

Structural patterns within the Tertiary basement of the Strait of Malacca

LIEW KIT KONG

Petronas Research & Scientific Services Sdn. Bhd.
Lot 1026, PKNS Industrial Estate
Ulu Kelang, 54200 Kuala Lumpur

Abstract: The Tertiary basement of the Strait of Malacca (Malaysian waters) slopes gently towards southwest. Northerly trending grabens have been mapped within the basement at discrete locations. These grabens, from south to north, are Kukup Graben, Johor Graben, Port Klang Graben, Angsa Graben, Sabak Graben, Southern Graben, Central Graben, Eastern Graben, East Penang Graben, West Penang Graben, North Penang Graben, MSS-XA Graben, and Northern Graben. The maximum depths of these grabens range from 900 metres to 4,000 metres. The Tertiary basement topography of some grabens has been altered by structural modification during ?Late Miocene. These grabens can be grouped into (1) Bengkalis Trough related grabens, (2) Pematang-Balam Trough related grabens, (3) Asahan Arch-Kepulauan Aruah Nose related grabens and (4) Tamiang-Yang Besar High related grabens. These graben groupings are situated between regional highs. These graben groupings are also elongated in northerly direction and may represent regional fracture zones. The zones are initiated during Lower Oligocene by right lateral shearing in the NW-SE direction.

INTRODUCTION

Regional structures within Peninsular Malaysia and northeastern Sumatra trend northerly. However, the Malaysia/Indonesia (Sumatra) international boundary which trends NW-SE, has limited the knowledge of the extension of these regional structures. Structural continuity between these two areas are often extrapolated. There are information gaps within the Strait of Malacca as published information about the geology of the Strait is limited. This paper attempts to provide some information about the Tertiary basement of the Strait of Malacca (Malaysian waters). The Tertiary basement referred in this study is the seismic basement or the economic basement as seen in seismic sections.

The Strait of Malacca (Malaysian waters) has been demarcated as PM 1 and PM 15 exploration blocks by PETRONAS (Fig. 1). Sun Malaysia Petroleum Company surveyed both blocks and had relinquished both blocks in 1992.

Stratigraphic schemes (Fig. 2) utilised by the operator are similar to those of the North Sumatra Basin (for PM 1) and the Central Sumatra Basin (for PM 15). It is believed that sedimentation within both blocks is related to these greater basins. The Tertiary basement (referred to the seismic basement) is interpreted to be the base of Upper Oligocene. Tertiary sedimentation in PM 1 (north

western margin area) began in a terrestrial environment with lacustrine to lagoonal shales (Bampo formation). Holomarine to inner neritic condition (Belumai formation) was established during Lower Miocene with carbonate reefs build-up on existing structural highs. Influx of coarse clastics in the middle Miocene marked the deposition of the Baong formation. The top of Baong formation is the Upper Miocene unconformity. Regional transgression has resulted in Post Baong sedimentation within a shallow marine environment (Murray, 1991). Within PM 15 grabens, three major stratigraphic sequences are identified: (1) Early graben fill which comprises lacustrine sediments (Pematang equivalent) (2) middle to late graben fill of fluvio-lacustrine deltaic sediments (Sihapas equivalent) and, (3) post-graben fill (Petani/Minas equivalent) with sediments of marine influence. They are separated by unconformities (Wong, 1990).

The objective of this study is to determine the structural patterns within the Tertiary basement of the Strait of Malacca (Malaysian waters) and attempt to relate these patterns to regional structures. To achieve these objectives, structural interpretation is performed on structural maps produced by Sun Malaysia Petroleum Co. These maps are scaled from 1:50,000 to 1:500,000. Geological reports (in-house, unpublished and published) regarding this region are also compiled.

REGIONAL ELEMENTS

Asahan Arch is a northerly trending regional basement high that separates the North Sumatra Basin from the Central Sumatra Basin (see Fig. 1). This arch probably extends to the west of Central Graben in PM 1. Based on sediment fill within the grabens, Murray (1991) interpreted that grabens

east of the Asahan Arch are associated with the Central Sumatra Basin and those west of the arch are associated with the North Sumatra Basin. In this paper, grabens association is based on Murray's (1991) criterion.

