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Origin and tectonic development of Malay-Penyu-West Natuna basins

H.D. TJIA

PETRONAS Research & Scientific Services Sdn. Bhd.
Lots 3288 & 3289, Kawasan Institusi Bangi
43000 Kajang, Selangor

Abstract: A Late Cretaceous hot spot arches up continental crust of the northern Sunda Shelf into the Malay Dome (new name). Its crest breaks into three rift arms that are now represented by the Malay, Penyu and West Natuna basins. Its triple junction is still one of the highest heat-flow areas of the region. By Middle Eocene time hot spot activity had ended allowing the basins to become aulacogens into which perhaps up to 12 km thick upper Oligocene and younger sediments accumulated. At the same time, hard collision of the Indian Subplate with Asia differentially pushes out elongated crustal slabs of Southeast Asia towards southeast along major NW-striking wrench faults, one of which is located in the basement rocks along the axis of the Malay Basin. Left-lateral motion along this Axial Malay (new name) fault zone develops east-west halfgrabens and grabens as special depocentres of the basin. By early Middle Miocene, the westward drive of the Pacific Plate is no longer buffered by spreading of the South China Sea Basin and causes reversals in slip sense along the wrench faults and other structural inversions. The Axial Malay faults now move right-laterally deforming the sediments in the halfgrabens and grabens into east-west anticlines and south-verging thrust faults. Other factors that have effected the regional stress field changes are the close approach of the northward moving Indian Ocean-Australia Plate, and by early Late Miocene also the opening of the Andaman Basin.

INTRODUCTION

The Malay, Penyu, and West Natuna basins are three of the Tertiary basins located on the northern Sunda Shelf. Hydrocarbons are produced from the Malay and West Natuna basins, while prospects have been located in the Penyu Basin (Fig. 1).

The Malay Basin is about 500 km long in northwest direction and attains a width of 200 km. Its north part changes into a northerly strike, parallel to the regional structures in the Gulf of Thailand. Over 14 km of pre-upper Oligocene and younger sediments completely fill the basin and thus obliterate any surface indication of a depression. Basement rocks drilled along the west and southeast flanks are granitoids (most probably of Cretaceous age), presumably Jurassic-Cretaceous sediments, and older metasediments that have been correlated with outcrops onshore Peninsular Malaysia. Deposition began with continental-type sediments and this depositional character dominates until late Miocene-Pliocene time, except for a period of regional marine transgression in late Early Miocene. After the Pliocene, marine conditions have prevailed. Stages in tectonic development comprise a pre-Late Oligocene transtensional regime, followed by quiet subsidence and basin filling until early Middle Miocene when regional transpression began to compress and fold basin-filling sediments (Figs. 2 and 3), which persisted up to Late Miocene; and was finally succeeded by epeirogenic subsidence during which period cross faults develop across the large anticlines (Ng, 1987; Md. Nazri Ramli, 1988). The initial transpressive period is probably associated with the expulsion of Southeast Asia as result of hard collision between the Indian subcontinental plate with Asia (Tapponnier *et al.*, 1982). In addition to initiation of basin development, basement faults along the basin's axis are interpreted to have slipped left-laterally, and in that way develop *en echelon* east-west trending grabens and half-grabens within the Malay Basin (Tjia, 1993a). Tectonic inversion that took place in the Middle to Late Miocene is probably caused by aggregate changes in movements of plates surrounding Southeast Asia. The westward movement of the Pacific Plate is no longer absorbed or buffered by spreading of the South China Basin (which ceased by late Early Miocene). In addition, the Australian Plate has encroached so far north as to have interfered with further expulsion of crustal slabs from Southeast Asia. During tectonic inversion, the axial basement faults have become right-lateral. This motion compresses the sediments that reside in the east-west grabens and half-grabens into anticlines and causes thrusting in the south part of the basin.

The Penyu Basin measures 200 km east-west and about 100 km across. The west end of the

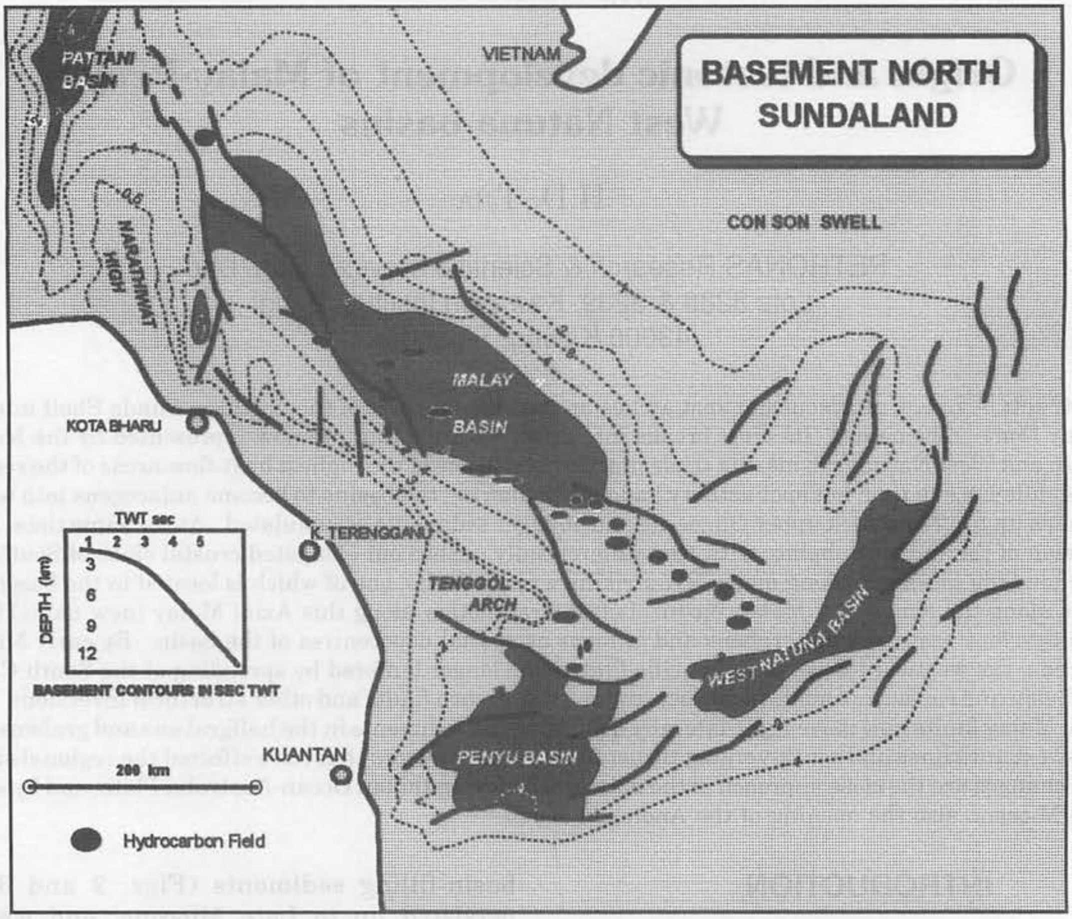

Figure 1. Outlines of the Malay-Penyu-West Natuna basins are shown by basement contour lines with intervals of one second two-way-time units. Conversion of TWT to depth in feet is shown as inset. Bold lines are major faults; hachures indicate directions of fault inclination.

