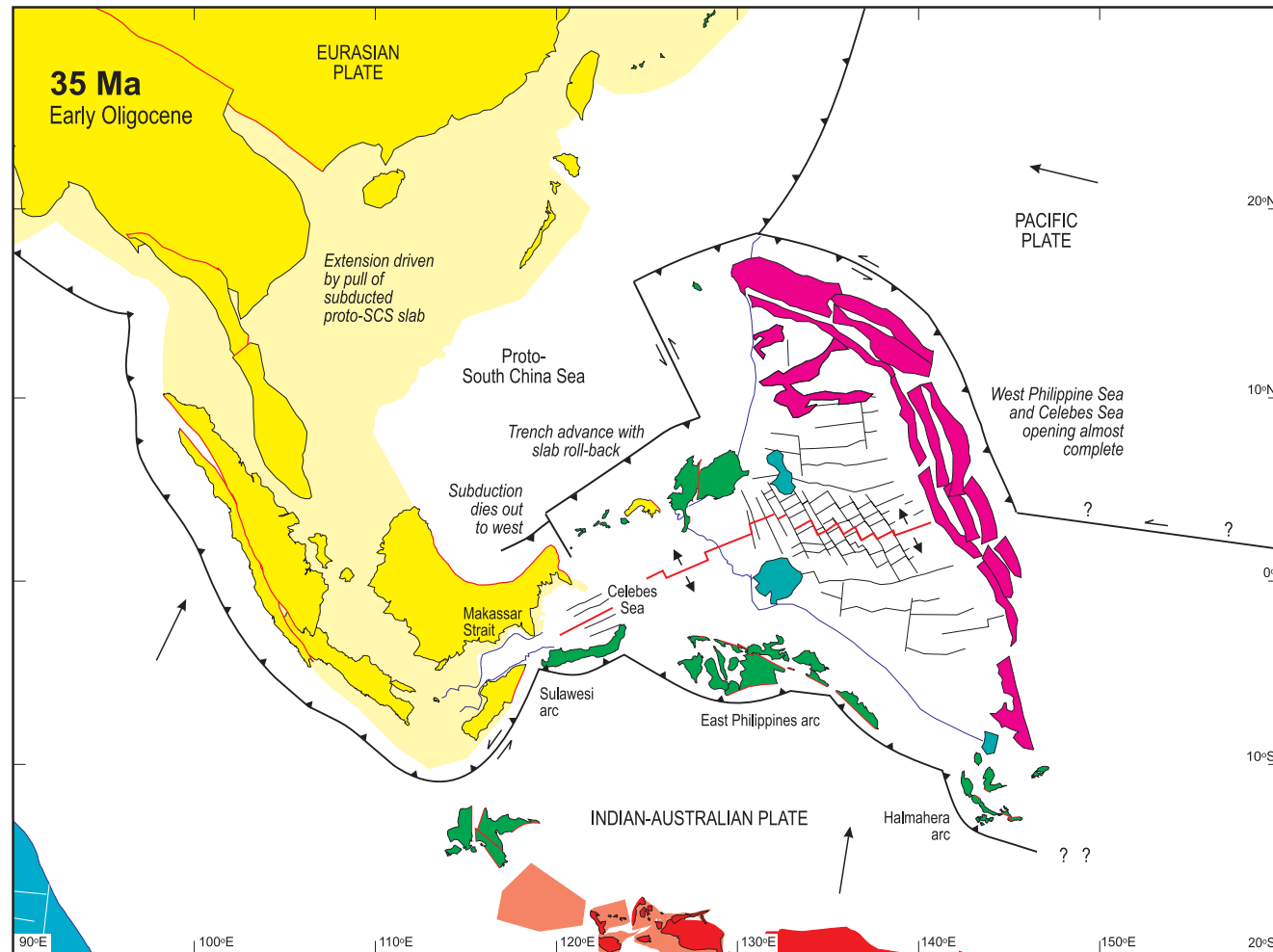
#### *Origin of the Celebes Sea*

If palaeomagnetic evidence for the rotation of Borneo is accepted there is a strong case to be made that the central West Philippine Sea, the Celebes Sea and the Makassar Strait formed part of a single marginal basin (Figs. 8 and 9) which

