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Southeast Asia reconstruction with a non-rotating Cenozoic Borneo

RICHARD W. MURPHY

Weybridge, Surrey
UK

Abstract: A reconstruction of Southeast Asia has been attempted which treats the Sunda block and the Philippine Sea Plate as (relatively) rigid blocks between 50 Ma and 15 Ma. The published reconstructions of Robert Hall (1996 version) have been utilised but modified from Borneo westwards in accordance with geological perceptions and prejudices assembled over thirty-six years of studying the region.

Sunda and the Philippine Sea are treated as rigid blocks that have not undergone disruptive internal deformation. In the case of Sunda, this means that Tertiary rift basins have formed but that there has been no oceanic crust developed except in the Andaman Sea on the west and the South China Sea on the east.

In this interpretation Indochina has been extruded about 700 km between 35 Ma and 15 Ma (maps are shown at five-Ma intervals, following Hall). Right-lateral movement along the Sumatra Fault/Andaman/Sagaing system is paired with left-lateral movement along the Red River Fault and its precursor, the West Baram Line.

The Philippine Sea Plate has moved great distances with an overall left-lateral displacement with respect to Sunda. Smaller blocks between Sunda and the Philippine Sea Plate with less control and with strong internal deformation have been treated in this reconstruction in a manner that accommodates the movements of the major blocks.

INTRODUCTION

The purpose of this paper is to provide an alternative reconstruction of Southeast Asia to the computer-based reconstruction of Hall (1996). For ease of comparison I have adopted the same 5-Ma time slice maps which Hall used except that the youngest map shown here is the 15-Ma stage. This reconstruction is not computer-based, except for the Philippine Sea Plate and surrounding areas, which have been taken directly from Hall (1996).

The reason for the alternative view revolves around the requirement in the Hall reconstruction for large-scale counterclockwise (CCW) rotation of Borneo between 20 Ma and 10 Ma, thereby necessitating a linked CCW rotation of Sunda, particularly the portions west of the Sunda Strait. This runs counter to my understanding which, although fragmentary and limited, visualises a clockwise (CW) rotation of Sunda, both taken as a single block and considered in terms of more local internal tectonic entities.

The mapped area contains two major plates: Sunda and the Philippine Sea. Although not large in worldwide terms, they nevertheless dominate the region. The premise of this paper is that these two plates have not been *disruptively* deformed internally since their formation and/or consolidation. Sunda, although highly deformed, has not been split into fragments with intervening ocean basins except along the western and eastern margins (Andaman Sea and South China Sea). The Philippine Sea Plate has not had disruptive volcanism or internal reorganisation since the end of spreading between 35 Ma and 30 Ma (Hall, 1996). In the Southeast Asian reconstruction drama Sunda and the Philippine Sea are the major players; all other elements have supporting roles (Fig. 1).

The thesis of this paper is that the Hall reconstruction of the Philippine Sea Plate (PSP) is correct but that major modification, detailed in the maps, is required in the reconstruction of Sunda. The PSP has moved WNW and rotated CCW episodically during Tertiary time. Sunda has remained attached to Eurasia but has undergone CW rotation and extrusion of about 700 km. Resolution of the tectonic problems resides in recognising the major left-lateral bounding fault sets of the *eastern* margin of Sunda and tying these to the left-lateral fault sets that form the *western* margin of PSP.

The technique used in generating the maps was to wed the PSP time slice maps of Hall with paleogeographic and paleotectonic maps of Sunda which have been many years in preparation. Smaller marginal elements, particularly in the Sulawesi region, were force-fit into the patterns dictated by the large plate movements.

The paleomagnetic evidence (see Hall, 1996, and references therein) is not wholly conclusive,

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but the most reliable data which require CCW rotation of Borneo are Cretaceous in age. Rotation seems likely to have been during Late Cretaceous time (Haile, 1997, personal communication), a period of intense, little-understood regional orogenic events providing ample room for large-scale block movements, rather than the more tightly constrained Tertiary.

The text of this paper is confined to a discussion of each individual time slice map, noting only the major features, particularly when events start or stop. Detailed discussion of each element is beyond the scope of this paper. Readers are referred to excellent recent regional papers such as Hall (1996) and Longley (1997).

The shortcomings of this paper are many and varied, but hopefully peripheral to the principal aim. Particularly unresolved are the nature and sequence of events inside the compartments involved in the left-lateral wrench zone between Sunda and the PSP. The Sulu Sea compartment, for example, could not have had bounding subduction zones of opposite vergence from 35 Ma to 15 Ma, as the maps show. Nevertheless long-lived subduction is required. It is likely that most, if not all, of the evidence has been destroyed and the problem requires further detailed investigation.

50 MA

At 50 Ma Sunda was a high-standing landmass attached to the southeastern margin of Eurasia (Fig. 2). There were no internal basins except perhaps for very small intermontane depressions.

