Tectonic evolution of SE Asia: introduction

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SE Asia is probably the finest natural geological laboratory in the world yet is still not geologically well known. It is a spectacular region in which the manifestations and processes of plate collision can be observed at present and in which their history is recorded. It is a region that must be understood if we are to understand mountain belts, arc development, marginal basin evolution and, more generally, the behaviour of the lithosphere in collision settings. Furthermore, the region is developing rapidly on the economic front, and a major part of this rapid development is built on natural resources. The geological reasons for the distribution of these resources are therefore of major importance for the inhabitants of the region and for attempts to discover and exploit them. These were some of the thoughts which stimulated the collection of papers (Fig. 1) in this volume.

In order to understand the development of this complex region an essential first step is to identify the key features of the active tectonics and determine how plates and sub-plate lithospheric fragments are moving. How successfully can rigid plate tectonics be applied in describing present tectonics? Where are the boundaries between plates? What are the rates at which different parts of the region are moving? The first part of this volume includes a number of papers which deal with these questions, based upon the application of GPS (Global Positioning System) measurements to determining the nature and rates of plate movements and plate boundary zone deformation, results from the BIRPS deep seismic reflection experiment in the Banda arc, the first to cross a modern active margin, and other geophysical and geological studies. **McCaffrey** provides a regional overview of recent GPS results and earthquake data bearing on the present plate tectonics. It is ironic that in such an active region the identification of several plates and determination of some important relative plate motions, critical to a full kinematic description, are still very uncertain. McCaffrey discusses the way in which motion is partitioned in obliquely convergent settings, almost the rule in SE Asia. Oblique convergence is commonly inferred in the past for SE Asia (as shown in many of the later papers in the volume) and is often used as an explanatory tool in orogenic belts elsewhere in the world. He draws attention to the deformation of the upper plate in these convergent settings and emphasizes the importance of a three-dimensional understanding of the process. In this rapidly evolving region, information from slip vectors and geodetic measurements will allow a fourth dimension of time to be included as data accumulate, which will raise the important problem of whether and for how long the present motions can be assumed to extend back into the past.

Two well-known areas of oblique convergence, the Sumatra and Philippine Sea plate margins, illustrate the realities of present tectonics, first in identifying small plates or smaller tectonic elements, and second in providing a kinematic description. The increase in obliquity of convergence between Java and north Sumatra has long been considered to result in thrusting normal to the subduction trench and arc-parallel movement on the Sumatran fault. However, as McCaffrey points out, this simple model does not predict some important features, such as subduction west of the Andaman Sea and differences in amounts of extension between north and south Sumatra. **Malod & Kemal** discuss evidence from marine surveys off Sumatra and propose that this area can be understood as a number of plate slivers between the trench and the Sumatran fault, with variations in the partitioning of movement in different parts of the Sunda forearc. This is explained as the result of differences in coupling between the subducting and overriding plates, possibly reflecting the presence of major structures on the subducting slab, notably an extinct spreading centre on the Indian plate. Further east, the Philippine fault and trench are also considered as the joint expression of partitioning of oblique convergence, but once again applying this simple model presents problems: how does this paired trench–fault system link southwards into the arc–arc collision of the Molucca Sea? **Rangin *et al.*** tackle the first important problem of what is actually present in the zone of transition by mapping structures from the south Philippines into Indonesia and determining which features belong