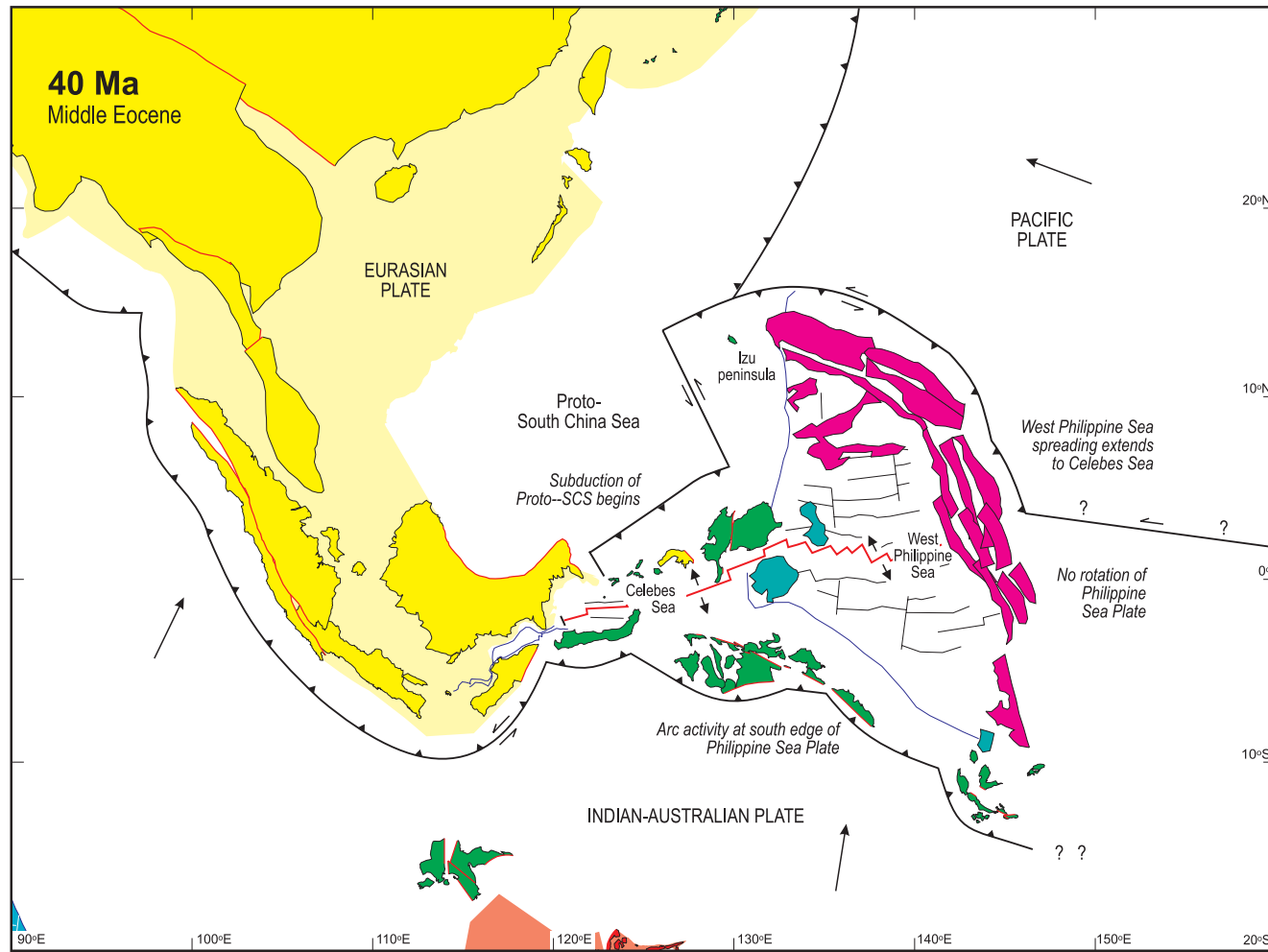
opened between late Eocene and mid Oligocene, and widened eastwards like the present South China Sea. This interpretation has been incorporated in the model and the palaeomagnetic data from the Celebes Sea and Philippine Sea can be reconciled in such a model. The author follows Hamilton (1979) and many others in interpreting the Makassar Strait as an extended area of crust, probably without oceanic crust, although this need not preclude the Neogene convergent tectonics suggested by Bergman *et al.* (1996) for its west Sulawesi margin. The reconstructions are least convincing for the period between 44 and 40 Ma when the Philippine Sea plate was rotating rapidly clockwise and the Celebes Sea was opening with counter-clockwise rotation. However, this difficulty may have more to do with the inadequacy of the data on which the timings of rotations are based. For the Philippine Sea plate all we can say is that there was rapid rotation between 50 and 40 Ma (Hall *et al.* 1995b) and more data from Paleogene rocks are needed to determine when and at what rate the rotation occurred. It may well have been fully complete by 45 Ma in which case there would be no difficulty with smooth opening of a basin narrowing west. For the Celebes Sea the position of the basin is consistent with a backarc setting related to northward subduction of Indian ocean lithosphere beneath west and north Sulawesi. Further east this setting appears less convincing because of the very large distance between the basin axis and the subduction zone (Figs. 8 and 9). There were at least three major basins which opened in SE Asia with a similar east-widening geometry: a Mesozoic proto-South China Sea, the Eocene-Oligocene Philippine-Celebes basin and the Oligo-Miocene South China Sea. The South China Sea opening has been interpreted as linked to India indentation (Tapponnier *et al.* 1982) and as suggested here may be related to subduction, but this explanation seems unlikely for the Philippine-Celebes basin. Perhaps these three basins reflect some other lithospheric mechanism related to the long-term subduction of lithosphere east and south of SE Asia.