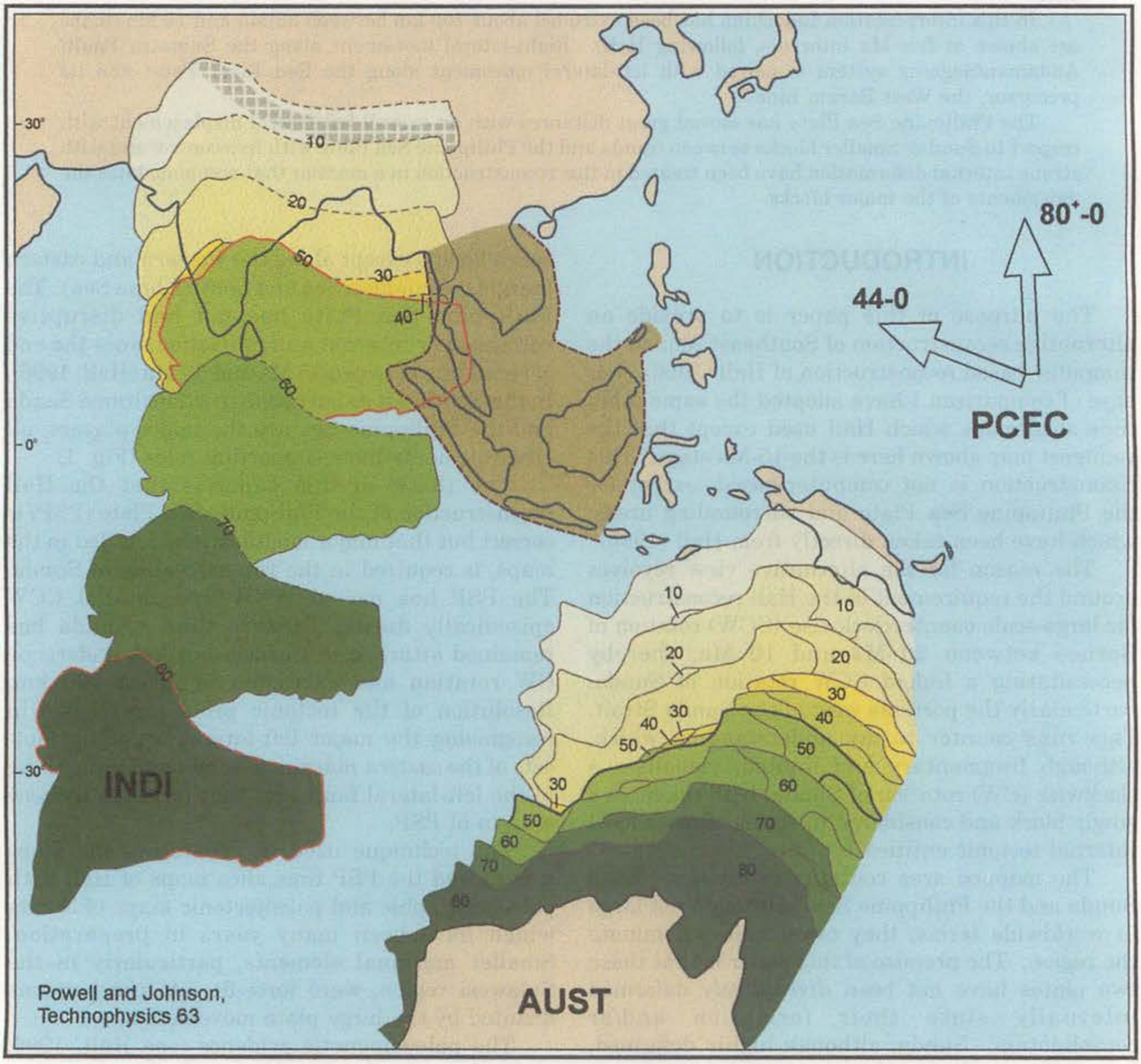

Figure 1. Reconstruction: Incremental kinematics.

It was bounded on the south by the Sumatra Trench with a somewhat more westerly trend than at present. The trench continued westward directly into the compressional zone at the southern margin of Eurasia in the region which was to become the Himal. The Shan scarp marked the western margin of Sunda, with shelfal to deepwater sediments pouring into the oceanic realm of the northward-moving remnant Tethys Ocean. The Andaman block trended NW. Sedimentation south of Sunda was confined to deepwater turbidites and pelagics.

East of Sunda lay the Proto South China Sea (SCS). The south China-northern Vietnam shelf was wider than at present and was rifting. The Luconia Shoals microcontinent was rifting away from the Subi Shelf-Vanguard Bank-Prince of Wales Bank-Rifleman Bank region of the extended Vietnam shelf. The Bunguran Trough was formed at the trailing edge of the Luconia movement. The leading edge of Luconia was riding on the westernmost element of the Proto SCS, driven by subduction under Borneo. (For an alternate view of this scenario see Moss, S.J., *in press,* "Embaluh Group turbidites in Kalimantan-evolution of a remnant ocean basin in Borneo during the Late Cretaceous to Paleogene".) The SE margin of Sunda was also rifting in the Barito Basin-Makassar Strait region.

The eastern margin of the Luconia Block is the West Baram Line, a major tectonic boundary in Borneo today. It was a left-lateral fault during the movement of Luconia and, because of its location, timing and orientation, can be viewed as an early phase of activity along the Red River Fault.

The PSP region is taken directly from Hall (1996) and the reader is referred to that paper for discussion.

Between Sunda and the PSP lay a series of major left-lateral transform faults which accommodated the motion between them. Their trend and spacing, as shown on the 50 Ma map, are compounded from the maps of Hall (1996) and most likely positions as deduced from iterating back and forth between the 5 Ma interval maps included here. Although not tied to a global reconstruction, they suggest an arcuate, SW-concave trend which persists throughout the reconstruction maps.

45 MA

The principal changes from 50 Ma lie along the western margin of Sunda and in the PSP. The INDI-EURA collision was destroying the final

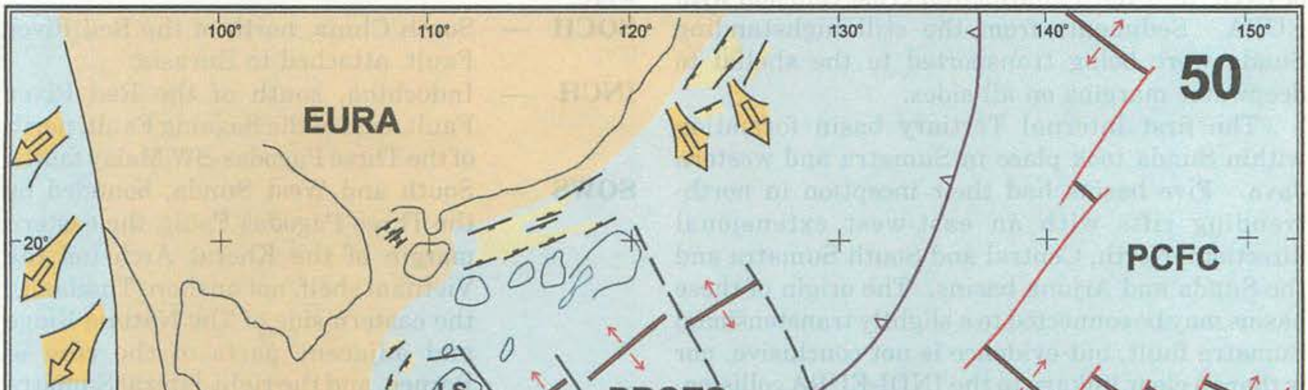

Figure 2. 50 Ma time slice map.

remnants of the Tethys Ocean. Clockwise rotation of tectonic elements in front of the Shan Scarp began the trench-to-transform conversion of that margin. The oceanic crust underlying the modern Irrawaddy delta front has migrated into the map area (Fig. 3).

Eastern Sunda block movements followed those of the 50 Ma map. Luconia was closing with western Borneo. Rifting in SE Borneo spread into the East Java Sea region at angles perpendicular to earlier rift trends. These rifts were being infilled by clastic sediments, coarse at the base but upward-fining into lacustrine source facies.

Major spreading and CCW rotation of the PSP was accompanied by subduction of most of the Northern New Guinea Plate. The North Arm of Sulawesi migrated southward as spreading started in the Celebes Sea.

