Formation of marginal seas in Southeast Asia by rifting of the Chinese and Australian continental margins and implications for the Borneo region

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Abstract: With the exceptions of the Okinawa and Ayu troughs, all the Southeast Asian marginal seas have formed by processes other than back-arc extension. The Andaman Sea is an ideal example of a leaky transform system. The West Philippine Sea, Banda Sea, Celebes Sea and Sulu Sea basins all appear to be remnants of former oceans now trapped behind younger arc-trench systems. The last three may be interpreted to be related to the post-Early Triassic rifting of the northern continental margin of Australia.

The South China Sea basin was probably formed by post-Early Cretaceous rifting of the continental margin of southeast China and is now trapped behind the Manila arc-trench system.

The rifting of Australia and China, and the associated sea-floor spreading, carried continental fragments northwards and southwards respectively. Borneo and the adjacent Philippines may have resulted from the coming together of these fragments to form the heterogeneous basement terrain over and around which Cenozoic sediments have accumulated.

The uplift of the marginal sea lithosphere to form ophiolitic terrains is considered to have resulted from the collisions of the continental fragments with each other or with arc-trench systems.

INTRODUCTION

Southeast Asia has the greatest concentration of marginal seas, but contrary to the popular view, most of them do not appear to have formed by back-arc extension. Indeed the term "back-arc" may be nothing more than a geographic description and many geologists now doubt that extension in the back-arc region is genetically related to active arc-trench covergent tectonics. In a recent classification of sedimentary basins, Kingston *et al.* (1983) have abandoned the term "back-arc" for the Tertiary basins of Southeast Asia lying on continental crust behind the arc-trench systems. They see such basins as resulting from a slight extensional component to major wrench or shear faults hence they use the term "wrench or shear basins." The Andaman Sea basin lies behind the Sumatran-Andaman-Burman arc-trench active plate margin, but its genesis is related to slight extension resulting from bending of the Sumatran-Sagaing wrench fault system. This basin may therefore be the ideal example of a "leaky transform system." In addition to the Andaman Sea, only the Okinawa and Ayu troughs are presently actively spreading. The Okinawa Trough is actively forming behind the Ryukyu volcanic arc and may be the only example of back-arc spreading according to the popular concept. The Ayu Trough is in a very enigmatic tectonic setting and has too low a heat flow and spreading rate to fit the model of marginal-sea generation.

All the other marginal seas of Southeast Asia are inactive, but there is no evidence that any one of them formed by back-arc extension, and all are better interpreted as remnants of former oceans trapped behind younger arc-trench systems.

MECHANISMS OF MARGINAL SEA FORMATION

Dickinson (1978) noticed a strong correlation between the facing direction of an arc-trench system, and its back-arc behaviour. Systems that face east (subduction towards the west) are commonly accompanied by marginal seas in the back-arc region, whereas systems that face west are characterized by back-arc thrusting. This is illustrated schematically in Figure 1 (A). Back-arc extension and spreading characterize the western margin of the Pacific and back-arc continental underthrusting characterizes the American cordilleran margin. Bostrom (1978) attributed these differences to the westward passage of the tidal bulge resulting from the earth's rotation assisting the western limb of the Pacific Rise spreading system. Marginal basins on the American side are prevented from opening by the westward motion of the Americas away from the Mid-Atlantic Ridge. Systems that face south are neutral, and have neither back-arc rifting nor thrusting. Dickinson (1978) further attributed the differences between back-arc rifting or thrusting to the dip of the Benioff Zone. For east-facing systems, the back-arc lithosphere would move away from the arc-trench system, which is anchored to the lithosphere by a steepened subduction slab (Fig. 1A). However, the analysis of Dickinson (1978) may be in error because most Southeast Asian marginal basins do not appear to have not resulted from back-arc spreading.

Figure 1B shows diagrammatically the formation of a marginal sea by entrapment of part of a pre-existing oceanic lithosphere by the development of a younger arc-trench system. The West Philippine Sea basin is an example, and the Banda Sea Basin may also be of this type. The once continuous oceanic lithosphere is interrupted by a flexure at which a subduction system develops. Thus, a distal part of the oceanic lithosphere is isolated or trapped behind a younger arc-trench system. In this case the marginal sea is in the back-arc of the arc-trench system, but is not genetically related to it, because the trapped oceanic lithosphere pre-dates the arc-trench system. This mechanism is most likely when the basin floor is older than the enclosing volcanic arc.

Figure 1A portrays a situation where extension in the back-arc region eventually leads to sea-floor spreading which is genetically related with and contemporaneous with the subduction system. This is back-arc spreading in the popular sense and is akin to mid-ocean ridge spreading. The Sea of Japan and the Okinawa Trough may be of this type.

A variation of this type is when subduction is at a high angle to the trench, so that there is a strong transform component to the subduction, leading to prominent transform faulting in the back-arc region. The Andaman Sea is a good example, where the sea is behind the Sunda Trench, but the motion is nearly parallel to the trench (Fig. 2). The prominent feature of the Andaman Sea is its transform faulting, connected by short *en echelon* spreading axes. This kind of system has been called a leaky transform system.