#### *Sulawesi Collisions*

The apparently simple tectonic configuration in Sulawesi of arc-ophiolite-continent is not the result of a single arc-continent collision (e.g. Silver *et al.* 1983a) but is a consequence of multiple collision events. The east Sulawesi ophiolite has an Indian ocean origin (Mubroto *et al.* 1994). Emplacement of the ophiolite on the west Sulawesi continental margin occurred at the end of the Oligocene (Parkinson 1991) and was followed by a change in plate boundaries at the beginning of the



**Fig. 8.** Reconstruction of the region at 35 Ma. Extension in the Sunda shelf and Eurasian continental margin was driven by pull of the subducted Proto-South China Sea slab. Active spreading of the Celebes Sea-West Philippine Sea basin ended at 34 Ma.



**Fig. 9.** Reconstruction of the region at 40 Ma. Subduction of the Proto-South China Sea began as a trench became active north of Zamboanga-Luzon, caused by rapid opening of the Celebes Sea-West Philippine Sea. Between 40-50 Ma the Philippine Sea plate rotated clockwise about a pole at 10°N, 150°E.

Miocene (Fig. 6). There is isotopic evidence from geochemistry of igneous rocks for very old continental crust beneath west Sulawesi (Coffield *et al.* 1993; Priadi *et al.* 1993; Bergman *et al.* 1996), probably of Australian origin, because of the extreme isotopic compositions. The ages of the oldest igneous rocks reported (Bergman *et al.* 1996) imply early Miocene underthrusting of Australian lithosphere. Since the early Miocene there have been at least two further collisions, in SW and east Sulawesi, as fragments of continental crust have been sliced from the Bird's Head microcontinent and transported west for brief periods on the Philippine Sea plate or the Molucca Sea plate which was partially coupled to the Philippine Sea plate.

#### *Bird's Head microcontinent*

The reconstructions suggest that the Sula platform and Tukang Besi platform formed part of a single large microcontinent with the Bird's Head at *c.* 15 Ma (Fig. 4). The model shows that movement of small continental fragments to their present positions can be explained easily if they were sliced from this microcontinent at different times and each moved with the Philippine Sea plate for a few million years before collision (Figs. 2-5). Thus, the driving force for these motions was the Philippine Sea plate. Temporary locking of the strike-slip system at the southern edge of the Philippine Sea plate required development of new splays of the fault which resulted in the transfer of continental fragments to the Philippine Sea plate. As each fragment docked at the western end of the fault system in Sulawesi, a new splay developed and a new fragment began to move. The cartoons of Hamilton (1979) for the Neogene development of the region are remarkably similar to the predictions of the model although the timing is somewhat different, mainly because of new information from east Indonesia. This model has been described informally as a 'bacon slicer' and this does seem a very appropriate description of the mechanics of the process. The present author differs in one important respect from many interpretations of this region in suggesting that these fragments, although colliders, are not the major causes of contractional deformation associated with their docking. They are merely passive participants riding on the Philippine Sea plate whose major role is to lock a fault strand on their arrival at the Sulawesi margin.

