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Structural development at the west-central margin of the Malay Basin

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Abstract: The regional elements in the west-central margin of the Malay Basin largely comprise a platform area and a hingeline zone which runs parallel (NW-SE) to the basin margin. The Tertiary basement of this margin is divided into three structural units based on fault trends and basement structural contours. The northern unit is characterised by fault trends controlled by basement highs. Central unit represents a zone of fault bifurcation. Within the southern unit, there is a fault zone which is aligned to the Dungun graben. The causative maximum horizontal compression acted on the pre-Tertiary basement is in the 20°–40° direction.

Right lateral wrenching could have occurred at the west-central margin of the Malay basin as early as Jura-Cretaceous and continued till pre-Oligocene. It has initiated the formation of Tok Bidan Graben and is shown by the occurrence of basement faults transecting the Jura-Cretaceous as well as pre-Oligocene sediments in the Tok Bidan Graben. Tok Bidan Graben resembled a rhomboid pull apart basin by right lateral wrenching. The continual right lateral wrenching during pre-Oligocene could have initiated the formation of NW-SE trending Dungun faults and its associated half grabens. The Dungun graben is located at the south-east end of the Dungun faults. This graben is also a right lateral wrenched rhomboid pull apart basin. The location of this graben at the south-east end of the Dungun faults suggested the movement of the Dungun faults in a dextral sense.

Right stepping *en echelon* faults within ?Miocene sediments in the Dungun Graben suggested a reversal of wrench movement during ?Miocene time. The stress regime within this graben changed from transtensional to transpressional. However, such reversal was not recorded in Tok Bidan Miocene sediments: the Dungun faults could have buffered the changes in stress during Miocene. The absence of wrench reversal in the Tok Bidan Graben indicated that Tok Bidan area could be stabilising during Miocene time. This Miocene reversal of wrench movement could be the manifestation of the changes in the stress regime within this portion of the basin. Changing stress direction is observed since Jura-Cretaceous. These changes could have resulted from the change of motion of the Pacific Plate and the progressive northward advancement of the Indo-Australian Plate during Miocene.

INTRODUCTION

The west-central margin of the Malay basin represents a flexure area between the eastern shore of Peninsular Malaysia and the Western Hinge Fault Zone of the Malay Basin (Fig. 1). This margin is elongated in NW-SE direction and flanked by the Tenggol Arch to the southeast. The northwest portion of this margin comprises a platform area. In this platform area, the thickness of Tertiary sediments is about 2 km and these sediments thicken towards the basinal area, reaching a thickness of 7 km. The Western Hinge Fault Zone (see Tjia, 1993) that trends NW-SE, separates the platform and the basinal area. The southeast portion of this margin is characterised by a convex-sloped basement and a NNW-SSE fault zone that is straddled by a number of half grabens.

The oldest drilled Tertiary sediments onlap onto this margin and comprise ?Oligocene non-marine sands and shale (Lasmo Oil [Malaysia] Ltd., 1990). The Upper Oligocene-Middle Miocene sedimentary sequence is predominantly non-marine to marginal marine, reflecting a gradual eustatic sea level rise. Upper Oligocene sediments represent non-marine fluvial and lacustrine drainage systems. Lower Miocene sediments are characterised by coastal plain sedimentation with a progressively stronger marine influence culminating in the Middle Miocene sea level highstand. Regional uplift has resulted in a Middle Miocene regressive sequence of sand and shales with thick coal measures. Deposition was almost continuous throughout the Upper Miocene and Pliocene and regional uplift occurred to the southeast. Marine influence increases upwards, culminating in open marine shales of the Pliocene trangression (Fig. 2).

The west-central margin of the Malay basin has been demarcated as PM 2 and PM 7 exploration blocks by Petronas. Lasmo Oil (Malaysia) Ltd. previously operated in PM 2 and WMC is currently the operator in PM 7.

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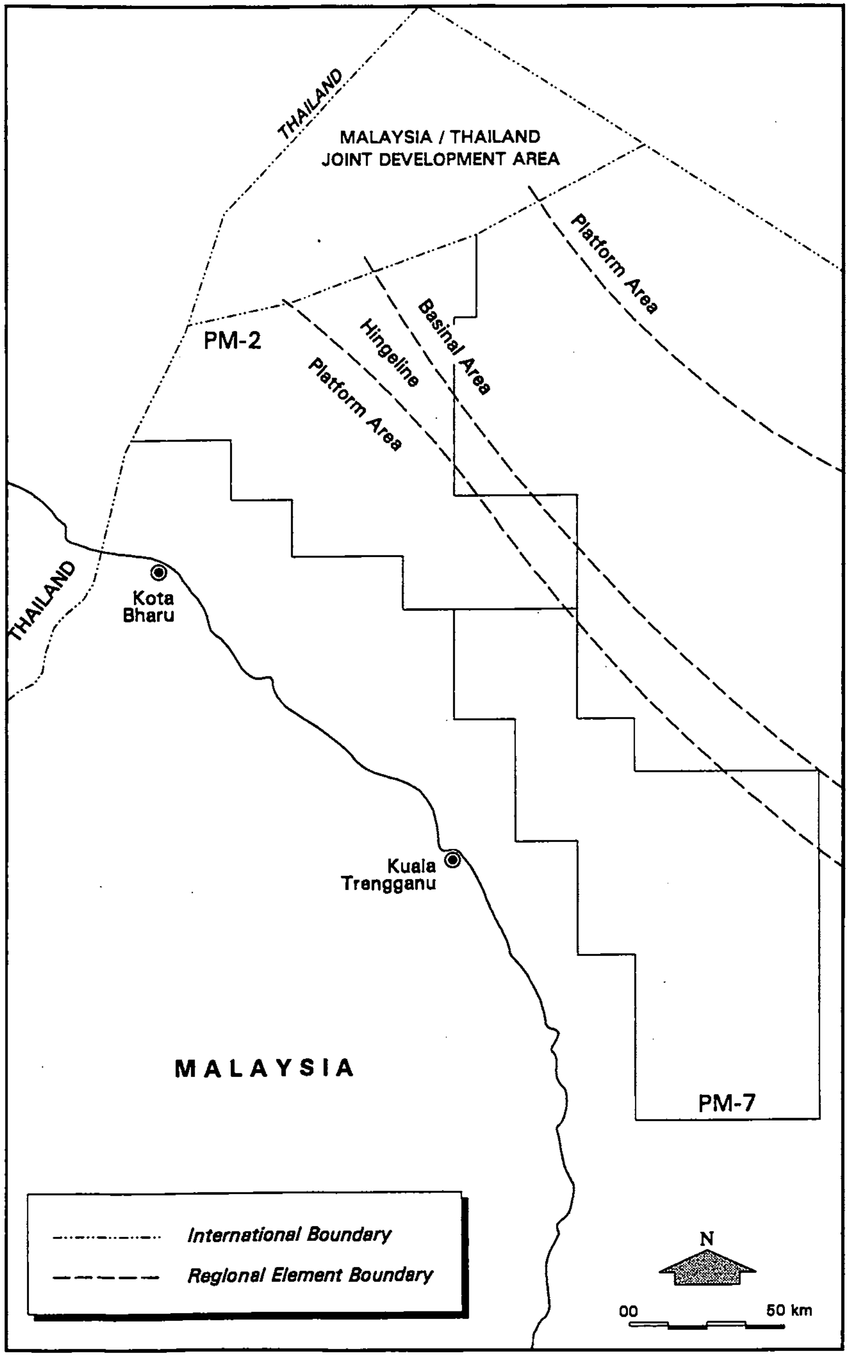

Figure 1. Location map showing the study area and regional elements in the Malay Basin.