Grabens or depressions west of the Asahan Arch overlie the Mergui Mircoplate (see Pulunggono and Cameron, 1984). Most of the area consists of

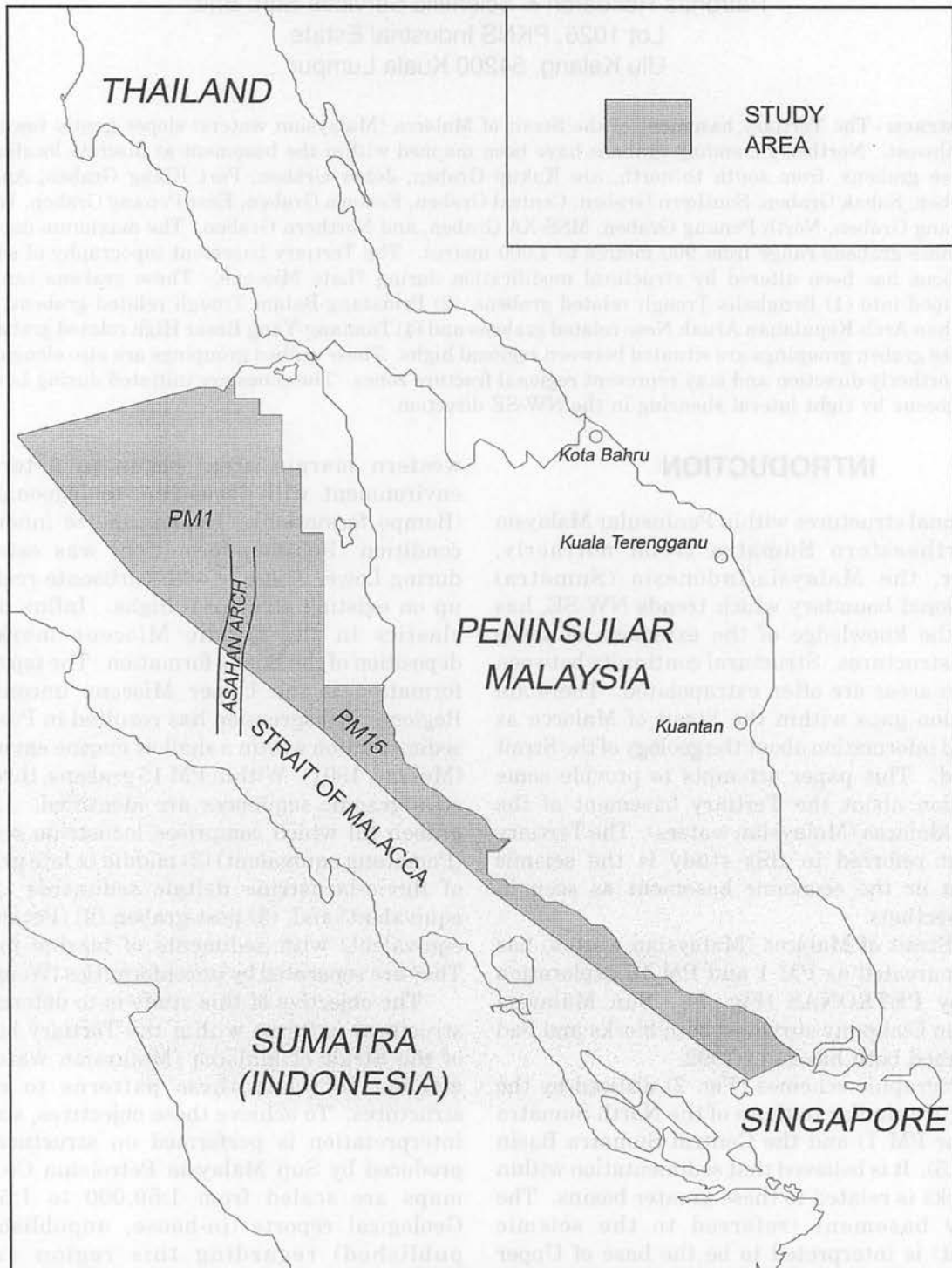


Figure 1. General location of the study area (PM 1 & PM 15). The area is within Malaysian waters of the Strait of Malacca.