The reconstructions of Tukang Besi and Sula with the Bird's Head do not account for the evidence for Australian crust beneath west Sulawesi by the late Early Miocene (Bergman *et al.* 1996). The extent of this continental crust was estimated and used to outline an additional frag-

ment (Figs. 5-9). If this is assumed to be beneath west Sulawesi by 17 Ma but is moved with the Philippine Sea plate from 21-17 Ma it fits back to the western edge of the Bird's Head microcontinent (Fig. 6). It is suggested here that this fragment records the earliest effect of the 'bacon slicer' and was the first block detached from the Bird's Head microcontinent. It separated as a result of the development of the Sorong Fault system at the southern edge of the Philippine Sea plate and, like the other fragments, moved with the Philippine Sea plate for about 5 Ma. On the basis of the 25 Ma reconstruction, it can be speculated the Bird's Head microcontinent was a single block at the end of the Oligocene formed by separation from Australia during the Mesozoic, to which had been added at least part of the east Sulawesi ophiolite. The reconstructions do not answer the question of the ultimate origin of the Bird's Head microcontinent, but they do require that the microcontinent has been moving with about the same motion as, and has remained in a similar position relative to, Australia for the past 25 Ma. Palaeomagnetic results suggest that the microcontinent was at least 10°N of the north Australian margin in the late Cretaceous (Wensinck *et al.* 1989; Ali & Hall 1995) but its early Tertiary position is not well constrained in the model. The pre-Neogene geology of the region suggests there may have been several important events in the development of the Banda Sea region (e.g. ophiolite emplacement and metamorphism described by Sopaheluwakan (1990) from Timor), which could record relative movement between Australia and the microcontinent in passage to their 25 Ma positions.

#### *Molucca Sea*

The model suggests that the Molucca Sea was a very wide area formed by trapping of Indian ocean lithosphere between the north Australian margin and the Philippine Sea plate arc when collision occurred at 25 Ma (Fig. 6). Thus, its age should be pre-Tertiary. It was eliminated by subduction on its east and west sides. Subduction probably began soon after the 25 Ma change in motion of the Philippine Sea plate on the west side of the Molucca Sea in the north Sulawesi-Sangihe arc, consistent with ages of arc volcanic rocks in north Sulawesi (Dow 1976; Effendi 1976; Apandi 1977). The Molucca Sea formed part of the Philippine Sea plate up to *c.* 15 Ma (Fig. 4 and 5) when east-dipping subduction began beneath Halmahera (Baker & Malaihollo 1996). Most of the subduction occurred on the west side so the Molucca Sea has remained partly coupled to the Philippine Sea plate. The double subduction system of the Molucca

Sea probably never extended north of its present northern edge into the Philippines. However, there was a oceanic area which was effectively continuous with, and north of, the Molucca Sea which was formerly the central part of the Celebes Sea-West Philippine central basin. In the reconstructions this northern part of the ocean is eliminated between 25 and 12 Ma and the Panay sector of the Philippine arc arrives at the western subduction margin at about 12 Ma. Slightly earlier (15 Ma) the Cagayan arc and Luzon arrive at the Palawan margin (Fig. 4) resulting in collision in Mindoro (Rangin *et al.* 1985). It may be one or both of these events in the Philippines which caused initiation of the east-dipping subduction system beneath Halmahera and the concomitant development of splays of the Sorong Fault system at the southern edge of the Molucca Sea. The reconstructions of the Philippines are too imperfect to be confident of the relationships between cause and effect but the timing of collision and age of the ophiolites in Mindoro (Rangin *et al.* 1985) and events in Panay (Rangin *et al.* 1991) are consistent with the model.