Some basins may open by continental rifting without any contemporaneous subduction. The Tasman and Coral Seas, which separate New Zealand from Australia, probably resulted from continental rifting (Weissel and Hayes, 1977; Weissel and Watts, 1979). In Southeast
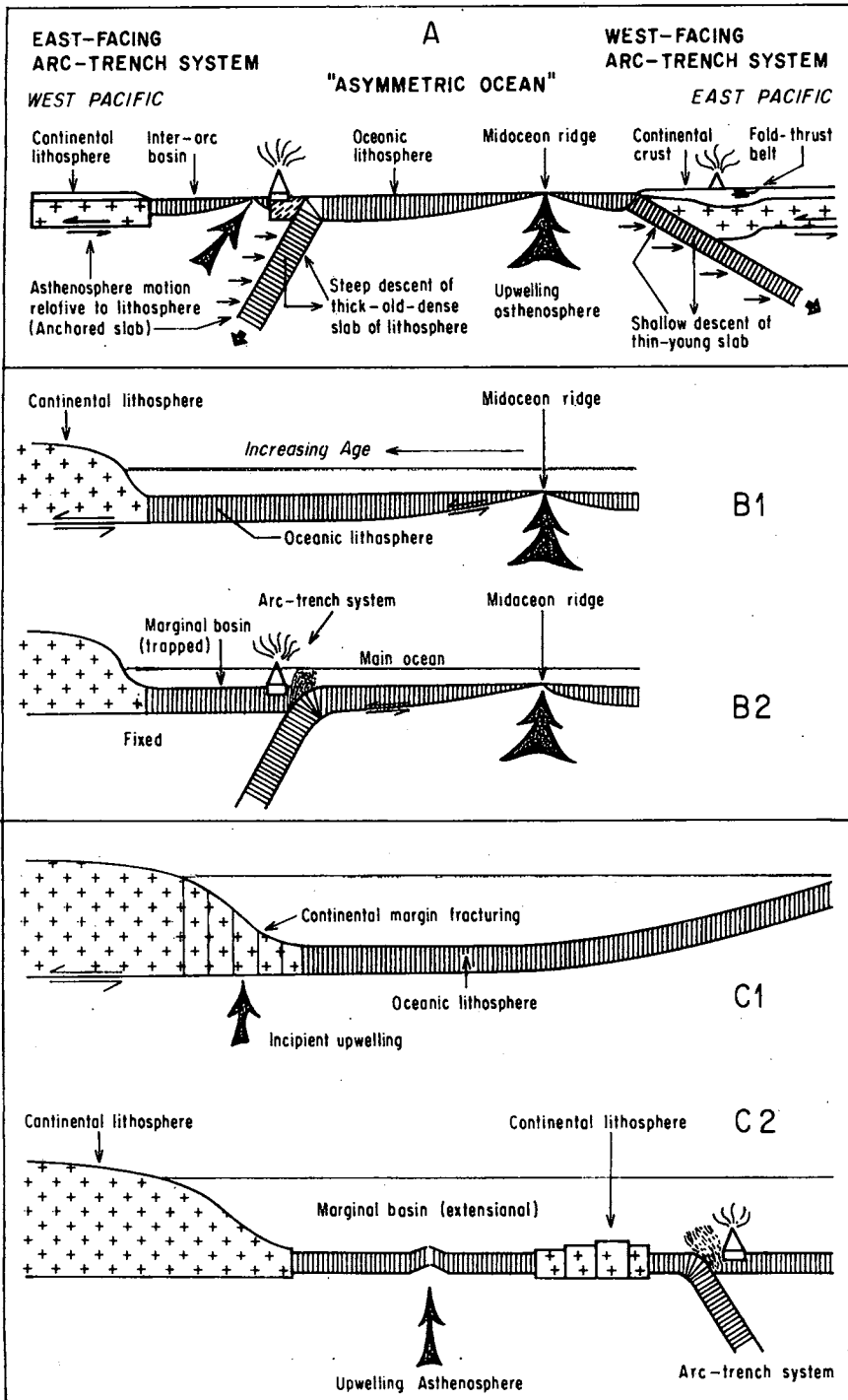
Fig. 1 Mechanisms for marginal sea formation. A: back-arc extension or thrusting dependent upon the Benioff Zone dip (after Dickinson, 1978). B: marginal sea formation by trapping of a distal part of an ocean behind a younger arc-trench system. C: Marginal sea formation by continental margin rifting.
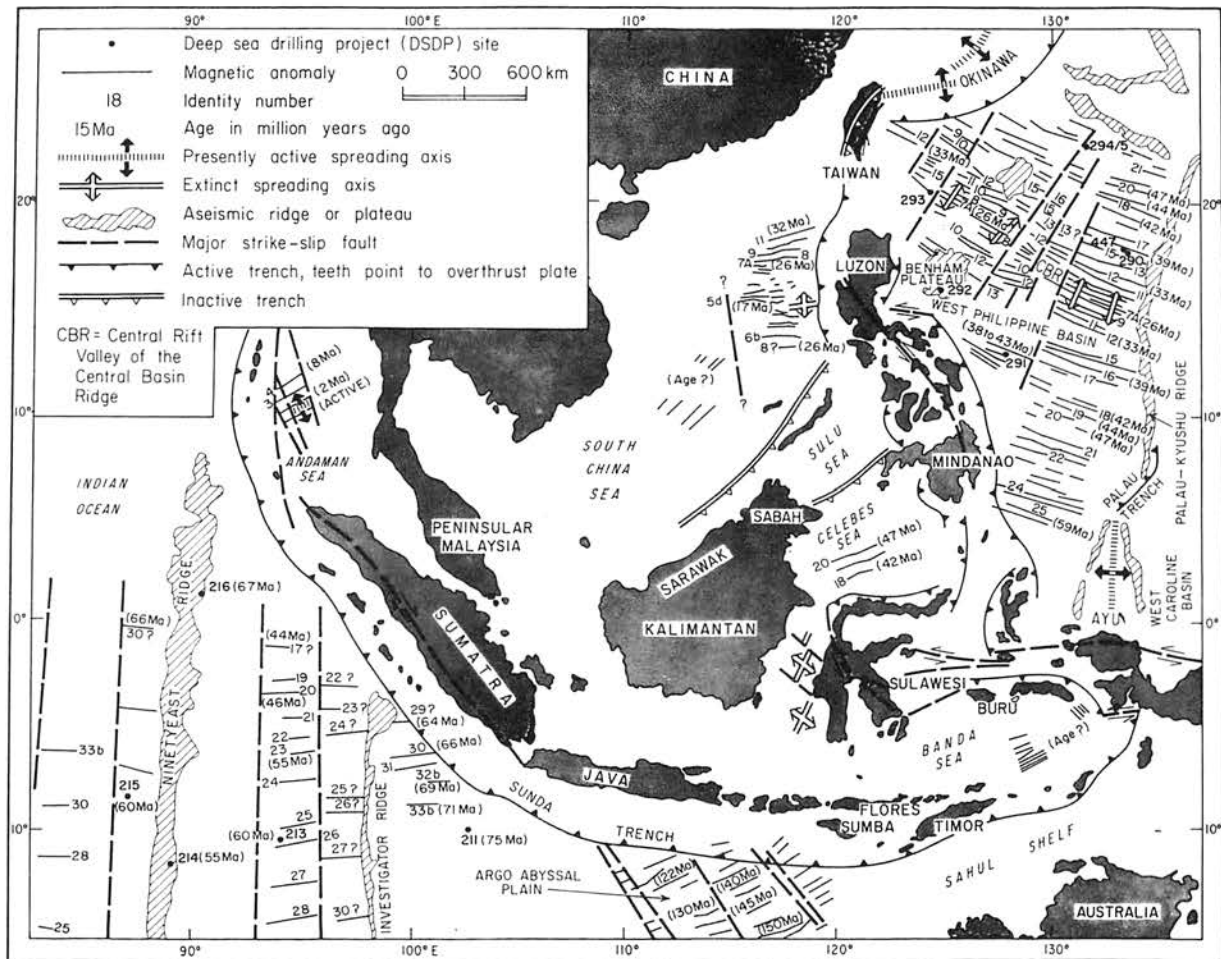
Deep sea drilling project (DSDP) site

Magnetic anomaly

18   Identity number

15 Ma   Age in million years ago

Presently active spreading axis

Extinct spreading axis

Aseismic ridge or plateau

Major strike-slip fault

Active trench, teeth point to overthrust plate

Inactive trench

0   300   600 km

CBR = Central Rift
Valley of the
Central Basin
Ridge

CHINA

OKINAWA

TAIWAN

LUZON

BENHAM
PLATEAU

WEST PHILIPPINE BASIN
(38 to 43 Ma)

MINDANAO

PALAU-KYUSHU RIDGE

WEST CAROLINE BASIN

AYU

PALAU TRENCH

CBR

293

292

294/5

290

291

SOUTH
CHINA
SEA

SULU
SEA

SABAH

CELEBES
SEA

INDIAN
OCEAN

ANDAMAN
SEA

PENINSULAR
MALAYSIA

SARAWAK

KALIMANTAN

SULAWESI

BURU

BANDA
SEA

NINETYEAST RIDGE

INVESTIGATOR RIDGE

SUMATRA

JAVA

SUNDA   TRENCH

FLORES
SUMBA   TIMOR

SAHUL
SHELF

ARGO
ABYSSAL
PLAIN

AUSTRALIA

216 (67 Ma)

215

214 (55 Ma)

213

211 (75 Ma)

33b

30

28

25

(66 Ma)
30 ?

(44 Ma)
17 ?

19
20
(46 Ma)

22 ?

23 ?

24 ?