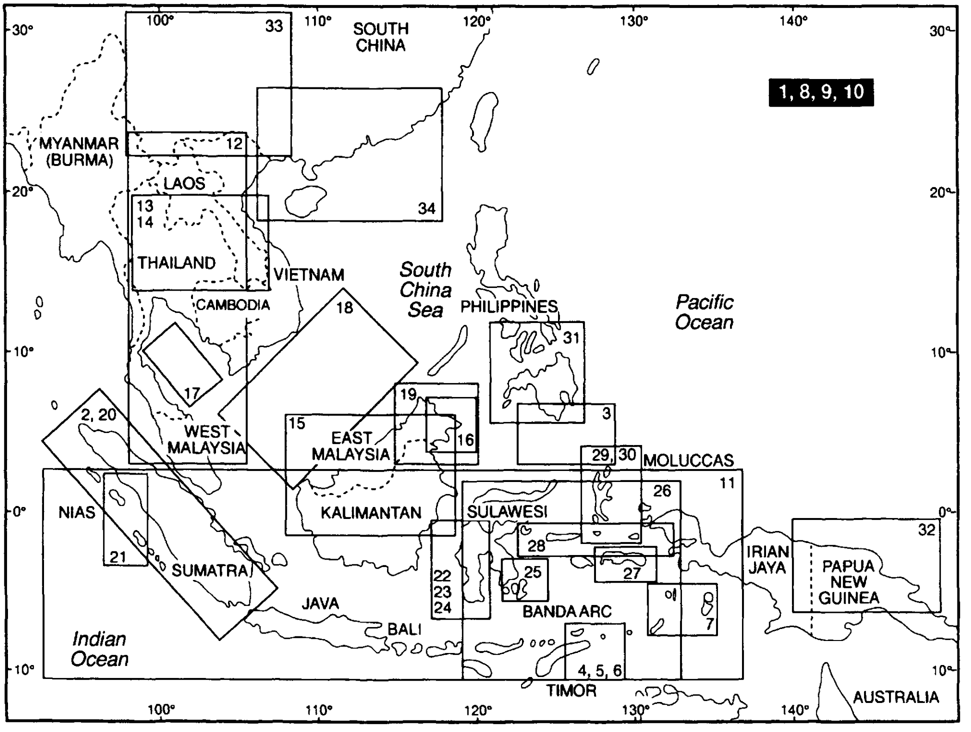

Fig. 1. Areas discussed in the papers in this volume. 1: McCaffrey; 2: Malod & Kemal; 3: Rangin et al.; 4: Richardson & Blundell; 5: Snyder *et al.*; 6: Hughes; 7: Milsom *et al.*; 8: Metcalfe; 9: Packham; 10: Hall; 11: Simandjuntak & Barber; 12: Richter & Fuller; 13: Stokes *et al.*; 14: Lovatt Smith *et al.*; 15: Hutchison; 16: Omang & Barber; 17: Ngah *et al.*; 18: Tjia & Liew; 19: Clennell; 20: Mccourt *et al.*; 21: Samuel & Harbury; 22: Wakita *et al.*; 23: Wilson & Bosence; 24: Bergman *et al.*; 25: Ali *et al.*; 26: Vroon *et al.*; 27: Linthout *et al.*; 28: Charlton; 29: Malaihollo & Hall; 30: Baker & Malaihollo; 31: Pubellier *et al.*; 32: Crowhurst *et al.*; 33: Wopfner; 34: Zhou *et al.*

to which plate, a demanding task. Their use of the technique of multibeam mapping, combined with geophysical evidence, is producing highly detailed maps, in many cases of much higher quality than those available for land areas nearby, and revealing unsuspected structures.