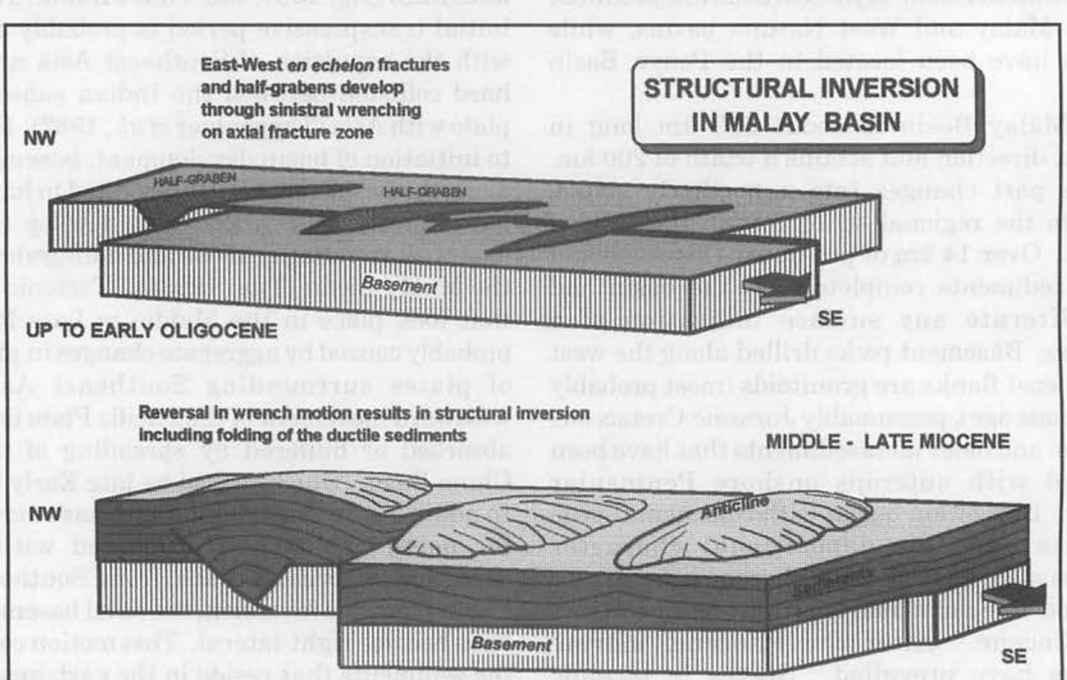

Figure 2. Schematic development of east-west *en echelon* fractures and half-grabens as consequence of left-lateral slip along interpreted Axial Malay basement faults in the Malay Basin (upper figure). Reversal of lateral slip sense during Middle-Late Miocene causes compression and folding of sediments filling the depressions (lower figure).

depression extends onshore under the Pahang river delta. To the north it is separated by the Tenggol Arch from the Malay Basin. A major NW-striking fracture (traceable over a length of 100 km), called the Rumbia fault, separates the Penyu Basin into two parts. In the west part, two east-west half-grabens dominate; the east part is characterised by NW to WNW-trending structures including eight half-grabens. More than 5 km thick sediments are contained in the deeper western part. Most fold axes are parallel to major faults and may therefore represent rollovers. In some areas are *en echelon* faults that suggest wrench movement. For instance, the Rumbia fault runs parallel to a zone of sigmoidal *en echelon* fractures indicative of left-lateral motion (Fig. 4). A preliminary account of the Penyu Basin was written by Khalid Ngah in 1975; recent exploration was by TEXACO. Its tectonic development began with pre-Late Oligocene north-south extension forming mainly east-west half-grabens in the entire basin. Alternatively, these east-west depressions may have been formed by left-lateral slip along the northwest-striking Rumbia and other faults parallel to it. In Late Oligocene to Middle Miocene, continued lateral slippage along the Rumbia fault may have rotated the half-grabens of the eastern part some 25 degrees in clockwise direction.

The West Natuna Basin has a broad crescentic plan concave towards north. In the west it begins with an ENE-trend that farther towards northeast becomes northerly. Its widest part is slightly more than 100 km; its length reaches 250 km (Fig. 1). Comprehensive accounts on the geology of the basin were published by Wongsosantiko and Wirojudo (1984) and by Daines (1985). During Early Oligocene, the West Natuna area was subjected to rifting and/or pull-apart processes that produced NE-trending halfgrabens into which non-marine sedimentation took place. Locally these sediments reach 4.5 km thickness. In Early Miocene, regional compression resulted in reverse faulting and strike-slip faulting on existing fractures and folding causing uplift of the half-graben fillings. The regional stress field was such that thrusting took place along N60°E and ENE fractures, and strike-slip motion occurred on east to ESE-striking (right-lateral) and north-trending (left-lateral) fractures (Fig. 5). Ginger *et al.* (1993) have determined several discrete inversion events beginning in earliest Miocene (23 Ma) and terminating in early Late Miocene (12 Ma). They also suggested that structural inversion generally occurred in the eastern portion of the basin and progressively spread westward. In Late Miocene to Early Pliocene, uplift and possibly also sea-level changes had sufficiently raised the anticlinal crests resulting in an unconformity in the stratigraphy. Marine Pliocene to Recent sediments are relatively undisturbed.

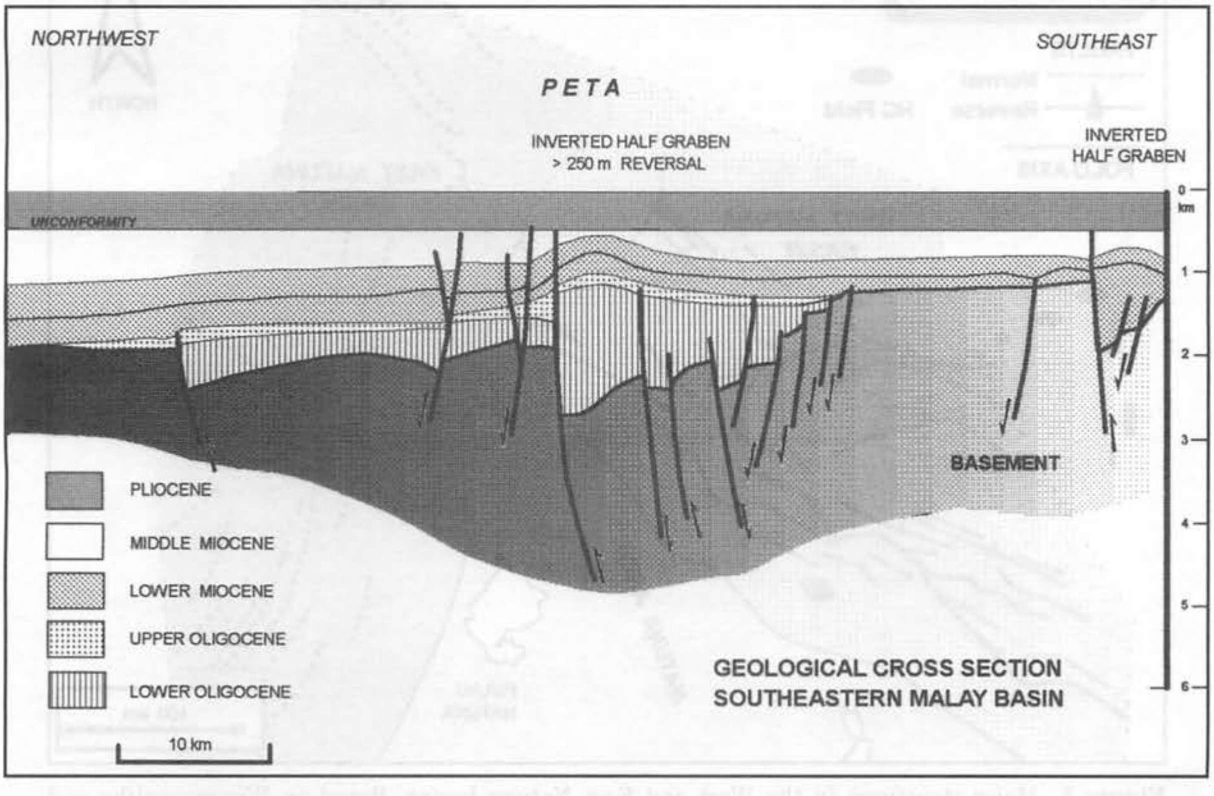

Figure 3. Geological cross section of the southeastern Malay Basin shows two inverted half-grabens.