40 MA

Major worldwide Early Tertiary plate tectonic reorganisation is reflected in this map (Fig. 4). The western Sunda margin become a pure transform margin by clockwise rotation of the fringing elements brought about by the northward passage of INDI into 'hard' continental crust collision with EURA. Sediments from the still highstanding Sunda were being transported to the shelfal to deepwater margins on all sides.

The first internal Tertiary basin formation within Sunda took place in Sumatra and western Java. Five basins had their inception in north-trending rifts with an east-west extensional direction: North, Central and South Sumatra and the Sunda and Arjuna basins. The origin of these basins may be connected to a slightly transtensional Sumatra fault, but evidence is not conclusive, nor is there a clear linkage to the INDI-EURA collision. In the attractive hypothesis of Peter Moulds (1989), east-west extension operating on a pre-Tertiary basement with a strong NW grain, inherited from a Late Cretaceous orogeny, produced the segmented map appearance of these north-trending rift basins.

Borneo underwent major changes. The Luconia collision caused uplift of the entire western Borneo region, including the southern Natuna Ridge. The central Borneo spine was emergent all the way NE to Sabah. Deltaic sediments derived from the uplift spread eastward south of the central spine in the Ketungau and Melawi basins. North of the central spine lay the narrow NE-trending Crocker Basin.

Another effect of the Luconia collision was to activate or emphasise the rifting of the South Arm of Sulawesi along the major, slightly arcuate left-lateral boundary fault between the Sunda realm and the PSP realm. The interpretation shown on the map is that a sliver was torn from eastern Sunda, bounded by complementary left-lateral and right-lateral wrenches.

To the east, the small ocean basins of the Celebes Sea and PSP were actively spreading between parallel left-lateral transforms. The following maps will show that displacement increased away from Sunda so that each block moved northward at a rate faster than the adjacent block on the west and slower than the one on the east. The relative positions of the South Arm, the Celebes Sea and the PSP become reversed. Initially, at 40 Ma, the South Arm occupied a position more northerly than the Celebes Sea spreading axis, which itself was north of the PSP axis. By 20 Ma these relationships were inverted. Using this mechanism the emplacement of the PSP east of Sunda can be established without the necessity of invoking rotation of Borneo.

35 MA

Major changes took place as Sunda was split into three major blocks by extrusion from the INDI-EURA collision (Fig. 5), involving mechanisms first suggested by Tapponier *et al.* (1982). The blocks were:

SOCH — South China, north of the Red River Fault, attached to Eurasia.

INCH — Indochina, south of the Red River Fault, east of the Sagaing Fault, north of the Three Pagodas-SW Malay faults.

SOWS — South and West Sunda, bounded by the Three Pagodas Fault, the eastern margin of the Khorat Arch (on the Vietnam shelf, not onshore Thailand), the eastern side of The Natuna Ridge and adjacent parts of the core of Borneo, and the right-lateral Sumatra Fault with extensions to the Sagaing Fault.

The extrusion story is given on the five maps between 35 Ma and 15 Ma, because they are the closest time slices to the likely inception of extrusion (36 or 38 Ma) and its termination (16.8 Ma).

Initially, SOWS extruded at a rate somewhat faster than did INCH. This, together with a slight degree of clockwise rotation of SOWS, opened the Sunda Rift basins:

Gulf of Thailand
Malay and Penyu basins
West Natuna basin
Cuu Long and Nam Con Son basins

These basins, which opened simultaneously, have markedly different basin-forming fault trends. Their location was apparently controlled by zones of weakness (such as accretionary belts between

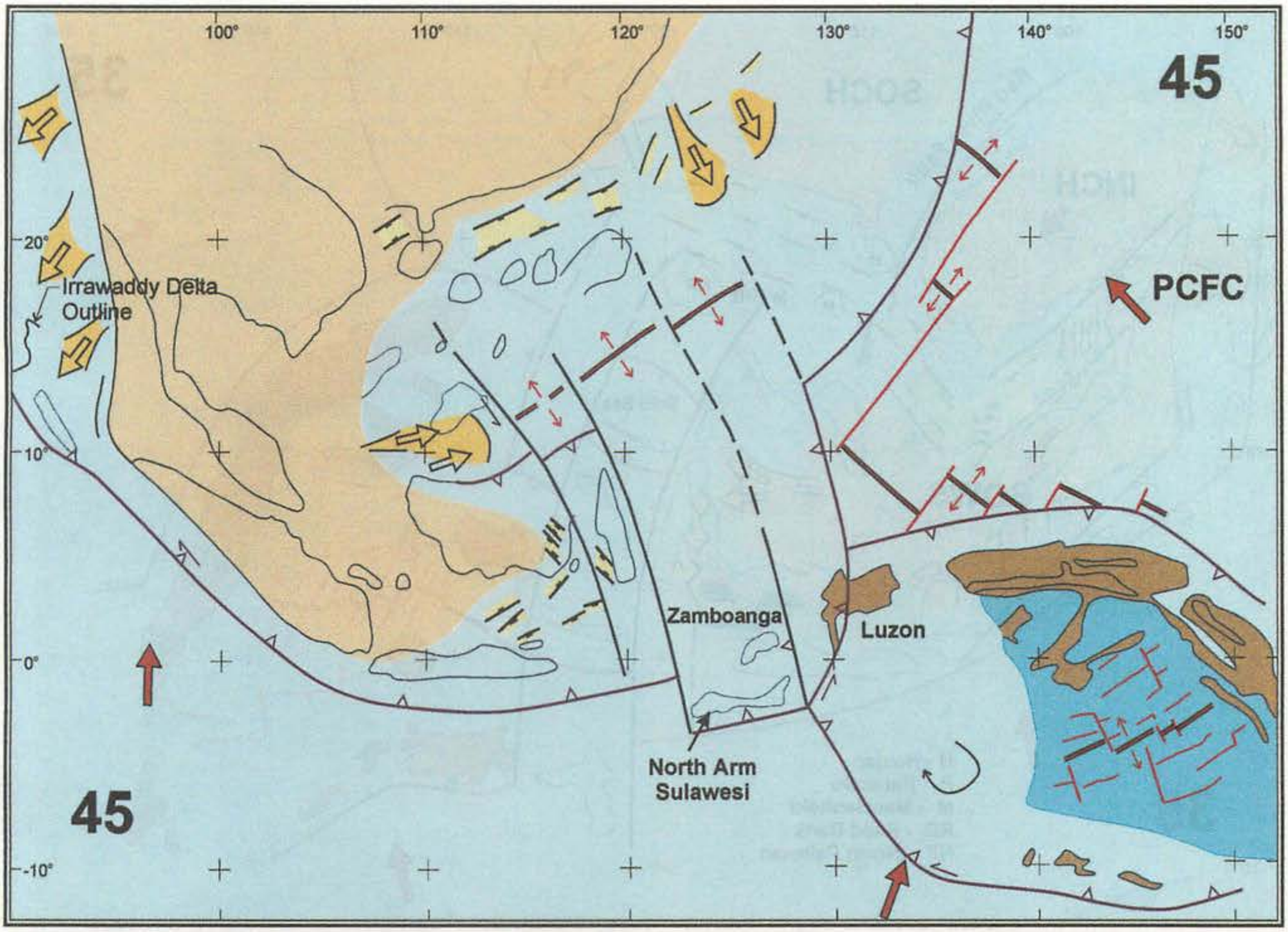

Figure 3. 45 Ma time slice map.