29 ?
(64 Ma)

30 (66 Ma)

31

32b
(69 Ma)

33b (71 Ma)

21

22
23
(55 Ma)

24

25 ?
26 ?

25

26

27

27 ?

28   30 ?

(60 Ma)

(8 Ma)

(2 Ma)

(ACTIVE)

(22 Ma)

(30 Ma)

(40 Ma)

(45 Ma)

(50 Ma)

20   (47 Ma)

18   (42 Ma)

(32 Ma)

7A   (26 Ma)

11

(33 Ma)

5d
(17 Ma)

6b

8?   (26 Ma)

(Age ?)

20
18

24

25 (59 Ma)

22

21
(47 Ma)
19 (44 Ma)
20 18 (42 Ma)

17 (39 Ma)

16
15

12 (33 Ma)

7A (26 Ma)

(33 Ma)

12

7A (26 Ma)

A47

(42 Ma)

(44 Ma)

(39 Ma)

(Age ?)

Fig. 2   The marginal basins of Southeast Asia, compiled from many sources given in the text (after Gatinsky et. al., 1984).

Asia, the South China Sea Basin has probably resulted from continental rifting of the China margin, and there are many continental fragments scattered on either side of the South China Sea Basin (Taylor and Hayes, 1983) suggesting that the Basin opened by continental rifting similar to the Tasman Sea, and its opening was unrelated to any subduction system. There are island arcs which now surround the South China Sea Basin, but their trends and ages do not show any genetic relationship to the opening of the sea itself. This kind of fracturing of continental crust forming a marginal basin is shown diagrammatically in Figure 1C.

THE SOUTHEAST ASIAN MARGINAL SEAS

The distribution of the seas and their magnetic anomalies and ages, where known, are shown in Figure 2.

A. Okinawa Trough

This seismically-active ENE - trending marginal basin is considered to have developed by back-arc rifting behind the active Ryukyu arc-trench system (Herman *et al.*, 1979). Presumably this basin was named a Trough by oceanographers before its exact tectonic significance was identified. Earthquake focal mechanism studies indicate extension, with low-angle normal faulting directed either towards the arc or towards the continental margin. The spreading centre is still incipient. No identifiable sea-floor spreading pattern has been discerned. Although there is an extremely slow spreading rate, the heat flow is high, with an average value of 4 HFU (170 mW m^{-2}).

B. West Phillipine Basin

This is the largest of the marginal sea basins, and is totally extinct. The Philippine Sea basin is divided by the north-trending Palau-Kyushu Ridge; west of the ridge lies the West Philippine Basin. East of the ridge lies the Parece Vela Basin, which is not described in this paper.

The magnetic anomaly map (after Shih, 1980) is summarized in Figure 2. The lineations trend 110°. The pattern is complicated in the centre by a large number of NNE - trending fracture zones. The combined data of anomalies and drilling suggest that the west Philippine Basin oceanic crust began forming before anomaly 25 (about 59 Ma ago), probably at a spreading ridge that was then the southern boundary of the Pacific Plate. The spreading rates fluctuated from 5.8 cm y^{-1} between 45 to 50 Ma ago, to 10.3 cm y^{-1} at 40 Ma ago to a steady 4.9 cm y^{-1} at the terminal period from 35 to 26 Ma ago. Spreading of the basin was active until anomaly 7a (26 Ma ago). The West Philippine Basin was probably formed by entrapment of Pacific Ocean lithosphere behind the Palau-Kyushu Ridge whichhas been shown by drilling to be a Late Cretaceous-Paleogene island arc (Kroenke and Scott, 1978).

The average heat flow values, excluding the trench areas, are around 1.45 HFU (Watanabe *et al.*, 1977). It is suggested that the Central Rift Valley of the Central Basin Ridges, which trends parallel to the magnetic anomalies, is the spreading axis which ceased activity 26 Ma ago (Figure 2). Heat flow as high as 3 HFU is found across the axis, falling away symmetrically on either side. This anomalous value suggests that the Central Rift Valley has had recent activity, and basalt dredged from its axis was radiometrically dated to be only 10 Ma (Watanabe *et al.*, 1977).

The pattern of magnetic anomalies indicates that the West Philippine Basin has drifted north about 15 to 20° of latitude and has undergone clockwise rotation by more than 50° since 35 to 40 Ma ago (Shih, 1980).

C. Ayu Trough

The eastern margin of the West Philippine Basin continues southwards into the Palau Ridge and Palau Trench system, and thence southwards into the Ayu Trough (Figure 2). As in the case of the Okinawa Trough, the terminology of trough is purely descriptive and has no plate-tectonic connotation.

Paleogene island-arc volcanic rocks are exposed in the Palau Group islands. The Palau and Ayu troughs separate the West Philippine Basin from the Caroline Plate (Weissel and Anderson, 1978). The Palau trench is not a typical oceanic trench. Its distance from the Palau Ridge is only 40 to 50 km. The Palau volcanic arc is completely extinct and only sparse and shallow seismicity occurs. Although the Palau arc-trench geometry suggests northwestwards subduction of the Caroline Plate beneath the West Philippine Basin, the lack of seismicity and volcanism suggest that subduction may have ceased. Weissel and Anderson (1978) suggest that the small ocean basin of the Ayu Trough contains a N-S trending, presently active, spreading axis. The basin has an extensional character and the relief lessens away from its central rift axis, which is free of sediments, but the sedimentary cover thickens to more than 300 m both eastwards and westwards. The seismicity in the central rift region indicates strike-slip motion rather than extension. The Ayu Trough has no recognizable magnetic lineaments, but Weissel and Anderson (1978) estimate that the margins of the basin formed in the Mid-Miocene, about 10 to 12 Ma ago. The evidence is that the trough represents an extremely slow rate of spreading of only 2 cm y^{-1} or less. However, the low heat flow values of less than 1 HFU cause doubt about its present day spreading.

D. Banda Sea Basin

The Banda Sea is of oceanic lithosphere almost completely enclosed by continental crust, and is the most convolute of all the marginal seas. Its details have been summarized by Bowin *et al.* (1980). Most of the Sea has a quiet magnetic field, and only in the south is there a limited occurrence of magnetic lineations, which trend 60 to 70°, but these are not constant enough for specific identification. There is therefore no direct evidence of age, but the parallelism of these anomalies with the Cretaceous anomalies of the Argo Abyssal Plain (Figure 2), which increase in age from the Sunda Trench towards the northern margin of Australia (Heirtzler *et al*, 1978), suggest that the Banda Sea may be also Cretaceous.

The heat flow values of the Banda Sea average 1.1 HFU (46 mW m^{-2}). These low values, together with the 5 km water depth, suggest an old age for the crust and that it has long been inactive. The low heat flow (generally less than 1.5 HFU) in the deeper parts is consistent with a Cretaceous age, and the Banda Sea Basin therefore probably represents Indian ocean lithosphere trapped behind the Timor-Banda arc-trench system (Bowin *et al.*, 1980). Some magnetic anomalies occur southeast of Seram and occupy a SE-trend. These have also not been identified, and their significance is uncertain.

E. Celebes Sea Basin

This is an extinct basin with a mean heat flow of 1.58 HFU corresponding to a crustal age of about 51 Ma using the model of Parsons and Sclater (1977).