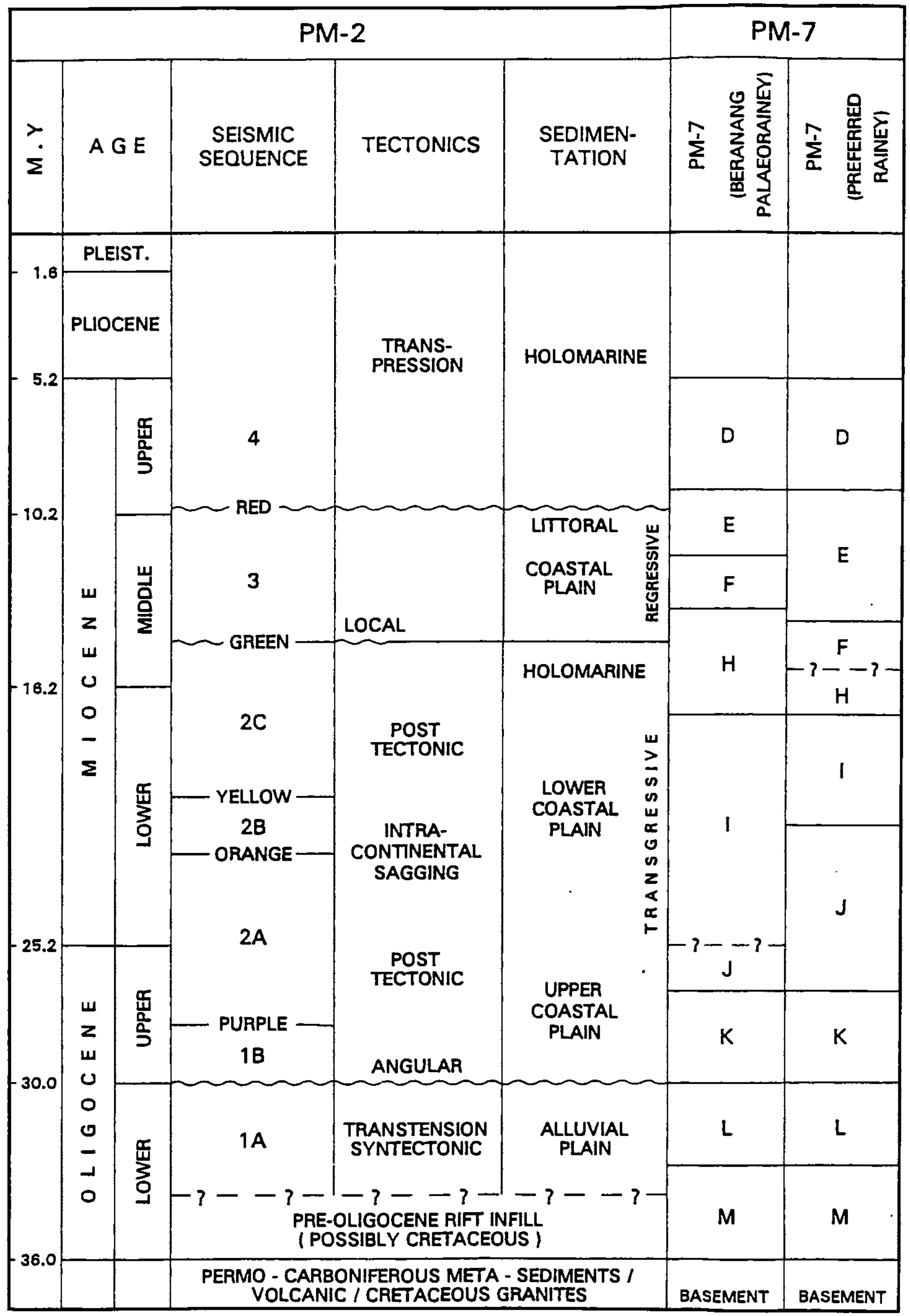

Figure 2. Stratigraphic schemes used by operators of PM 2 and PM 7.

The objective of this study is to examine the structural development within the west-central margin of the Malay Basin during Tertiary. To achieve this objective, structural interpretation is performed on the time structure maps produced by Lasmo Oil and WMC. The time structure maps utilised are either scaled at 1:50,000 or 1:100,000.

BASEMENT STRUCTURES

Based on the fault trends and basement structural contours, the study area is divided into three structural units; northern, central and southern unit. From north to south the trend of the basement changes: from NW-SE to NNW-SSE. The trend of the basement could represent the paleotopography of the study area as it resembles the present coastlines of Kelantan and Terengganu. The faults progressively become steeper from the north to the south. Local paleohighs are either fault associated (located on the upthrown block) or non-fault associated.

Northern unit

Within the northern unit, the basement structural contour generally trends NW-SE dipping towards northeast and faults are either perpendicular or oblique to this structural trend (Fig. 3). Major fault trends are NNE-SSW (more faults dip ESE) and NW-SE and their length could reach 30 km. The largest fault within this unit has a heave of 3.5 km and throw of 1,200 msec. The geometrical relationship between the fault trends is random. However, most of the faults are either parallel or oblique to the two regional basement highs. The horizontal spacing between faults are wider in this structural unit than in other structural units. There are two regional basement highs situated in the east and west sectors of this unit. The western basement high plunges towards NNE whilst the eastern basement high plunges towards NW. The latter basement high is highly faulted by northerly faults. Situated between these two regional basement highs is the Tok Bidan Graben. Local paleohighs in this unit are normally non-

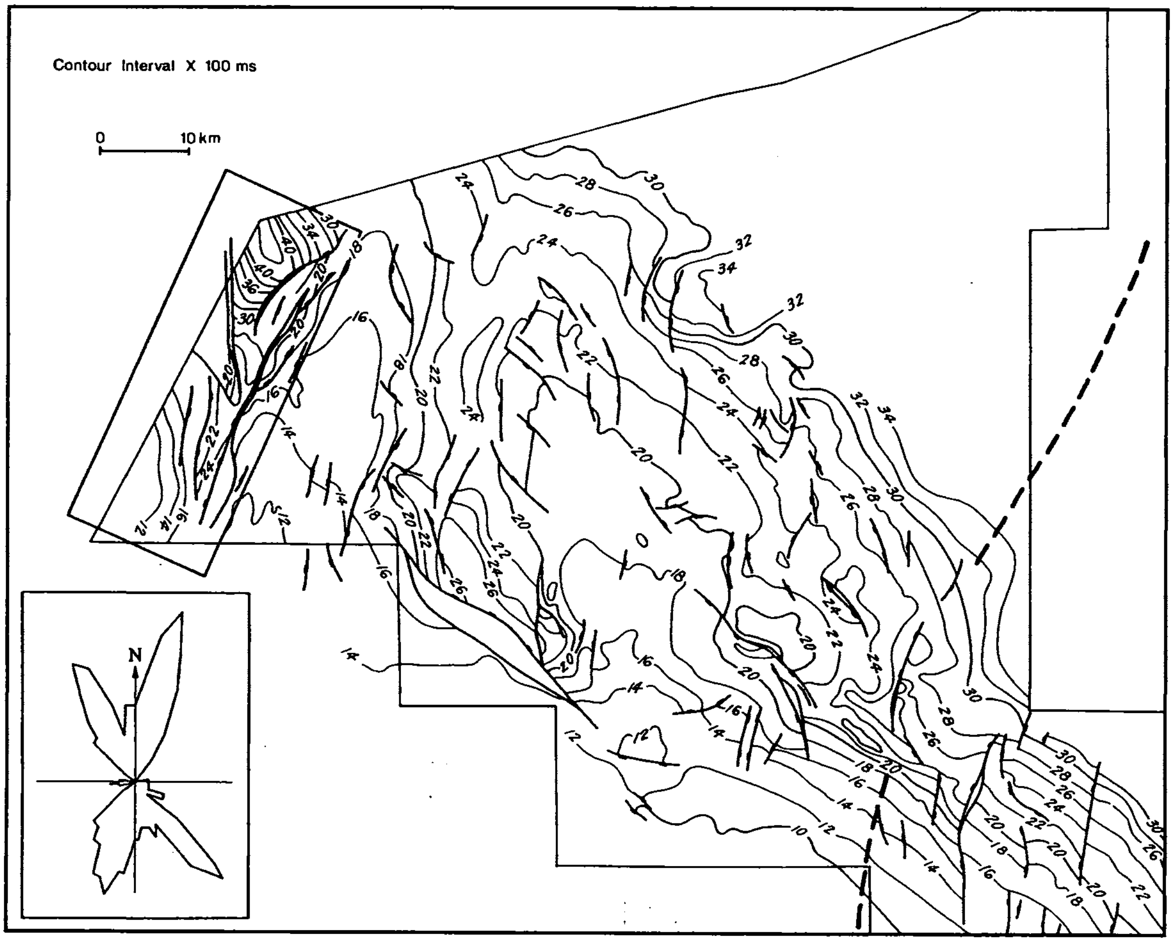

Figure 3. Northern unit showing two basement highs plunging towards north and two dominant fault trends; NNE-SSW and NW-SE. Inset shows the rosette of strike frequencies of faults within the northern unit.

fault associated. They are either elongated N-S or NW-SE. *En echelon*, NE-SW trending faults are found within the western area of this structural unit. This configuration resembles a fracture zone with right lateral movement. Paleolows within the platform area are elongated NW-SE and N-S.

Central unit

The central unit represents a transition in structure elements between the northern and southern unit (Fig. 4). The basement structural contour changes within this unit from NW-SE (northern unit) to NNW-SSE (southern unit). The basement contour generally dips toward NE and is relatively steeper than other units. The fault trends are oblique to its basement structural trend. Major faults trend N-S (more faults dip west) and NNW-SSE. The largest fault mapped in this unit has a length of more than 20 km, throw of 500 msec and heave of 0.6 km. Fault trends are aligned along a curved bend, indicating a transition of fault trends from those of the northern to those of the southern unit. Local paleohighs in this unit are fault-associated and are normally elongated parallel to the faults (NNW-SSE or NW-SE).

Southern unit

The basement structure in the southern unit trends NNW-SSE dipping towards ENE with a convex slope (Fig. 5). Its faults are either parallel or oblique to this basement trend. The dominant faults trend NNW-SSE (more faults dip ENE). Minor oblique or cross faults trend N-S. The largest fault reaches a length of more than 40 km with a vertical throw of 2,200 msec and a heave of 1.8 km. Faults are closely spaced and aligned to the Dungun Graben and the intensity of faults decreases basinward. Local paleohighs within the western area of this unit are not associated with faults and are elongated either NNW-SSE or NW-SE. Within the eastern region, paleohighs are fault associated and located on the western side of the fault (upthrown block). Two grabens run NNW-SSE through the centre of the southern unit. The basement of the grabens comprises regional northwest-southeast trending faults interconnected by north-south oblique faults. The basement of these grabens deepen towards northeast. The larger graben in the south (Dungun graben; named by WMC geologists) reaches a depth of 3,000 msec in the northeast of the graben. The smaller unnamed graben (in the north) deepens towards northeast to a depth of 1,600 msec. The geometric relationship between these grabens indicates that the grabens are small pull apart basins due to right lateral shearing (refer to Fig. 5).