shallow-depth pre-Tertiary basement which slopes gently in southwest direction. Thicker Tertiary sediments are located at the northwest margin of PM 1. Its north west margin area lies on the eastern shelfal (Malacca Platform) extension of the North Sumatra Basin (Fig. 3). Grabens east of the Asahan Arch are bounded by the Pre-Tertiary

basement outcropping onshore Peninsular Malaysia to the northeast and the Kuantan High to the south east. Kepulauan Aruah Nose, Sembilan High and Bengkalis Trough are located on the south west margin of these grabens (Fig. 4). Most of this area also slopes gently in southwest direction.

M.Y	AGE		PM 1		PM 15		
			Formation	Sedimentary Environments	Formation	Sedimentary Environments	
10	Pleistocene		Post Baong	Coastal to Inner neritic	Minas Equivalent	Shallow marine to Lower coastal plains	
	Pliocene			Middle neritic			
	20	Miocene	Upper	Inner neritic	Petani Equivalent	Lacustrine to Fluvio-Deltaic	
			Middle	Baong	Coastal to Inner neritic		
		Oligocene	Lower	Belumai	Holomarine Inner neritic		?
			Upper	Bampo	Continental at the base and marine towards the top		Pematang Equivalent
	30	Eocene	Lower	Parapat			
			Tampur				
	40	Eocene					
50	Eocene						
60	Paleocene						
		Basement (Undifferentiated)		Basement (Undifferentiated)			

Figure 2. Generalised stratigraphic schemes of PM 1 and PM 15 utilised by operator. These schemes are similar to those used in North Sumatra Basin and Central Sumatra Basin, respectively. Adapted from Murray (1991) and Wong (1991).

GRABENS ASSOCIATED WITH NORTH SUMATRA BASIN

Davies (1984) described the Tertiary structural evolution of the North Sumatra Basin as a consequence of its position along the trailing edge of the counter-clockwise rotating "Sunda Mircoplate". He elaborated that from Eocene to Lower Oligocene, the Sunda Mircoplate and the Indian-Australia Plate converged at high acute angle. The convergence of these Plates has generated northward propagating, dextral overstepping wrench faults along the western edge of the continental mircoplate. The configuration of the present North Sumatra Basin was a consequence of the geometrical inter-relationship of these wrench fault systems.

The grabens west of the Asahan Arch are on the eastern shelfal (Malacca Platform) extension of the North Sumatra Basin. These grabens lie in the northern part of the Strait of Malacca, offshore western Peninsular Malaysia. Geologically, they are situated on the northeast part of the Tampur

Platform of the North Sumatra Basin. The northerly trending Tamiang High and Yang Besar High of the Tampur Platform extend into this grabenal area (see Fig. 3).

Grabens in this area are generally northerly trending with the bounding fault to the east. The major depocentre lies to the west in Indonesian waters and the grabens become progressively shallower towards the east (Murray, 1991). Two of the larger grabens are Northern and MSS-XA graben. Basement surface in this area inclines gently towards southwest and faults trend NE-SW (Fig. 5). Across the international border towards Sumatra, the basement surface becomes variable and basement highs are elongated in N-S or NNW-SSE direction.

NORTHERN GRABEN

The NNE elongated Northern Graben is situated near the western margin of PM 1 Block and near the Malaysia/Indonesia international boundary. Basement contour deepens towards SW.