The arguments surrounding the tectonics of the Banda arc, and some of the complexities of the collision zone, for example its curvature, age of the Banda Sea, and significance of deep basins such as the Weber trough, also illustrate the difficulties of linking simple kinematic models to reality. Very recently two BIRPS deep seismic reflection profiles have crossed the Banda arc and imaged the deep structure of the central part of the Australia–SE Asia collision zone. **Richardson & Blundell** discuss how deep reflectors can be linked to recent seismicity, and their connection to structures on land. They identify two sets of divergent structures in the collision zone: a southern set dipping in the same direction as subduction is related to the subducted Australian margin, whereas a northern set, in the upper plate, is antithetic, and more recent. They argue that these structures changed orientation and migrated north because buoyant continental crust blocked the subduction zone, although Australia continued to move north. Using the BIRPS images to estimate the volume of material in the collision zone they infer that an earlier Neogene collision event, involving a separate microcontinental fragment or outer margin high, must have preceded the present phase of collision which began at about 2.4 Ma. **Snyder *et al.*** draw attention to unusual features of the BIRPS 'Timor' sector of the Banda orogenic zone, including a Bouguer anomaly and thin sediment cover implying a thicker continental crust than normal beneath the accretionary complex, a very narrow forearc, and presence of the volcano Gunung Api in the backarc. Like Richardson & Blundell, they infer the presence of additional Australian margin crust but suggest it formed either a promontory of the Australian margin or a pre-breakup extensional basin within the former passive margin, now inverted and thickened. Also like Richardson and Blundell they deduce that the deformation has advanced across the collision zone, causing crustal fracturing in the backarc region and allowing magmatic uprise and underplating beneath Gunung Api. **Hughes *et al.*** have reprocessed part of the Timor section to bring out the details of the Timor trough and the accretionary wedge developed on its northern flank. Australian shelf sediments are clearly imaged, relatively undisturbed, and beneath a low-angle decollement above which are highly deformed sediments stacked in a complex set of thrust sheets indicative of the northward underthrusting of the Australian continent. However, a covering drape of sediment indicates that deformation in this area has been inactive for about 1 Ma.

One feature that has bedevilled discussions of the Banda arc is the significance of the deep troughs which parallel the arc, which in a superficial way have characteristics of trenches, but when studied more carefully seem to be in the wrong position. **Milsom *et al.*** present evidence that the deformation front between Australia and the Banda arc extends between the Kai islands, in the region of maximum curvature of the arc, rather than following the apparent subduction-related feature of the Aru trough. They conclude that the arc must have been a continuous feature before collision with a curvature acquired recently.

The present setting of the region is both the start and the end point in attempts to comprehend its development. The start, because an understanding of what is present provides the first clues of what has happened in the past few millions or tens of millions of years, leaving traces in the slabs beneath the arcs, the arcs themselves, and in the stratigraphic record of the arc regions as well as the Sunda continental shelf further north. The end, because the present is the result of what has happened in the past, and many of the present features of the region may be explicable only in terms of what has now disappeared and can only be inferred. Thus, our understanding of the region and its development is an iterative synthesis, each new step forward requiring a reconsideration of present and past. The second section of the volume therefore begins with three overview papers intended to synthesize earlier observations which may provoke new research improving and extending our present regional understanding.

Metcalfe reviews the pre-Cretaceous development of SE Asia and east Asia and shows that the region has grown by addition of allochthonous terranes which separated from different parts of Gondwana. Their northwards movement was accompanied by the opening and closing of three successive oceans: the Palaeo-, Meso- and Ceno-Tethys. Assembly began with the formation of Cathaysia in the Late Devonian–Early Carboniferous and its growth continued within the Palaeo-Tethys in the later Palaeozoic. As the Meso-Tethys opened by Late Carboniferous-Early Permian rifting of the northern margin of Gondwanaland so the Palaeo-Tethys began to close, and so subsequently did the opening of the Ceno-Tethys result in elimination of the Meso-Tethys. The final stage of the reassembly of Gondwana in Asia is not yet complete but the present complexity of the region, as well as the comprehensive grasp of so many disciplines in earth science required to attempt the task of describing its development, give an indication of Metcalfe's achievement in producing a comprehensible synthesis.

A description is an essential step in identifying the driving processes and modelling the development of the region. Reconstructing SE Asia in the Cenozoic requires a description of India–Eurasia collision, the motion of the Philippine Sea plate and the present collision of Australia with eastern Indonesia. Eurasian extrusion models have proved popular with many workers in SE Asia, partly because of the striking similarities of plasticine models to tectonic maps, and partly because they offer a means to explain and link different events. As with many major advances, the extrusion model has also been effective in provoking other new ideas and the search for new evidence. **Packham** considers the relationships between the observed geology and different models of the region, reviewing the timing of different events, the evidence from crustal volumes for extrusion, and the relationship between predicted and observed palaeomagnetic measurements. In east Asia and western SE Asia the estimates of rates and amounts of movements predicted by the extrusion model, and those that can be determined, are becoming much closer. The inadequacies of the fit cannot just be explained as weaknesses of the model but also emphasize the variable quality of data and their uncertainties. Packham concludes that a regional understanding of SE Asia requires a better understanding of the timing of deformation, especially uplift, in the Himalayas and central Asia, a clearer picture of whether rotations detected using palaeomagnetic data are regional or local, and much new stratigraphic information, particularly in the eastern part of the region.

