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Meridian-parallel faults and Tertiary basins of Sundaland

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Abstract: The pre-Tertiary core of Sundaland contains numerous North-South striking regional faults in addition to, but fewer major faults in Northwest and other directions (Fig. 1). One N-S regional fault extends from the Thailand-China border via the Gulf of Thailand and Peninsular Malaysia into Central Sumatra is the longest at ~2,000 km (abbreviated as TBB for Thai-Bentong-Bengkalis). Two other long faults are the Vietnam Shear off the east coast of Indochina and another N-S fault in the gulf parallel to TBB. The other regional faults range in length between 200 km and 700 km. In the Malay Peninsula, the TBB coincides with the Raub-Bentong suture that existed since the Middle Triassic. Faults within the suture shows overprinting of normal faulting (down to east), upon dextral slip that in turn post-dated sinistral slip. N-S faults in the peninsula are considered the oldest set and date from the Jurassic or earlier. The TBB segment in Sumatra is the Bengkalis trough on which dextral slip had continued to affect Miocene strata. Similarly, N-S regional faults in the Tertiary basins of North Sumatra, Central Sumatra, South Sumatra, Sunda basin complex, Arjuna basin, Central Thailand basin complex, Mekong, Nam Con Son, Malay and Penyu basins deformed strata as young as early Late Miocene. These regional faults show mainly dextral slip except the Peusangan (North Sumatra) and the northerly trending faults in Terengganu (Peninsular Malaysia). Left-lateral slip implies that the Terengganu faults are lag structures in the general extrusion of SE Asian crustal slabs towards SE and S. The sinistral slip on the Peusangan fault is attributed to spreading of the Andaman Sea basin since about 11 Ma ago. The geological history suggests that by the Middle Triassic, Sundaland had combined into a single microplate. Some of the meridian-parallel faults, such as the TBB probably have existed since that time. Other N-S faults may be younger, but perhaps most developed in the Mesozoic and a number of these structures became reactivated in the Cenozoic. It seems probable that lateral slip directions were different at different times, but that the latest tectonic displacement sense had been dextral. The origin of most of the N-S regional faults is problematic. The Vietnam Shear may be attributed to the opening of the South China Sea basin from Oligocene to about mid-Miocene. The TBB is a mid-Triassic suture between continental blocks. Those N-S faults traversing Cenozoic sediments are probably reactivated pre-Tertiary structures. The widespread distribution of these faults in Sundaland may mean that the entire region participated as a single unit in large-scale translations or rotations that have been suggested by paleomagnetic studies. Or, was Earth's rotation responsible for the formation of regional N-S faults in Sundaland?

The regional meridian-parallel faults of Sundaland have functioned as (1) originators/initiators of Tertiary basins such as the Mekong and Nam Con Son, as (2) determinants of basin location (Central Thailand and the Gulf of Thailand; sub-basins: Balam-Pematang troughs, Bengkalis trough, Benakat gully, Asri, Seribu, Arjuna, and relatively small basement depressions in the Malacca Strait), and as (3) modifiers of basin geometry (Peusangan fault in the North Sumatra basin; the large dextral offsets of fold series in the Malay basin). N-S faults across fold crests of the Malay basin are non-tectonic and formed by tightening of the folds in a persistent compressive stress regime.

INTRODUCTION

In geographical terms, Sundaland comprises the Sunda Shelf, Strait of Malacca and adjacent larger Sunda islands (Sumatra, Java, Borneo) and Peninsular Malaysia (Fairbridge, 1966). Geologically, Sundaland corresponds with approximately the same region that became tectonically stabilised at the transition of the Mesozoic and Cenozoic. Northward, geological Sundaland grades into Indosinia (Fig. 1). Many of the major faults within the core region strike north-south. Regional faults of other directions, notably those striking NW to NNW do exist, but are fewer in numbers. Several of these N-S faults are closely associated with north-south elongated Tertiary basins, such as faults (3) and (4) in the Gulf of Thailand and in central Thailand (Fig. 2). The Vietnam Shear (fault 8) separates continental crust in the west from oceanic and attenuated continental crust of the South China Sea basin to its east. The regional faults striking northwest are A in Sumatra,

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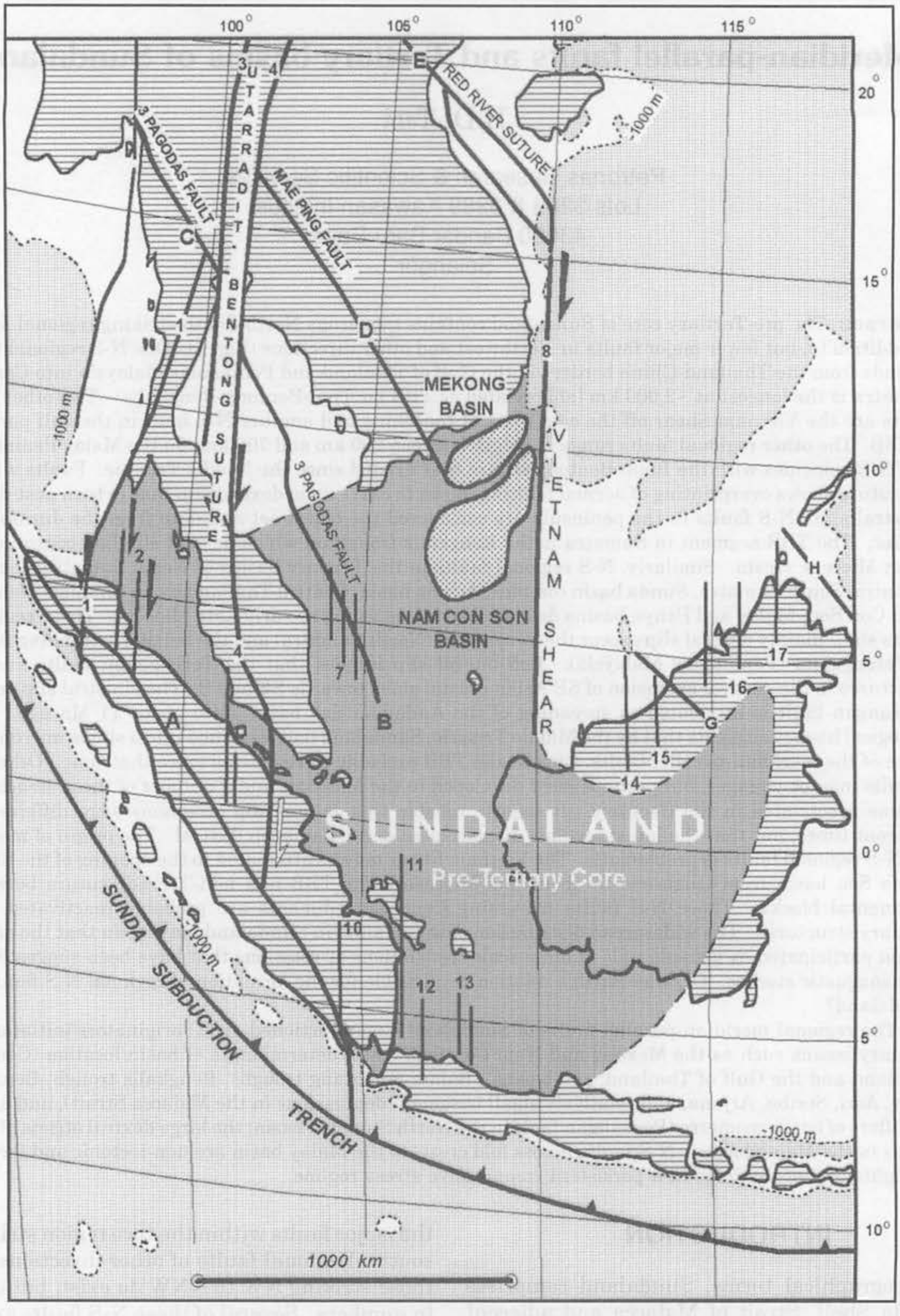

Figure 1. Major North-South and some regional faults of SE Asia. Notice that of faults in other directions, only those of regional extent are shown. Compiled from various sources listed in the References. 1. Peusangan-Ranong-Klong Marui; 2. Arun-98 Fault-Tanjung Pura-Tanjung Morawa; 3. Central Thailand and Gulf of Thailand north-south basins associated with N-S faults; 4. Bentong- Bengkalis line; 5. East Tectonic zone in Peninsular Malaysia; 6. Terengganu group of N-S faults; 7. N-S faults in Malay basin; 8. Vietnam Shear; 9. Kerumutan Line; 10. Lematang trough; 11. Bangka fault; 12. Sunda fault; 13. Arjuna fault; 14. Balingian fault; 15. Tubau fault; 16. Pangi fault; 17. Kadamaian fault; A. Sumatra fault zone; B. Axial Malay fault zone; C. Three Pagodas fault zone; D. Mae Ping (Wang Chao) fault zone; E. Red River fault zone and Yinggehai basin; G West Baram-Tinjar Line; H Balabac fault.

B-C in Myanmar-Indochina, D and E in Indochina. Two important but shorter NW faults are the West Baram-Tinjar Line (G) and the Balabac fault (H), both located outside Sundaland proper. Only one regional fault set striking north-northeast is known: the Ranong-Marui fault (1) along the Thai segment of the peninsula. Elsewhere in the region are only known shorter NE-faults, such as in the South Sumatra basin (see Fig. 7).