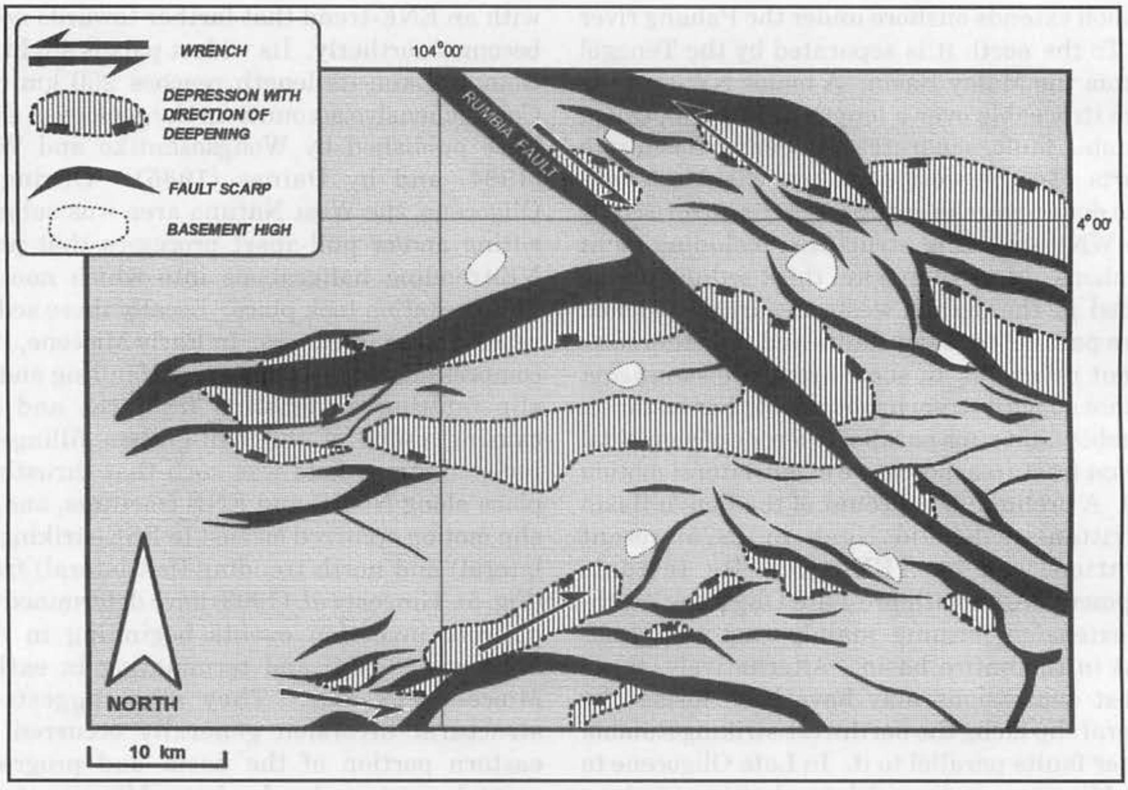

Figure 4. Geological structures of the base of the Tertiary in the Penyu Basin. Note the *en echelon* sigmoid fractures in the upper centre and the different orientations of depressions west and east of the Rumbia Fault. Arrow couples indicate sense of lateral fault slip in NW and right-lateral slip in about NE direction. The base map is simplified after an unpublished report by Texaco (1990) held by Petronas.

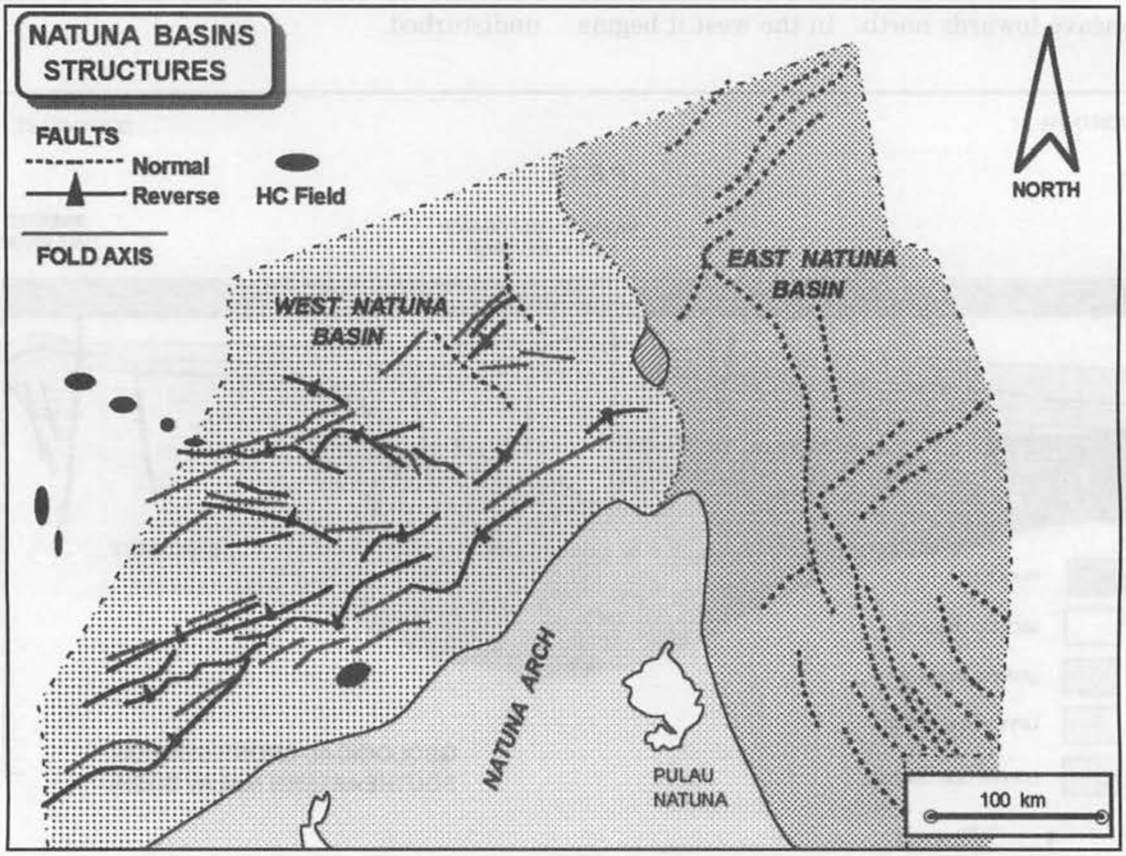

Figure 5. Major structures in the West and East Natuna basins. Based on Wongsosantiko and Wirojudo (1984).

TECTONIC DEVELOPMENT

Available information suggests the following tectonic development of the Southeast Asian region that contains the Malay-Penyu-West Natuna sedimentary basins.

LATE CRETACEOUS

Onshore Peninsular Malaysia diastrophic activity during Late Cretaceous comprises strike-slip motion along several major faults, alkali basalt flows in Segamat, Johor (K-Ar date of 62 Ma or Palaeogene, but considered too young due to argon loss by Bignell and Snelling [1977], and instead to represent Late Cretaceous), and not uncommon radiometric ages of granitic complexes. K-Ar ages of 67 Ma for the granitoids of the Setong Complex in Kelantan; of 69 Ma for the Gunung Ledang granitoid, and of 81 Ma for the granitoid body Batang Melaka-Batu Tiga, both in Johor; are shown on the regional geological map (Geological Survey of Malaysia, 1985). Hutchison (1973, 1989) adds Rb-Sr ages of 65-70 Ma (Setong Complex), 78 Ma (Gunung Ledang), and a K-Ar age of 70 Ma for the Gunung Pulai granitoid in south Johor. From the Sunda Shelf, Katili (1973) publishes Late Cretaceous granitoid ages of 86.5 Ma (Anambas island), 85 Ma (Tambelan island) and quotes from N.S. Haile (1971) 73 Ma and 75 Ma granitoid ages from the Natuna islands. The Con Son Swell that separates the Mekong Basin from the Con Son Basin consists mainly of block-faulted granitoids. An age of 97 Ma (Cenomanian) is reported among their radiometric ages (T. Minh *et al.*, 1991, cited by Mauri *et al.*, 1993). Zaiton Harun (1992) shows that Late Cretaceous (83.6 Ma) strike-slip motion probably took place along the north-striking Genting Peras fault on the Selangor/Negeri Sembilan border. An unpublished K-Ar date for Bukit Tinggi gneiss, west Pahang, is 83.9 Ma and may indicate the timing of shearing along the NW-trending fault zone of the same name. The localisation of small Tertiary (recent palynological studies suggest Eocene age) basins, such as Batu Arang in Selangor and Lawin in Perak, has been attributed to renewed activity along adjacent strike-slip fault zones; the Kuala Lumpur and Baubak fault zones, respectively.