The key role of palaeomagnetic data in developing regional models is a theme discussed by **Hall** in an attempt to produce a kinematic model for the whole of Cenozoic SE Asia. At the centre of the region is the island of Borneo from which rotations recorded appear to be in conflict with those predicted by an indentation model. Further east, new data from the Philippine Sea plate confirm long-term clockwise rotations of the whole plate suggested by many earlier studies. The attempt to synthesise these results suggests that, even if Cenozoic extrusion of continental fragments from east Asia is accepted, this has not been the most important driving force in the development of the marginal basins of eastern SE Asia. According to this model, development of marginal basins was linked physically and temporally, and opening appears to be mainly subduction-related rather than indentor-driven. This new model does suggest some possible configurations for the region which are different from those previously accepted and may provoke reconsideration of some evidence, especially the habit of looking for local explanations of tectonic phenomena. The animation which accompanies the paper reminds us that regional events may have causes outside the immediate area, and the manifestation of plate movement changes may propagate gradually across the whole region, as plate boundary changes in one area cause changes in others. Several aspects of the model, such as the proposed ages of some basins, for example the Banda Sea, remain to be tested by ocean drilling, palaeomagnetic work, and stratigraphic and structural studies.

The remaining papers in the volume are arranged broadly in geographical order. **Simandjuntak & Barber** illustrate the variation in orogenic styles from different parts of Indonesia. The present diversity and complexity of tectonic processes in SE Asia may provide keys to the interpretation of other orogenic belts. The differences in the history of deformation within the region may leave traces other then geological structures and **Richter & Fuller** discuss the still thorny question of the implications of palaeomagnetic data from Sundaland and Indochina. They conclude that different parts of Sundaland and Indochina have deformed in different ways; some parts as small blocks with rotations indicating local deformation, some extrusion-driven rotation, principally in Indochina, and some parts recording the results of deformation dominated by the oblique subduction of the Indian plate. Distinguishing between such areas for the whole SE Asia region is an important task for geologists and palaeomagnetists for the future.

Even the most carefully constructed regional kinematic models are totally dependent on basic data revealing the timing of tectonic events and the evidence for them. The papers concerned with areas around the South China Sea suggest the need for revisions of models as well as new interpretations of relationships between effects and supposed causes. In Laos, **Stokes *et al.*** argue that suturing of the Shan-Thai and Indochina blocks occurred in the Late Jurassic and that the Indosinian Orogeny, currently assumed to be of Permian or Triassic age is significantly younger than commonly assumed. Based largely on seismic data, **Lovatt Smith *et al.*** suggest regional tilting, compressive folding, reverse faulting and basin inversion in Thailand record important phases of structural development which pre-date the currently assumed Tertiary age of structuring. If correct, these interpretations have implications for hydrocarbon exploration and potential. **Hutchison** draws attention to the contrast between tectonic models of the South China Sea region and the geology of Borneo and proposes that the term Rajang Group should be more carefully applied. An older turbidite sequence, assigned to the Rajang Group proper, represents an accretionary prism compressed and uplifted between the Schwaner Mountains volcano-plutonic arc and a South China Sea microcontinent during an Eocene orogeny. Similar but younger turbiditic rocks deformed by a Miocene orogeny are interpreted not as deposits of a forearc, but as derived from the eroding and uplifted Rajang Group, and should be separated from it. A further record of the late Mesozoic or early Tertiary subduction setting of the NE Borneo margin is to be found in the large Darvel Bay Ophiolite Complex of Sabah. Mineralogical and geochemical studies by **Omang & Barber** suggest its formation in a supra-subduction zone environment, but with complexities due to high T–low P deformation along a transform fault. High P–T garnet pyroxenites and amphibolites found as clasts in Miocene rocks were derived from a metamorphic sole underlying the complex, formed during subduction and emplacement of the ophiolite.