Figure 1 demonstrates the remarkable presence of meridian-parallel faults in Sundaland. It is noteworthy that the neighbouring East Indian Ocean plate has extremely long north-south structures: transform faults several thousand kilometres long. Also striking N-S is the prominent Ninety East Ridge. This is an aseismic ridge and is considered to record the northward progression of the East Indian Ocean plate past a hot spot, now extinct and located at the south end of the long ridge. It is beyond the scope of this paper to speculate about a possible relationship between the N-S structures in the adjacent oceanic plate with those occurring in the Southeast Asian continental plate. The linearity and regional extent of the north-south faults in Sundaland suggest these structures to have been associated with significant strike-slip movements. Most that have been studied show right-lateral displacements, while left-lateral offsets are rare. Some of the regional N-S faults were active up into the Late Miocene; others are known to have been in place since the advent of the Mesozoic. Is the parallelism of old and younger north-south faults just a fortuitous coincidence, or do the younger faults follow existing zones of weakness? In recent years Cretaceous and younger paleomagnetic records have been interpreted to

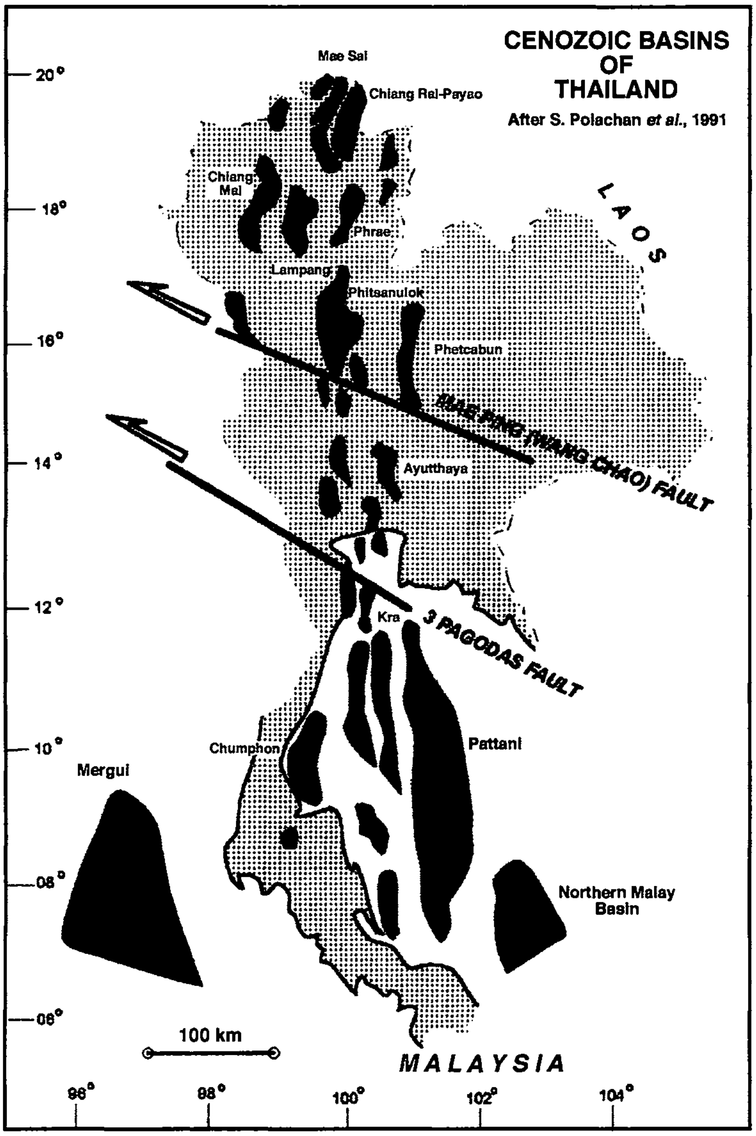

Figure 2. North-South belt of Tertiary basins in Thailand after Polachan *et al.* (1991).

indicate separate movement histories of certain parts of Sundaland. However, the consistent meridian-parallel fault strikes distributed over such a wide region further indicate that at least during the Tertiary, Sundaland has been a single tectonic block. Any translational or rotational displacement should have left generally similar magnetic records within Sundaland. In this article will be discussed the geometry and origin(s) of regional north-south faults and their relationship to Southeast Asian Tertiary basins. The discussion will be based on published and on some unpublished information from a number of well-explored areas.

NORTH SUMATRA BASIN

The North Sumatra basin is filled by more than 10 km of Tertiary sediments. About 40 per cent of the basinal area is onshore and the remainder underlies the shelf to the east (Fig. 3). Tectonic elements comprising pre-Tertiary basement highs, basin outlines and troughs at basement level, show strong N-S alignments (Fig. 4), while the general Tertiary, structural grain of Sumatra is NW-SE. From a study of regional time structure maps, surface geology maps, and seismic cross sections, four major strike-slip faults trending between 5 degrees west of north and north were identified (Fig. 3; Gondwana, 1981; Situmorang and Barlian Yulianto, 1985). Drag folds, distinct offsets, some exhibited at basement level, and in strata as young as Late Miocene indicate dextral slips on these faults. The gas-bearing Arun Reef strikes oblique to the Arun fault, an orientation consistent for the structure to have experienced dextral drag along the fault. The Arun fault is traceable over 150 km distance. The 98 Fault (named after its alignment along this meridian) is more than 210 km long and forms an up to 15 km wide zone striking west by north. The pre-Middle Miocene beds (Baong Formation) are dextrally offset some 50 km, while throw at not more than 600 m is comparatively insignificant. The fault zone is also marked by a N-S band of relatively low geothermic gradient sandwiched between areas of high heat flow. The Tanjung Pura fault is more than 10 km wide and strikes 350°–355°. Right-lateral slip is indicated by drag folds at the surface and by a drastic change

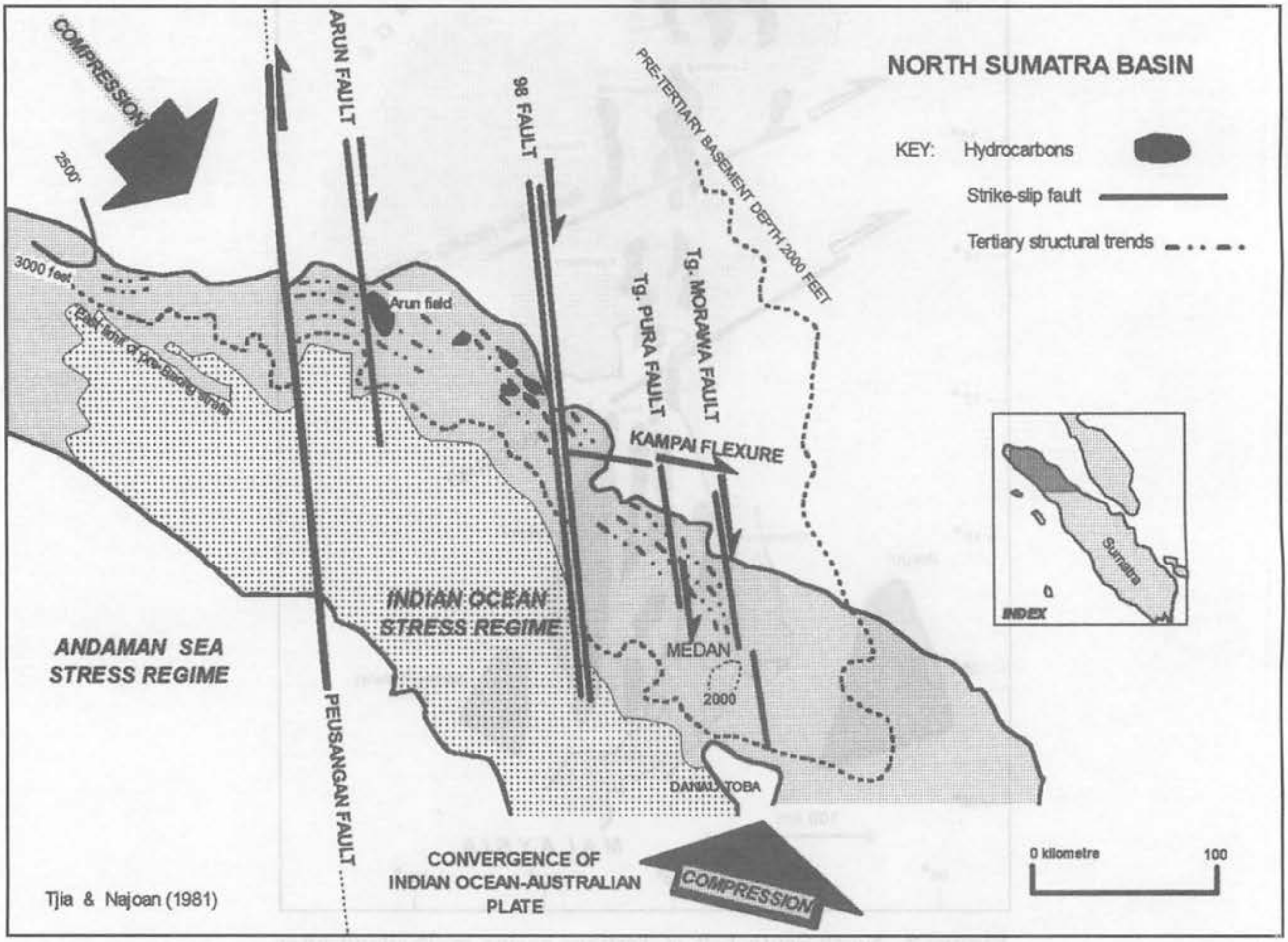

Figure 3. North-south faults in the North Sumatra basin, Indonesia (Gondwana, 1981).

of isopach patterns, especially in the Middle Baong sands. The 8-km wide Tanjung Morawa fault zone strikes 350°–360°. All these northerly trending fault zones are distinct from the Middle Miocene Baong Formation to deeper levels. Above this formation, the wrench faults manifest by wide zones of ductile deformation.

Alignments of volcanic centres (including the active Bur ni Telong and the Bur ni Geureudong), linear formation boundaries, bathymetric lineaments in the Indian Ocean off North Sumatra, and the distinct change in Tertiary structural trend from the general NW-SE to a WNW-ESE strike have been interpreted as representing a major west-by-north fault, the Peusangan fault (Tjia, 1977). The fault follows the long, linear middle course of the Peusangan river. Lateral displacements shown by some of the above features amount to at least 9 km in left-lateral sense. The Peusangan fault is parallel to the four major faults of Northern Sumatra mentioned earlier but shows wrench motion in the opposite sense. The different motion senses have been attributed to a difference in stress regime. Northern-most Sumatra to the west of the Peusangan fault has probably been subjected to stresses resulting from spreading of the Andaman basin. Curray *et al.* (1978) put the onset of spreading at 10.8 Ma. The dextral slips on the Arun, 98, Tanjung Pura and Tanjung Morawa faults resulted from the convergence direction of the Indian Ocean-Australian plate with this segment of Southeast Asia (Fig. 3).