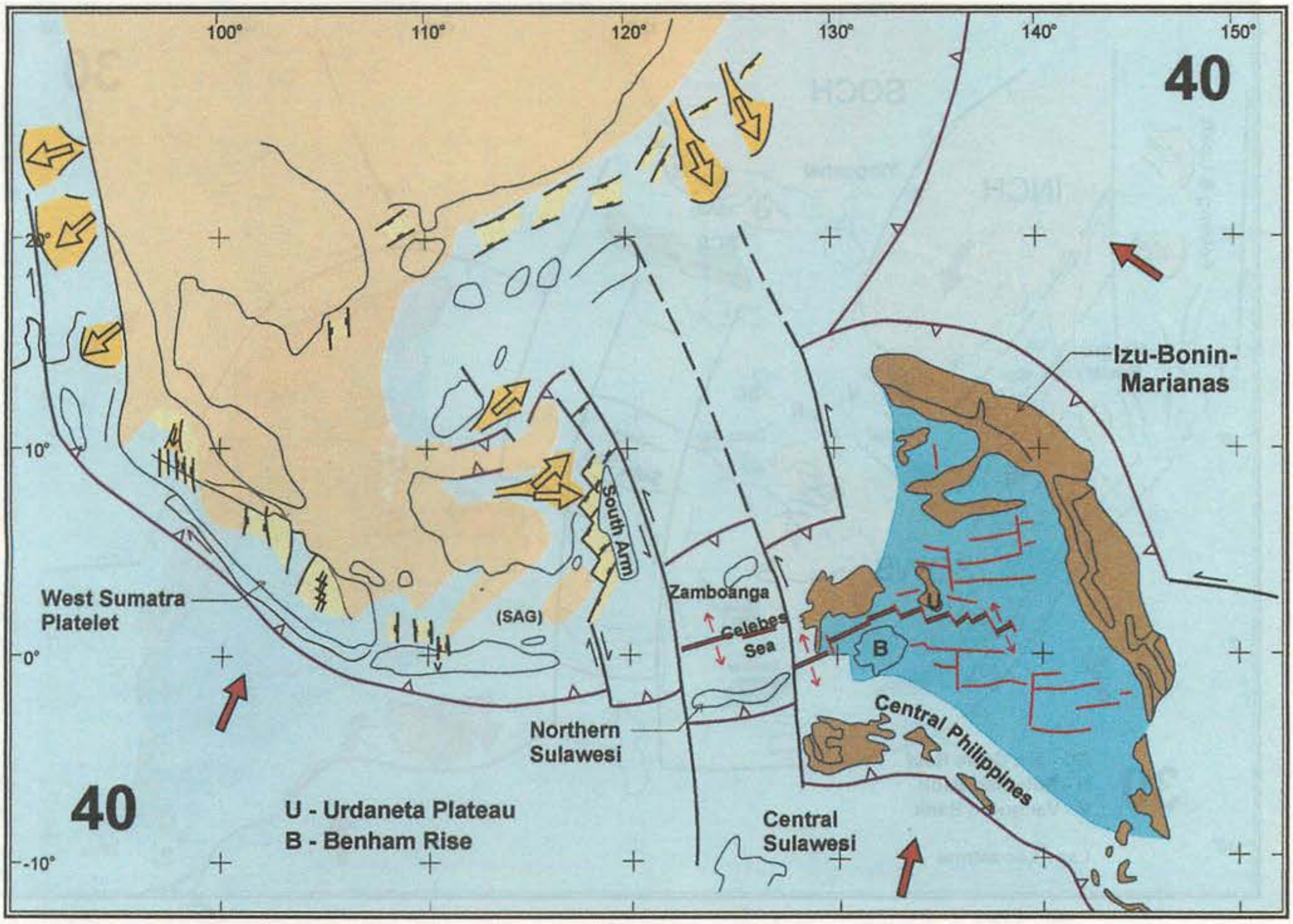

Figure 4. 40 Ma time slice map.