Within the Sunda shelf are sedimentary basins of the South China Sea and adjacent areas which record a link between east Asian tectonics and the plates beyond the subduction zones bounding SE Asia. The importance of pre-existing structures in controlling tectonic development is often forgotten and **Ngah *et al.*** suggest that the Malay, Penyu and West Natuna basins originated in the Late Cretaceous as three rift arms that developed during doming of continental crust above a mantle plume. The hydrocarbon potential of these basins was subsequently influenced by changes in stress patterns which **Tjia & Liew** argue resulted from the interplay of Eurasian extrusion driven by Indian indentation, and changes in directions and rates of motion of the plates in the Pacific and Indian Oceans. Borneo is situated in the middle of this region at the south side of the South China Sea and ought to record the effects of these changes. The geology of Sabah is therefore of considerable regional interest since, if Borneo has rotated, it is an area where the consequences should be most obvious. **Clennell** discusses the interplay between large-scale regional plate motions (his 'far-field tectonics') and pre-existing structures and local tectonic influences for the development of the unusual circular basins of Sabah. These papers on sedimentary basins show that we are still some way from clearly linking local and regional tectonics. Tjia and colleagues show that there were reversals in the sense of movement on important faults, that the effects of fault movements differ from area to area, and that there is still uncertainty in the timing of fault movements. Clennell infers that basins in Sabah appear not to record some tectonic events because they were decoupled due to the thicknesses of underlying muds and mélanges.

Sumatra is an area where a long history of subduction should be recognizable since the island is usually considered to have been situated above the northward-subducting Indian plate from at least the Mesozoic. Despite this there appear to be distinct periods characterized by igneous activity, separated by intervals with little or none. **McCourt *et al.*** use isotopic dating and geochemistry to identify plutonic episodes and their character, which they link to plutonism elsewhere in Sunda margin. Understanding the tectonic significance of the igneous episodes needs to be the next step forward. McCourt *et al.* speculate that variations in the obliquity of convergence, and collision of allochthonous terranes are implicated, although Neogene and younger strike-slip faulting complicates the picture. It would be useful to consider the Cenozoic history of this margin in the light of known plate motions, although the major uncertainty here is not the motion of the Indian plate but the orientation and position of Sumatra; different regional models show very different configurations for the early Tertiary. The Cenozoic history of this margin is clearly complex as indicated by other papers in the volume and **Samuel & Harbury** show that this complexity is still far from understood. In their paper, based on detailed studies on land in the Sumatran forearc islands, principally Nias, they interpret the Mentawai fault system not as a strike-slip fault, but as an extensional structure with late contractional reactivation. If correct, at least one of the plate slivers of the forearc proposed by Malod & Kemal either does not exist or is of very recent origin. Samuel & Harbury's work also illustrates the importance of field-based studies in providing a firm stratigraphic basis for the interpretation of other evidence, such as seismic and marine geophysical evidence, and they infer a long extensional history for the Sumatran forearc, with major extensional structures later reactivated, again with possible links to changes in plate motions such as the angle of convergence.