These diastrophic activities are interpreted to be related to a hot spot located approximately at 04° North/105°30' East, or at the triple junction of the Malay, Penyu and West Natuna basins. For this general area, Mohd. Firdaus Abdul Halim (1993, Fig. 8) indicates the highest heat flow in excess of 110 mW/m^2. Elsewhere along the axis of the Malay Basin average heat flow is also high reaching almost 100 mW/m^2. LEMIGAS (Indonesia) also finds for the West Natuna Basin an above normal average geothermal gradient of 39.7°C/km and an average heat flow of 2.06 HFU (Mohd. Firdaus Abdul Halim, PRSS internal report dated 2 December 1991).

This hot spot, presumably composed of a mantle plume, appears to have developed a circular regional uplift that possesses an estimated radius of 500 km (Fig. 6). The name MALAY DOME is proposed for the uplift. Remnants of the dome are still recognisable as three high sectors of pre-Tertiary basement: (1) The Tenggol Arch/Pahang Platform/ most of Peninsular Malaysia; (2) the Khorat or Con Son Swell, and (3) the Johor Platform/Anambas/ Natuna islands/Paus-Ranai High.

In plate-tectonic theory, it is widely accepted that a crustal dome commonly splits into three, and rarely four, crestal rifts. The three T or Y-shaped rift arms may continue to enlarge lengthwise and across their widths depending on sustained mantle-plume upwelling or otherwise. Further spreading of the rift arms eventually produces ocean basins. If on the other hand the mantle plume is small and only produces initial spreading, one or all three rift arms become regional grabens radiating from a triple junction (see Fig. 6). Such failed rift arms are known as aulacogens and usually become depocenters for thick piles of sediments. The inverted T-shaped planimetric pattern of the Malay, Penyu and West Natuna basins form three prongs radiating from a triple junction (Fig. 6). The relatively high positions of pre-Tertiary basement rocks (indicated by 1, 2 and 3 on the figure) are interpreted to represent relicts of the Late Cretaceous Malay Dome. Their high positions are not always pronounced due to subsequent differential denudation, epeirogenic subsidence, and substantial wrench motions along faults traversing the domal region (see below).

MIDDLE EOCENE

The Indian Subplate first collides with Asia in Early Eocene and then as "hard" collision in Middle Eocene or approximately 45 Ma. Tapponnier *et al.* (1982) proposed that this collision and continuing northward push of India into Tibet have caused crustal slabs of Southeast Asia to be extruded along mainly NW wrench faults. The differential motions of the crustal slabs towards southeast were such as to produce sinistral slips along the wrench faults, such as the Red River, Mae Ping (other names: Mekong, Tonle Sap, or Wang Chao fault) and Three Pagodas (Fig. 7). In the figure, NW-striking Axial Malay faults are interpreted as extensions of the Three Pagodas fault. The Hinge-line (H) and Dungun (D) faults, however, show dextral slip senses relative to the region on their east side. Onshore Peninsular Malaysia, strike-slip fault motions are indicated by K-Ar ages of sheared granitoid (north-south Bukit Berapit fault in central Perak State, 46 Ma and 53.4 Ma; Zaiton Harun, 1992), and the close association of small Cenozoic basins with major strike-slip faults (Kuala Lumpur and Baubak fault zones). Dextral slip along the north-trending Ping-Teris (see Tjia, 1993b) and segments of the Bentong Suture also seems probable. The segments of the suture that may have moved during this time are located in the Central Sumatra Basin and in the Gulf of Thailand, two regions of known tectonic activity during the Tertiary up to Mio/Pliocene.

Left-slips along the northwest-striking Axial Malay faults produce east-west halfgrabens and grabens within the Malay Basin. These depressions serve as loci for thicker Cenozoic sedimentation. Until today, the basement along the axial zone has yet to be penetrated by seismic. In a specially processed deep seismic section across the basin,

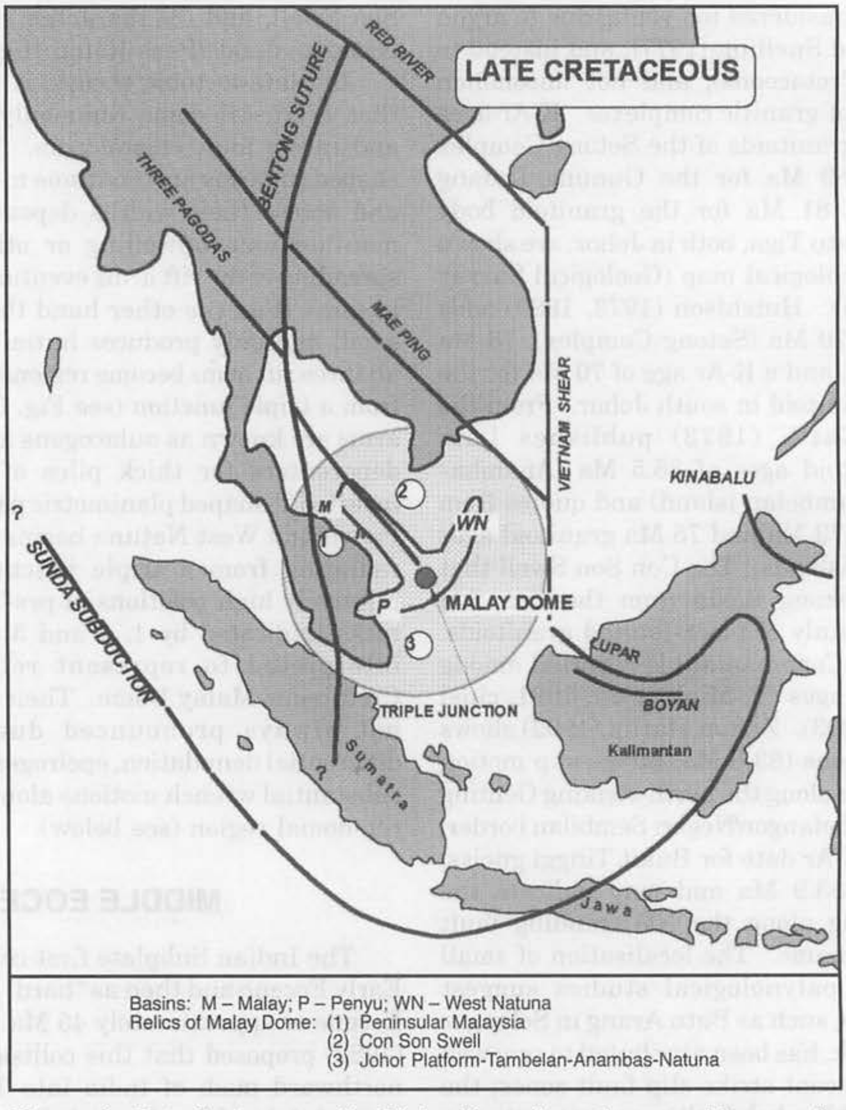

Figure 6. Late Cretaceous: The Malay Dome formed over a rising mantle plume whose centre lay beneath the triple junction (asterisk) of the Malay (M), Penyu (P) and West Natuna (WN) basins; 1, 2, and 3 are presently high basement sectors of the Malay Dome. Other active structural elements are the Red River Suture (S), greater Bentong Suture (B), Boyan subduction trench (Bo), Lupar subduction trench (L), and part of the Sunda subduction trench, including the Meratus (Me) segment in Kalimantan. KS or Kinabalu Suture was still a wide and deep sea underlain by mafic rocks. The East Sabah terrane (ES) was still attached to continental Asia. The positions of major structures that will become active subsequently are that of Mae Ping fault (MP), Three Pagodas fault (3P), and the Vietnam Shear (V).