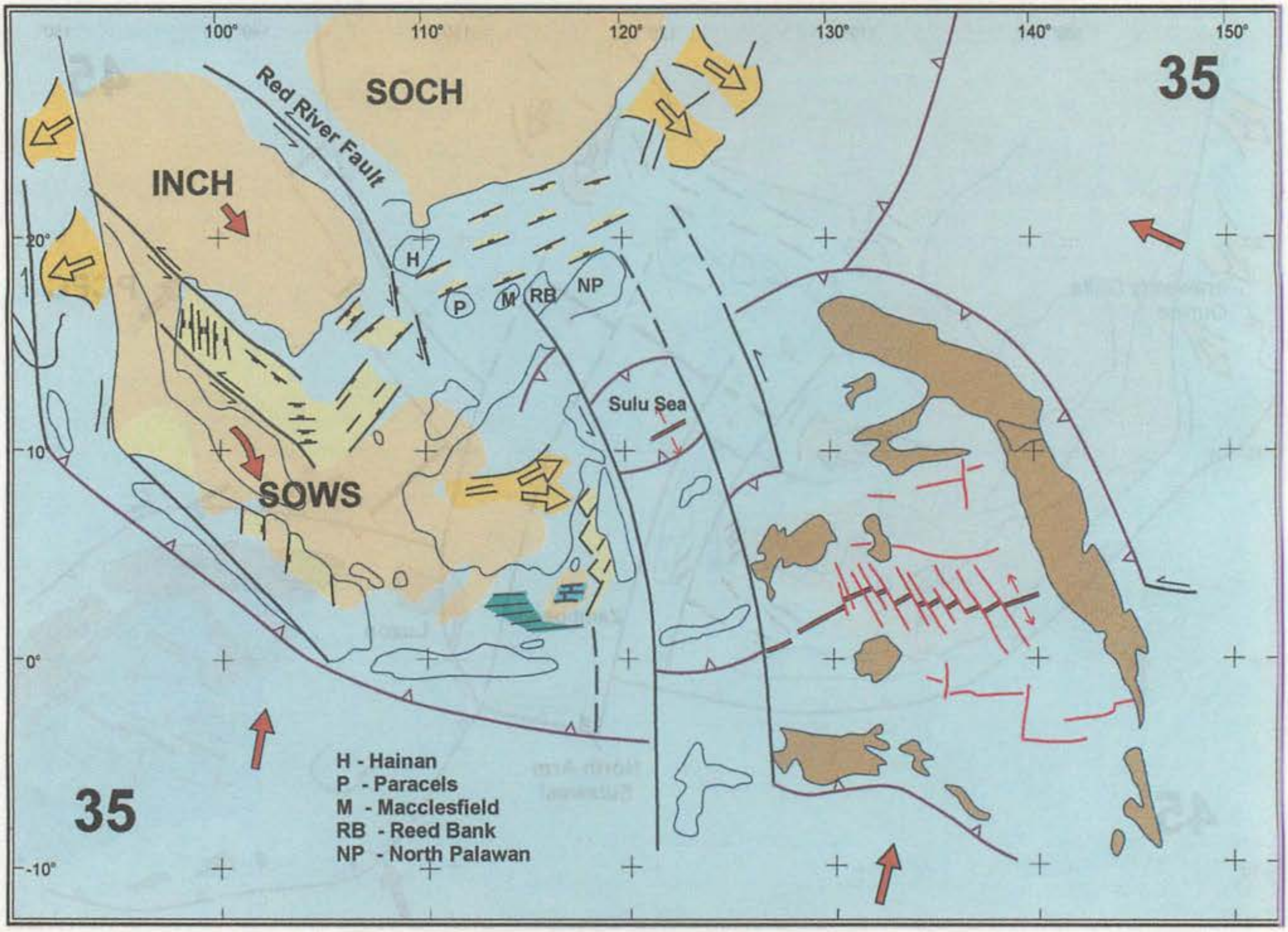

Figure 5. 35 Ma time slice map.

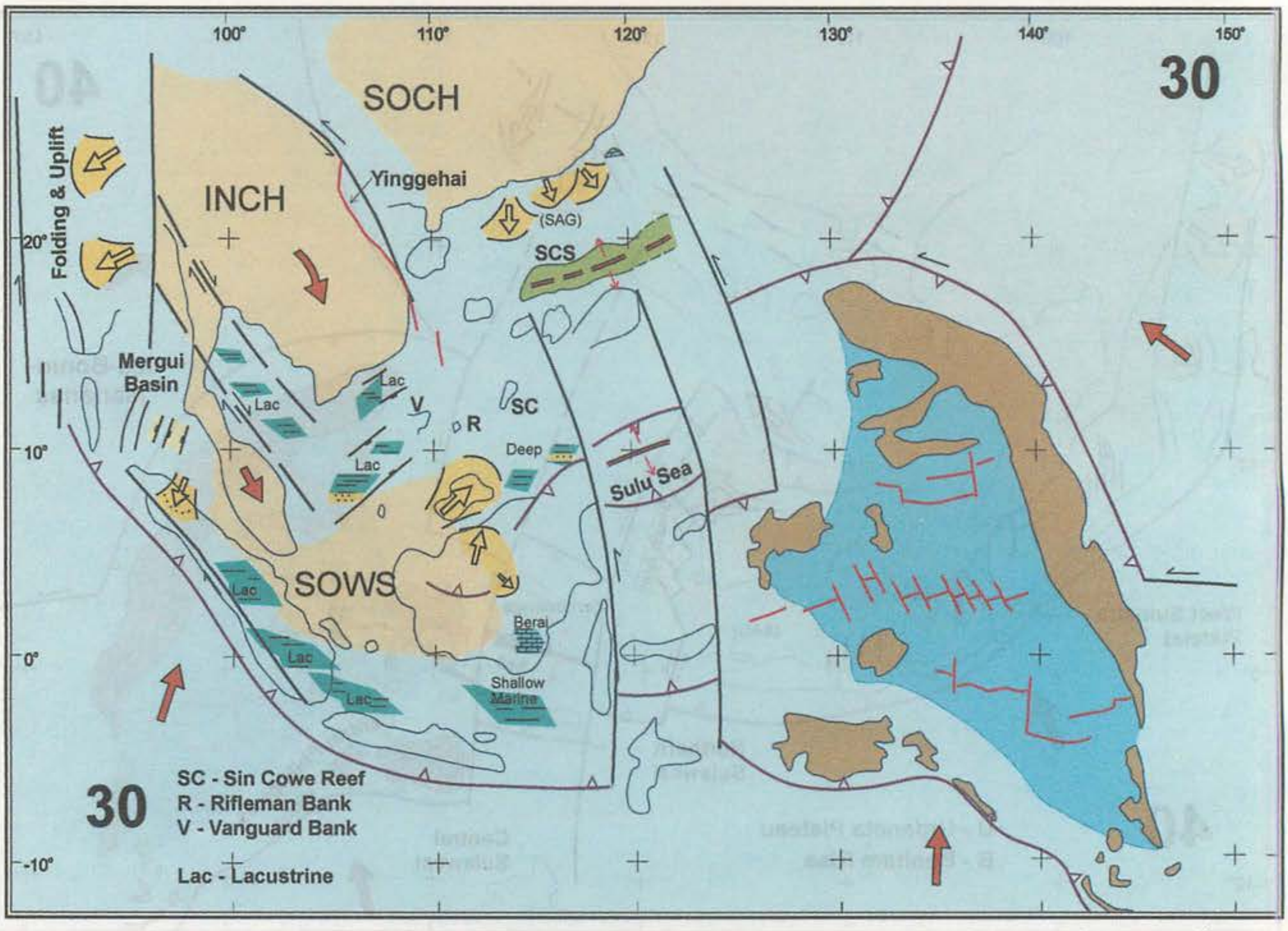

Figure 6. 30 Ma time slice map.

granite batholiths), basement grain and lithology and their position between rigid crustal blocks.

In the Sumatra-West Java rift basins, the rift phase ceased and basins were dominated by deposition of lacustrine shales, many of which formed the principal source rock intervals of the basins.

Formation of the modern SCS commenced with the extrusion of INCH and SOWS along the left-lateral Red River Fault. A complex and unstable triple junction was formed where the Red River fault intersected the South China rifts and the little-understood fault complex along the east Vietnam margin (Jim Granath, 1997, personal communication). The ensuing fault-fault-ridge (FFR) triple junction, with both faults having the same sense of movement, was inherently unstable and must have given way to complex tectonic developments which remain to be unravelled. Extrusion of INCH and SOWS, together with slab pull at the trenches along NW Borneo and the Sulu Sea, was the apparent driving mechanism for the SCS opening.

The faults drawn on the relevant time slice maps emphasise the linkage of the fault-bounded compartments in the zone between Sunda and the PSP. Thus, Reed Bank and North Palawan are thought to be on the same block as the Sulu Sea and the Celebes Sea further south. East of this compartment Luzon slides northward as the leading element of the PSP.