The magnetic anomalies shown in Figure 2 are taken from Weissel (1980). He identified anomalies 18, 19, and 20, trending 65°, representing a Late Eocene crustal age of 42 to 47 Ma. The lineations increase in age towards the NW and are sub-parallel to those in the Banda Sea and Argo Abyssal Plain, indicating that the Celebes Basin and the Banda basin may have been trapped progressively by younger subduction systems, but both were once part of a larger ocean.

F. Sulu Sea Basin

The Sea is divided by the submerged volcanic Cagayan Ridge into a NW or Outer Sulu Sea containing a thick sedimentary fill, and an Inner Sulu Sea floored by oceanic crust (Mascle and Biscarrat, 1979). Much of this oceanic crust had been subducted beneath the young Sulu Archipelago arc-trench system. Heat flow measurements at depths greater than 4 km average 2.12 HFU. By interpolation between the known ages, heat flow and water depths in the South China and Celebes Seas, an Oligocene age is predicted for the oceanic crust of the Inner Sulu Sea (Weissel, 1980). Unfortunately no magnetic anomalies have been identified.

G. South China Sea Basin

The abyssal floor lies at depths of 3.7 to 4.4 km. Heat flow values average 2.1 HFU (85 mW m^{-2}) in the thickly sedimented northern part. In the southern part the values are more scattered but average 2.8 HFU. These values allow prediction of an Early Miocene to Early Oligocene age (Taylor and Hayes, 1980). The water depths suggest an age of Oligocene to Eocene. Taylor and Hayes (1980) have compiled the magnetic anomalies (Figure 2), which show a symmetric pattern of sea-floor spreading from Mid-Oligocene to Early Miocene (32 to 17 Ma ago). The trends are approximately E-W, and a relict spreading centre coincides with the E-W linear chain of seamounts near 15°N. Magnetic quiet zones occur landward of the slope-basin boundary of the China and Reed Bank block margins. The quiet zone boundary is associated with a characteristic free-air gravity minimum and probably marks the location of the transition from oceanic to continental crust.

There is a set of NE - trending magnetic anomalies to the west of the basin, whose ages have not been identified. However a major discontinuity between this ill-defined set and the main E-W set is required near 115°E, but it has not been identified (Taylor and Hayes, 1980).

The South China Sea Basin did not form by simple back-arc spreading of any known volcanic arc (the Yanshanian volcanic arc was extinct before rifting began), and appears to have resulted from continental margin rifting, rather like the evolution of the Tasman Sea. Taylor and Hayes (1983) have shown an interpreted sequence of events leading to the formation of the South China Sea Basin (Figure 3). Their interpretation is strongly supported by the work of Hinz and Schlüter (1983) on the Dangerous Grounds area of the South China Sea off SW Palawan. The seismic stratigraphy indicates continental crust, and dredged samples of continental rocks of Triassic to Cretaceous age contain well-preserved plant

fossils. Such rocks could only have come to the neighbourhood of Borneo by rifting from the major continent of China.

H. The Indian Ocean Basin

Attention is confined only to those parts of the Indian Ocean which lie east of the Investigator Ridge.

The sea-floor spreading of the Indian Ocean has been divided into three distinct episodes in a model based on magnetic anomalies whose identification has been reinforced by data from several DSDP sites (Johnson *et al.*, 1976; Curray *et al.*, 1982).

The Mesozoic spreading episode resulted from the separation of India from Australia, and the history is recorded in the Argo Abyssal Plain between the Sunda Trench and northwest Australia (Figure 2). Details are given in Heirtzler *et al.* (1978). The magnetic anomalies are M 10 to M 25, ranging from 122 Ma (Early Cretaceous) to 153 Ma (Late Jurassic).

The anomalies trend 60° and increase in age in a SSE direction from the Sunda Trench towards the continental margin of Australia. The water depth exceeds 5.6 km. The anomalies are offset by major fracture zones. Much of this Mesozoic oceanic lithosphere has already been subducted beneath Java (Figure 2). Spreading rates have been calculated at only 3.5 to 4.8 cm y^{-1}. South of the area covered in Figure 2 at about 20° S, the magnetic anomalies trend 30°, rather than 60°, in the Wallaby Plateau east of the Wharton Basin. Thus, although the initial rifting of Australia is dated at Late Jurassic (153 Ma), the early rifting stage and Mesozoic spreading pattern are likely to have been a complex one, not yet fully resolved (Veevers, 1982).

The change in spreading direction from the Wallaby Plateau to the Argo Plain suggests that the two terrains may be related to different fracture systems, and that while India separated towards the NW, another continental fragment (or fragments) may have moved more northerly. Jurassic and Cretaceous oceanic lithosphere is common in Borneo and the Philippines (the Chert-Spilite Formation and underlying ophiolitic basement). These remnants of Jurassic-Cretaceous lithosphere must logically be associated with continental crustal fragments rifted from the northern Australian margin, and complexly brought together with continental fragments which were translated southwards as a result of the development of the South China Sea Basin.

I. The Andaman Sea

Spreading of the Central Basin is in a NNW direction. The spreading axis in the north Central Basin is linear, trending NE - SW. Away from the axis it makes a rectilinear pattern with short segments of spreading axes offset by transform fault segments (Curray *et al.*, 1982). Southwards it appears that the opening of the Sea is transformed into the right-lateral Sumatran Fault System. To the north the spreading is in turn transformed into the right-lateral Sagaing Fault of Burma. Good magnetic anomalies have been found in the rift valley to the south where there is little sediment cover. They show that the Central Basin opened 13 Ma ago in Middle Miocene times. Spreading rates have been calculated at 3.72 cm y^{-1}. The upturned edges to the rift valley are interpreted as indicating continuing spreading.

The Andaman Sea therefore appears to have commenced as a leaky transform system, but seems to be in the process of developing a more continuous spreading axis trending NE - SW and linking the two major transform faults. Slight extension on the Sumatran-Sagaing transform fault system may be attributed to its bending resulting from the Indian collision.

MICROCONTINENTS BETWEEN CHINA AND AUSTRALIA

From the above review, it appears that many of the marginal seas of Southeast Asia are related to the break-up of the northern margin of Australia or the southeast margin of China. This break-up would have detached continental blocks, and sea-floor spreading behind them would have carried the continental blocks into the Borneo-Philippine region.

The microcontinental blocks which I have identified are shown in Figure 4 and this section gives brief reasons for their identification. The meeting ground of the blocks coming from Australia with those coming later from China is in and around Borneo. This large island is therefore composed of a heterogeneous and patchy continental basement terrain for the accumulation of Cenozoic sediments which partly or wholly cover and surround them. This paper is not concerned with the blocks which have earlier coalesced to form Sundaland. That topic is covered in an accompanying paper by Gatinsky and Hutchison (1986).

BLOCK RIFTED FROM SOUTHEAST CHINA

The continental shelf of SE China began breaking up during the later phases of the Yanshanian "orogeny" in later Cretaceous times, as shown in Figure 3 and documented by Taylor and Hayes (1983).

1, 2, Paracel Islands and Macclesfield Bank

Wells drilled by the Petroleum Company of the People's Republic of China have encountered Paleozoic and possibly Precambrian basement beneath the Paracel Islands, and Cretaceous granites and metavolcanic rocks beneath the China Shelf (Taylor and Hayes, 1983). Limited work has been carried out by Ludwig et al. (1979) who conclude that the region is of continental crust characterized by graben-and-horst blocks. Quaternary limestone and phosphorite reefs on the Paracel Islands have been uplifted and conspicuously folded by recent orogenic movements. The overall structure of the region is of a thin sedimentary cover upon continental basement.