A good stratigraphic base is fundamental to attempts to interpret the tectonic evolution of the region and **Wakita *et al.*** provide an example of how this is achieved by detailed radiolarian studies. The Bantimala Complex and Balangbaru Formation of south Sulawesi record critical events in the accretionary growth of the SE Sunda margin and dating based on micropalaeontological evidence is difficult to obtain and interpret since the turbidite sequences yield few fossils, and these may be reworked. Radiolaria, which can often be assigned to narrow zones, provide an additional means of comparing the ages of different lithological units and suggest the Bantimala Complex and Balangbaru Formation are contemporaneous, requiring a modification of previous tectonic interpretations. From the same region **Wilson & Bosence** show how redeposited limestones of the Tonasa Limestone Formation can be used as indicators of tectonic activity. Detailed measured sections, well dated by fossils, illustrate how a very clear palaeogeographic picture can be deduced and linked to larger-scale tectonics. Their results provide a basis for regional interpretation and will be of considerable interest to those exploring for hydrocarbon in the frontier regions of east Indonesia. Sulawesi is currently much less well-known than it deserves to be, especially considering its large size and critical position at the Eurasia–Australia–Pacific junction, and recent results have shown that simple tectonic models for its development need reconsideration. **Bergman *et al.*** present data from west Sulawesi which will need to be incorporated in new models and speculate on possible solutions. Of considerable interest is the evidence, based on isotopic studies, for a magmatic contribution from old Australian-type continental crust to the Tertiary plutonic rocks of west Sulawesi. Bergman *et al.* also focus attention on the structures around the Makassar Strait. This has previously been widely accepted to be an extensional basin but they interpret it as a foreland basin bounded by converging Neogene thrust belts, with the late Miocene western Sulawesi magmatic arc recording continent–continent collision. The collapse of the orogenic belt is seen as the cause of young extension in the region. The rapid changes predicted by the model are certainly consistent with the variety and speed of tectonic processes currently observed in SE Asia.

The Neogene collisions of continental fragments in Sulawesi are a principal cause of its geological complexity and **Ali *et al.*** provide some insights into how tectonic models can be tested using palaeomagnetic data. In Buton, large rotations are recorded, but are apparently very local, and were very rapid. This work reinforces the value of, and need for, many more palaeomagnetic studies in SE

Asia in order to separate local from regional motions. Buton is one of several continental fragments which are now being reassembled in SE Asia. These include Australian and Sundaland material but their origin can often only be inferred from indirect arguments, commonly controversial. **Vroon *et al.*** suggest that isotopic evidence can contribute to solving this problem and show how different types of continental crust can be characterized by analysis of igneous and sedimentary rocks. They suggest that different parts of east Indonesia have provenances in southern New Guinea, north Australia, Pacific New Guinea and Sundaland, leaving the tectonicians with an additional tool but, in this area, some additional problems to solve.

In the midst of the continental fragments of east Indonesia are the deep basins of the Banda Sea, as yet unsampled by the ocean drilling programme, and of uncertain age. **Linthout *et al.*** report new isotopic ages from Seram implying Neogene spreading in the southern Banda Sea before ophiolite obduction on Seram in the Late Miocene. These ages are broadly consistent with ages of rocks recovered during recent dredging in the Banda Sea and with the tectonic reconstructions of Hall, although the great depths and low heatflow measurements remain apparent inconsistencies. On the north side of the Banda Sea the Sorong fault system separates Australia from the Philippine Sea and Molucca Sea plates and terminates in the continental fragments of east Sulawesi. The timing of movement on the strike-slip faults has never been clear, although recent work suggests this plate boundary zone became a strike-slip system in the early Miocene. The timing of movements and the distribution of continental crust in this region is of major interest, not least in the search for hydrocarbons, since this is an area of established production, recent discoveries, as well as active exploration, all linked to Australian crust. Based on stratigraphic arguments, **Charlton** argues that two of the basins, the Salawati basin of western New Guinea and the Tomori basin of eastern Sulawesi, were originally a single sedimentary basin, now separated by latest Miocene to Quaternary movements on the fault, implying a left-lateral displacement of about 900 km. Movement on the fault system is one of the latest complications in the development of east Indonesia; on the south side of the fault system is Australian crust while on the north side are the arc–arc collision of the Molucca Sea and the clockwise-rotating Philippine Sea plate. In the fault zone, which includes several major splays, are fragments of both Philippine Sea and Australian origin and Bacan is one of the islands which includes rocks of both provenances. Bacan therefore offers the possibility of elucidating some of the history of the plate boundary zone, and establishing the timing of tectonic events. **Malaihollo & Hall** report new stratigraphic data from Bacan which record the early arc history of the Philippine Sea plate and the arrival of continental crust, providing a basis for distinguishing different tectonic models. **Baker & Malaihollo** discuss the timing of volcanism in the islands of Halmahera immediately north of Bacan, which records the initiation of subduction of the Molucca Sea plate beneath Halmahera and the development of the present-day arc–arc collision. Volcanism began in the middle to late Miocene and migrated northwards implying that the double subduction system was established between about 15–12 Ma. This evidence still remains to be incorporated in models linking east Indonesia to the Philippines. **Pubellier *et al.*** provide further evidence from the southern Philippines critical to linking the two areas and understanding the development of the present tectonic setting described earlier in the volume by Rangin *et al.* Once again, the theme of partitioning of oblique convergence is emphasized. In addition, there are complications reflecting Neogene changes in plate motions and the complexities of intra-arc deformation. Strain has been partitioned between several orientations of faults, reactivated at different stages as thrusts and wrench faults, as well as subduction zones. Of particular interest is the way in which this development has resulted in intra-arc extension and fragmentation within the Philippines.