CENTRAL AND SOUTH SUMATRA BASINS

Four major N-S troughs are known from the Central Sumatra basin. Two of these, the Balam

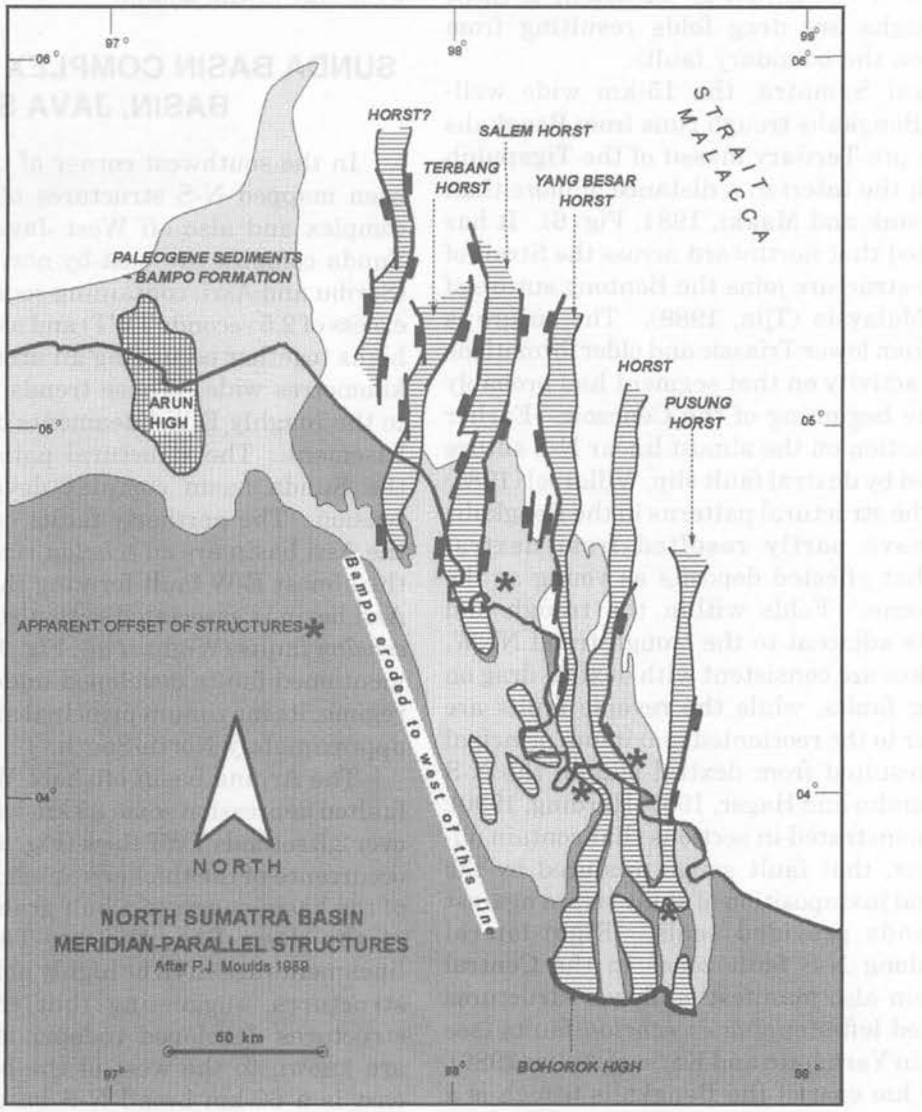

Figure 4. North-south basin and horst pattern in the North Sumatra basin. After Moulds (1989).

and Pematang troughs, occur between 100°40'E and 101°00'E longitudes (Fig. 5). Northerly striking folds are present in the Pematang trough. Parallel to the shoreline is a wide zone of reverse faults verging SW. Northward across this zone into the Strait of Malacca, the N-S trend is continued by a basement high known as the Aruah-islands nose. The trend persists into Malaysian waters as a wide zone containing the Angsa, Port Kelang and Sabak grabens. The Port Kelang graben possesses strong N-S structural elements and borders. The combined length of these N-S structures across the strait is about 200 km. North-south control by the Balam and Pematang troughs does not extend into beds younger than the lower Miocene strata. Middle Miocene and younger deposits have acquired the NW-SE, so called Sumatra trend. Some hydrocarbon fields contained in structural highs near the edges of the two troughs (such as Benar, Duri, Duri Baratlaut) are elongated NNW-SSE. The direction of elongation is consistent if these structural highs are drag folds resulting from dextral slip on the boundary faults.

In Central Sumatra, the 15-km wide well-defined N-S Bengkalis trough runs from Bengkalis island to the pre-Tertiary massif of the Tigapuluh Mountains in the interior; a distance of more than 200 km (Eubank and Makki, 1981; Fig. 6). It has been suggested that northward across the Strait of Malacca, the structure joins the Bentong suture of Peninsular Malaysia (Tjia, 1989). The suture is only known from lower Triassic and older formations and tectonic activity on that segment had probably ceased by the beginning of the Cenozoic. Earlier left-lateral motion on the almost linear N-S suture was succeeded by dextral fault slip. Villaroel (1985) interpreted the structural patterns in the Bengkalis trough to have partly resulted from dextral wrenching that affected deposits as young as the Middle Miocene. Folds within the trough and reverse faults adjacent to the trough trend NNW. The fold strikes are consistent with dextral drag on the bounding faults, while the reverse faults are perpendicular to the reoriented maximum principal stress that resulted from dextral slip on the N-S faults (see Handin and Hager, 1957; Harding, 1990). Villaroel demonstrated in sections that contain oil-water-contacts, that fault gouge produced by the wrenching and juxtaposition of shaly strata against reservoir sands provided seals. Right-lateral wrenching along N-S fault zones in the Central Sumatra basin also manifest as flower structures and associated left-stepping *en echelon* faults (see illustrations in Yarmanto and Karsani Aulia (1989).

Some 70 km east of the Bengkalis trough is a 50-km broad area marked by the occurrence of N-S faults. Provisionally, this belt of N-S faults may be called the Tebingtinggi zone after one of the large islands traversed by the zone. Both Tebingtinggi and Bengkalis North-South zones form clear interruptions of the NW structural grain of Sumatra.

The South Sumatra basin is separated from the Central Sumatra basin by a broad area that is marked by one major and several other NE-striking faults, known as the Jambi depression (Fig. 7). This direction is perpendicular to the NW-SE "Sumatra" trend expressed as basement lineaments. In addition, a distinct, 25-km wide N-S structural element occurs as the Benakat gully (Fault 10 on Fig. 1; see also Pulunggono, 1983). The gully is bounded by *en echelon* NNE-striking normal faults; the overall structural pattern suggesting right-lateral component of displacement on the bounding faults. The Benakat gully can be traced over a distance of about 150 km between the eastern shoreline of Sumatra and the Bukit Barisan on the west side of the island.

SUNDA BASIN COMPLEX AND ARJUNA BASIN, JAVA SEA

In the southwest corner of the Java Sea have been mapped N-S structures of the Sunda basin complex and also off West Java (Fig. 8). In the Sunda complex are east-by-north trending basins (Seribu and Asri; containing sediment thickness in excess of 2.5 seconds TWT) and associated basement highs together occupying an area about a hundred kilometres wide. These trends are perpendicular to the roughly E-W lineaments of the pre-Tertiary basement. The structural pattern suggests that the Sunda basin complex developed from E-W tension. The northerly faults on the west side of the Asri basin are *en echelon* right-stepping, while the almost E-W fault forming the south end of the Asri basin is associated with also right-stepping *en echelon* faults (Wight *et al.*, Fig. 17, 1997). If all the mentioned faults developed under the same stress regime, its maximum principal stress direction was approximately North-South.

The Arjuna basin offshore West Java is a N-S faulted depression some 35 km wide with sediments over 2.5 seconds TWT thick (Fig. 8). The preferential occurrence of the thicker sequences on the east side of the basin suggests a half-graben. In this region of the Java Sea, the pre-Tertiary basement lineaments are ENE or highly oblique to the Arjuna structures, suggesting that the two groups of structures developed independently. N-S faults are known to the west of the basin, while to the east is a 60-km broad N-S basement horst. The horst separates the Arjuna basin from the Belitung basin farther to the east. This is a half-graben

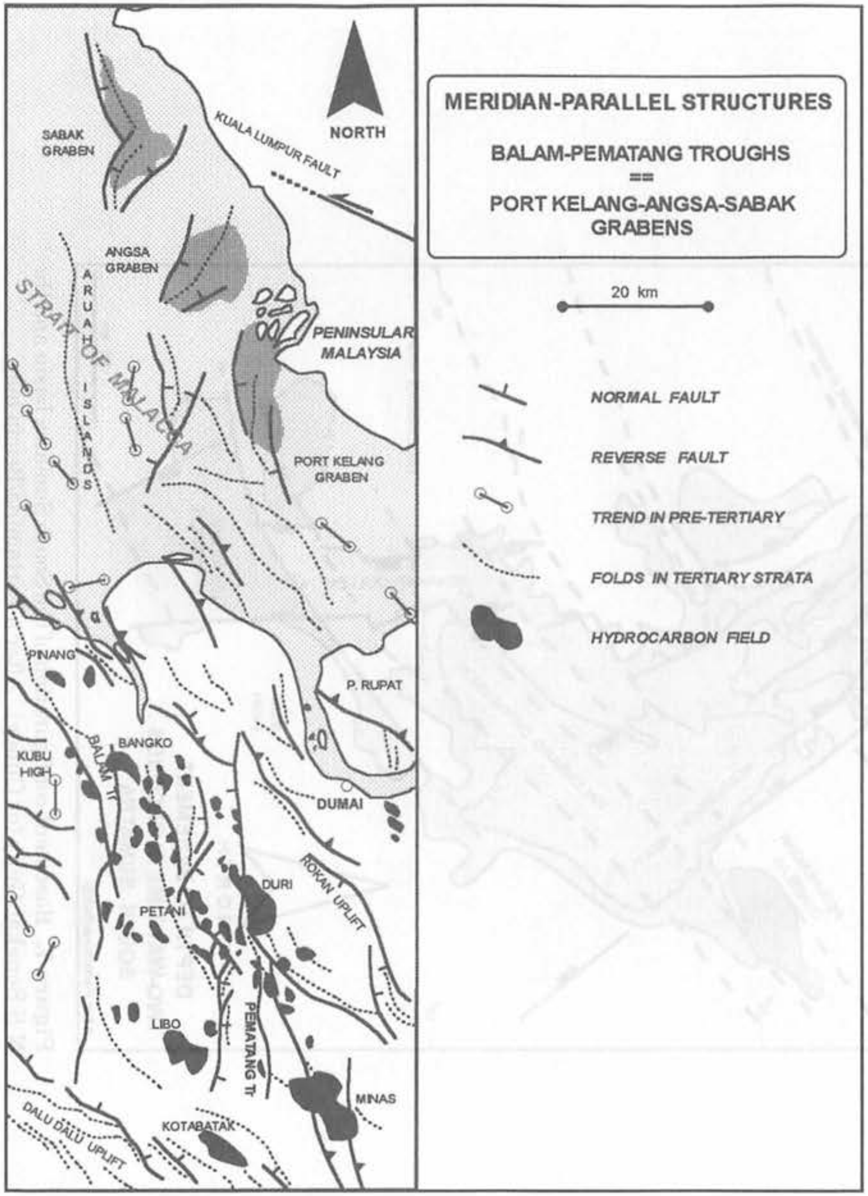

Figure 5. The Sumatran Balam-Pematang troughs and extensions in the Strait of Malacca. Source: Yarmanto and Karsani Aulia (1989) and various articles in the Proceedings of Indonesian Petroleum Association conventions.