EVIDENCE FOR WRENCH MOVEMENT

Wrench movement within this margin are identified by the presence of pull apart basins or *en echelon* faults. Wrench faulting can be recognised by the presence of *en echelon* extension gashes (Fig. 6). Tjia (1972) showed that as a fault moves laterally, reorientation of the stress field occurs. Tension gashes will form parallel to the reorientated maximum principal stress. These secondary fractures are formed by the reoriented maximum compression from first order shearing. Hence, the orientation of zones of *en echelon* fractures can be utilised to indicate the sense of displacement of the main fault.

On the western side of northern structural unit (highlighted in Fig. 3), *en echelon* sigmoid fractures of lengths between 5 to 15 km are found aligned within the 20°–50° sector. These fractures are interpreted as tension gashes formed by a right lateral first order shear zone of 8 km width with a strike of 20°. The probable compressional direction for this shear zone is within the 20°–110° sector.

A pull apart basin is recognised by the rhomboid orientation of the fractures that form the boundaries of the basin. Crowell (1974) suggested that pull apart basins are formed by the local bending of an initially straight fault (zone) that led to the formation of a step-like geometry along strike-slip faults (Fig. 7).

Dungun Graben

The Dungun Graben is situated northwest of the Tenggol Arch. This graben has a rhombic shape and is elongated in NNW-SSE direction. Within the Dungun Graben, the paleoenvironment sequences are interpreted to have changed progressively from lacustrine to deltaic and to fluvial sediments. The basement is probably entirely of metamorphic or crystalline origin (Rainey Exploration, 1992).

The pre-Tertiary basement map (?pre-Oligocene) shows that this graben comprises regional northwest-southeast trending faults interconnected by north-south diagonal faults. The basement deepens towards northeast and ends with a large fault that demarcate the northeast boundary of this graben. This fault reaches a length of more than 40 km with a vertical throw of 2,200 msec and a heave of 1.8 km. The southwest portion of this graben is characterised by numerous NW striking step faults and its highly faulted compared to its northeast counterpart. The NNW-SSE plunging basement high within the southwest portion of this graben suggests compression within this portion of graben (Fig. 8).

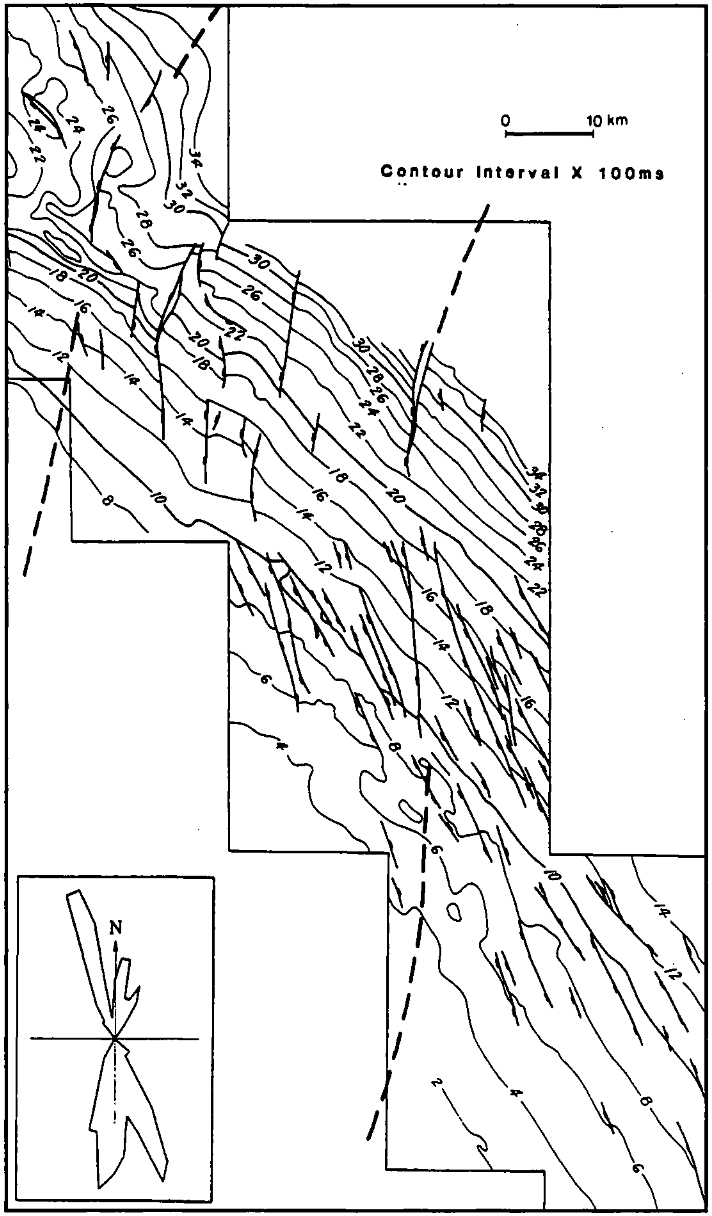

Figure 4. Central unit showing changing of basement trend from NW-SE (northern portion) to NNW-SSE (southern portion). Dominant fault trends are N-S and NNW-SSE. Inset shows the rosette of strike frequencies of faults within the central unit.

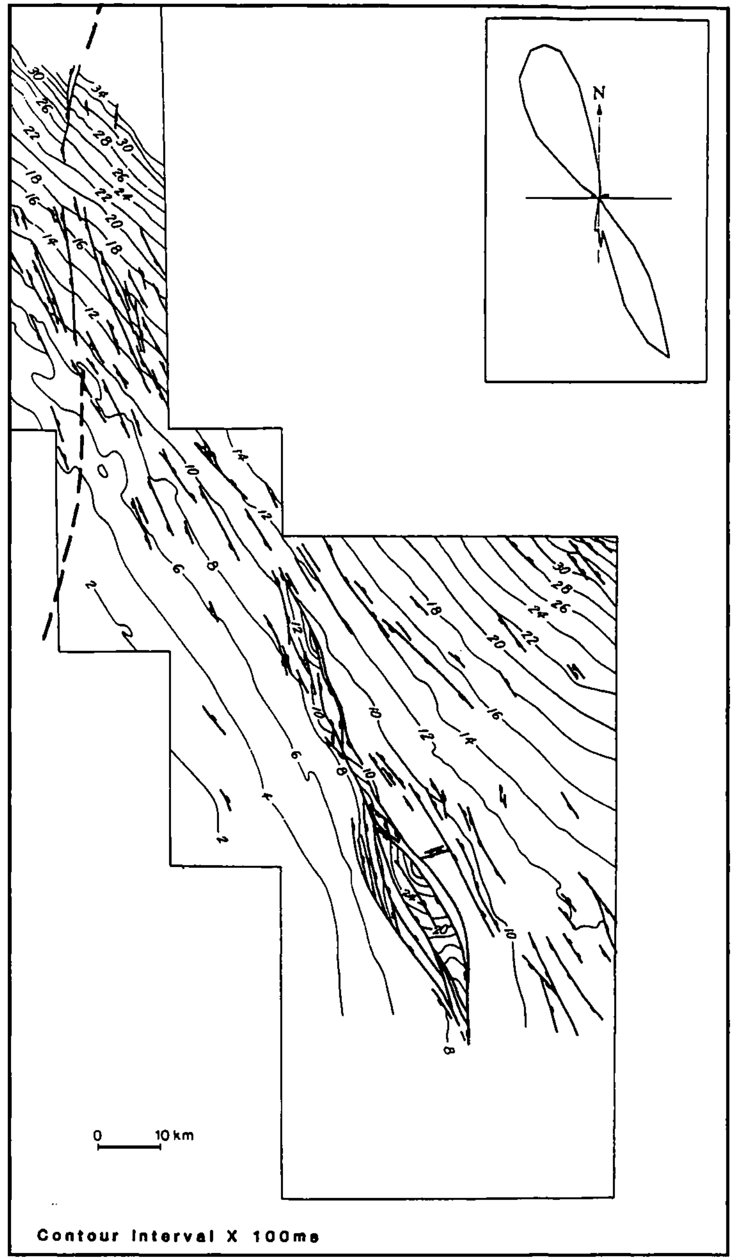

Figure 5. Southern unit showing basement with a convex slope. Majority of the faults strike NNW-SSE and N-S. A rhomboid graben is observed. Inset shows the rosette of strike frequencies of faults within the southern unit.