3, 4, Spratley Islands, Dangerous Grounds, Reed Bank

The region is underlain by a faulted and stretched crust of continental origin (Hinz and Schlüter, 1983). The oldest rocks sampled by dredging are Upper Triassic to Jurassic slightly metamorphosed deltaic sandstones and siltstones containing plant fragments, and dark green mudstones containing shells of Late Triassic to Early Jurassic age in the Dangerous Grounds area. Younger sediments form a drape over this older basement. A well drilled to 4201 m in the Reed Bank bottomed in a Lower Cretaceous sequence of siltstone, shale, coal beds, and sandstone-conglomerate, unconformably overlain by Paleocene shelf limestone (Taylor and Hayes, 1980).
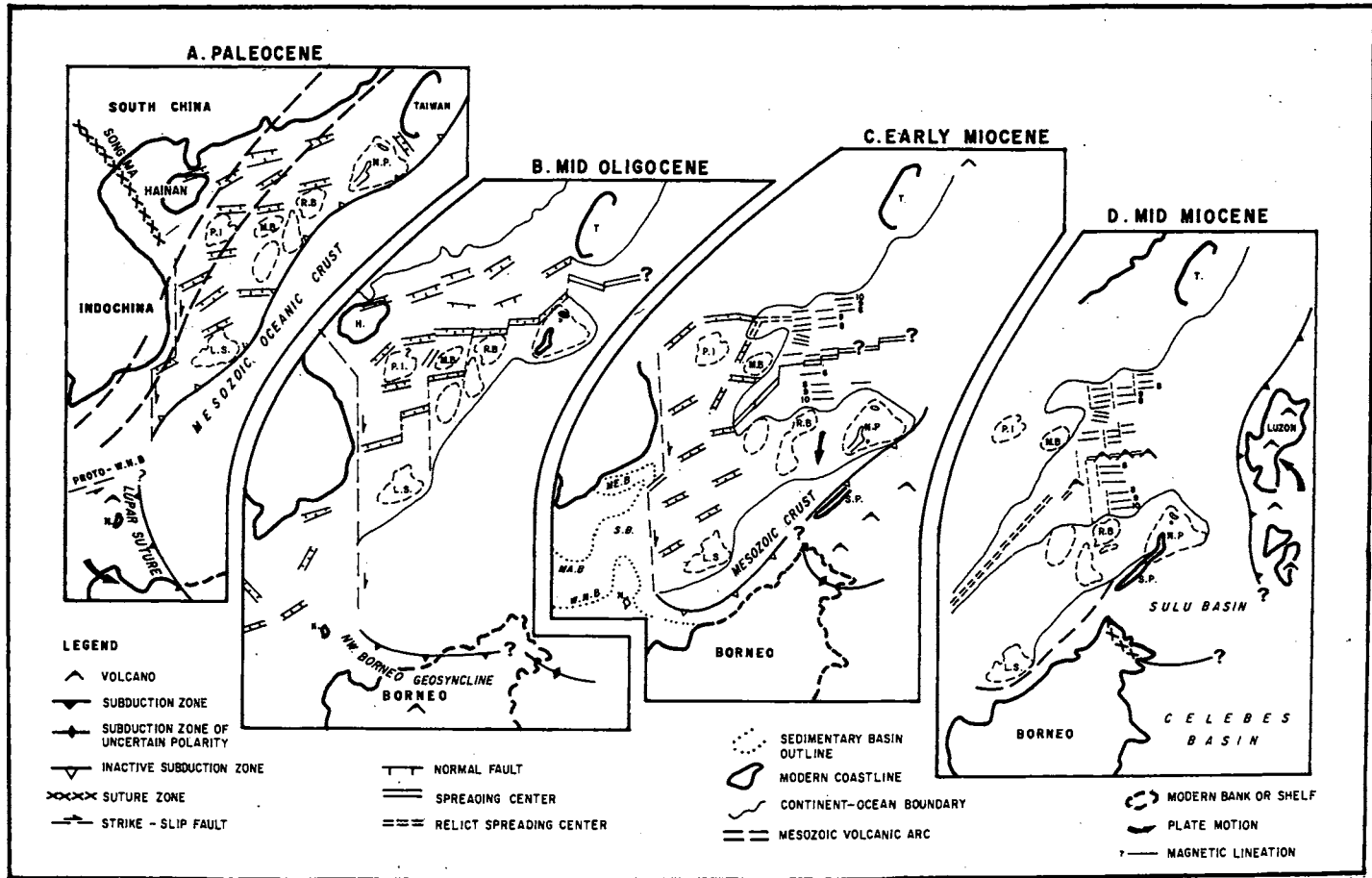
Fig. 3 The evolutionary scenario for the opening of the South China Sea Basin, summarized from Taylor and Hayes (1983) P.I. = Paracel islands, M.B. = Macclesfield Bank, R.B. = Reed Bank, L.S. = Luconia Shoals, T = Taiwan, H. = Hainan, N.P. = North Palawan, N. = Natuna, MA.B. = Malaya Basin ,W. N.B. = West Natuna Bank, S.B. = Saigon Basin, MEB. = Mekong Basin.
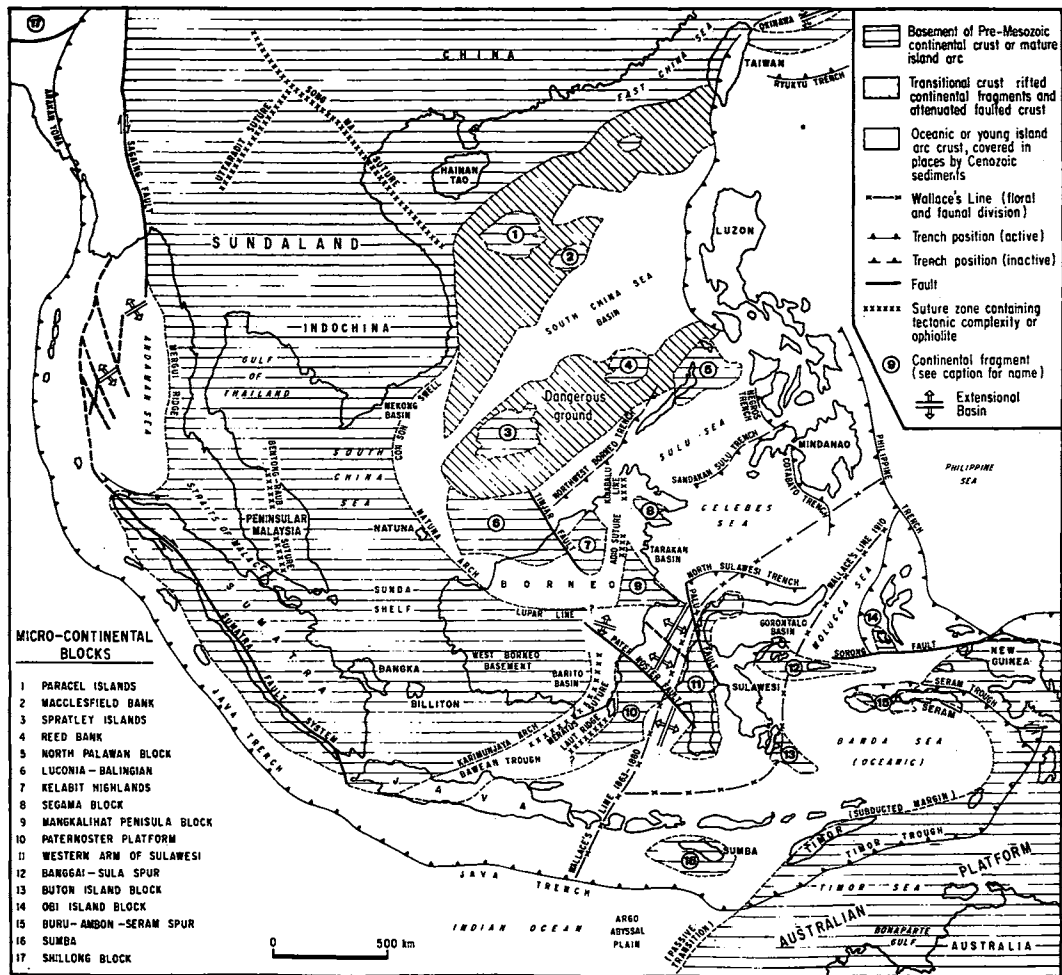
Legend