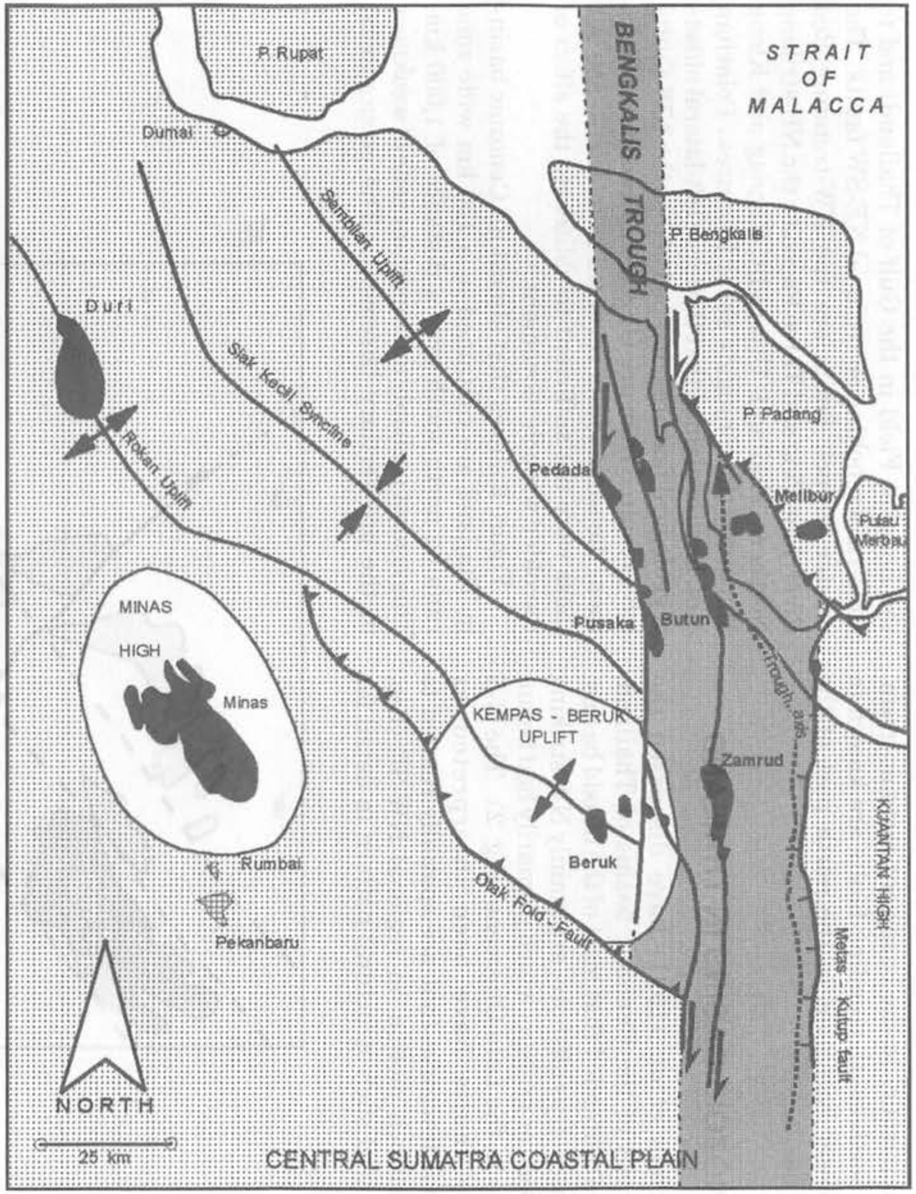

Figure 6. The Bengkalis Trough in the Central Sumatra Basin. After Heidrick and Karsani Aulia (1933).

elongated parallel to the basement tectonic grain. Roughly north-south trending faults are known in the shallower basement in the north part of the Belitung basin.

CENOZOIC BASINS IN THAILAND

Polachan *et al.* (1991) have discussed the development of the Cenozoic basins of Thailand. They have contended that most of the 60 odd basins, onshore as well as offshore, are mainly N-S striking half-grabens or grabens which primarily had begun to develop in the Late Oligocene (Fig. 2). The N-S bounding faults have been interpreted as extensional fractures that are spatially related to dextral wrench motion on regional NW-SE (Leo, 1997, showed such structural pattern in detail for the Bongkot Field in the Gulf of Thailand) and to sinistral wrenching on regional NE-SW faults. The master wrench faults are the NW-trending Red River, Mae Ping and Three Pagodas; the NE-striking Northern Thailand, Uttaradit, Ranong and Klong Marui are the conjugate shear fractures. Polachan *et al.* have explained that the large left-lateral offsets of geological features mapped across the NW-faults have resulted from pre-Oligocene wrenching. Since then, the same faults reversed in motion sense but these were not sufficient to obliterate the effect of the older wrench movement.

Figure 2 shows that almost all Cenozoic basins in Thailand are contained in a 150 km wide zone running north-south over a distance of 1,000 km. This is most probably an important zone of weakness in the pre-Tertiary basement. The geographical

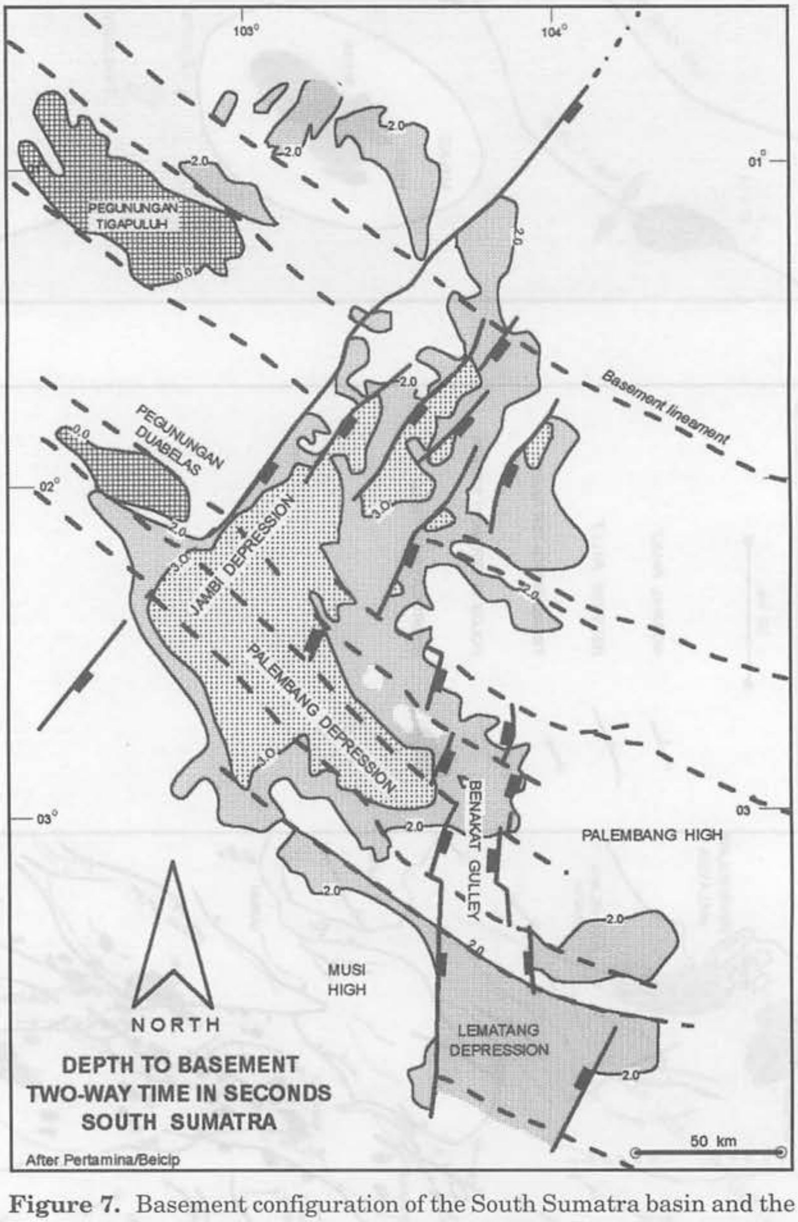

Figure 7. Basement configuration of the South Sumatra basin and the N-S Benakat Gully (or Gulley). After a Pertamina/Beicip map.

distribution of the basins appears left-laterally offset as much as 75 km along interpreted faults running subparallel to the Mae Ping and Three Pagodas faults.

From the available published information one may agree with Polachan's *et al.* kinematic model for the development of the N-S Cenozoic basins in Thailand. However, one may further conclude that those basins had preferentially formed within a N-S tectonic belt in the pre-Tertiary basement This tectonic belt extends from the Gulf of Thailand to the northern border in central Thailand.

MEKONG AND NAM CON SON BASINS, SOUTH CHINA SEA

The Mekong and Nam Con Son basins are epicontinental and are located offshore southern Vietnam (Fig. 9), containing over 7 km and over 10 km of Tertiary sediments and volcanics, respectively. The oldest sediments known from the Mekong basin are Oligocene; those in the Nam Con Son basins are upper Lower Miocene. The Mekong basin is almost 500 km long, 100 km wide and is elongated in N55°E direction (CCOP, 1991). Its pre-Tertiary basement has been faulted into many horsts and grabens elongated in NE or ENE directions. Overall these structures form groups of S-shaped patterns. A major normal fault cuts N-S across the west end of the basin. The basin is separated by a broad NE-striking basement high, the Con Son Swell, from the Nam Con Son basins to the south.