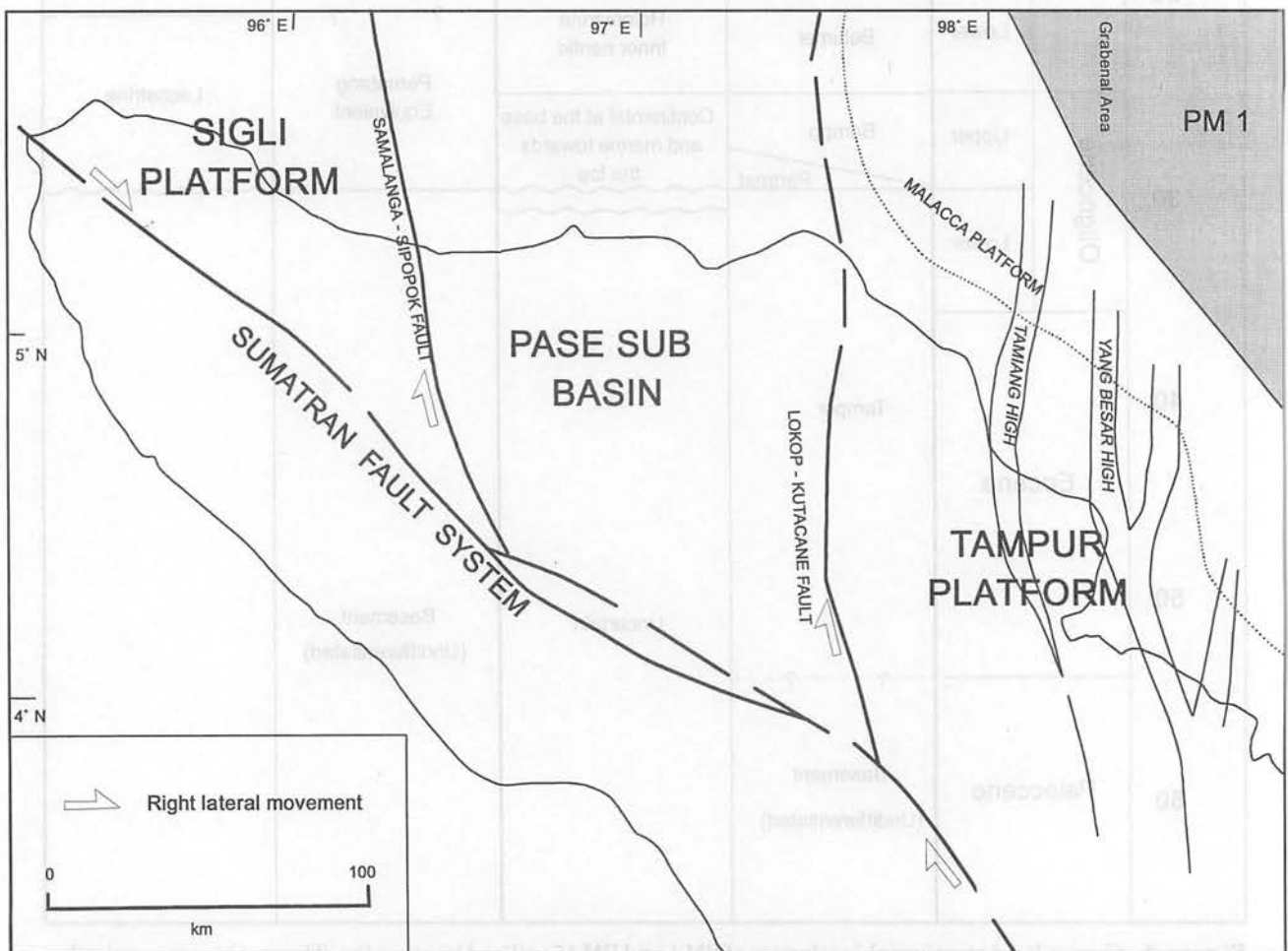


Figure 3. Tectonic elements of North Sumatra Basin. Three main tectonic elements are Tampur Platform, Pase Sub Basin and Sigli Platform. PM 1 is situated on the Malacca Shelf. Adapted from Sosromihardjo (1988).

Faults mapped in this graben trend north and NE, and are interconnected. Most major faults are located on the eastern flank of this graben. The size of this graben is estimated to be 20 km x 10 km. The maximum depth of this graben is 2,400 metres (Fig. 6).

Two unnamed depressions have been mapped 90 km west of Pulau Langkawi. These depressions are elongated in the north direction. Faults bounding these depressions are north and NE

trending. Depression c deepens eastward and depression d deepens westward. The length of these grabens is about 30 km (see Fig. 5).

MSS-XA Graben

This half graben is elongated in NNE direction with a major fault demarcating its eastern margin. This NNE fault is 40 km long. Basement deepens towards east. The maximum depth of this graben is 2,600 metres (see Fig. 6).