- Basement of Pre-Mesozoic continental crust or mature island arc
- Transitional crust rifted continental fragments and attenuated faulted crust
- Oceanic or young island arc crust, covered in places by Cenozoic sediments
- ⊬⊬ Wallace's Line (floral and faunal division)
- ▲▲ Trench position (active)
- ▲▲ Trench position (inactive)
- —— Fault
- ××××× Suture zone containing tectonic complexity or ophiolite
- ⑨ Continental fragment (see caption for name)
- Extensional Basin

MICRO-CONTINENTAL BLOCKS

1 PARACEL ISLANDS
2 MACCLESFIELD BANK
3 SPRATLEY ISLANDS
4 REED BANK
5 NORTH PALAWAN BLOCK
6 LUCONIA – BALINGIAN
7 KELABIT HIGHLANDS
8 SEGAMA BLOCK
9 MANGKALIHAT PENISULA BLOCK
10 PATERNOSTER PLATFORM
11 WESTERN ARM OF SULAWESI
12 BANGGAI – SULA SPUR
13 BUTON ISLAND BLOCK
14 OBI ISLAND BLOCK
15 BURU – AMBON – SERAM SPUR
16 SUMBA
17 SHILLONG BLOCK

Map labels: CHINA, TAIWAN, RYUKYU TRENCH, EAST CHINA SEA, HAINAN TAO, SUNDALAND, INDOCHINA, GULF OF THAILAND, MEKONG BASIN, KON SON SHELF, SOUTH CHINA SEA, LUZON, SOUTH CHINA SEA BASIN, Dangerous ground, SULU SEA, MINDANAO, PHILIPPINE SEA, PENINSULAR MALAYSIA, NATUNA, CELEBES SEA, TARAKAN BASIN, PHILIPPINE TRENCH, MERGUI RIDGE, BERGONG SPUR, SUNDA SHELF, BORNEO, LUPAR LINE, NORTH SULAWESI TRENCH, WALLACE'S LINE 1910, MOLUCCA SEA, GORONTALO BASIN, SOROKO FAULT, NEW GUINEA, BANGKA, WEST BORNEO BASEMENT, BARITO BASIN, BILLITON, SULAWESI, SERAM TROUGH, SERAM, JAVA TRENCH, SUMATRA FAULT ZONE, BANDA TROUGH, KARIMUNJATA ARCH, LAUT RIDGE, BANDA SEA (OCEANIC), SUMBA, TIMOR SEA, TIMOR TROUGH, PLATFORM, JAVA TRENCH, INDIAN OCEAN, ARGO ABYSSAL PLAIN, WALLACE'S LINE 1863-1890, AUSTRALIA, BONAPARTE GULF, ANDAMAN SEA, SUMATRA, SAGAING FAULT, PGS RESERVOIR, 0 500 km

Fig. 4 Distribution of the pre-Mesozoic continental basement of Southeast Asia (after Hutchison, 1984).

5, North Palawan Block

The geological nature of this Calamian Group is obviously exotic in an island-arc setting. The Calamian Group contains the oldest rocks of the Philippines, and they are distinctly continental.

The oldest rocks of Mindoro are a metamorphic basement of amphibolite, schist and slate commonly associated with marble and quartzite. The basement complex is correlated with Permian formations on Palawan and with Carbo-Permian limestone on Carabao island off the NW tip of Panay. The basement complex is overlain by Jurassic strata, beginning with a basal conglomerate and including ammonite-bearing arkose, greywacke, mudstone and chert. The fossils indicate a Late Jurassic age (Hashimoto and Sato, 1968) . The continental basement block extends along Palawan as far as the Ulugan Bay Fault, west of which ophiolitic island-arc rocks are in fault contact with the older continental rocks. Hinz and Schlüter (1983) interpret this ophiolitic terrain as having been allochthonously thrust northwards over the underthrust microcontinent of Dangerous Grounds - Reed Bank.

On Palawan the oldest rocks are schist, phyllite, slate and quartzite. In northern Palawan, this sequence is overlain by Middle Permian sandstone, tuff and slate (Hashimoto and Sato, 1973), and Middle to Upper Permian fusulinid limestone. The Middle Triassic is represented by conodont-bearing cherts which overlie unconformably the Permian sequence. On the Calamian islands, to the north, Fontaine (1979) described Rhaetic (Jurassic-Triassic) limestone overlying unconformably radiolarian cherts.

There can be little doubt that the Calamian Province represents an older continental fragment displaced southwards by the opening of the South China Sea.

6, Luconia-Balingian Province

The most important features of the Luconia Province are Middle Miocene carbonate reefal build-ups, flanked and overlain by open marine and coastal plain clays and sands of Late Miocene age (Epting, 1980). This province must owe its stability and high geothermal gradient of 42°C km^{-1} to an underlying continental basement (Hutchison, 1984). The carbonate buildups developed on basement horst structures, and the most likely interpretation is that the basement is of material rifted from southeast China (Figure 3). To the south of Luconia lies the Balingian Province, which also is characterized by a high geothermal gradient of 41°C km^{-1}, suggesting a continental basement (Hutchison, 1984). The Upper Eocene to Lower Miocene Balingian Formation, of fluvial and estuarine channel sands with overbank clays and coals, corresponds in part to the onland Setap Shale and Nyalau Formations. The Luconia-Balingian province extends as far east as the major Tinjar Fault (Figure 4) and as far south as the Bukit Mersing Line (Hutchison, 1975). South of this Line is the Sibu Zone composed of eugeoclinal Rajang Group, which presumably does not rest on a continental basement.

The anomalous character of the Luconia-Balingian Province was earlier documented by Haile (1974), who interpreted it as the Miri miogeoclinal zone of the Northwest Borneo Geosyncline. Haile (1969) sought a foreland or continental attachment in the South China Sea region to the north. In my view, his interpretation was correct. The continental foreland is SE

China and the Luconia-Balingian Province probably represents a rifted part of the Atlantic-type miogeoclinal margin of the Chinese craton. The eugeoclinal Sibu Zone may be interpreted as Late Cretaceous to Eocene Rajang Group turbiditic sediments deposited upon Mesozoic oceanic crust, and subsequently severely compressed and metamorphosed in the greenschist facies as the Luconia-Balingian Province micro-continent drifted south towards the West Borneo Basement region of Sundaland. The pillow basalts of Bukit Mersing (Kirk, 1968) may be interpreted as an uplifted slice of the oceanic crustal basement upon which the Rajang Group was deposited. Whereas the Lupar Line along the Kuching Zone miogeoclinal margin of the West Borneo Basement was an active convergent plate margin (Tan, 1979), there is little likelihood that the Bukit Mersing Line was ever a subduction site, but it was characterized by minor granitoid and rhyolite-ignimbrite activity.