The Nam Con Son basins form a complex of depressions and highs dominated by N-S trends (Fig. 9 and CCOP-map, 1991). Three of the major N-S faults are indicated on Figure 9. These faults appear to coincide with those named by Matthews *et al.* (1997: Huong Dong Bac, Lan Tay and Eastern faults). Based on differences in dominant sub-basin elongation, three broad bands in N-S direction across the Nam Con Son basin complex can be distinguished. In the east is the longest band, 150 km wide, that contains sub-basins elongated N50°E and N-S. The middle band, a hundred kilometres wide, has sub-basins trending N30°E and N-S lineaments. The western-most band is characterised

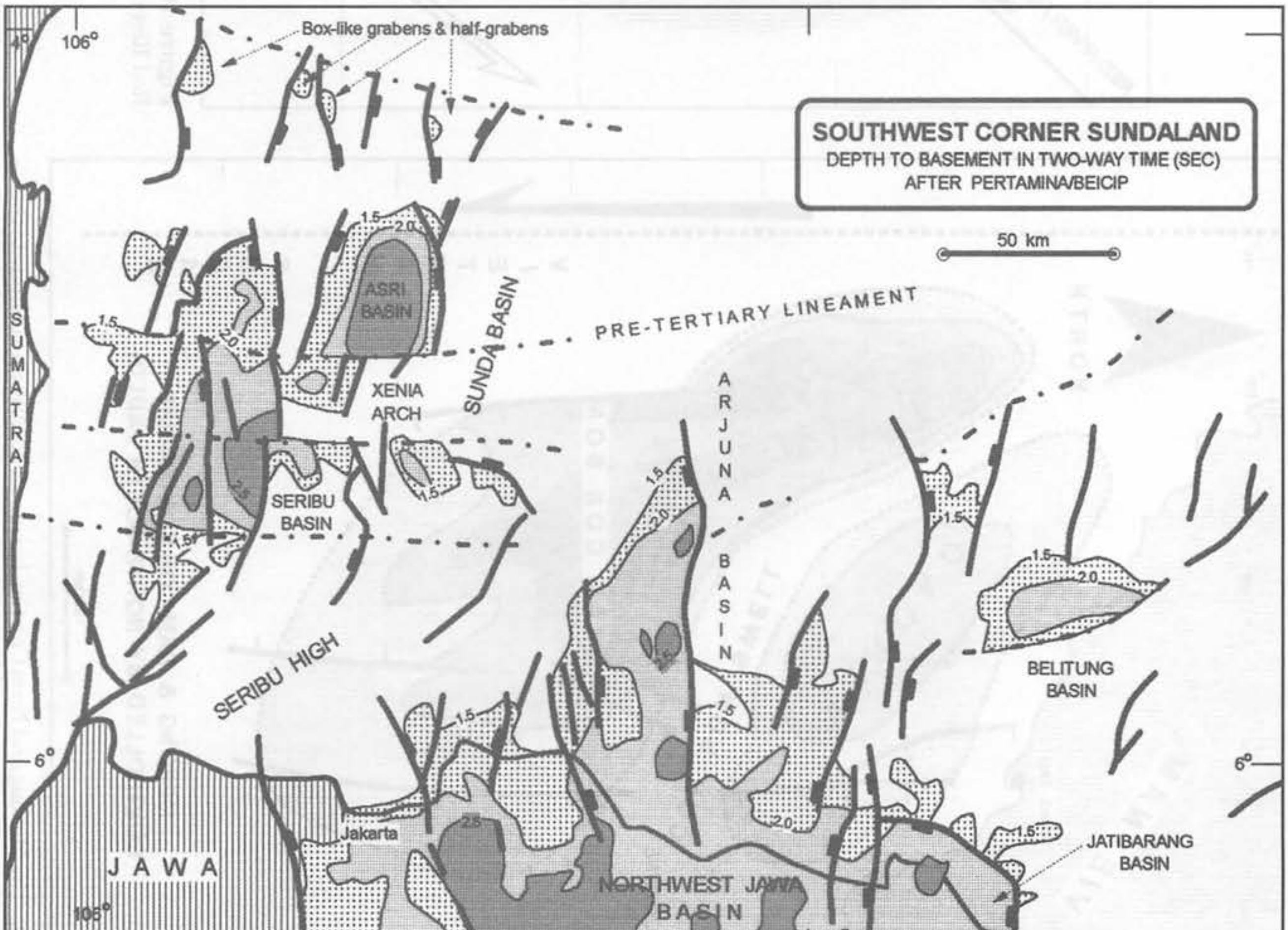

Figure 8. The Sunda basin complex and Northwest Java basin with north-trending structures. SW corner of the Java Sea, Indonesia. After Pertamina/Beicip map.

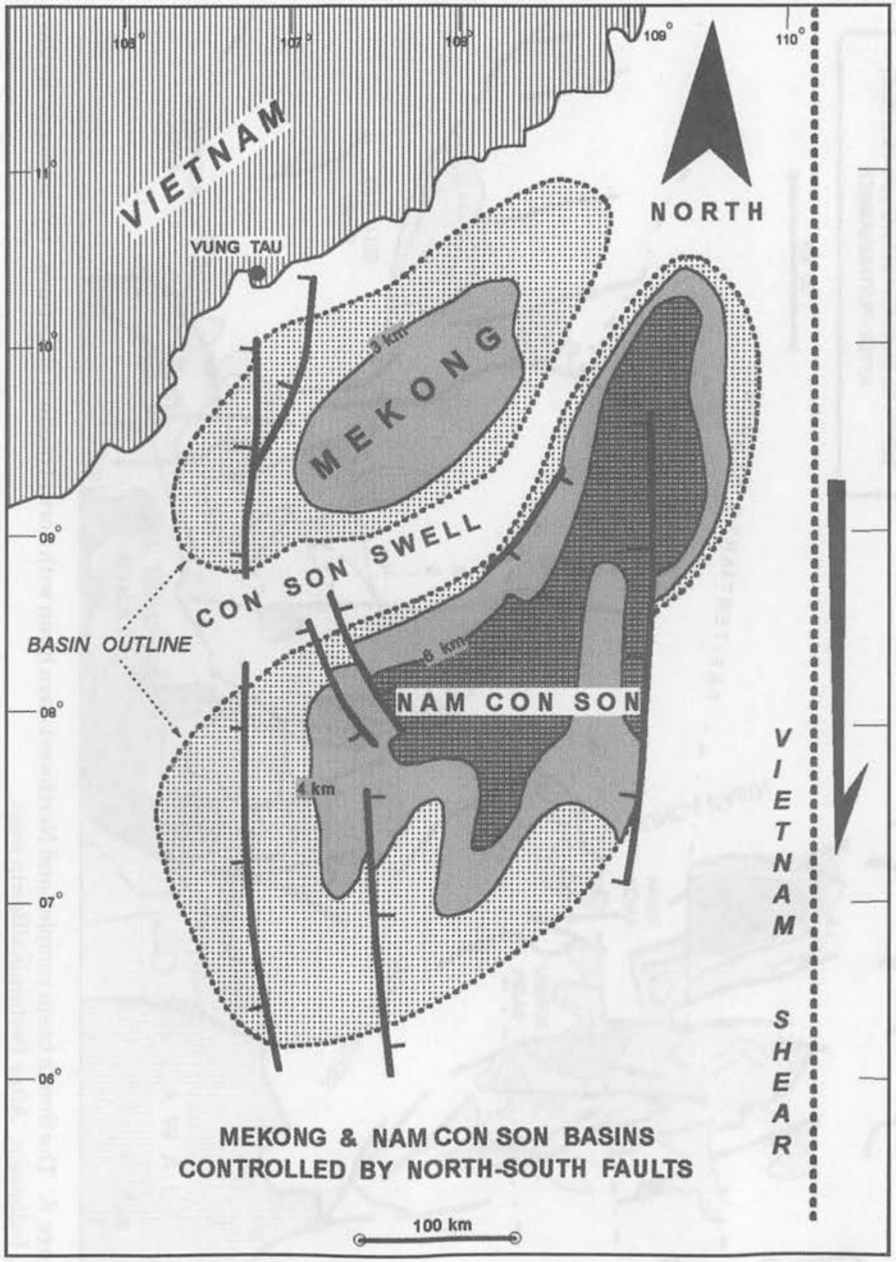

Figure 9. The Mekong and Nam Con Son basins strike NW and oblique to the N-S Vietnam Shear. Other regional N-S faults are within the basins. Modified after CCOP map (1991).

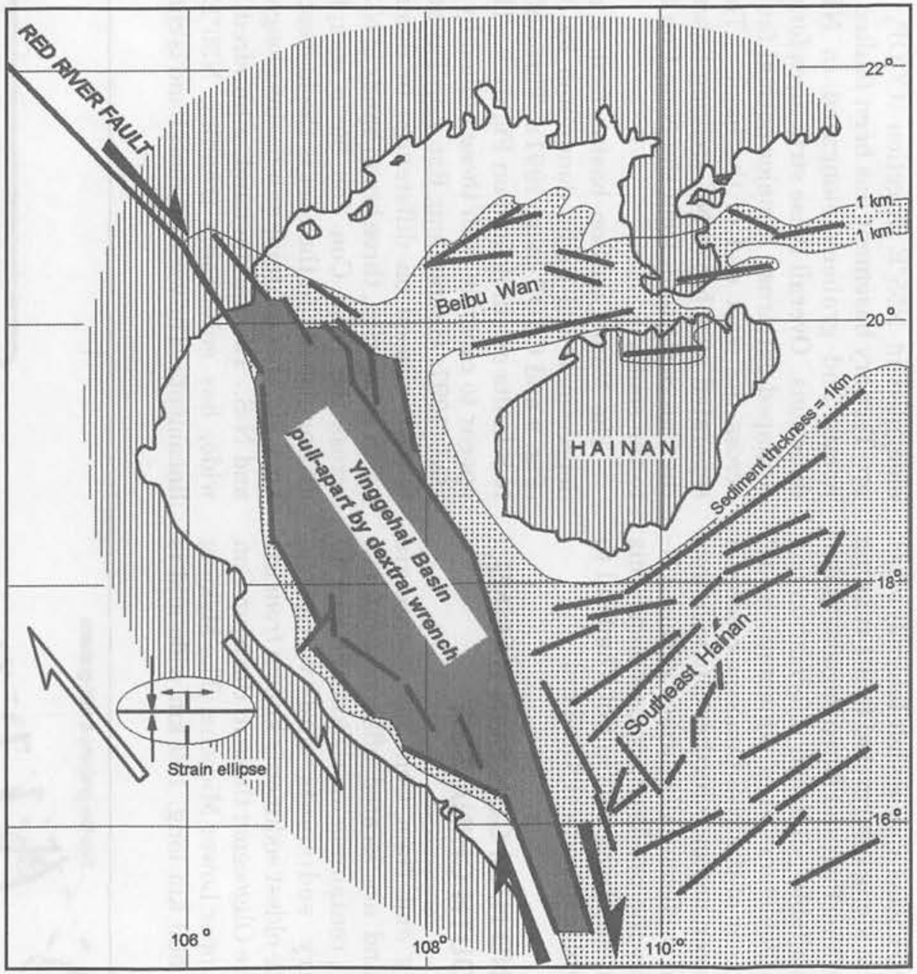

Figure 10. The NW-trending Yinggehai basin-plan suggests dextral slip on the Red River fault zone and the Vietnam Shear. Modified after CCOP map (1991).

by N-S sub-basins and highs distributed over a width of about 130 km.