30 MA

Continued extrusion of the SOWS block led to compression along its leading edge (Fig. 6). This took the form of inversion of the Indo-Burman Ranges in a transpressional setting, thereby erecting a barrier to deltas building westward from the Shan Scarp and initiating southward progradation in the Irrawaddy valley. Moderate folding arched Sumatra, producing open folds in the forearc and backarc positions (present-day terminology). The Java forearc was also folded. This folding marked the end of the Paleogene wedge phase in the above-mentioned basins.

The Sumatra Fault gradually converted from transtensional to transpressional movement. Translation of crustal blocks in the West Sumatra platelet beyond the barrier of the tip of North Sumatra induced crustal extension in the region to the north. Rifting east of the Mergui Ridge opened the Mergui Basin.

In the SCS, oceanic crust was inserted commencing at 32.8 Ma (Chron 11). Once sea floor spreading started, rifting along the south China coast froze and the sag phase began. The Red River Fault took an extensional right-hand bend at the deteriorating triple junction south of Hainan, causing the opening up of the ultra-deep Yinggehai Basin. Within the SCS, the Paracels and Macclesfield Bank became cut off as the spreading system settled into a NNW-SSE pattern east of the fault bounding the east side of Macclesfield Bank.

The Sunda Rift basins shifted into sag phases with widespread lacustrine shale deposition, thus providing rich oil-prone source rocks.

Deltas built out from the Sunda Shelf in NW and central Borneo. A major delta covered the Luconia block, with NW-trending shorelines being pushed toward the northeast. Complex patterns of faulting, uplift and volcanism in central Borneo produced isolated basins with considerable topography and intricate stratigraphy while the outer margins were sites of deepwater shale deposition.

The Early Tertiary rift basins of SE Kalimantan and the East Java Sea were filled to the brim and became carbonate and carbonate-shale platforms.

25 MA

Like the 40 Ma time slice, the 25 Ma map marks a critical phase of basin development in Southeast Asia (Fig. 7). It is also a time of great change in a worldwide sense. The Aquitanian problem in Europe, Chron 6A-6C in the ocean basins, the spread of the Antarctic ice sheet and the inception of the Green Tuff basins of the Northwest Pacific are manifestations of this change. In Southeast Asia the start of the Neogene wedge of sedimentation, although time-transgressive regionally, can be pegged to the 25 Ma map. Effects in Southeast Asia are listed below from west to east.

Continued movement along the Sumatra Fault coupled with bending toward the right (north) terminated spreading in the Mergui Basin, as it no longer lay at in the proper orientation relative to the fault to serve as the extensional direction. Extension was transferred across the Mergui Ridge to a second rift basin, which is unnamed and which also aborted slightly later.

The intermontane basins of northern Thailand began with widespread rifting, probably connected with intersecting patterns of active wrench faults, at about this time.

Deltas spread southward in the Sumatra and West Java basins, marking the inception of the Neogene wedge. These wedge-base sands, together with wedge-base carbonates, are the major reservoirs for hydrocarbons in the basins. Units involved are the Arun Limestone and (subordinate)

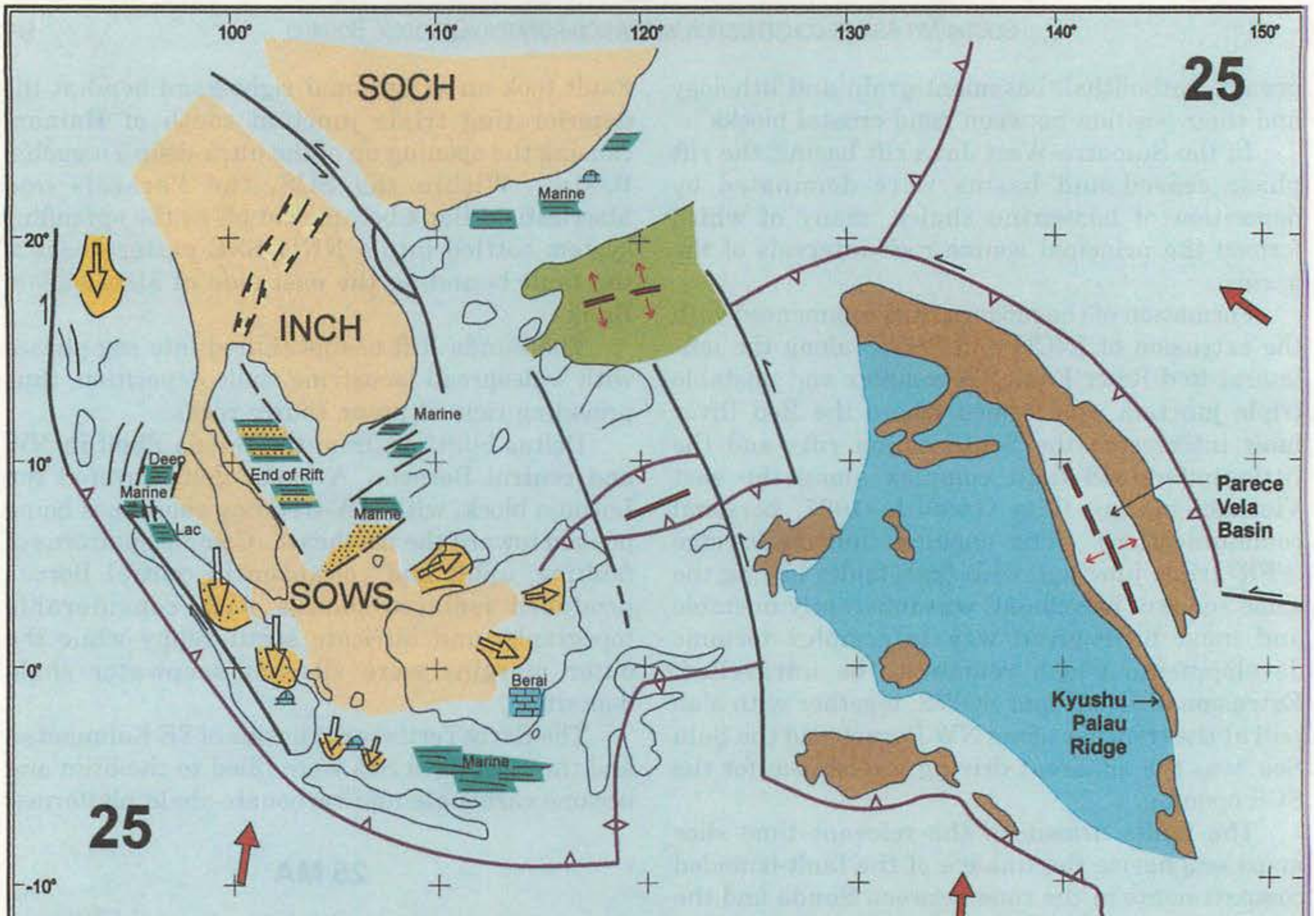

Figure 7. 25 Ma time slice map.