7, Kelabit-Long Bawan Province

The Kelabit Highlands is an extensive area of interior Borneo underlain by mudstone which commonly contains coalified plants and thick lignites, thin lenses of limestone, and rare conglomerates, forming the Kelabit Formation (Haile, 1962). A large number of salt springs occur throughout the area of mudstone outcrop (Wilford, 1955). Fossils indicate both an Early Oligocene and an Early Miocene age. Reconnaissance field mapping in adjacent Kalimantan (BRGM, 1982) shows the eastward continuation as the Long Bawan Formation characterized by well-bedded friable purple argillites, and intercalated feldspathic sandstone and arkose beds. The presence of underground evaporites is strongly suggested by the extensive occurrence of salt springs. Three or four coal seams, up to 1.5 m thick, are intercalated within the sandstones. Eastwards the Long Bawan Formation grades abruptly into deeper-water facies which may be correlated with the southern extension of the turbiditic Crocker Formation. The Kelabit and Long Bawan formations have been interpreted to be deposited in a fluvio-deltaic to coastal-lagoonal environment. Palaeontological data in Kalimantan suggest a Cretaceous to Early Eocene age (BRGM, 1982).

Since the Kelabit-Long Bawan Province is extensively surrounded by turbiditic deposits of the Rajang Group it is an attractive hypothesis to suggest that its underlying basement may be of rifted continental crust, upon which the coastal-lagoonal formations were deposited before it rifted off the continental shelf (of China?). The buried salt deposits suggest a rifting environment. Stability of the Block is also indicated by long-persistent reef limestones around its margins (Adams, 1965). The province is poorly known and remote. However Haile (1962) recommended it is worthy of investigation by the petroleum industry.

8, Segama Block

In the Middle Segama valley, the "Crystalline Basement" rocks are predominantly ophiolitic with different degrees of metamorphism. However, along the Litog Klikog Kiri, a tributary of the Segama River, the gabbroic part of the ophiolite is intruded locally by granodiorite and coarse biotite tonalite (Kirk, 1968). Some of the granitoids contain up to 2.25 wt. % K_2O and therefore are thought to have risen from a buried continental basement. The granitoids have imposed a contact aureole on the ophiolitic rocks. The oldest K:Ar date was obtained from biotite extracted from the tonalite (Leong, 1971), giving an Early Jurassic age of 210 Ma.

The so-called "Crystalline Basement" of Sabah is predominantly ophiolitic and forms the basement to the region. The only clue to an underlying unexposed continental basement is the potassic granitoid, described above, which must have its source in underlying material other than ophiolite. The possiblity of a continental basement beneath the predominantly ophiolitic "Crystalline Basement" is an attractive hypothesis but evidence is lacking.

9, Mangkalihat Peninsula Block

This block is in faulted contact with the Tertiary Kutei Basin to the south and the Tarakan Basin to the north. Its geology is poorly known, but includes Early Devonian corals (Rutten, 1940). The region seems to be an old island-arc terrain composed of andesite, dacite, radiolarian chert, limestone and arkose. However, numerous biotite granite and granodiorite plutons occur in the Long Laai region (BRGM, 1982). Their association with tin mineralization clearly implies some continental basement in this region.

BLOCKS RIFTED FROM SUNDALAND

10, Paternoster Block

This is a stable continental fragment that appears to have once been continuous with West Sulawesi when it was attached to Borneo before the Early Tertiary opening of the Makassar Strait. Little is known of the Paternoster basement, except that it makes a stable margin for the Kutei Basin to the north and the Meratus Graben to the west. The only reference to its geology is in Rose and Hartono (1978). A thin basal conglomerate, derived from igneous and metasedimentary pre-Tertiary basement, was deposited only in the west and NW of Apar Bay. Elsewhere fine to coarse sandstone, in places pebbly, overlies the pre-Tertiary basement. Limestone was established as a platform over the Paternoster Block during the latest Eocene through Oligocene and into the Early Miocene, and on many parts of the block, limestone deposition has continued to the present.

11, Western arm of Sulawesi

Western Sulawesi consists of two distinct terrains, namely Northern and Western. The former is interpreted as a young volcanic arc built on oceanic basement, whereas western Sulawesi displays a more continental character, interpreted as being formerly attached to Borneo before the Early Tertiary opening of the Makassar Strait.

The oldest rocks are pre-Tertiary metamorphic rocks, mostly of blueschist and greenschist facies and radiolarites forming a tectonic melange. Granite intrusion has superimposed metamorphism on the melange. In the south, these rocks are overlain unconformably by an Upper Cretaceous shale-greywacke-arkose flysch succession locally intercalated with volcanic rocks (Van Leeuwen, 1981). Calc-alkaline volcanism began as early as the Paleocene, and coal-bearing sediments were laid down to the west of the arc. Both calc-alkaline and alkaline feldspathoidal lavas were extruded in the Middle Miocene.

BLOCKS RIFTED FROM NORTHERN AUSTRALIA

In a recent paper, Pigram and Panggabean (1984) described the rifting of the northern margin of Australia, and identified the following microcontinents: 12, Banggai-Sula; 13,

Buton Island; 14, Obi Island; and 15, Buru-Ambon-Seram; they excluded 16, Sumba, which is also a microcontinent (Figure 4) .

On Sumba a sequence of Mesozoic carbonaceous strata forms the basement which had been tilted and intruded by dykes of calc-alkaline plutons (Chamalaun *et al.*, 1981). Jurassic ammonoid and Jurassic or Cretaceous pelecypod fragments have been found. The basement is overlain by Miocene pelagic chalk. Sumba appears to be a microcontinent which has separated from the north Australian margin during Mesozoic rifting, and was carried north by spreading of the Argo Abyssal Plain.

It is therefore seen that Southeast Asia, lying between China, Australia and the eastern continental core of Sundaland, is composed of numerous microcontinental fragments which have rifted off the major continental masses. An approximate line of delineation between the fragments from China and those from Australia is given by the faunal and floral division line of Alfred Russel Wallace (George, 1982).

OPHIOLITIC AND MELANGE TERRAINS

The ophiolitic and melange terrains of Southeast Asia are shown in Figure 5, which is an up-dated revision of the compilation of Hutchison (1975) and Wiryosujono and Tjokrosapoetro (1978). Only those ophiolites which lie between China and Australia are of immediate concern in this paper. Whereas the marginal seas are of oceanic lithosphere formed as a result of the Mesozoic-Cenozoic rifting of the China and the Australia continental margins, the ophiolite terrains may be interpreted as similar oceanic lithosphere which has been uplifted as a result of tectonic collisions involving the microcontinental blocks which drifted ahead of the sea-floor spreading.

The following notes up-date the descriptions of Hutchison (1975) and Wiryosujono and Tjokrosapoetro (1978):

The Serabang Line (Haile, 1973) is probably a continuation of the Lupar Line, which Tan (1979) showed to have resulted from tectonic activity along the margin of Sundaland. The Pakong Mafic Complex is a partial ophiolite, associated with the Lubok Antu Melange. Lines of granitoid plutons, to the southwest of the ophiolite-melange lines, indicate that the plate margin was active from Late Cretaceous through to Miocene times.