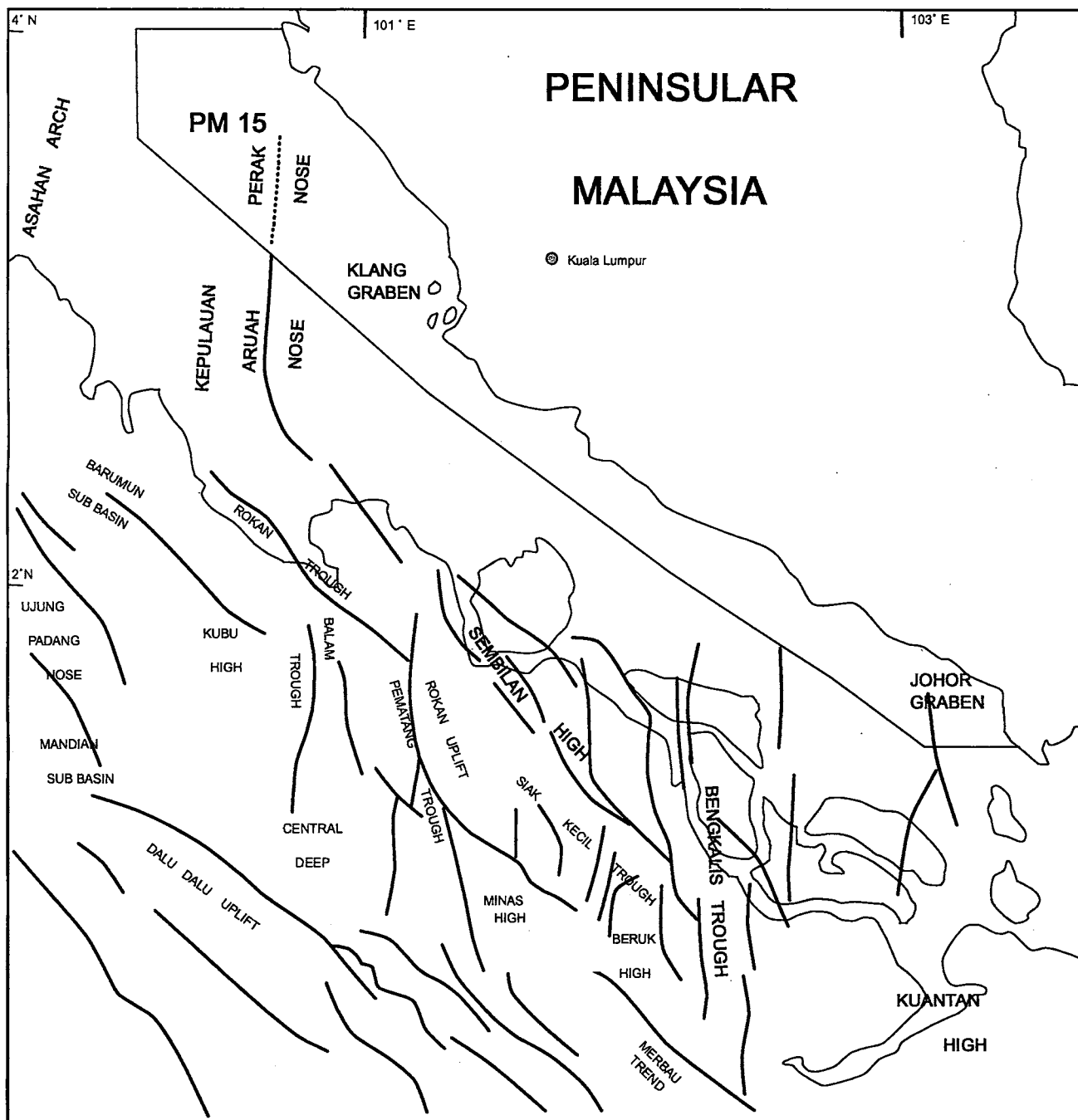


Figure 4. Tectonic elements of Central Sumatra Basin. Note the N-S and NW-SE orientation of regional Highs and Troughs. Kepulauan Aruah Nose is named as Perak Nose in Malaysian waters. Adapted from BEICEP (1985) in Greenway and Goh (1989).