### *Philippines*

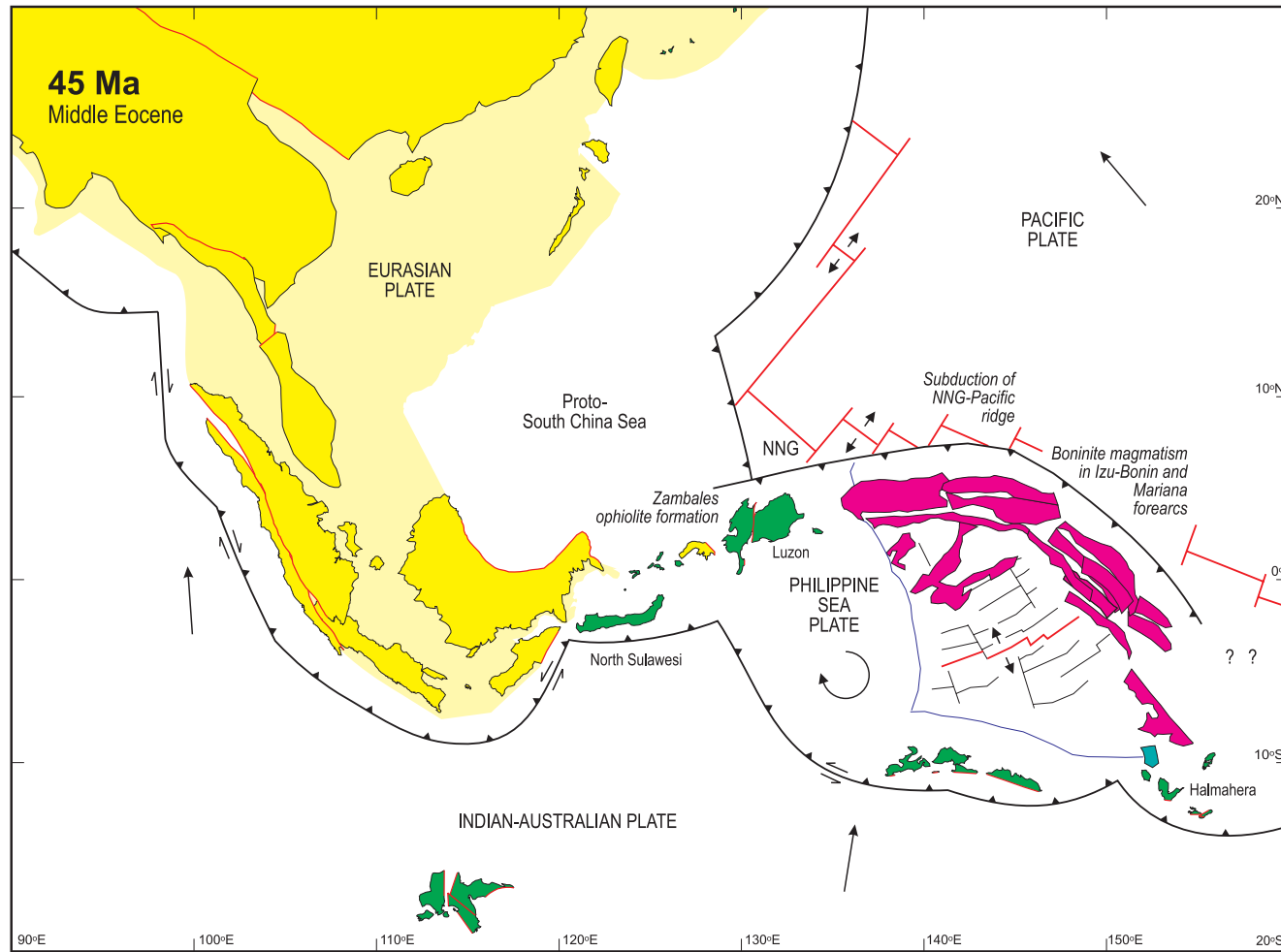
The Philippines are difficult to reconstruct, for a number of reasons. Our understanding of Philippines geology and evolution is still insufficient, although considerable advances have been made in recent years as a result of investigations in the region (see for example, Sarewitz & Karig 1986; Stephan *et al.* 1986; Rangin 1991; and references therein). Reconstructions using the outlines of present-day fragments can be only approximate since much new crust has been added by arc processes. In order to describe the Philippines more precisely many more fragments need to be used and this is currently beyond the capacity of the ATLAS program. However, it seems that rigid plate tectonics may be an inadequate tool to describe the evolution of the area. At present this is illustrated most clearly at the south end of the archipelago where plate boundaries are ill-defined probably because there is a significant amount of within-plate deformation (Rangin *et al.* 1996). Karig *et al.* (1986) have drawn attention to the way in which at present only a small part of the Philippines is completely coupled to the Philippine Sea plate, and how in the past it is likely that coupling was never complete across the entire Philippine system because of strike-slip faulting. Because of the situation of all the Philippine fragments at the edge of plates it is probably unwise to rely too heavily on the evidence of arc volcanism to infer arc continuity. At the present it is clear that some volcanism is related to subduction on the west side of the Philippines, some may be related to sub-

duction at the Philippine Trench, and some may not be directly related to subduction. Switching of subduction from one side of the Philippines to the other has almost certainly occurred in the past (e.g. Schweller *et al.* 1983; Karig *et al.* 1986). Some arcs may also be eliminated completely during collision as one arc overrides another, a process that is underway in the Molucca Sea.