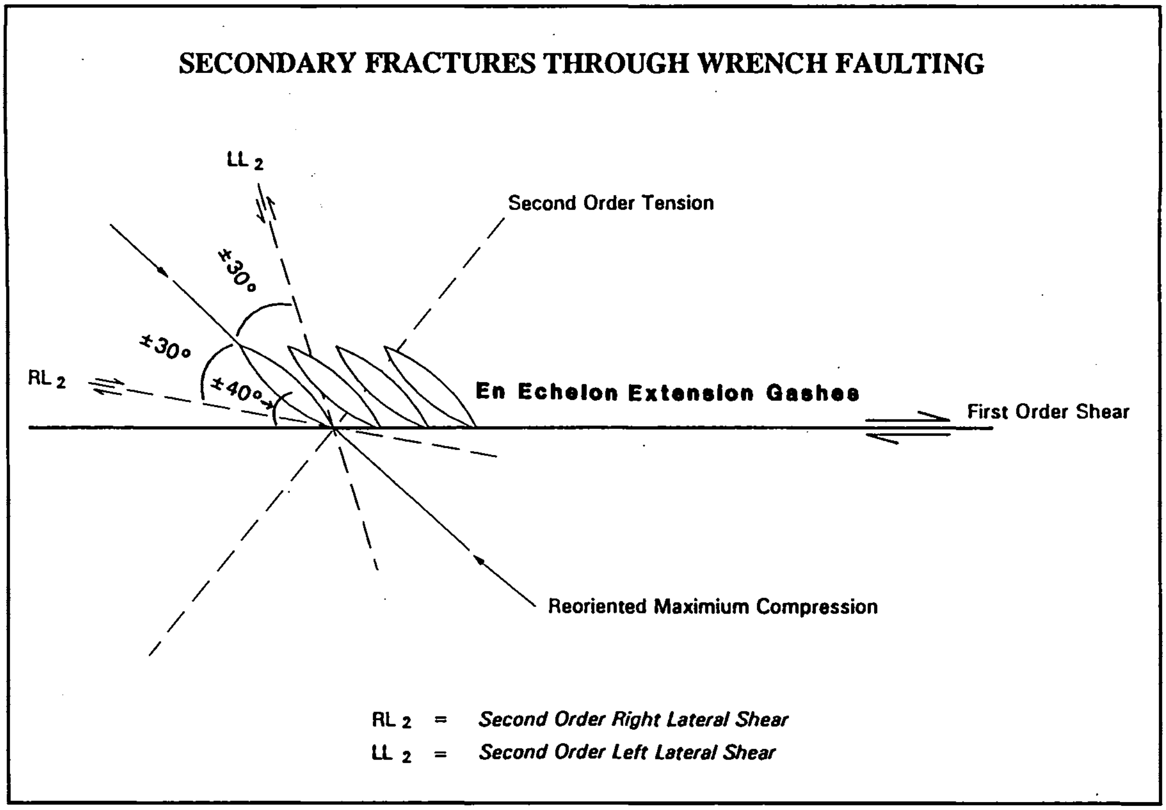

Figure 6. Secondary fractures through wrench faulting (adapted from Tjia, 1972).

Based on the three smaller fault-bounded and sediment-filled depressions that are situated north of Dungun Graben, Tjia (1993) has interpreted a right lateral displacement of 16 km along the northeast boundary of the Dungun Graben.

The Tertiary basement (?Oligocene) of this graben comprises three different structural units separated by faults; western, central and eastern units (Fig. 9). The eastern unit is underlain by the major fault that denotes the northeast boundary of this graben. The beds dip steeply towards west with few NW-SE faults. The central unit is characterised by right stepping *en echelon* faults that trend WNW-ESE and a gently NNW dipping basement. On the average, this unit is at lower elevation than other units, suggesting a higher subsidence than other units. Bifurcating NW-SE and N-S faults dominate the western unit of this graben. The basement within this unit deepens towards ENE.

During ?Miocene (Fig. 10), the central and western unit remain active as evidenced by the presence of right stepping *en echelon* faults and highly faulted zone within its respective unit. Towards ?Pliocene, the intensity of faults within the Dungun Graben area decreases (Fig. 11). Most of the faults strike northerly and are concentrated in the western portion of the Dungun graben. This could be the manifestation of the reactivation of the highly faulted zone within the pre-Tertiary basement.

Figure 12 depicts the schematic structural features of the Dungun Graben. During ?pre-Oligocene, right lateral wrenching initiated the formation of this graben. The basement has a highly faulted zone on the western portion. Towards ?Oligocene, this graben becomes structurally divided into three units. The eastern unit is a zone of transpression with lateral wrench movement. Different geologists (from WMC) have mapped the faults on the western portion of this unit either as reverse or left lateral faults. The central unit is basically a zone of transtension and is characterised by right stepping *en echelon* faults. However, transpressional structures (reverse or left lateral faults) are mapped on the eastern portion of this unit. The western unit is also a zone of transtension with bifurcating NNW striking faults. The eastern portion of this unit also shows transpressional structures. These ?Oligocene structures are also mapped in ?Miocene sequence. From the spatial relationship between these three units, it is interpreted that left lateral wrench movement has occurred within the Dungun Graben during ?Miocene. Left lateral movement has occurred along the western boundary of eastern unit, eastern boundary of central unit and eastern boundary of western unit. The (?)contemporaneous left lateral

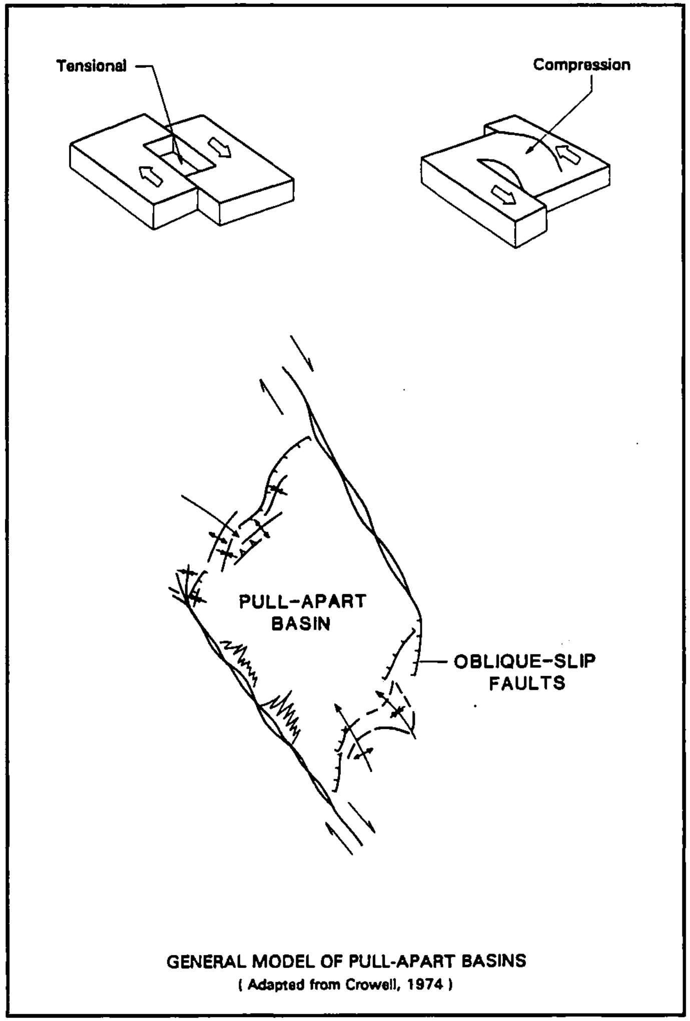

Figure 7. General model of pull-apart basins (adapted from Crowell, 1974).

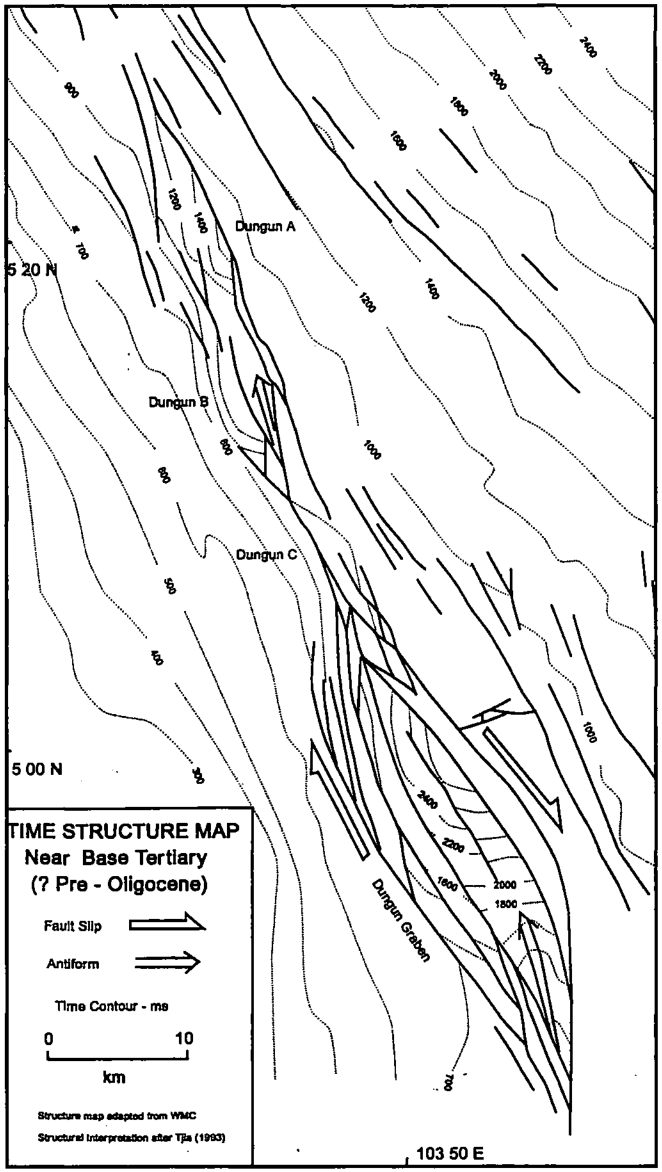

Figure 8. Dungun Graben and other half grabens straddled along the Dungun Fault. Based on WMC Petroleum (Malaysia) Sdn. Bhd. (1990). Structural interpretation based on Tjia (1993).