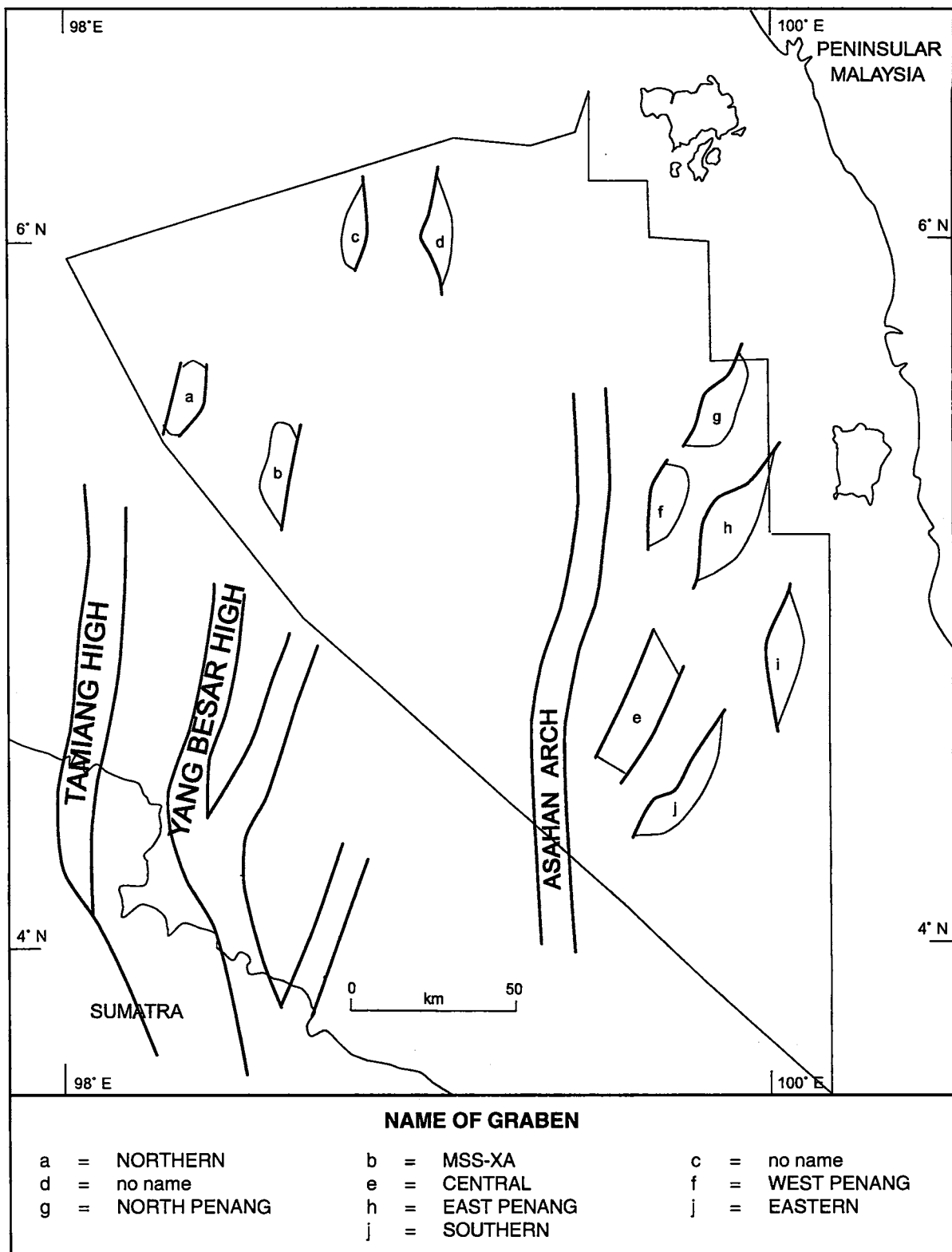


Figure 5. Northerly trending grabens in PM 1. Tamiang high and Yang besar High extend into grabenal area. Simplified from graben summary map from Dyer *et al.* (1991) and Sosromihardjo (1988).