However, the reconstructions do provide some useful limits on what is feasible. Most of the Philippine islands probably formed part of an arc at the southern edge of the Philippine Sea Plate before the early Miocene (Figs. 7-10) as shown earlier in the reconstructions of Rangin *et al.* (1990). The choice here for the position of Luzon (Figs. 6-10) shows that the geological evidence for subduction can be satisfied in ways other than by including all the Philippines in this arc. Since the early Miocene (Fig. 2-6) the Philippine fragments have moved in a very narrow zone, mainly as part of the Philippine Sea plate, within which there appears to have been a substantial component of strike-slip motion (Sarewitz & Karig 1986). Most subduction under the Philippines was oblique, mainly at the western edge, and north of Mindanao. The Philippines are an ephemeral feature. They will probably end up as a composite arc terrane smeared onto the Eurasian continental margin which will be impossible to unravel. The great depths of young sedimentary basins in close juxtaposition to areas of high emergent topography suggest that lithospheric processes operating in this region are not well described by current plate tectonic concepts, and in some ways the Philippines are reminiscent of Pre-Cambrian greenstone belts. There seems no evidence that the Philippines are the result of a collision of two opposed arcs, progressively zipping up southwards towards the present-day Molucca Sea as shown in some reconstructions (e.g. Lewis *et al.* 1982; Rammlmair 1993). In particular, there is no evidence that the west-facing Halmahera arc extended north of the present north edge of the Molucca Sea into Mindanao (Quebral *et al.* 1995).

### *Banda Sea*

The age and origin of the Banda Sea has long been the subject of dispute. Several workers have suggested it is relatively old, possibly Mesozoic, with the Banda Sea representing trapped oceanic crust (Katili 1975; Bowin *et al.* 1980; Lapouille *et al.* 1986; Lee & McCabe 1986) whereas others have preferred a much younger, late Tertiary, age (Hamilton 1979; Carter *et al.* 1976; Réhault *et al.* 1995). Silver *et al.* (1985) suggested that the North Banda Sea may include crust of Pacific origin and identified the Banda ridges as continental



**Fig. 10.** Reconstruction of the region at 45 Ma. The North New Guinea-Pacific spreading centre was subducted causing forearc magmatism and massive extension of the NE margin of the Philippine Sea plate. The movement direction of the Pacific plate changed as a result between 45 and 40 Ma.



fragments based on dredging, a conclusion supported by more recent dredging (Villeneuve *et al.* 1994). Since some of the magnetic lineations of supposed Mesozoic age cross the Banda ridges the inferences based on magnetic anomaly ages may be wrong. Many of the lineations are parallel to the structural fabric of these continental areas (Silver *et al.* 1985; Réhault *et al.* 1991). Despite this, there still appears to be a widespread acceptance that the Banda Sea is floored by old oceanic crust (e.g. Hartono 1990).

This is not a conclusion supported by the reconstructions in this paper. In these the Banda volcanic arc is fixed to west Sulawesi during the late Neogene and the arc-trench gap is assumed to have maintained its present width. Timor and the islands of the outer Banda arc are fixed to Australia for the same period. The Bird's Head micro-continent, including the island of Seram, has been moved, as described above, to satisfy the constraints imposed by reconstruction of the Molucca Sea and the distribution of the deep subducted slabs inferred from seismicity. The reconstructions that result show that before *c.* 10 Ma the gap between Seram and Timor (Fig. 4) was filled by oceanic crust, now subducted beneath the Banda arc, which could indeed have been of Indian ocean origin and Mesozoic age. Timor arrived at the trench at *c.* 4-3 Ma consistent with geological data from Timor (e.g. Carter *et al.* 1976; Audley-Charles 1986; Harris 1991). However, before *c.* 10 Ma the relative distance between Timor and Seram is maintained (Figs. 4-6) suggesting there was no subduction in the eastern Banda Sea area. The reconstructions suggest subduction began at *c.* 10 Ma (Fig. 3), resulting in the eastward propagation of the volcanic arc consistent with the very young age of the volcanoes in the inner Banda arc (Abbot and Chamalaun 1981; McCaffrey 1989). The north Banda basin extended as Seram moved east and the arc propagated east. The eastward movement of Seram is consistent with tectonic inferences from present seismicity (McCaffrey 1989) and geological observations on Seram (Linthout *et al.* 1991). The arc propagated east to the longitude of Seram at *c.* 5 Ma (Fig. 2) which is close to the age of the well-known ambonites of this area. The reconstructions also show the south Banda basin extending rapidly between 5 and 0 Ma. Therefore, both the north and south Banda Sea can be interpreted as having an extensional origin and to have opened during the late Neogene. These interpretations are consistent with the age of young volcanics dredged in the Banda Sea (Réhault *et al.* 1995). The great depth of the south Banda Sea is still a problem, although it is known that Parsons & Sclater's (1977) age-depth relationships often do not hold in small ocean basins. Van Gool *et al.*