The Boyan Melange Belt trends NNW and separates the Melawi from the Ketungau Tertiary basins. The melange contains blocks of limestone, gabbro and ultramafic rocks in a phyllitic matrix (Williams *et al.*, 1984). The matrix contains Late Cretaceous fossils. The margin of the West Borneo Basement and its shelf, the Kuching Zone, is therefore more complex than formerly recognized.

Dating of the Darvel Bay-Labuk-Palawan ophiolite is difficult because most of it is metamorphosed to some degree (Hutchison, 1978). The oldest radiometric date is 210 Ma (Early Jurassic age) (Leong, 1971). However the Cretaceous to Eocene Chert-Spilite Formation (Kirk, 1968) logically should be considered to be the upper layer of the ophiolite. It is equivalent in age to the crust of the Banda and Celebes seas. Hinz and Schlüter (1983) have shown that the Palawan part of the ophiolite melange had been uplifted because of
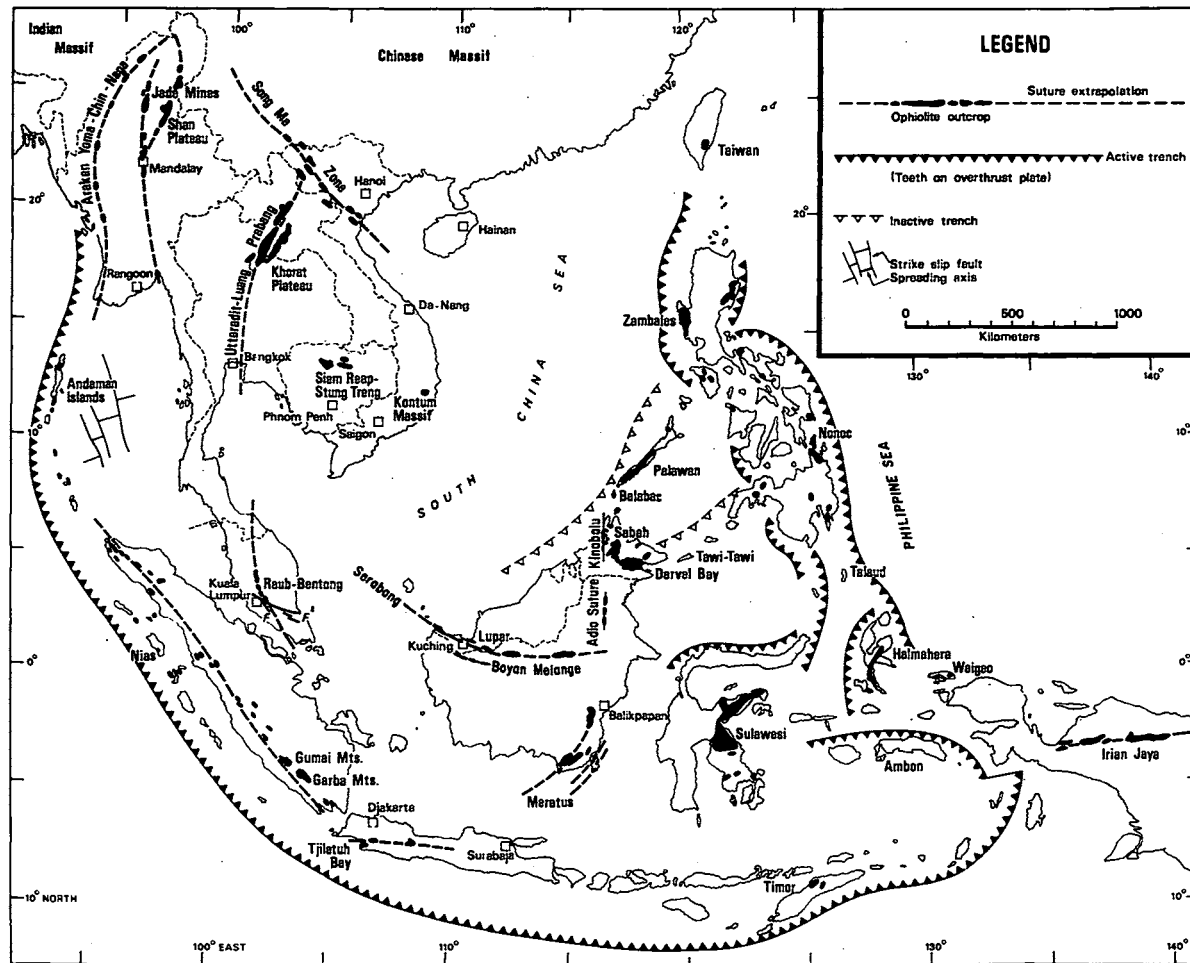
Fig. 5 The distribution of ophiolite and melange belts in Southeast Asia, based on Hutchison (1975) and Wiryosujono and Tjokrosapoetro (1978).

under-thrusting' of the Reed Bank-Dangerous Grounds micro-continent beneath the Pala-wan terrain, which is considered to be allochthonous and to have been overthrust towards the northwest.

It is likely that the whole ophiolite terrain of Sabah has been underthrust to some extent by continental crust rifted either from Australia or China, but older volcanic arcs have also been involved in the collision processes.

The Sabah and north Kalimantan region is now known to be more complex, and the Adio Suture (BRGM, 1982) appears to be the southward continuation of a tectonic line which includes the Wariu melange of Kota Belud, and the north-south fracture zone through Mount Kinabalu (Figure 5).

The major Zambales ophiolite has been described in detail by Hawkins and Evans (1983) who conclude that the massif pre-dates the opening of the South China Sea, and Schweller *et al.* (1983) believe that its eastwards tilting and uplift is a result of the eastwards under-thrusting of the lithosphere of the South China Sea along the Manila Trench.

The Meratus ophiolite and melange are being remapped by Sikumbang (1984) who believes that the ophiolite and imbricated rocks were emplaced along the southeast margin of Sundaland as a result of a collision with an actively subducting plate margin in Late Jurassic to Early Cretaceous times. The peridotites are overlain unconformably by shallow-water late Lower Cretaceous marine strata.

SUMMARY

The ophiolites of the region between China and Australia represent a fragmented history of sea-floor spreading which extended from Early Jurassic to Miocene times. The ophiolites have been uplifted by various processes, but the coming together of continental blocks from the north and colliding with those coming from the south must have played a fundamental role in the uplift. Some areas of oceanic lithosphere have not been underthrust by continental lithosphere, and still remain extinct marginal seas such as the Sulu, Celebes and Banda Seas. Continuing and on-going compression, as Australia converges on Southeast Asia, will in future result in the uplift of the marginal sea lithosphere to form more ophiolitic terrains in the region.

Complex anti-clockwise rotations have been documented for the continental blocks of Southeast Asia; for example by Haile *et al.* (1977) for Borneo and by Fuller *et al.* (1983) for the Philippines. Nevertheless, the parallel magnetic lineations of the Argo Abyssal Plain and of the Banda and Celebes Seas, which are in turn parallel to the elements of the Sulu Sea, appear to suggest a simple pattern for the marginal seas, in conflict with the complexities of the continental blocks. Understanding of the region has not advanced to a stage where these apparent conflicts can be resolved.

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