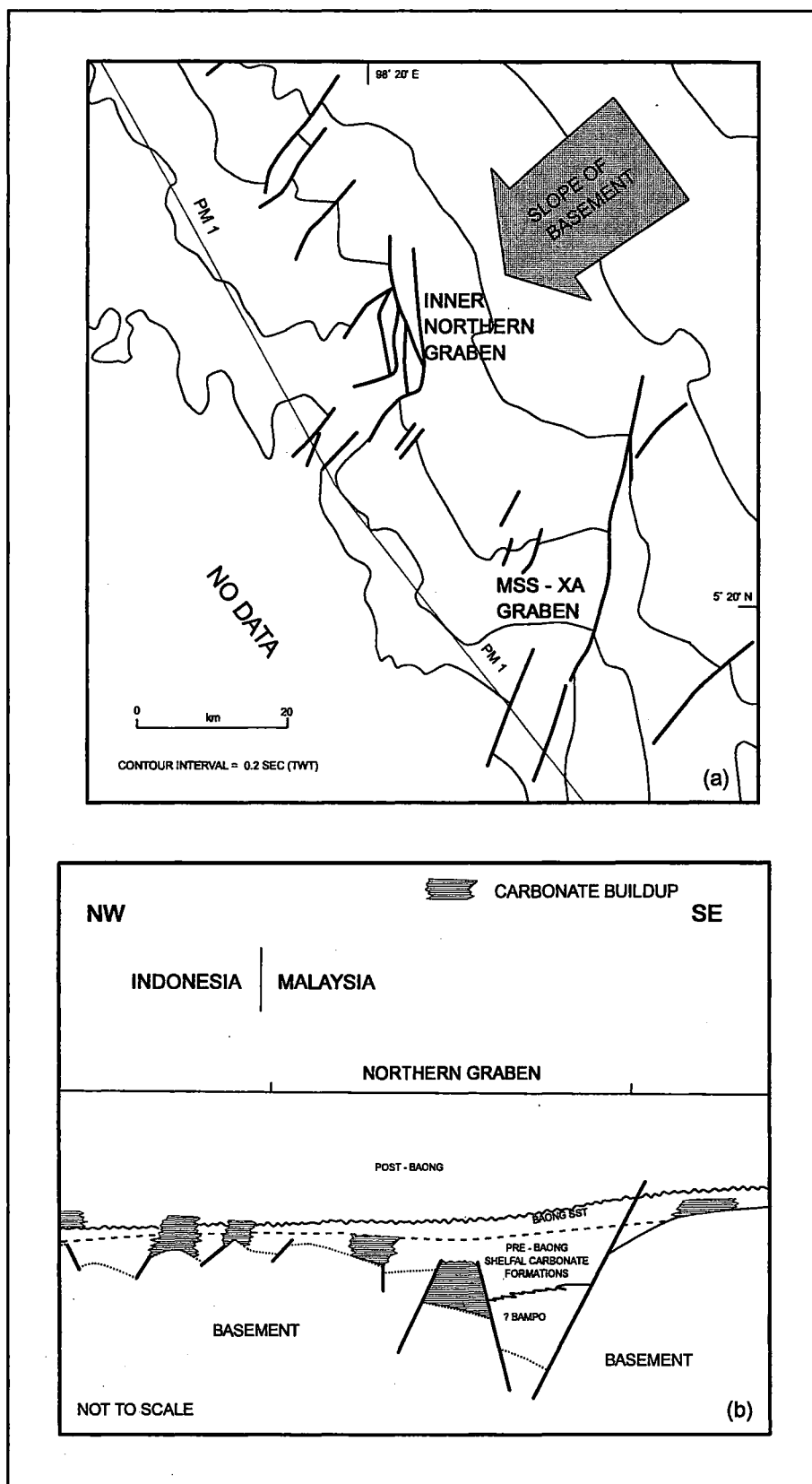


Figure 6. (a) Inner Northern Graben with interconnected N-S and NE-SW faults on the eastern flank. Extracted and simplified from basement time structure map of Sun Malaysia Petroleum Co. (1989). (b) Schematic cross section of Northern Graben. Major faults are located at the eastern margin of the graben. Carbonate build-ups at local highs. Section simplified from Sun Malaysia Petroleum Co. (1989).