Between the continental crust of Indochina and the Sunda Shelf in the west and the South China Sea basin in the east is a regional N-S lineament for which the name "Vietnam Shear" is proposed. This lineament is shown in Taylor and Hayes (1983) and extends from 17°N to 3°N latitude. At the north end, the Vietnam Shear joins the NW-trending Red River fault by way of the Yinggehai or Song Hong basin. Roques *et al.* (1997) shows the north end of the Vietnam Shear to be associated with left-stepping, *en echelon* extensional faults. The pattern of these three structures: basin, NW Red River fault, the associated *en echelon* faults, and N-S Vietnam Shear suggests that the Yinggehai basin is a pull-apart depression (Fig. 10). In that case, the Vietnam Shear and the Red River fault moved as dextral wrench faults. Roques *et al.* had also interpreted the fault pattern they described as a dextral wrench system (their Fig. 10, p. 351). Dextral slip on the Vietnam Shear could explain the NE-striking Mekong and Nam Con Son sub-basins to have developed as mega-tension gashes (Fig. 11). Earlier slip on the Red River fault was left-lateral (Tapponnier *et al.*, 1982, 1986).

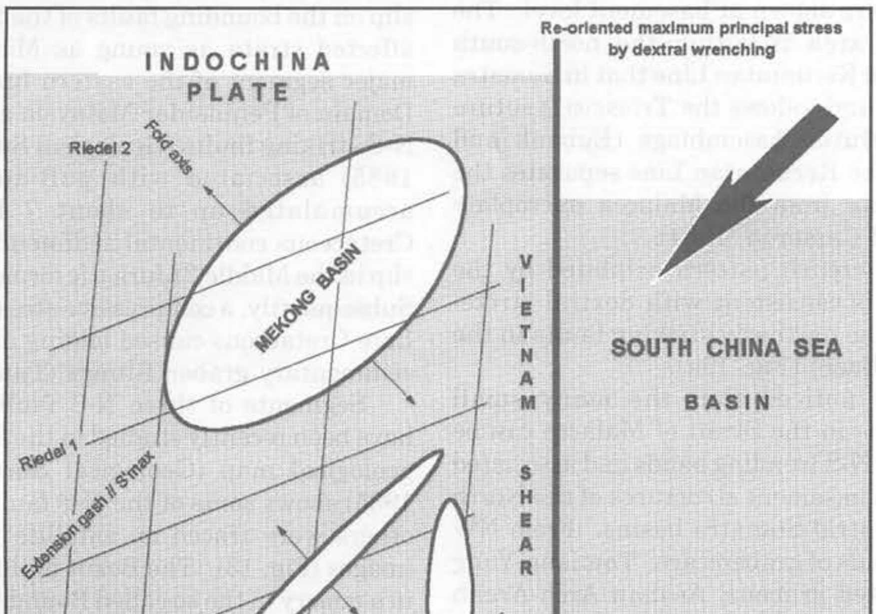

Figure 11. Model explaining the origin of the Mekong and Nam Con Son basins as mega-tension gashes resulting from dextral wrenching along the Vietnam Shear.

CENTRAL GRABEN, STRAIT MALACCA

In the pre-Tertiary basement of Strait Malacca, south of the Langkawi Islands were mapped several depressions. The larger depression is now known as the Central Graben, 20 km wide and 55 km long in N-S direction (Liew, 1995). The graben's axis roughly coincides with the 99°42'E meridian. The long axis strikes a few degrees east by north. The pre-Tertiary basement of the Central Graben contains numerous narrow sub-grabens and horsts trending NNE to NE which is oblique to the axis. The *en echelon* arrays of narrow grabens suggest dextral wrenching parallel to the strike of the Central Graben (Fig. 12a). On existing maps, no bounding faults are shown at basement level. The Central Graben area is within the north-south trending, so called Kerumutan Line that in Sumatra bends southeast and follows the Triassic(?) suture named as the Mutus Assemblage (Eubank and Makki, 1981). The Kerumutan Line separates the Mergui microplate from the Malacca microplate (Pulunggono and Cameron, 1984).

The dextral wrench pattern exhibited by the Central Graben is consistent with dextral strike-slip faulting on the northerly striking faults in the North Sumatra Basin (Fig. 12a).

Liew (1995) noticed that the many small basement grabens in the Strait of Malacca can be grouped into four N-S trending bands and associated these bands with basement structures of the North Sumatra and Central Sumatra basins. From NW to SE the N-S bands of grabens are: Tamiang-Yang Besar High related grabens; Asahan Arch-Aruah Nose related grabens; Pematang-Balam Troughs related grabens, and Bengkalis Trough related grabens. Liew proposed that the bands of grabens represent *en echelon* zones of weakness in the pre-Tertiary basement that were reactivated by dextral wrenching parallel to the NW-SE elongation of the Malacca Strait. The southwestern limit of this zone is the dextral Sumatra Fault, but no representative regional fault is known on the northeastern side of the strait.

MERIDIAN FAULTS IN PENINSULAR MALAYSIA

Onshore Peninsular Malaysia, N-S fault zones are known to cut across rocks as young as Cretaceous (Fig. 12b). The Geological Survey of Malaysia (1992) has maintained that this trend represents the oldest fault set. The other important fault zones striking in the NNW-WNW sector are considered younger. Individual N-S fault segments are in the 50 to 70 km range. The longest combined fault set is the Bentong Suture that extends from southernmost Thailand to Malacca on the Strait of Malacca, a N-S distance of 400 km. The suture most probably continues across the strait as the Bengkalis Trough of Central Sumatra (Fig. 6). The suture zone is as wide as 18 km within which can be distinguished a western zone of schist and phyllite with large serpentinite lenses and an eastern zone of olistostrome. Olistoliths or matrix contain fossils ranging from Ordovician up to Lower Triassic. Before the end of the Triassic, a Gondwana crustal fragment in the west docked along the suture with Cathaysia in the east (see e.g. Metcalfe, 1988; Tjia, 1989). Faults associated with the suture show evidence of left-lateral followed by right-lateral and finally overprinted by normal faulting. Dextral slip on the bounding faults of the Bengkalis Trough affected strata as young as Middle Miocene. A major segment of the eastern limit of the Central Domain of Peninsular Malaysia also includes large N-S striking faults (Geological Survey of Malaysia, 1985) associated with pull-apart basins that accumulated up to about 7 km of Jurassic-Cretaceous continental sediments. Dextral strike slip in the Middle(?) Jurassic formed the pull-aparts. Subsequently, a compressive stress regime in Early/Late Cretaceous caused folding and/or uplift of the sedimentary graben fillings (Tjia, 1996).

Segments of three N-S faults in Terengganu have been recently studied in the field. The regional geological map (Geological Survey of Malaysia, 1985) shows some of the N-S fault segments, while others were traced on satellite thematic mapper images (Fig. 13). The Besut fault zone was studied in a quarry in the so called Boundary Range Granite at the border between Kelantan and Terengganu states. The radiometric age of the granite is Carnian (227 Ma). The sheared rock in the quarry has strikes between 345° and 360°, dipping 70 degrees east. One of the shear zones is 25 m wide; the fracture planes are smooth or subhorizontally striated, indicating a response to wrenching (Fig. 14). Spalling flakes on the fault planes probably indicates left-slip. The regional geological map shows across this particular locality a straight 45-km long fault. Near the southern end of this fault, a stream outcrop shows it to comprise more than 20-m wide flasered granitic rock next to flasered hornfels of the country rock. The coarse foliation exhibited by the flasers strike between 155° and 180° and dips are very steeply westward. Associated slickensides are subhorizontal and prod steps indicate left-lateral slip. The Besut fault zone follows the 102°25' East meridian and seems to continue offshore along the straight eastern boundary of the Narathiwat High in the Gulf of Thailand.

The Kampung Buluh fault belt strikes northerly

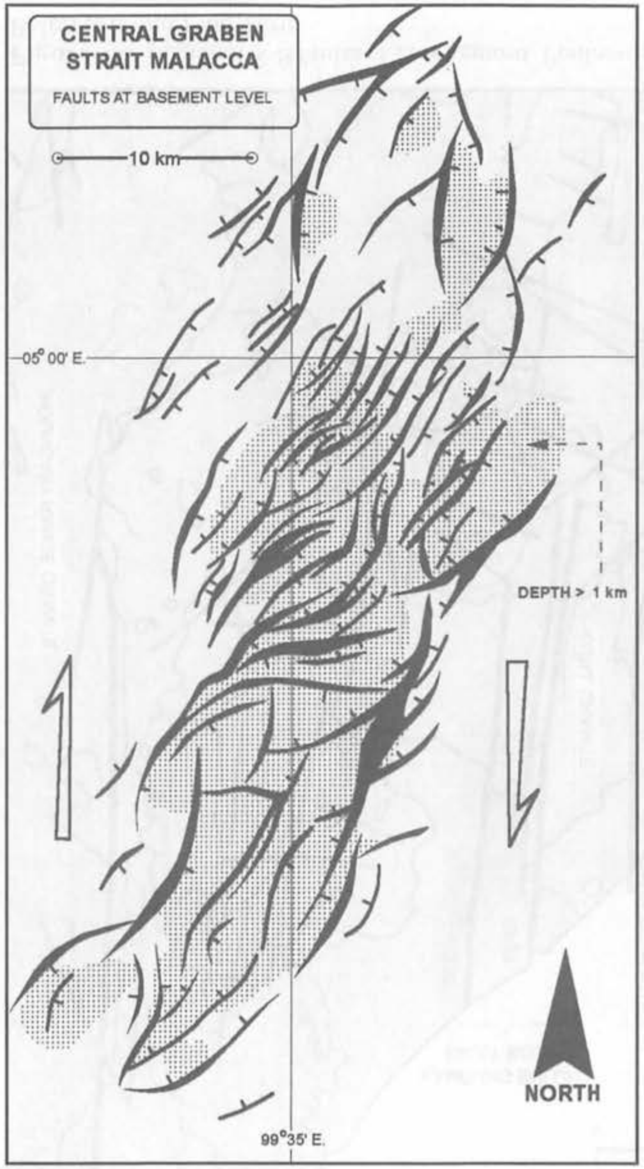

Figure 12a. *En echelon* fault pattern in the Tertiary sediments of the Central Graben, Strait of Malacca, consistent with dextral wrenching parallel to the N-S long axis of the depression. Modified after Liew (1995).