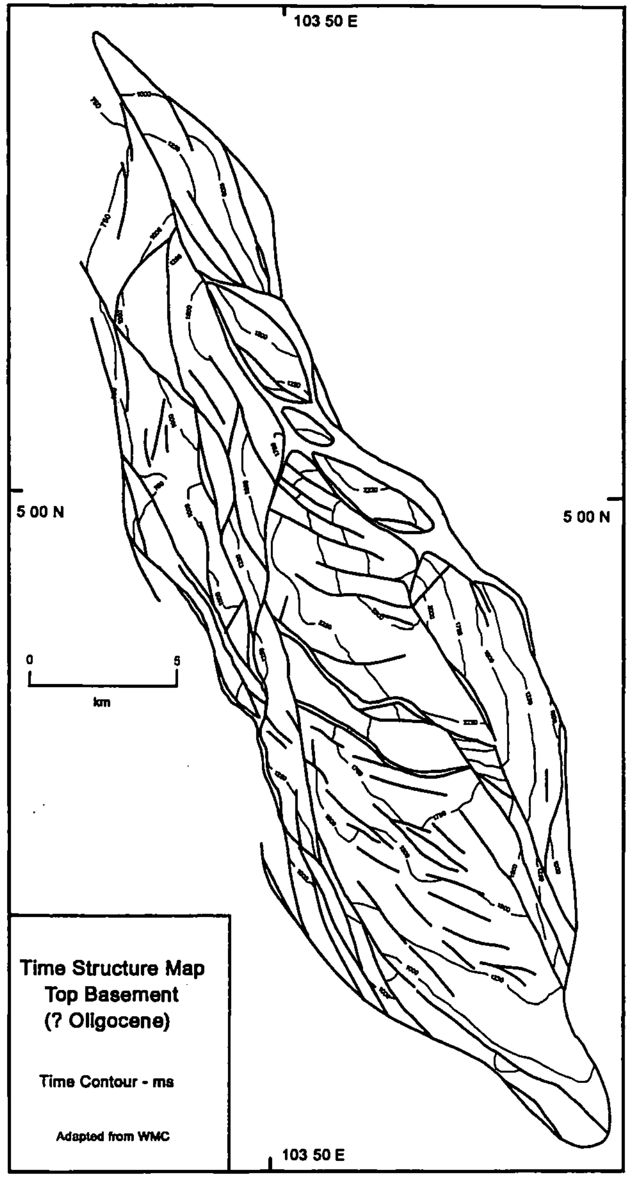

Figure 9. Tertiary Basement of Dungun Graben. Based on WMC Petroleum (Malaysia) Sdn. Bhd. (1990). Time Contour Map of Top Basement, Block PM7. Note the presence of three structural units within this graben.

movement along these areas has created right stepping *en echelon* faults within the central unit. During ?Pliocene, only northerly faults on the western portion of the graben are observed. These faults are mostly likely normal faults as Pliocene is a period of structural quiescence within the Malay Basin.

Tok Bidan Graben

The Tok Bidan Graben is situated approximately 50 km north of Pulau Perhentian Besar. This graben is flanked by a NNE plunging basement high to the west and a NNW plunging basement high to the east (Fig. 13). The later basement high is highly faulted by northwesterly fractures. The basement of this graben has a rhombic shape. It resembled a pull apart basin which could be initiated as early as Jura-Cretaceous by right lateral wrenching. This graben is elongated in the NW-SE direction. The length of the NW-SE boundaries is approximately 30 km whilst the NNW-SSE oblique faults reached a length of 20 km. There is a large NW striking fault bounding the southwest margin of this graben with a length of 30 km and vertical throw reaching 800 msec. This fault is connected with the NNW oblique faults on the western margin of the graben. The northeast margin of this graben is bounded by SE striking step faults downthrowing to SW. These faults are connected with SSE striking diagonal faults on the

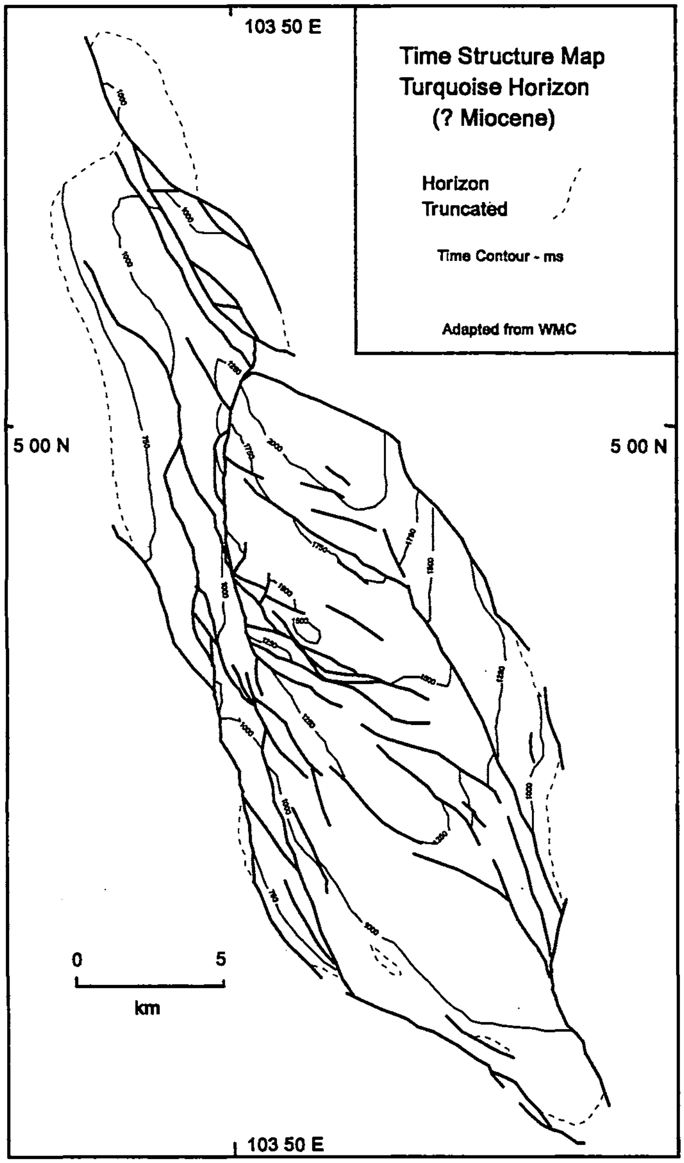

Figure 10. Miocene(?) time structure map of Dungun Graben. Based on WMC Petroleum (Malaysia) Sdn. Bhd. (1990). Time Contour Map of Turquoise Horizon, Block PM7. Note the prominent right stepping *en echelon* faults in the Central unit.

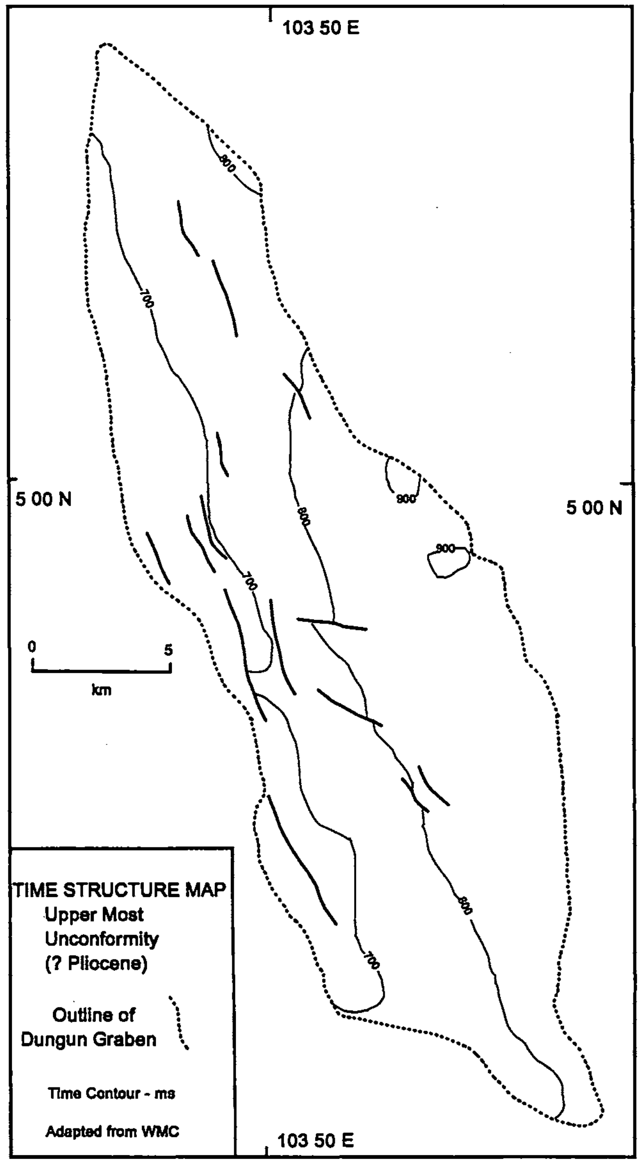

Figure 11. Upper Most Unconformity time Structure Map (?Pliocene). Based on WMC Petroleum (Malaysia) Sdn. Bhd. (1990). Time Contour Map of Upper Most Unconformity, Block PM7. Note the presence of northerly trending faults in the western portion of the graben area.