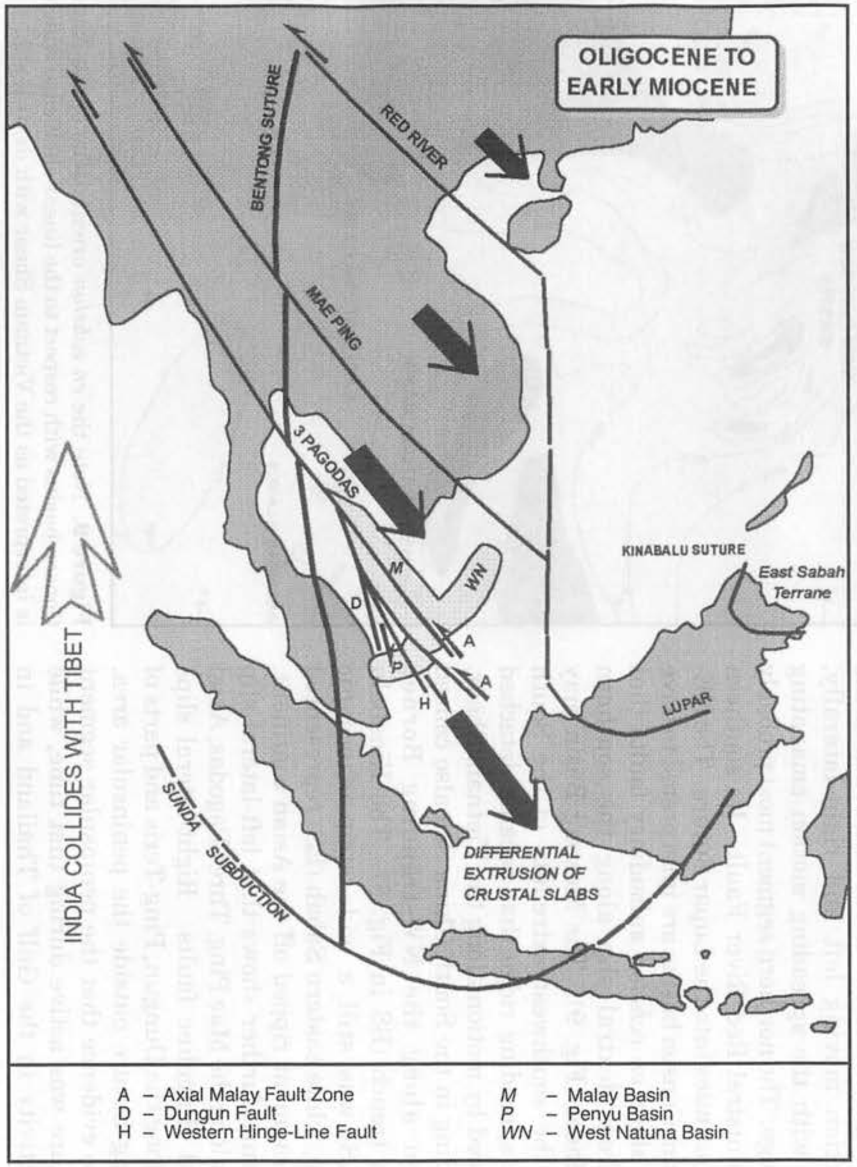

Figure 7. Middle Eocene: Differential extrusion of crustal slabs of Southeast Asia causes strike-slip motions on major faults. Abbreviations that are not yet explained by the caption of Figure 6 are: A = Axial Malay faults, H = Western Hingeline fault, D = Dungun fault.

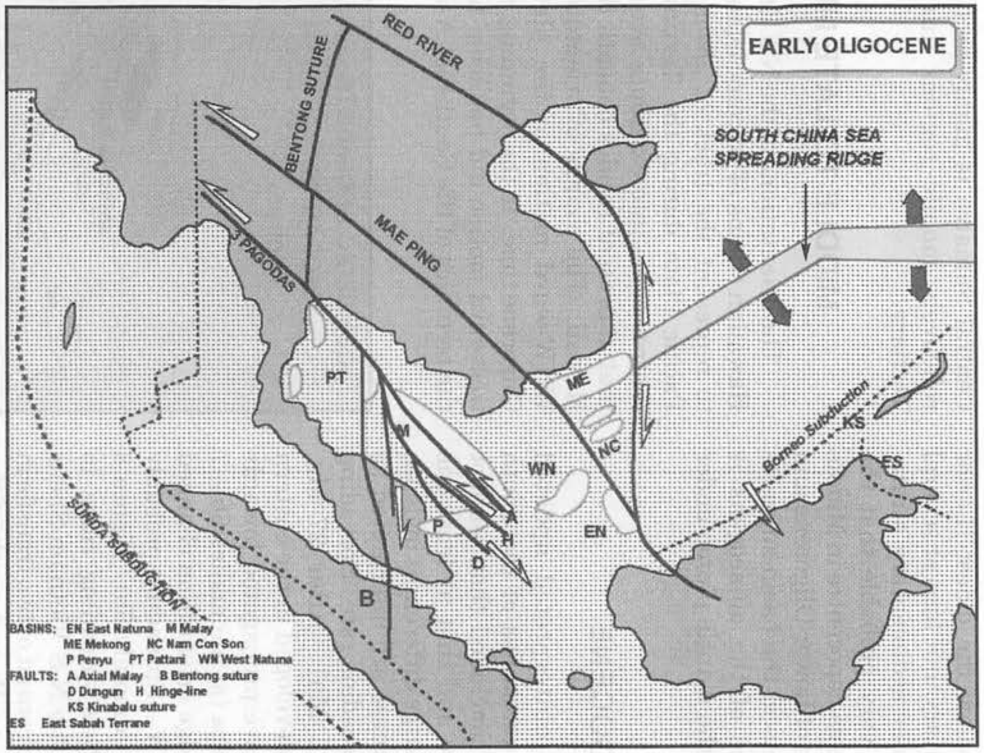

Figure 8. Late Oligocene: Extrusion of Southeast Asian crustal slabs encounter interference from the opening of the South China Basin (SCS). Abbreviations are: BS = Borneo subduction trench; basins: EN = East Natuna, Me = Mekong, NC = Nam Conson, Pa = Pattani. Other abbreviations are explained in Figures 6 and 7.

subhorizontal reflectors below the oldest (Lower Oligocene) known sedimentary unit hint at several kilometres more of yet older sedimentary strata. In other words, it seems very probable that the Malay Basin began to serve as depocentre in Middle Eocene time. The presence of Lower Oligocene and presumably older sediments in the basin suggests that continued subsidence of the aulacogens is associated with cooling of the mantle plume under the Malay Dome.

LATE OLIGOCENE

Briais *et al.* (1993) reinterpreted updated information on magnetic anomalies of the South China Sea region. They concluded that seafloor spreading was asymmetric and that at least one ridge jump had occurred. Large differences in depth of basement and its roughness are interpreted as indicating variations in spreading rate. Spreading began at anomaly 11 (32 Ma). After 27 Ma, spreading seemed to have developed in the eastern part of the basin and to have propagated towards southwest in two major steps (at anomalies 6b – 7 and at anomaly 6). The ridge orientation changed from almost E-W to NE-SW. Spreading probably stopped at about 15.5 Ma (anomaly 5b). Figure 8 shows the South China Sea spreading ridge to consist of two segments. The N-S Vietnam Shear (new name) is interpreted to consist of two transform faults, its segments to the north and south of the ridge junction moving left and right-laterally, consistent with the spreading motion emanating from the ridge. The northern segment most probably joins the sinistral Red River Fault. Its southern segment continues into the Lupar Suture. The NE-striking Nam Conson basins are interpreted to have developed along *en echelon* subsidiary faults that resulted from dextral slip along the southern Vietnam Shear (Fig. 9). The Mekong Basin may represent the southwest extremity of the South China Sea spreading ridge that became detached and displaced by motion along the Vietnam Shear. The spreading in the South China Sea also caused subduction along the NW-trending Borneo subduction trench (BS in Fig. 8). The Kinabalu Suture (KS) was still a wide strip of oceanic lithosphere, while eastern Sabah (ES) represented a crustal fragment ripped off the Asian continent.