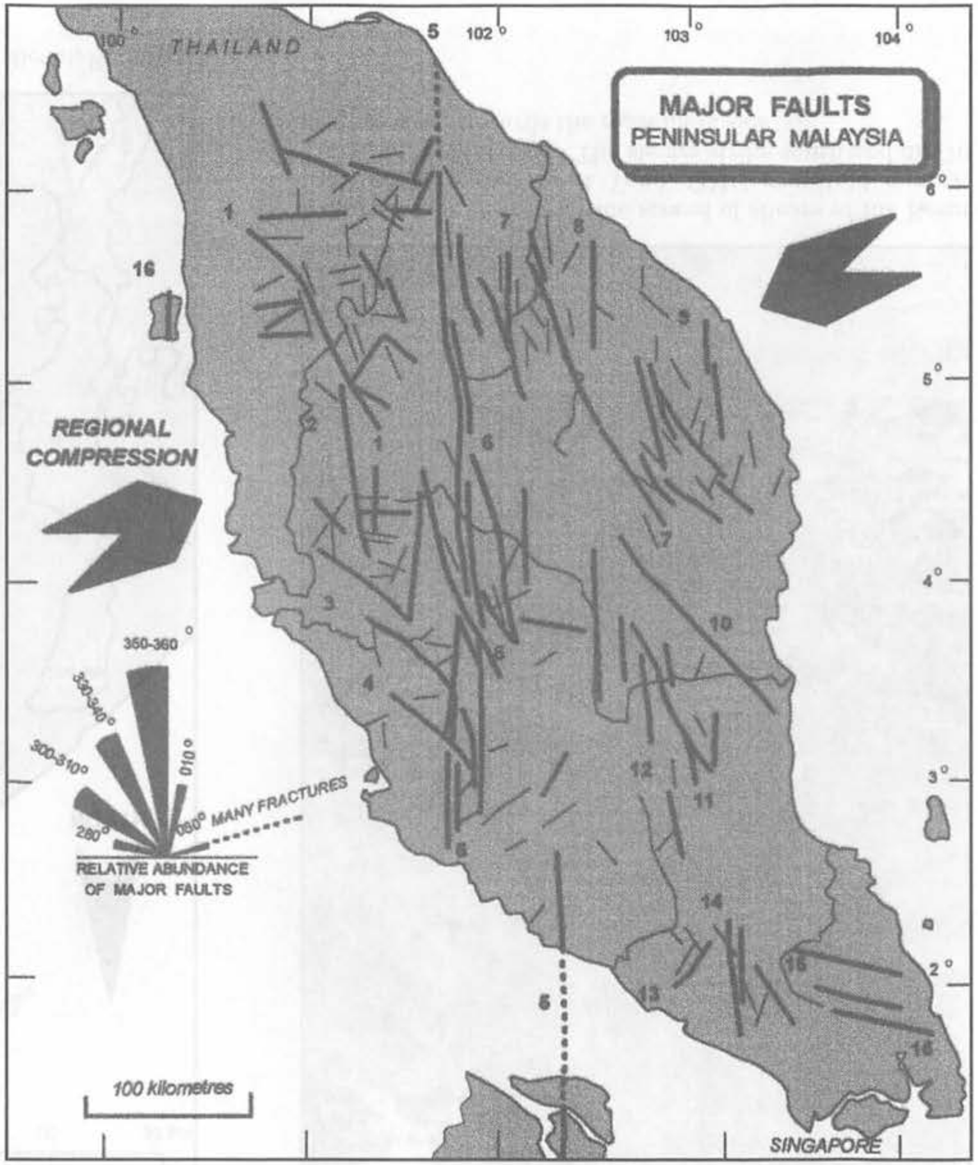

Figure 12b. Major faults in Peninsular Malaysia compiled from published maps by the Geological Survey of Malaysia and from Landsat satellite images.

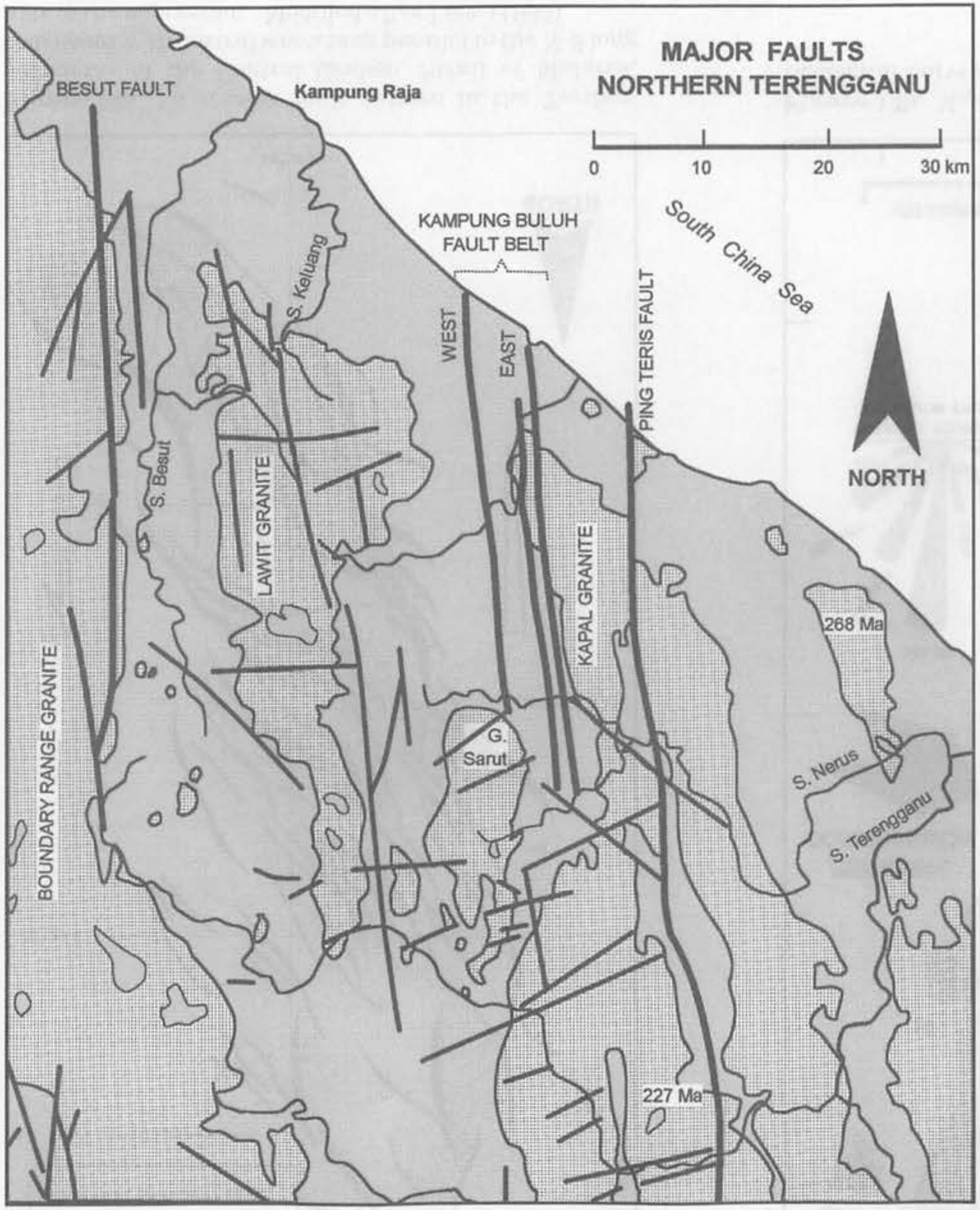

Figure 13. Regional N-S faults of Terengganu, Peninsular Malaysia: Besut, Kampung Buluh belt and Ping-Teris.

Figure 14. A 25-metre wide strand of shears of the Besut fault zone in the Bukit Yong, QMC granitoid quarry, Terengganu, Malaysia. The shears strike south and dip 70 degrees west (towards the right hand side).

subparallel to 102°45'E to 102°47'E meridians. Extrapolated to the north, the fault belt seems to graze the Tok Bidan structure and extends into the so called Mid-Ridge prospect of the Malaysia-Thailand Joint Development Area. The Kampung Buluh fault belt is identified by two subparallel fault zones in the Bandar Permaisuri (former name Kampung Buluh) area and another Northerly striking fault zone 3 km more to the east. The western Kampung Buluh fault zone is defined by several metres-wide strands of mylonite or breccia. One of the strands, 6 metres wide, strikes 350° and dips 80 degrees east. It consists of phyllonite enclosing metasandstone boudins, larger fault-sliced metasandstone clasts, and contorted quartz bodies. Planar quartz veins and dykes parallel to stratification and foliation are post-faulting emplacements. Younger vertical faults cut the phyllonite mass. These younger faults either strike 310° and have left-lateral drag, or strike 10° with right-lateral drag. To the west and to the east of the major fault strands are several other parallel, metres-wide fault strands. Drag along these major faults (strike 350°, dip 80° east) is always sinistral. Across the strike, the fault zone is at least 100 m wide. The fault zone is within Carboniferous metasediments according to the regional geological map. Part of the eastern Kampung Buluh fault zone outcrops in the north slope of Bukit Cenggal, where the rocks are silicified pelite and schist deformed into tight isoclinal folds striking north with limbs that dip very steeply west or are vertical. Three folding phases can be distinguished. Folding phases 1 and 2 were coaxial, strike N-S and produced the tight isoclines. The third and youngest folding phase produced broad warps about east-west trending axes. Granitoid sills are also isoclinally folded. Over a width of more than a hundred metres across the strike, the outcrop is laced by north-striking, often more than a metre-wide mylonite bands and intervals encasing schist and quartz boudins. Left-lateral drag is indicated. The total width of the eastern Kampung Buluh fault zone may be more than 600 m. This is suggested by the presence of north-striking shear zones in partly weathered schist-phyllite in a roadcut some 500 m east of the studied outcrop.