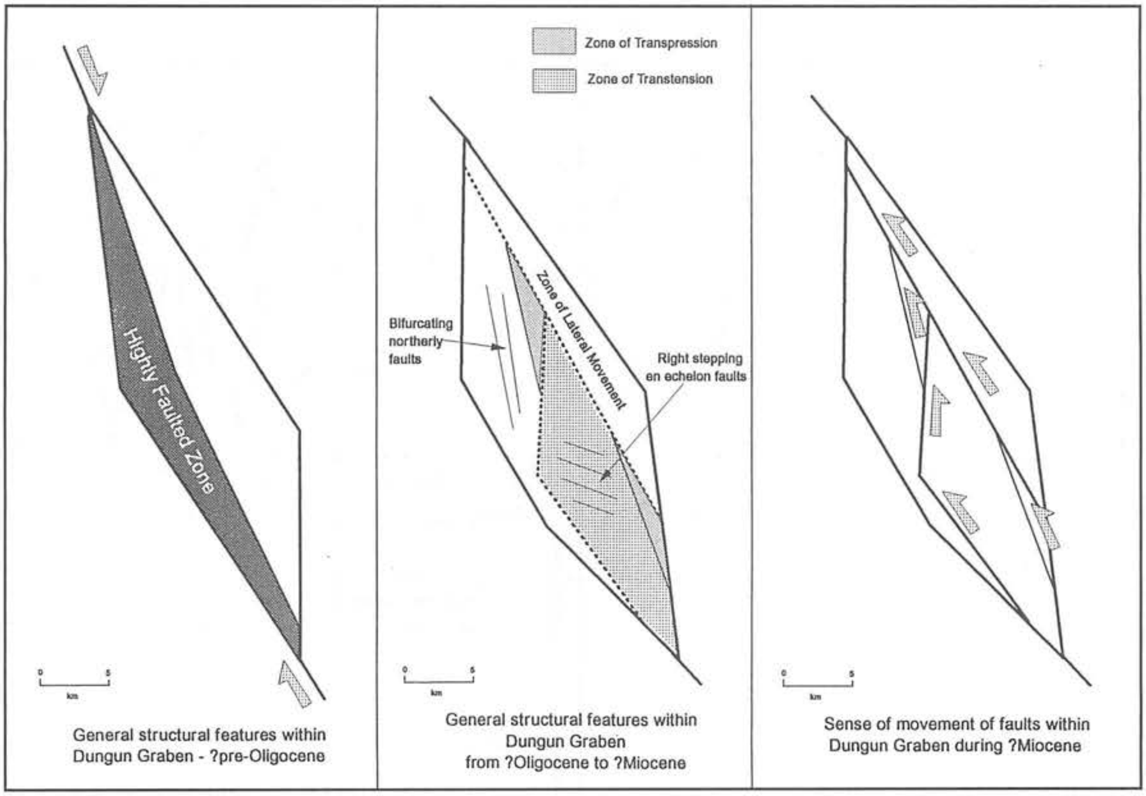

Figure 12. The schematic structural features of the Dungun Graben.

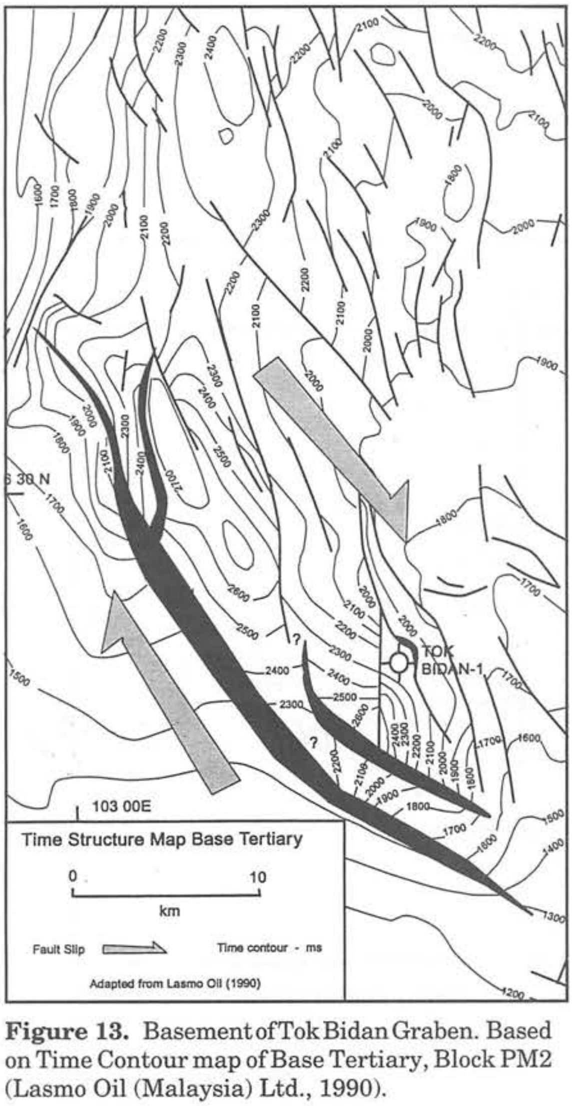

Figure 13. Basement of Tok Bidan Graben. Based on Time Contour map of Base Tertiary, Block PM2 (Lasmo Oil (Malaysia) Ltd., 1990).

eastern margin of the graben. Generally, the basement deepens towards south-west. There are three depocentres in this graben with the two deeper depocentres situated in the western portion of the graben. These depocentres are elongated parallel to the axis of this graben. The depocentre on the eastern portion of the graben elongated north-easterly and is cut with a south striking oblique normal fault.

The Lower Oligocene structure map shows that Tok Bidan graben inclines gently towards northeast and only NNW oblique faults that bisect the graben were active (Fig. 14). During Lower Miocene, Tok Bidan graben still inclined gently towards northeast with only northerly trending faults on the eastern portion of the graben (Fig. 14). Tjia and Liew (1993) interpreted that these faults could be normal faults due to upwarping. However, the faint *en echelon* arrangement of these faults could also suggested that continued dextral wrenching has acted along NW basement faults.

Figure 15 shows a NE-SW cross section of Tok Bidan Graben. Basement faults are believed to have formed since Jura-Cretaceous; Jura-Cretaceous conglomeratic sediments overlie Permo-Carboniferous sediments with an angular unconformity During Jura-Cretaceous, both sets of east and west dipping faults are active. However, the east dipping faults could be relatively more active as the Permo-Carboniferous basement inclined westward. Jura-Cretaceous sequence has

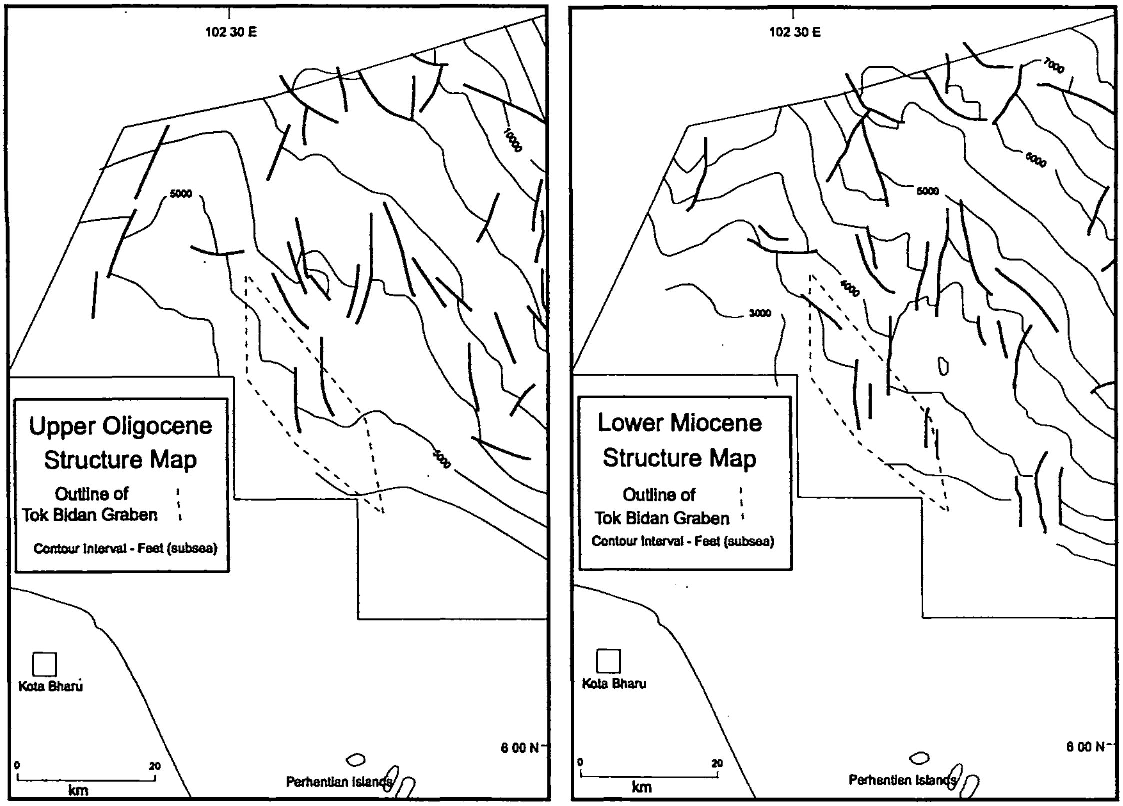

Figure 14. Structure maps of the Upper Oligocene and Lower Miocene around the Tok Bidan Graben area. Based on Lasmo Oil (Malaysia) Ltd., 1990.