The figure further shows that left-lateral slip continued along the Mae Ping, Three Pagodas, Axial Malay, and Hingeline faults. Right-lateral slips occurred along the Dungun, Ping-Teris and parts of the Bentong Suture outside the peninsular area. There is no evidence that the peninsular segment of this suture was active during that time, while tectonic activity in the Gulf of Thailand and in Central Sumatra is highly probable as these are relatively mobile regions during most of the Tertiary.

MIDDLE TO LATE MIOCENE

The orientations of the NW Emperor and WNW Hawaiian chains of volcanic islands are considered to represent the track of absolute motion of the Pacific Plate during the Tertiary. The volcanic centres came into existence over a mantle plume that at present resides beneath the major island of Hawaii. The change of orientation from NW into WNW-ward motion of the plate took place in Oligocene time. In the beginning, the post-Oligocene westward motion did not seem to have influenced the tectonics of the Southeast Asia region, because

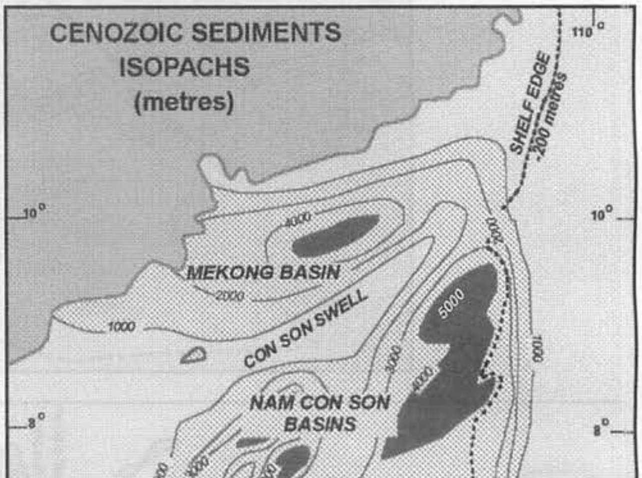

Figure 9. Note the *en echelon* orientations of the Nam Conson basins with respect to the linear shelf edge which is interpreted as the Vietnam Shear with dextral slip.

the motion was probably partially absorbed by subduction along the Marianas and Philippine trenches, and was partially buffered by north-south opening of the South China Sea Basin. However, in early Middle Miocene (magnetic anomaly 5b) the spreading of this basin stopped and most of the Borneo Subduction Trench became inactive. Most probably, the termination of this spreading allowed the westward push of the Pacific Plate to exert its influence upon the western Southeast Asian region by changing its stress fields. The stress-field changes are most distinctive for the southern part of the region. There, the influence of the east by north directed approach of the Indian Ocean-Australian Plate had also become significant by its proximity. At that time this plate seemed to have prevented, or at least hampered, further south-to-southeastward expulsion of crustal slabs of Southeast Asia. The combined effects of the westward moving Pacific Plate and the approaching Indian Ocean-Australia Plate resulted in reversals of slip sense along major strike-slip faults in addition to creating widespread middle Miocene unconformities in the Tertiary stratigraphy of the region. The Red River fault had become right-lateral and at its junction with the Vietnam Shear a large pull-apart depression, the Yinggehai Basin, came into existence (Fig. 10). It is not known if the Mae Ping fault reversed its slip sense, but the Axial Malay faults changed slip sense and had become right-lateral (Fig. 2). This slip sense caused structural inversion in the Malay Basin (Tjia, 1993a): The upper parts of half-graben fills became uparched into east-west striking anticlines and in places basin sediments also popped out of the depressions (Fig. 3). In the southern part of the Malay Basin, the dextral slip sense along the Axial Malay faults produced E-W thrust-faults verging south. The Western Hingeline Fault seemed to have continued wrenching left-laterally and produced anticlines positioned as drag folds consistent with sinistral sense of fault motion. The Dungun Fault, subparallel to the Western Hingeline Fault reversed its slip sense and became left-lateral (Fig. 11). The Rumbia Fault, which may be the southern extension of the Dungun Fault in the Penyu Basin, probably caused clockwise rotation of existing east-west halfgrabens in the eastern half of the basin. Inverted structures in the northwestern Malay Basin indicate that there its north-trending faults also reversed their slip sense into left-lateral (Fig. 12). In the Central Sumatra Basin, that was the southern segment of the Bentong Suture remained active and displayed right-lateral slip sense during this period (see Villaroel, 1985; Tjia, 1989). Onshore the Malay Peninsula, the suture remained inactive; its status elsewhere on the Southeast Asian continent and in the Gulf of Thailand is not known. On Figure 10 two other major, dextral slip faults are shown: Fault 98 and Arun Fault in the North Sumatra Basin (Gondwana, 1981) are now interpreted to continue northward and across the Thai-Malay Peninsula as the Ranong and Khlong Marui faults (Geological Survey Division, 1983), respectively.

Curray *et al.* (1979) concluded that the Andaman Basin began to open before 10.8 Ma (early Late Miocene). The right-lateral Sumatra Fault (Katili and Hehuwat, 1967) and right-lateral Sagaing (also known as the Shan) Fault in Myanmar are thus transform faults. Dextral slip along the Sumatra Fault is also compatible with the direction of the Indian Ocean-Australia Plate movement. The spreading direction of the Andaman Centre explains left-lateral slip along the east-of-north striking Peusangan Fault (Tjia, 1974).

In the West Natuna Basin the reoriented stress field developed the Udang Anticline and thrusting along N60°E faults (Daines, 1985; Fig. 13); further also right-lateral and left-lateral slips along WNW-ESE and N-S faults.

During this period, newly active fractures include the Banggi left-lateral fault offshore northern Sabah (see Fitch, 1961), the Tinjar Fault (or also known as the West Baram Line; Bol and van Hoorn, 1980) that onshore Sarawak forms a distinct NW-trending tectonic boundary and that offshore separates hydrocarbon provinces. Up to 45 km long dextral separations along N-S faults in the Malay Basin may represent results of strike-slip faulting during this period (Tjia, 1993a). North-trending linear borders of basement highs in the Nam Conson basins may be faults, and the planimetric pattern of these lineaments and the NE-trending basins suggest dextral slips along the lineaments (Fig. 9).

POST MIOCENE

In all three basins, post-Miocene sediments are essentially horizontal although some faults are inherited from the underlying already-deformed sequences. In the Malay Basin, north-south faults on the anticlinal crests have been attributed to tensional stress in post-Miocene time.

CONCLUSIONS

Granite ages (73 Ma to 86.5 Ma) on Natuna, Anambas and Tambelan islands; above normal geothermal gradients in the Malay basin (average 51.4°C/km) and West Natuna (average 39.7°C/km) basin; and their physiographic pattern inclusive a triple junction suggest that these basins originated