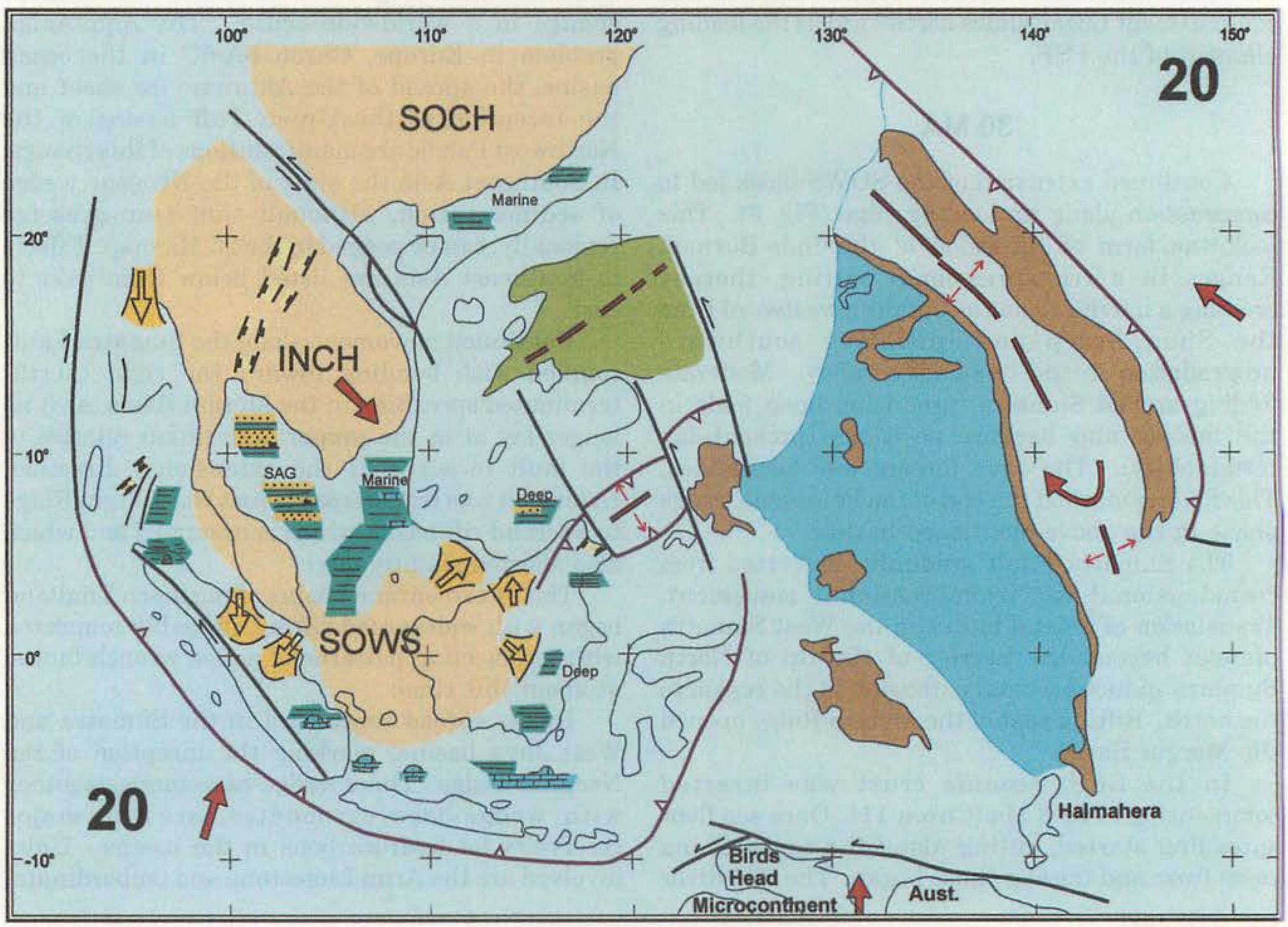

Figure 8. 20 Ma time slice map.

Belumai Sandstone in North Sumatra; the Sihapas Sandstone in Central Sumatra, and the Talang Akar Sandstone and Batu Raja Limestone in South Sumatra and the West Java basins (an alternate terminology is employed locally in Java).

Rifting shifted to sag basin deposition in the Sunda rift basins. The Malay Basin, for example, was converted from a nonmarine rift into a tidally-dominated marginal marine sag basin. In northern and central Kalimantan, deltas began prograding seaward rapidly.

In the SCS the NNW-SSE pattern of spreading began shifting to a NW-SE spreading direction. An arm of oceanic crust was inserted between Macclesfield Bank and Reed Bank. Central Sulawesi sutured with the arrival of the ophiolite and oceanic suites of the Northeast and Southeast Arms.

20 MA

In the Andaman region, the second rift basin, west of the Mergui Ridge, aborted and a new rift direction began (Fig. 8). The new rifts trended NE rather than NNE, a direction which was stable with regard to the north-trending splay faults between the Sumatra Fault on the south and the Sagaing Fault on the north. These rifts evolved into the Andaman Sea small ocean basin.

For the main Sunda core this was a time of relative quiescence. Deltas were in decline in the Central and South Sumatra basins, giving way either to wedge-middle shales and/or carbonates building at delta-top positions as clastic input waned. In the Malay Basin important marginal marine sands were entering, as in Group I, but the West Natuna, Nam Con Son and Cuu Long basins were wholly marine, with deposition of mainly beach and bar sands. The Java Sea basins were carbonate-shale platforms. In Borneo, however, delta progradation continued to dominate as deformation and uplift of early Tertiary basins furnished abundant coarse clastics.

The spreading pattern in the SCS shifted completely into a NW-SE direction. Concurrently, the spreading axis propagated toward the southwest. Luzon underwent major CCW rotation and some 700 km NW translation (Hall, 1996).