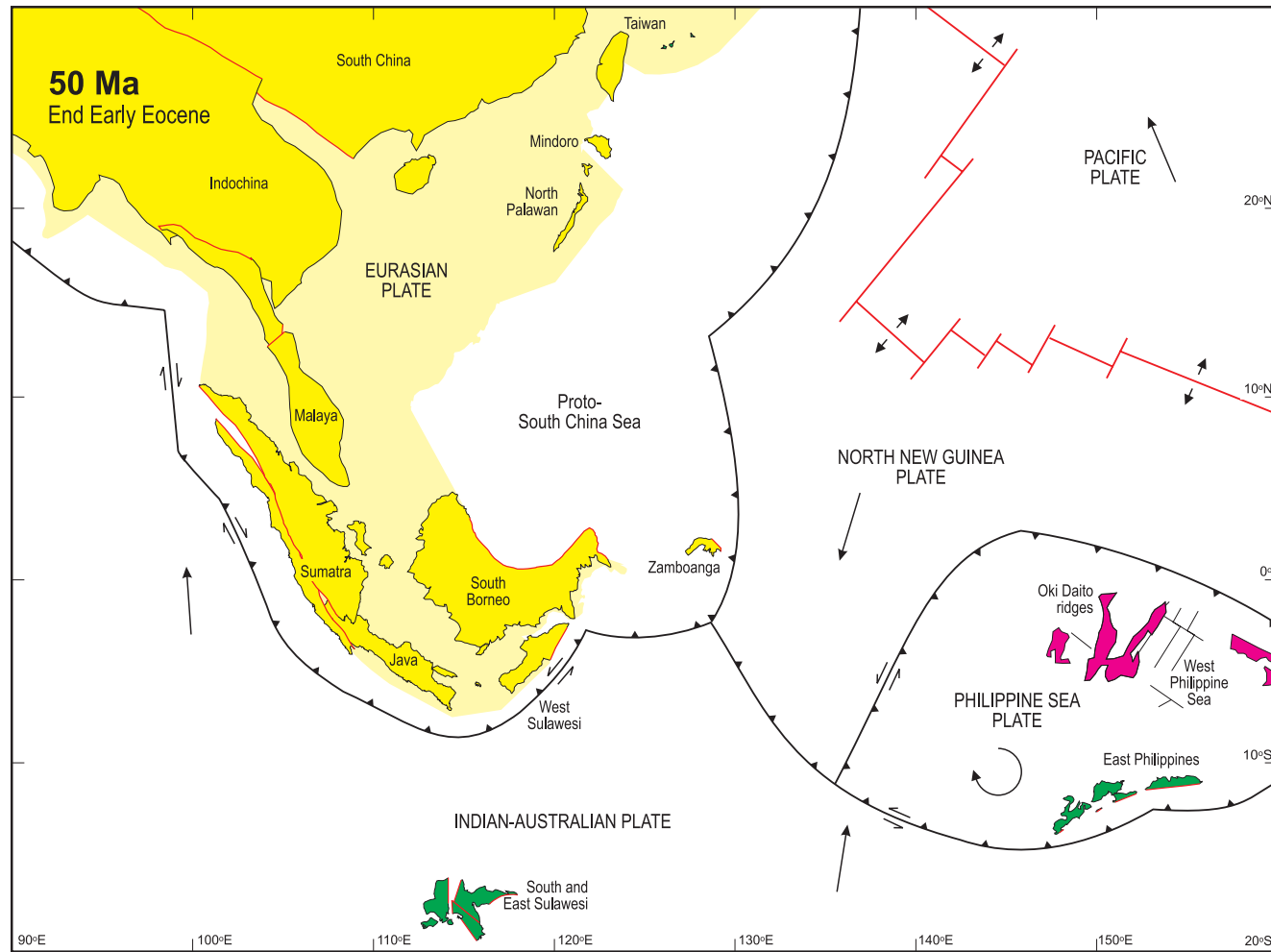
(1987) recorded high heat flows in several NW Banda Sea basins and suggested that they are not isostatically and thermally compensated.