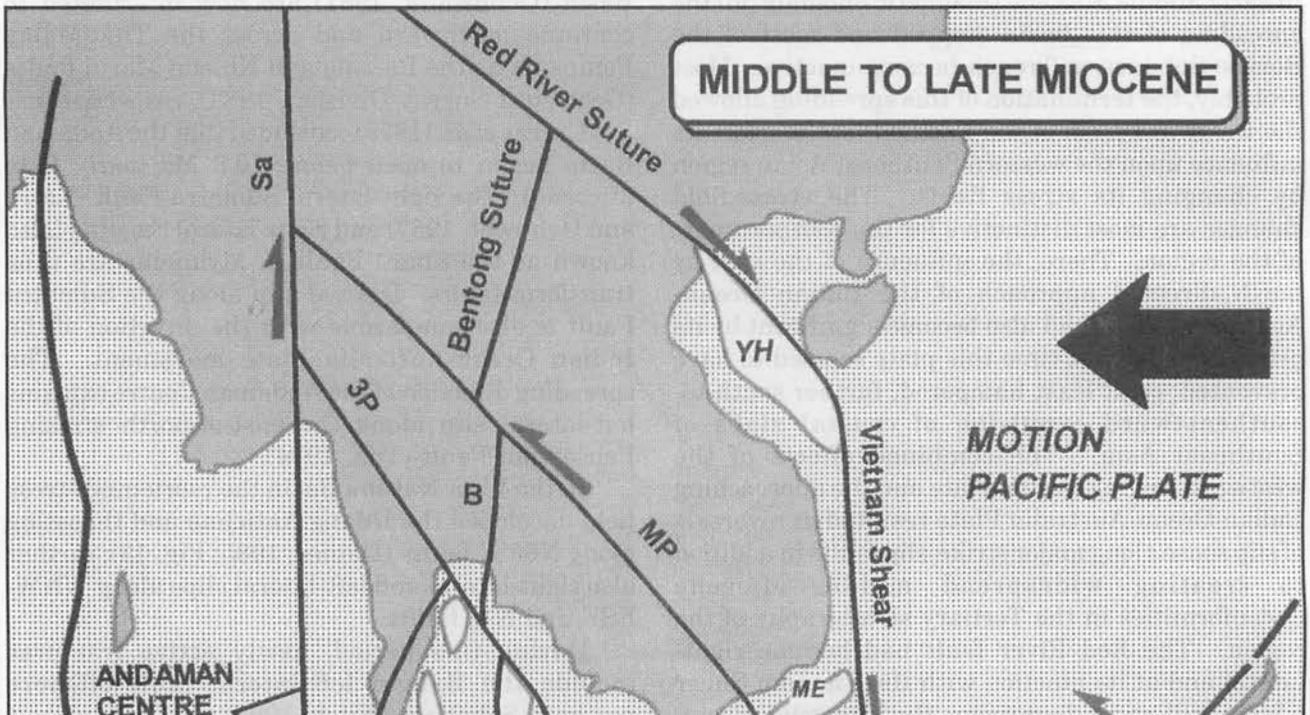

Figure 10. Middle to Late Miocene: Spreading of the South China Basin is terminated allowing the westward push of the Pacific Plate to affect tectonic processes in Southeast Asia. Reversals of slip sense causes inverted structures in the Malay-Penyu-West Natuna basins and opened the Yinggehai (Y) Basin as a pull-apart depression. By 10.8 Ma the Andaman Basin is spreading causing dextral slips along the Sagaing (Sa) and Sumatra (Su) transform faults. The Dulang (Du) fault is representative of important dextral slip faulting in the Malay Basin, but the timing of wrench activity is uncertain. Other abbreviations: C = Con Son, Pe = Peusangan, Ar = Arun, Bg = Banggi faults.

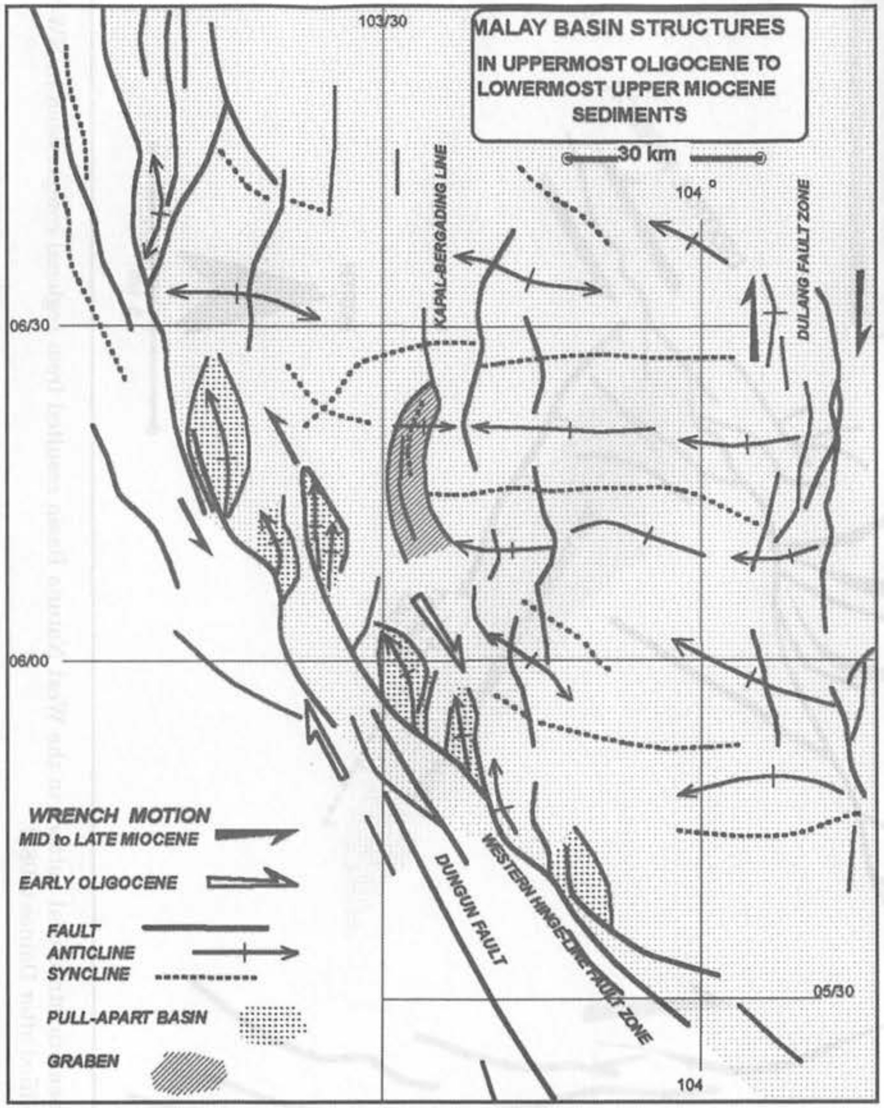

Figure 11. Structures on the west flank of the Malay Basin. A through G are pull-apart depressions developed along the (Western) Hingeline fault zone when it slipped right-laterally. Anticlines within those pull-aparts are orientated by subsequent, left-lateral slip along the same fault zone.

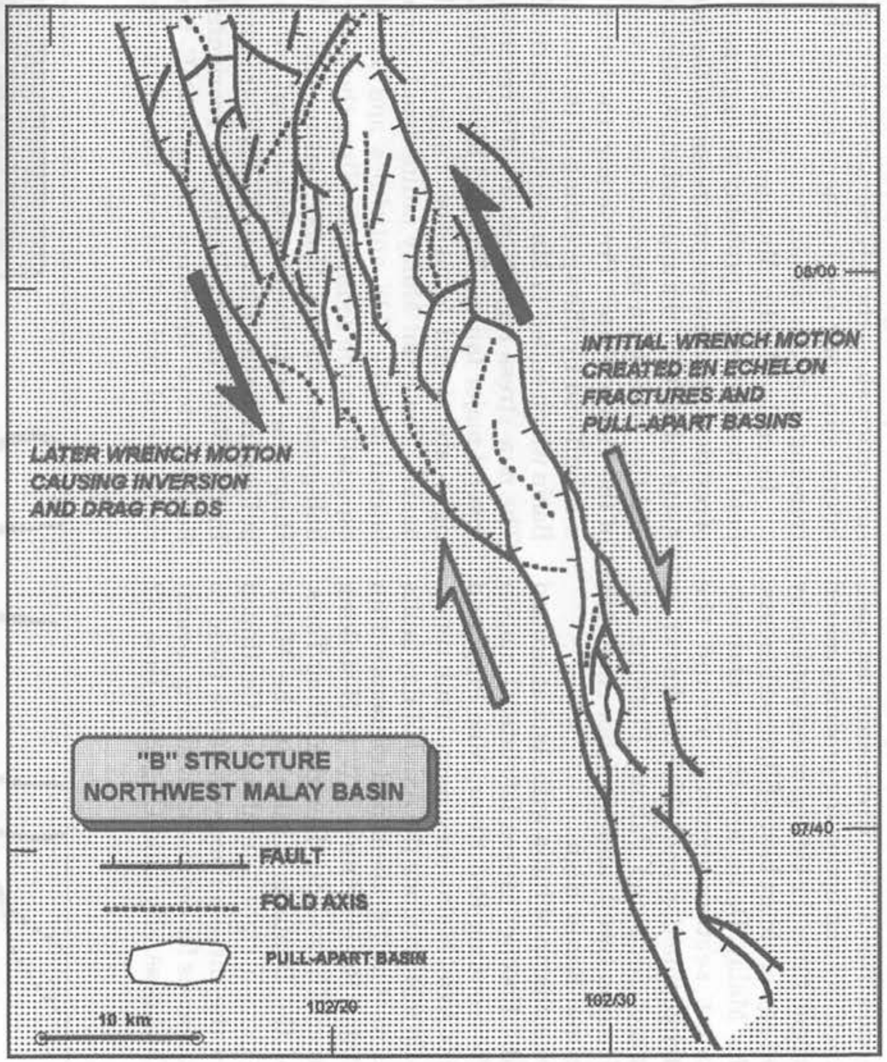

Figure 12. Structures in the northwestern Malay basin are products of earlier dextral followed by sinistral strike-slip movements along the NNW fault zone.