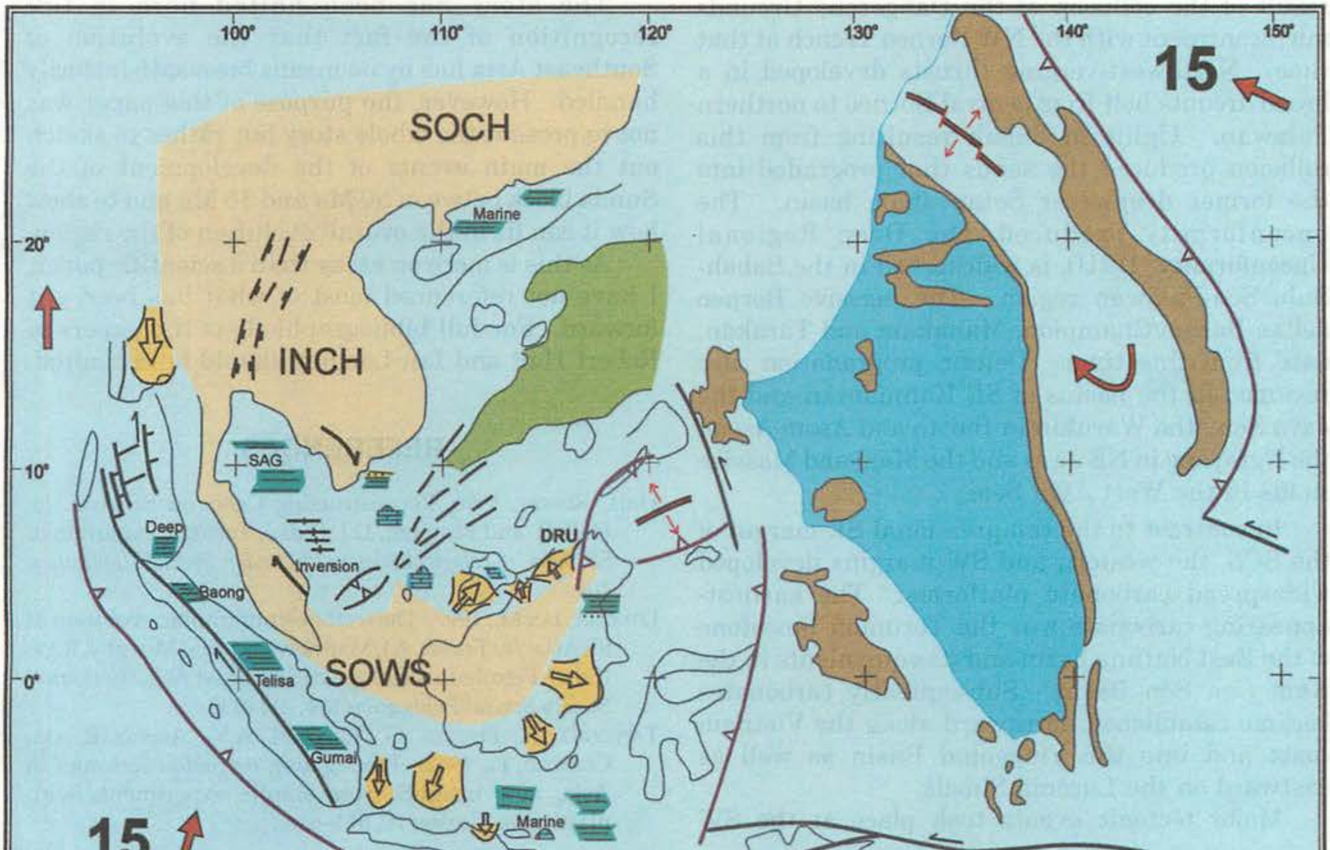

Figure 9. 15 Ma time slice map.

15 MA

Between 20 Ma and 15 Ma tectonic differentiation in Southeast Asia intensified, and it becomes very difficult to make valid generalisations. Many of the events described in this section were sequential, and it is best to consider each area separately.

Rifting in the Andaman basin continued, but oceanic crust did not appear until about 11 Ma. The Irradaddy Delta had advanced southward and was now supplying sediment to the wholly marine Martaban Basin (Fig. 9). The Mergui Basin sank to bathyal depths. Wedge-middle shales reached their widest extent in the Sumatra basins, but not everywhere at the same time. Compression and uplift in the Barisan Range was a consequence of CW rotation of Sunda about a pole of rotation in the Assam Syntaxis, thereby making the continuing right-lateral offset along the Sumatra Fault increasingly transpressional. Uplift of the Barisan locally produced sands which were shed west to east into the Sumatra basins.

The SCS spreading axis continued to insert oceanic crust and propagate SW until cessation of activity about 16.8 Ma. Spreading ceased as a result of the collision of the Dangerous Grounds microcontinent with the NW Borneo Trench at that time. Northwest-verging thrusts developed in a broad arcuate belt from central Borneo to northern Palawan. Uplift in Sabah resulting from this collision produced the sands that prograded into the former deepwater Setap shale basin. The unconformity produced, the Deep Regional Unconformity (DRU), is widespread in the Sabah-Sulu Sea-Palawan region. The massive Borneo deltas-Baram/Champion, Mahakam and Tarakan, date from this time. Deltaic progradation also resumed in the basins of SE Kalimantan and the Java Sea: the Warukin in Barito and Asem Asem, the Ngroyang in NE Java and the Main and Massive sands in the West Java Sea.

In contrast to the compressional SE margin of the SCS, the western and SW margins developed widespread carbonate platforms. The earliest-appearing carbonate was the Terumbu limestone of the East Natuna basin and its equivalents in the Nam Con Son Basin. Subsequently carbonates became established northward along the Vietnam coast and into the Yinggehai Basin as well as eastward on the Luconia Shoals.

Major tectonic events took place at the SW corner of the SCS. Rifting associated with the propagating ridge penetrated the Vietnam shelf edge and formed a fan-shaped set of normal faults which converge on a point near the north end of the Natuna Ridge. This Middle Miocene rift system was superimposed on the older Oligocene basin-forming rifts.

The point of convergence is about 6°10' North, 118°50' East. To the southwest lies the severely inverted West Natuna Basin. Both the rifting to the NE and the compression to the SW occurred over the same time span and appear to be mechanically linked. The causative mechanism is to be sought in the interaction between an extruding INCH block against a stationary SOWS block (the 'second extrusion'), causing inversion of the West Natuna Basin, and the SW propagation of the SCS spreading ridge.

Extrusion of INCH against a stationary SOWS set up a compressional right-lateral couple in the southern Malay Basin, causing the formation of the basin-centre *en-echelon* detached folds that are the main hydrocarbon traps in the basin.

CONCLUSION

The story has been halted here in full recognition of the fact that the evolution of Southeast Asia has by no means been satisfactorily handled. However, the purpose of this paper was not to present the whole story but rather to sketch out the main events of the development of the Sunda block between 50 Ma and 15 Ma and to show how it can fit in the overall evolution of the region.

As this is more an essay than a scientific paper, I have not referenced most of what has been put forward. For full bibliographic lists the papers of Robert Hall and Ian Longley should be consulted.

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