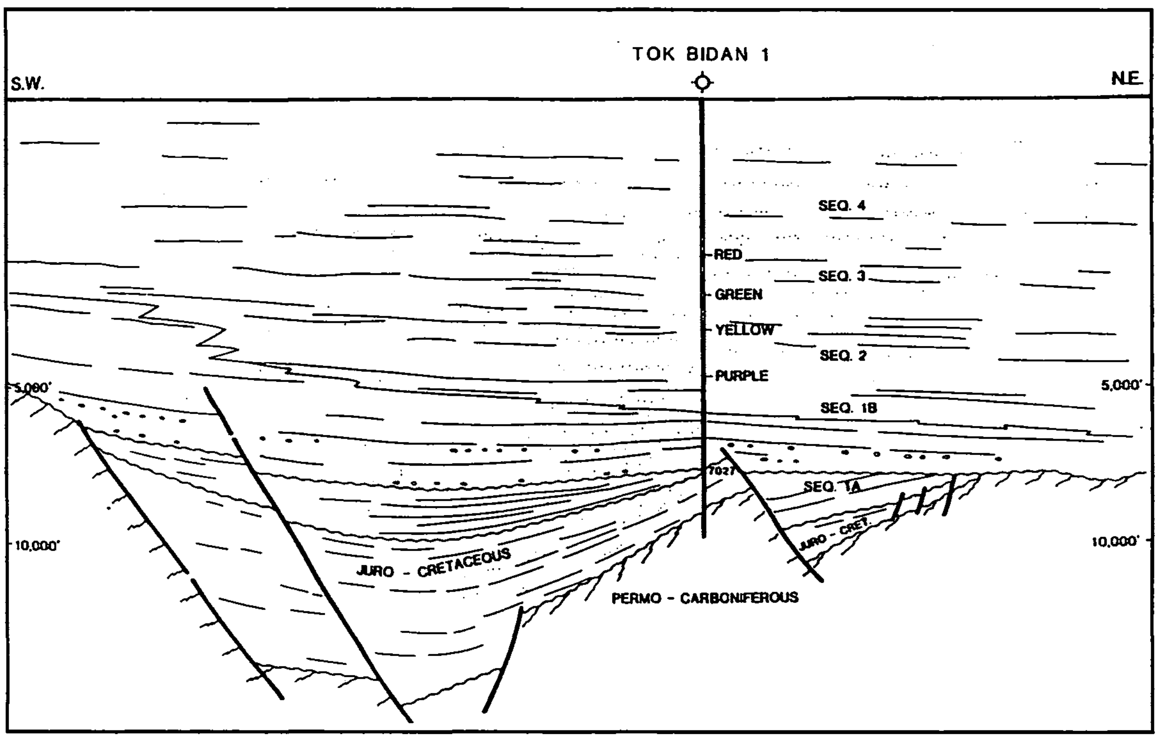

Figure 15. Cross section across Tok-Bidan-1 showing general stratigraphy and structure. Adapted from Lasmo Oil (Malaysia) Ltd., 1990.

sagged in the middle of the graben due to rifting or pull apart of the graben. Progressively towards Lower Oligocene, only the east dipping faults remain active. This continued activation of east dipping faults has further inclined the Permo-Carboniferous basement westward. During Lower Oligocene, the Tok Bidan Graben continues to rift or pull apart. This is shown by the sagging of sequence 1A sediments. An angular unconformity separated sequence 1A (Lower Oligocene) from sequence 1B (Upper Oligocene). After the angular unconformity period, east dipping faults are reactivated again. No faults are seen affecting Miocene sequences.

STRESS SYSTEM

Basement structures

The Tok Bidan Graben is elongated in the 130°–310° direction and lateral movement is believed to be parallel to this direction. The orientation of the rhombic shape of this graben suggests right lateral wrench movement. The compressional direction that formed this graben acted within the 310°–40° sector.

The Dungun Graben is formed by a 145° striking right lateral fault. This right lateral movement along this main fault has created a subsidiary stress system which formed the N-S tensional oblique faults. The compressional direction that formed this graben acted within the 325°–55° sector.

Combining the compression sectors of the shear zone in the northern structural unit (20°–110°), Dungun Graben (325°–55°) and Tok Bidan Graben (310°–40°), the possible compressional direction that acted within the west-central margin of the Malay Basin during pre-Oligocene was within the 20°–40° sector (Fig. 16). However, it must be qualified that it is assumed that all these stress indicators were contemporary structurally active during pre-Oligocene.

Change of stress system

Another method to analyse the stress system within this margin is to select stress indicators for each period and determine the change in stress direction. Tok Bidan Graben is deemed to be stress indicator for ?Jura-Cretaceous, Dungun Graben is for ?pre-Oligocene and left stepping *en echelon* faults within Dungun Graben is for ?Miocene. Figure 17 shows the compressional sector for each stress indicator. The compressional sector for each stress indicator is not the same. If it is assumed that shear will occur 30° (Moody and Hill, 1956) from the maximum horizontal compressional direction, then the maximum horizontal compression direction for ?Jura-Cretaceous is 160°–340°, ?pre-Oligocene is 175°–355° and ?Miocene is 135°–315°. Due to limited stress indicators for each period, the actual maximum compressional direction is doubtful. However, it is certain that there has be changes in maximum compressional direction within this margin since Jura-Cretaceous.

From Jura-Cretaceous to Lower Oligocene, Tok Bidan Graben is under trantensional state (Fig. 18), in which pull-apart or rifting occurred, resulting in the subsidence and tilting of the graben basement. Not much can be interpreted about the stress regime of this graben from Upper Oligocene onwards as stress indicators are lacking. It is debatable whether within this graben, transtensional state occurred continuously or episodically from Jura-Cretaceous to Lower Oligocene.

As for the Dungun graben, there is a transition from a transtensional to a transpressional regime sometime within the Oligocene-Miocene boundary. The nature of this transition is questionable: whether it has occurred gradually or abruptly.

Despite the uncertainty of the nature of the stress system within this margin, it can be concluded that one or more changes of stress direction and stress regime has occurred since Jura-Cretaceous.

The change in the stress system within this margin could be attributed to the changes in the tectonic stress field in Sunda Land during Tertiary. Tjia and Liew (1993) concluded that the varying degrees of interference of plate motions coupled with changes in movement directions and/or rate of the Pacific Plate, Indian Ocean-Australian Plate, and possible expulsion of Southeast Asian crustal slabs following the collision of the Indian Subplate with the Eurasian Plate has caused the changes in the tectonic stress field.

SUMMARY AND CONCLUSIONS

Figure 19 shows that there are characteristic differences between different basement structural units in terms of fault trends, basement contours and geological features. The Northern unit is characterised by faults which are controlled by basement highs. These faults could have been formed during the Jura-Cretaceous and were reactivated during pre-Oligocene. The Central unit shows a convergence of N-S faults and NNW-SSE faults. The N-S faults represent pre-Tertiary faults on onland Peninsular Malaysia. The NNW-SSE faults could have been formed during the formation of the Malay Basin. Regionally, the Central unit represents a zone of fault bifurcation in which the Dungun fault begin to splay from the Hinge Line fault zone (Fig. 20). Within the Southern unit, there is a zone of closely spaced faults (interpreted

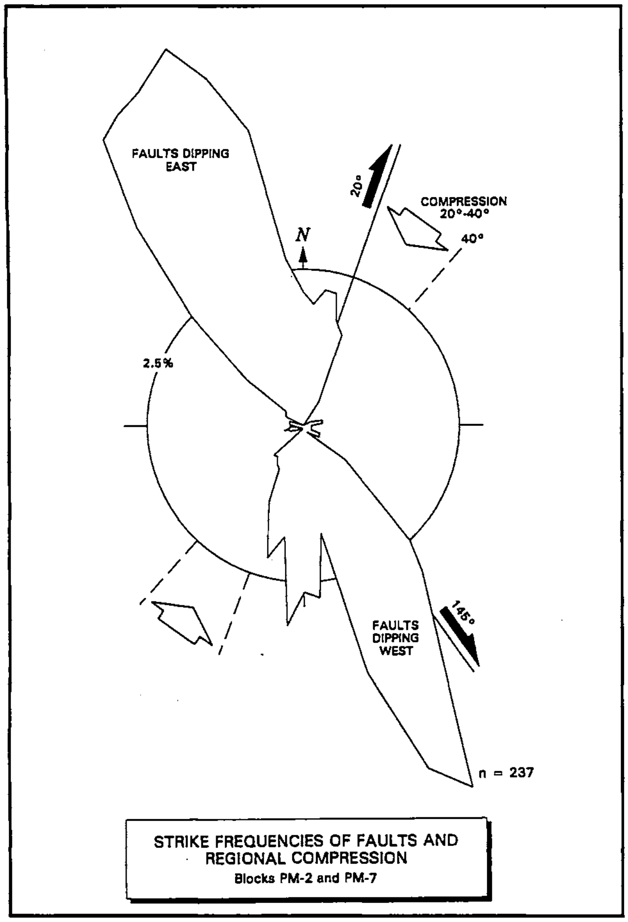

Figure 16. Strike frequencies of faults and regional compression within the west-central margin during pre-Oligocene. Number of readings (n) = 237.