as aulacogens developed in the Malay Dome (new name) positioned over a Late Cretaceous hot spot. The hot spot activity and updoming probably ceased by Middle Eocene time; the timing being implied by the estimated age of oldest basin-filling sediments. Relicts of the Malay Dome are three, relatively high basement sectors centred around the interpreted triple junction and which are known as the (1) Tengggol Arch and Pahang Platform, (2) Khorat or Con Son Swell, and (3) Johor-Anambas islands-Paus and Ranai High.

The hard collision of India with Asia at around 45 Ma (Middle Eocene) causes left-lateral motion along the NW-trending Red River, Mae Ping, and Three Pagodas-Axial Malay (new name) fault zones. This strike-slip motion along the Axial Malay faults develops east-west half-grabens and grabens within the larger Malay Basin. Other NW to N-striking faults (Western Hinge-line, Dungun, Ping-Teris, and parts of the Bentong Suture) in the Malay Dome region move in right-lateral sense. Continued subsidence of the three aulacogens cause these to serve as depocentres for sediments reaching several kilometres thickness. By Late Oligocene time (32 Ma) the spreading of the South China Basin causes subduction along the NW Borneo Trench, and right-lateral slip along the southern part of the north-trending Vietnam Shear.

In early Middle Miocene the regional stress field changed, most probably as aggregate results of restricted southward progression of the Southeast Asian subplate by the approaching Australian Plate, and the, since then unrestrained westward motion of the Pacific Plate. Previously, the latter motion was buffered by the spreading of the South China Basin which ended 17 Ma ago or late Early Miocene. The new stress regime causes slip reversals along several major faults. The Red River fault becomes right-lateral and forms the Yinggehai pull-apart basin. The Axial Malay faults also become right-lateral forming E-W anticlines and thrust faults especially in the sediments filling the grabens and half-grabens of the Malay Basin. The Western Hinge-line fault becomes left-lateral, compressing pull-apart basin-fills into N-NNW trending folds. In the West Natuna Basin, the reoriented stress field develops thrusting along N60oE fractures, right-lateral and left-lateral motion along WNW

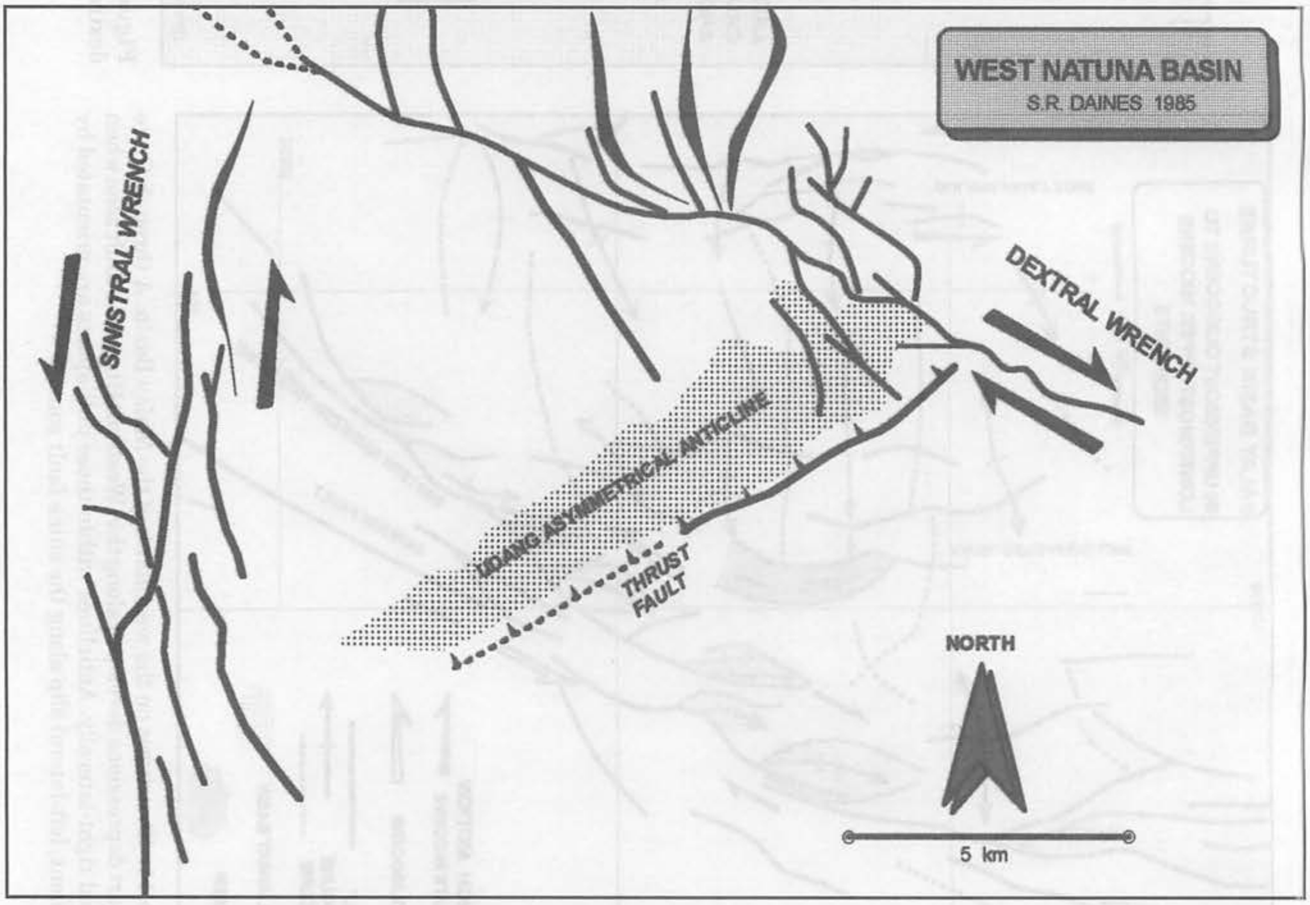

Figure 13. Kinematic structural pattern in the West Natuna Basin resulted from regional compression in NW-SE direction. Simplified after Daines (1985).

and N-trending faults, respectively. Inactive have become the NW-Borneo subduction (spreading of the South China Basin stopped), and the Bentong Suture segment in the Peninsula. New activity takes place as left-lateral slips along the NW-N striking Banggi and Con Son faults. In the NW corner of the region, the Andaman Basin begins to spread (early Late Miocene, before 10.8 Ma) causing right-slips along the Sagaing (in Myanmar) and Sumatra transform faults. Tectonic mobility in the Malay Dome basins ends before Pliocene. Henceforth, epeirogenetic crustal movements have developed cross faults with essentially downdip motion on anticlinal crests.

The Malay, Penyu and West Natuna basins are thus characterised by an origin as aulacogens in continental lithosphere and that subsequently experienced structural modifications through transtensional (Middle Eocene-Early Oligocene) followed by transpressional (early Middle Miocene to Late Miocene) stress regimes. These stress regimes were associated with large-scale wrench faulting responding to the (a) Indian Subplate collision with Asia, (b) westward drive of the Pacific Plate, (c) spreading of the South China Sea Basin, (d) its termination in late Early Miocene, (e) approaching northward progression of the Indian Ocean-Australia Plate, and (f) since early Late Miocene, for at least the northwestern part of the Southeast Asian region, with the opening of the Andaman Basin.

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