The interplay of subduction and strike-slip faulting is a theme which appears in many of the papers in the volume. Ancient strike-slip motion is often difficult to demonstrate and quantify and is consequently often neglected. However, there is evidence, traditionally linked to the convergent component of collision, which may be differently interpreted. **Crowhurst *et al.*** show that fission track data suggest that the Papuan metamorphic rocks may be interpreted as representing early Neogene extension after arc collision, rather than contraction-related metamorphism. These arguments may be applicable in other parts of SE Asia where fission track and isotopic ages are revealing unsuspected events, very young ages, and short time periods for the very complex tectonic evolution of many parts of the region.

The volume concludes with two papers from south China accompanied by interpretations of the timing and significance of events. **Wopfner** suggests that the Baoshan and Tengchong Blocks in western Yunnan have a Gondwana origin, supported by the presence of Upper Palaeozoic glaciomarine deposits, cold-water faunas and Glossopteris. The terranes separated from Gondwana in the Early Permian and docked with

Cathaysia in the Late Triassic, although Tertiary strike-slip faulting on the Nujiang Line has juxtaposed the two terranes. **Zhou *et al.*** reinterpret part of the history of SE China, diverging in particular from the traditional practice of relating major unconformities to separate orogenies, and suggesting instead that they record different stages in the evolution of a single orogeny following early Mesozoic collision between the South China and the South China Sea blocks.

SE Asia is one of the most exciting regions of the globe for any earth scientist. The size, difficulties and practicalities of the region demand a long-term investment of effort but the rewards are illustrated by the papers in the volume. These give an insight into how the history of the region will be uncovered, as well as providing an overview of present regional tectonics and its development. Because of the rapid rates of movements in many parts of the region new geodetic tools and increasingly refined methods of examining earthquake data mean that realistic and rapid tests of regional and global plate models are possible. The challenge for the future is to examine how far interpretations of these data can be pushed back into the past, to improve kinematic descriptions and models, and to identify the processes which have led to the complexity of the region and which can be applied to older orogenic belts. In these tasks, there remains an important role for the field geologist as well as those developing and applying new technologies. An improvement of our understanding will have benefits for knowledge as well as for the many inhabitants of the region, in helping to develop its resources and mitigate its hazards.

This Special Publication arose from a conference on the Tectonic Evolution of SE Asia held at the Geological Society in London in December 1994. In addition to the reasons outlined above for the conference, the London University SE Asia Research Group wished to mark the retirement of Dr A. J. Barber in 1994. Tony Barber initiated several of the studies which are presented as publications in this volume and was instrumental in developing the programme of the SE Asia Research Group over many years, particularly by fieldwork throughout the region. We wish him a long and happy retirement.

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