#### *Caroline Plate and New Guinea*

The consequences of fixing the Caroline plate to the east side of Ayu Trough for Caroline-Pacific boundary motion are that there has been predominantly left-lateral motion since 25 Ma, minor oblique convergence between 15 and 5 Ma and minor oblique extension between 5 and 0 Ma (Figs. 2-6). The timing of convergence and extension are partly dependent on the model since the period of 15-5 Ma was chosen as the interval of the main opening of the Ayu Trough, based on Weissel & Anderson (1978). However, these conclusions are consistent with the evidence of young oblique extension in the Sorol Trough (Weissel & Anderson 1978). The northern New Guinea arc terranes have been omitted from the reconstructions for simplicity and because there are insufficient data to reconstruct them adequately. However, the reconstructions do predict that there would have been relatively little convergence between the northern Australian margin and the Caroline plate during the Neogene. Most of the convergence that is required should have occurred in the past 5 Ma (Fig. 2) and would have been oblique. At the present day it appears that much of the convergence is distributed (McCaffrey & Abers 1991; Puntodewo *et al.* 1994) implying that only a proportion need be absorbed by subduction. This is consistent with the shallow seismicity associated with the New Guinea trench and lack of active volcanoes (Hamilton 1979; Cooper & Taylor 1987), and the absence of Neogene volcanicity in Irian Jaya and the Bird's Head (Pieters *et al.* 1983; Dow & Sukanto 1984). The reconstructions require young (5-0 Ma) underthrusting on the sector of the New Guinea trench east of the Bird's Head as interpreted by Hamilton (1979) and Cooper & Taylor (1987) but not north of the Bird's Head, consistent with observations of Milsom *et al.* (1992). The apparent complexity of the northern New Guinea margin (cf. Pigram & Davies 1987) appears to be due less to multiple collisions than to strike-slip faulting and fragmentation of the arc which collided with the Australian margin in the early Miocene. No reconstruction has been attempted here of the SW Pacific north and east of New Guinea, and the reader is referred to Yan & Kroenke (1993).

#### **Final Comments**

The reconstructions presented here differ significantly from earlier attempts to describe the



**Fig. 11.** Reconstruction of the region at 50 Ma. The early rotation of the Philippine Sea plate began.

development of SE Asia. Daly *et al.* (1991) and Lee & Lawver (1994) neglect the rotation of the Philippine Sea plate and this accounts for major differences in our interpretations of the eastern parts of the region. Rangin *et al.* (1990) modelled clockwise rotation of the Philippine Sea plate and their reconstructions are quite similar to those here for the Philippines region but the models differ on the position of the Philippine Sea plate, the rotation of Borneo, and the position of Luzon. As noted earlier, these differences are partly a consequence of different interpretations of inadequate data. Thus, even if these new reconstructions are rejected they do at least serve to draw attention to the need for many more good quality palaeomagnetic data from the region, in addition to geological data, particularly on the timing, chemistry and character of volcanic activity. Biogeographical data could also be especially useful in testing the different interpretations of the region and there is a need for a joint approach from botanists, zoologists and geologists. If the large frame is used it also becomes clear how much one is limited by the area, by the extent of possible oceanic crust, etc.; these limitations are much less obvious in local reconstructions where it is easier to move problems outside the area of immediate interest.

The reconstructions suggest that the indentation of Eurasia by India has played a much less important role in the development of SE Asia than often assumed. They suggest that collision of the Australian continent has driven major rotations, and that the movement of smaller plates, such as the Philippine Sea plate and the Borneo microplate, is the result of the northward movement of Australia. Events which are thus 'caused' by movements of such plates may therefore be the consequence of more fundamental regional movements. Thus, caution is necessary in correlating events of similar age and interpreting their causes. The difficulties of reconstructing the Philippines are partly due to our still inadequate knowledge of this region but may

also reflect our limited understanding of arc processes, particularly at the lithospheric scale. The intra-oceanic history of the region leaves a poor record; arcs are ephemeral features on the geological time-scale and may disappear completely, a process currently underway in the Molucca Sea. Probably the most difficult feature to incorporate is the role of strike-slip faulting. Like Karig *et al.* (1986) and Rangin *et al.* (1990) the present author considers that strike-slip faulting has played a major part in the development of the Philippines and the reconstructions confirm that there is limited space for the convergent motions often inferred from the arc volcanic record. These reconstructions also point to the importance of strike-slip faulting in other parts of the region such as Borneo and New Guinea, and suggest a need for re-examination of data and interpretations based on purely convergent collision models.

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