The Ping-Teris N-S fault zone runs along 102°53'E meridian and may continue offshore along the west edge of the Northwest Malay basin. It is a major dextral strike-slip fault that onshore appears to separate black carbonaceous phyllite in the east from banded, grey tuffaceous(?) metapelite on its west side. One segment of the fault zone was studied in an earth quarry near Kampung Padang Ping on a right-hand tributary of the Telemong river in Terengganu. The outcrop is of black, carbonaceous phyllite striking north and dipping almost vertically east. Over a total width of 30 metres across the foliation, at least five fault zones, each 0.5 m to 1.5 m wide, striking 345°–350° dipping 77 degrees east alternate with phyllite sequences. Contorted quartz bodies of several decimetres across are encased in the phyllite. On a phyllonite surface are fault striae that pitch 30 degrees towards SSE with fault-plane markings, such as bruised steps, pluck spalls and fault drumlins, indicative of right-lateral displacement. Thin 90/90 fractures cross the fault zones and are associated with left-lateral drag. Another outcrop north of the quarry shows the Ping-Teris fault as a dextral wrench.

MALAY BASIN, SOUTH CHINA SEA

The 500 km long and 200 km wide Malay basin mainly trends NW but its northern part rather suddenly changes into N-S direction (Fig. 15). The change in strike occurs around the 103°15' East meridian, which is also marked by the presence of N-S regional fault zones: the Ular-Kuda and Kapal-Bergading. West of these fault zones, folds and faults strike north; to their east in the main basin, folds and basement faults strike approximately E-W. The main basin is now considered to have originated as an aulacogen in pre-Oligocene time (Tjia, 1994). Subsequently, this major, NW-trending zone of weakness in the pre-Tertiary basement accommodated the extrusion of Southeast Asia by becoming a sinistral wrench fault, to which the name Axial Malay fault was given. The wrench motion produced E-W half grabens and grabens that became special loci of deposition. Beginning in late Early Miocene and continuing into Late Miocene, reorganisation of plate movement patterns in this part of the world caused the Axial Malay fault slip sense to reverse. This reversal produced inverted anticlines of the half-graben fills and the overlying strata. The location of anticlines and their E-W strikes were predetermined by the orientation of the half-grabens and grabens in the basement (Tjia and Liew, 1996). Continued compression has tightened the anticlines and produced N-S tension faults across the crests.

In the main Malay basin the existence of several other regional N-S faults are suggested by the offset of fold bundles and by zonal alignment of smaller faults. Some of the smaller faults are *en echelon*, consistent with dextral slip. Along the major N-S faults, dextral displacements amount to ~60 km on the Dulang fault and ~40 km on the Mesah fault (Fig. 15). In an earlier paper (Tjia, 1994) I have mistakenly proposed that these large dextral offsets on the regional N-S faults post-dated the anticlines, whose juxtapositions show the displacements. It has been pointed out by colleagues that N-S faults that could represent the Mesah fault zone cut sequences older than the upper Lower Miocene I-Group (Md Nor Mansor and Rudolph, 1993). From the current understanding that the anticlines occupy pre-Oligocene half-grabens, I have to conclude that the large dextral offsets on the regional N-S faults of the Malay basin may be contemporaneous with left-lateral slip on the Axial Malay fault, that is, taking place in pre-late Early Miocene time.

CONCLUSIONS

Regional meridian-parallel faults are well represented in the continental part of Southeast Asia. The longest is the ~2,000 km Central Thailand-Bentong-Bengkalis Fault zone (fault # 4 on Fig. 1). Two other important structures are the Gulf of Thailand fault (3) and the Vietnam Shear (8). Other regional N-S faults have known lengths between 200 km and 700 km. The apparent absence of N-S regional faults in eastern Sundaland, including Kalimantan is probably only for want of regional studies. The Bentong Suture in Peninsular Malaysia existed since the Middle Triassic and other N-S faults in the peninsula are usually considered as the oldest set, that is Jurassic or older. The southern extension of the Bentong Suture into Central Sumatra — the Bengkalis Trough — has dextral faults active up to Pliocene time. Similarly, the N-S faults in the Sumatra hydrocarbon basins, in the Malay basin, in the Sunda basin, and in the NW-Java basin appear to have been active into the Miocene or probably even into the Pliocene. Exceptional left-lateral slip senses on regional meridian-parallel faults are on the Peusangan fault in North Sumatra, the Besut and Kampung Buluh faults in Terengganu state of Malaysia. The slip sense on the Peusangan fault is probably due to spreading of the Andaman Sea basin that began almost 11 Ma ago. The sinistral offsets of the Terengganu faults are of unknown origin, but the faults could be secondary structures associated with

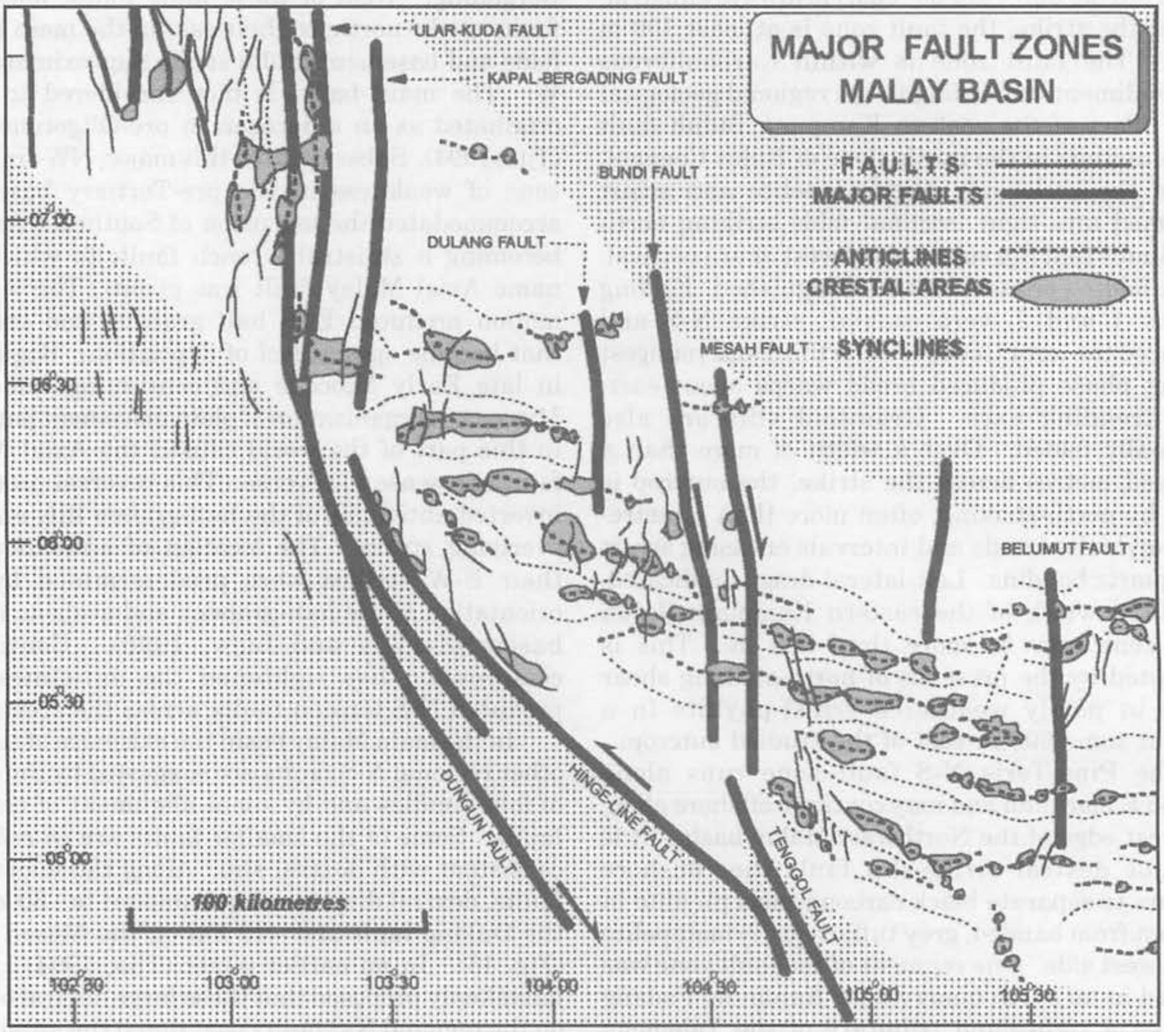

Figure 15. Major fault zones and folds in the Malay basin. Modified from Tjia and Liew (1996).

SE-ward extrusion of the Indochina-Sunda plate.

The regional N-S faults of Southeast Asia have functioned as (1) initiators/originators of Tertiary basins (Mekong and Nam Con Son basins), as (2) determinants of basin location (Central Thailand and Gulf of Thailand basins; as sub-basins in the Sumatran and Java Sea oil basins: Balam-Pematang troughs, Bengkalis trough, Benakat gully, Asri, Seribu, Arjuna basins, and relatively small basement depressions in the Strait of Malacca), and (3) as modifiers of basin shapes (Peusangan fault in the North Sumatra basin; the tens of kilometres dextral offsets of major folds in the main Malay basin by the Mesah, Bundi and Dulang faults). Of indirectly tectonic origin are relatively minor N-S faults that developed in the crests of growing anticlines in the Malay basin. It is believed that tightening of the anticlines is the cause of these faults.

Its geological history indicates that by the Middle Triassic, continental Sundaland had amalgamated into one plate. Some of the meridian-parallel faults, such as the Bentong Suture, have very probably existed since that time. Other N-S faults may be younger, but perhaps most originated in the Mesozoic and were reactivated during the Cenozoic. The extensive distribution of N-S faults in Southeast Asia implies that since late Triassic time, translational or rotational movements must have affected the region as a unit. The origin of most of these regional N-S faults is problematic. The Vietnam Shear can be attributed to opening of the South China Sea basin following an existing zone of weakness in the crust. The Bentong-Bengkalis lineament is a suture between two continental subplates. North-South regional faults transecting Cenozoic strata appear to represent reactivated pre-Tertiary faults. Figure 1 also shows several long, N-S faults in the Cenozoic rocks of northern Borneo. Could it be that the N-S geofractures developed on account of rotation of the Earth? In that case, regional N-S faults may have formed in brittle lithosphere throughout geological time. That possibility is beyond the scope of the present paper that mainly aims at drawing the attention to the general occurrence of meridian-parallel faults and their association with Tertiary sedimentary basins.

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