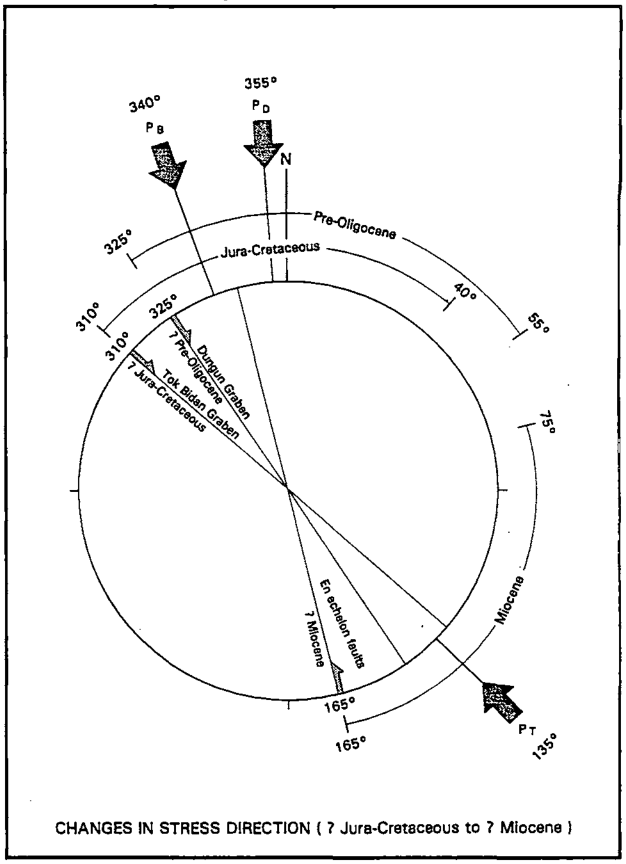

Figure 17. Changes in stress direction since Jura-Cretaceous.

as the Dungun fault — strike NNW-SSE) which is aligned to the Dungun graben (rhomboid pull-apart basin). These structural features could be related to the formation of the Malay Basin during the pre-Oligocene. Compression within the 20°–40° sector acted on the west-central margin of the Malay Basin during pre-Oligocene.

Lateral wrench movement is determined by the structural analysis of Tok Bidan Graben and Dungun Graben. The orientation of the rhombic shape of these two grabens suggested that they were initiated by right lateral wrench movement. Formation of Tok Bidan Graben could be initiated as early as Jura-Cretaceous and was reactivated ?contemporary with the initiation of Dungun Graben. This indicated that right lateral wrench movement was dominant within this margin from ?Jura-Cretaceous to pre-Oligocene. The reversal of wrench movement within this margin is recorded within the ?Miocene sequence in the Dungun Graben. Right stepping *en echelon* faults can be traced faintly to upper most unconformity (?Pliocene) within the graben. However, within the Tok Bidan Graben, such reversal was not shown on time-structure maps. One possible reason for the absence of the indicators of reversal is that Tok Bidan area could be stabilising during Miocene: the Dungun faults could have buffered the changes in stress during Miocene. Maximum horizontal compression direction has been changing since Jura-Cretaceous. The stress regime for both grabens before Oligocene is transtensional. Transpressional state is only observed in Dungun Graben during ?Miocene.

Within the context of the formation of the Malay Basin, the pull apart grabens in the west central margin of the basin may indicate that the Malay Basin formed as a transtensional pull apart basin. The area between the Dungun fault and the Lebir/Lepar fault could represent a structural domain (Fig. 20) within the west margin of the Malay basin. This structural domain could have deformed and/or moved independently from other structural domains during the development of the Malay Basin. As sedimentation is controlled by structural development, the sedimentation pattern within this

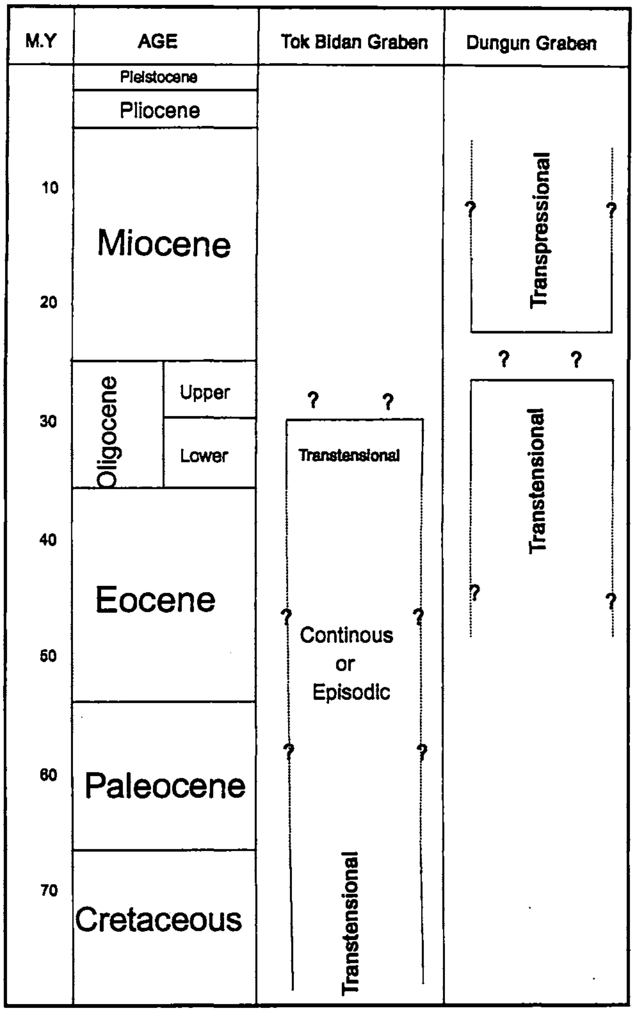

Figure 18. Stress regimes within the Tok Bidan Graben and Dungun Graben since ?Jura-Cretaceous.

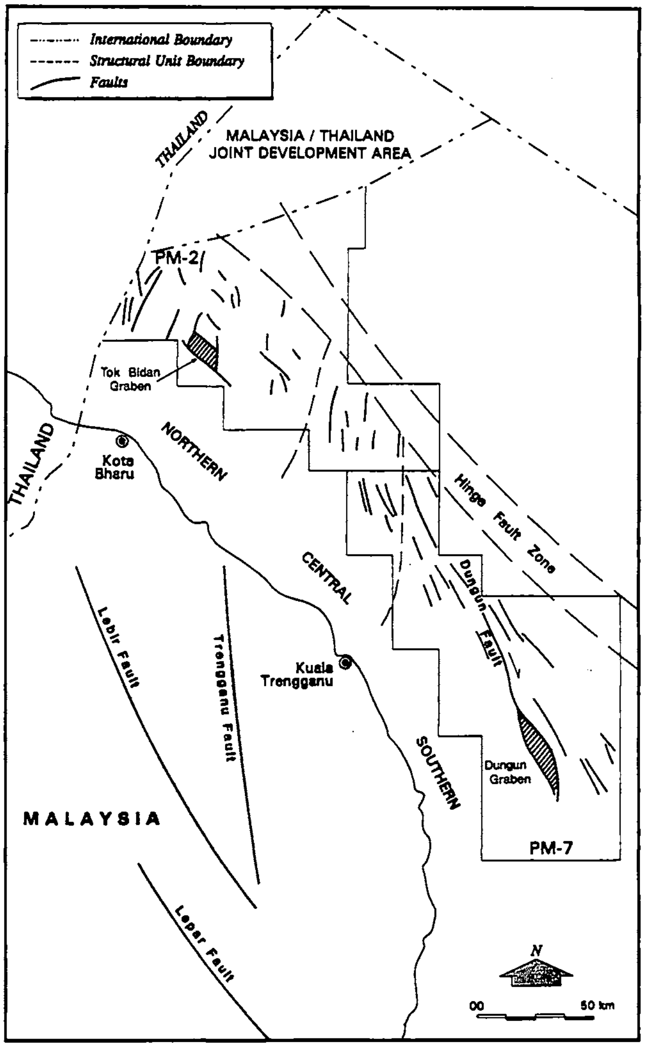

Figure 20. Structural map showing relationship between structural units and major faults in the east coast Peninsular Malaysia.

	NORTHERN UNIT	CENTRAL UNIT	SOUTHERN UNIT
FAULT TRENDS	i) NNE - SSW (More dip ESE) ii) NW - SE	i) N - S (More dip West) ii) NNW - SSE	i) NNW - SSE (More dip ENE) ii) N - S
BASEMENT CONTOUR	Dip NE Structural highs plunges NW and North	Dip NE and ENE Steeper than other units	Dip ENE Convex slope
INTERESTING GEOLOGICAL FEATURES	Right lateral shear zone - 20° Tok Bidan Graben	Structural transition zone between Northern and Central unit	Dungun fault Grabens - small pull apart basins by right lateral shear - 45°
TERTIARY BASEMENT FORMATION	Tertiary basement interpretated to be Lower Oligocene		
REGIONAL COMPRESSION	20° - 40° (NE - SW sector)		

Figure 19. Summary of the characteristics of basement structural units within the west-central margin of the Malay Basin.

domain could differ considerably from other domains in the Malay Basin. Hence, hydrocarbon prospectivity could be different.

The reversal of wrench movement within this margin is ?contemporaneous with the inversion tectonics in the Malay Basin. Tjia (1993) has documented new evidence of inversion tectonics in the Malay Basin and concluded that the changing regional compressional of Miocene time has caused the inversion. During Miocene, the Pacific Plate changed motion from an earlier NNW direction to a westward direction. This change was recorded by the change in the trend of Emperor Seamount and Hawaiian Ridge at 43 Ma. Coupled with the northward progression of the Indo-Australia Plate, the stress system within the Malay Basin was changed during Miocene.

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