GRABENS ASSOCIATED WITH CENTRAL SUMATRA BASIN

The Central Sumatra Basin is one of a series of back arc basins developed linearly along the leading edge of the Sunda Platform, as a result of the subduction of the Indian Ocean Plate beneath the Southeast Asian Plate. This basin was formed during the east-west extension in Late Cretaceous/Early Tertiary (Daly *et al.*, 1987).

The grabens east of the Asahan Arch are believed to be the north eastern extensions of the Central Sumatra Basin. These grabens lie in the southern part of the Strait of Malacca. They occupy the north-eastern margin of the Central Sumatra Basin.

Five main grabens (Central, Sabak, Angsa, Port Klang and Johor) are believed to be structurally and genetically similar to those of Central Sumatra Basin. The structural styles within these grabens are characterised by Eocene to early Miocene east-west extension related to rifting and graben formation, followed by late Miocene (or ?Pliocene) compression and uplifting, resulting in structural inversion, change in basin depocentre and formation of structural traps. Wong (1990) suggested that this very active NE-SW compression formed most of the present day structures with fold axes generally paralleling the underlying NW-SE basement grain. The Johor Graben appears to have undergone a relatively more severe compression phase during late Miocene-Pliocene time as indicated by intense faulting and uplift.

CENTRAL GRABEN

This graben is the largest mapped graben in PM 1. It is situated about 80 km southwest of Pulau Pinang. Geologically, it is located to the east of the intersection of the Malacca Platform and the Asahan Arch. The length of this graben is about 60 km and the width is about 20 km. Variable topography characterises the basement of Central Graben. Numerous depocentres within this graben are elongated NE-SW. Major faults demarcating the limit of the graben are NE-SW trending whereas faults within the graben are north-south trending. The deepest part of this graben is estimated to be over 4,000 metres. Basement surrounding this graben is about 550 msec deep (Fig. 7a). Compressional features such as folding of sedimentary sequences and ?wrench-faulting have affected the basement and younger sequences (Fig. 7b). These features indicated that basement topography has structural overprint.

Structurally, this graben can be divided into a number of sub-basins which have the appearance

of full or half grabens. Murray (1991) interpreted that these features are formed during a phase of extension in the Oligocene, with later structural modification due to right lateral wrenching in the late Miocene.

A NNE half graben (Eastern Graben) is mapped 30 km east of Central Graben. A curvilinear NNE fault major bounded the western margin of this graben. This fault is about 35 km in length. The maximum depth of this graben is 970 metres. Basement slopes westward (see Fig. 5).

Three grabens are mapped north of Central Graben; East Penang Graben, North Penang Graben and West Penang Graben. These grabens are probably the northward extension of the Central Graben. These grabens are situated about 30 km west of Pulau Pinang. The maximum depths of these grabens are range from 900 metres to 2,800 metres. Basement of all these grabens slopes down westward with a major fault demarcating its western margin. These curvilinear faults control the size of these grabens and are parallel to the elongation of the grabens. The length of these faults range from 20 km to 55 km. East Penang Graben and North Penang Graben are elongated in the NE direction whereas West Penang Graben is elongated in the north direction (see Fig. 5).

SOUTHERN GRABEN

This NE-SW elongated half graben is situated 90 km west of Pulau Pangkor. A major SE downthrowing fault demarcates the western margin of this graben. This fault has a length of 50 km, a maximum heave of 2.5 km and a vertical throw of 800 msec. The graben deepens towards NW, reaching a depth of more than 2,300 metres. The length of this graben is controlled by the major fault and maximum width of this graben is 20 km. Faults parallel to the major fault are found within the graben (Fig. 7a).

SABAK GRABEN

This curvilinear N-S graben is situated 25 km south of the Sg. Bernam mouth. The Kepulauan Aruah Nose is located west of this graben. A major fault is located on the western margin of this graben. The maximum depth of this graben is about 2,400 metre (Fig. 8). There are two depocentres within this graben. They are separated by north trending faults. The southern depocentre is elongated NNW and has been mapped seismically. This depocentre occupies an area of 35 km x 15 km. The northern NNE trending depocentre has been defined by bouguer gravity anomaly. This northern depocentre is estimated to be about 1,500 metres deep.

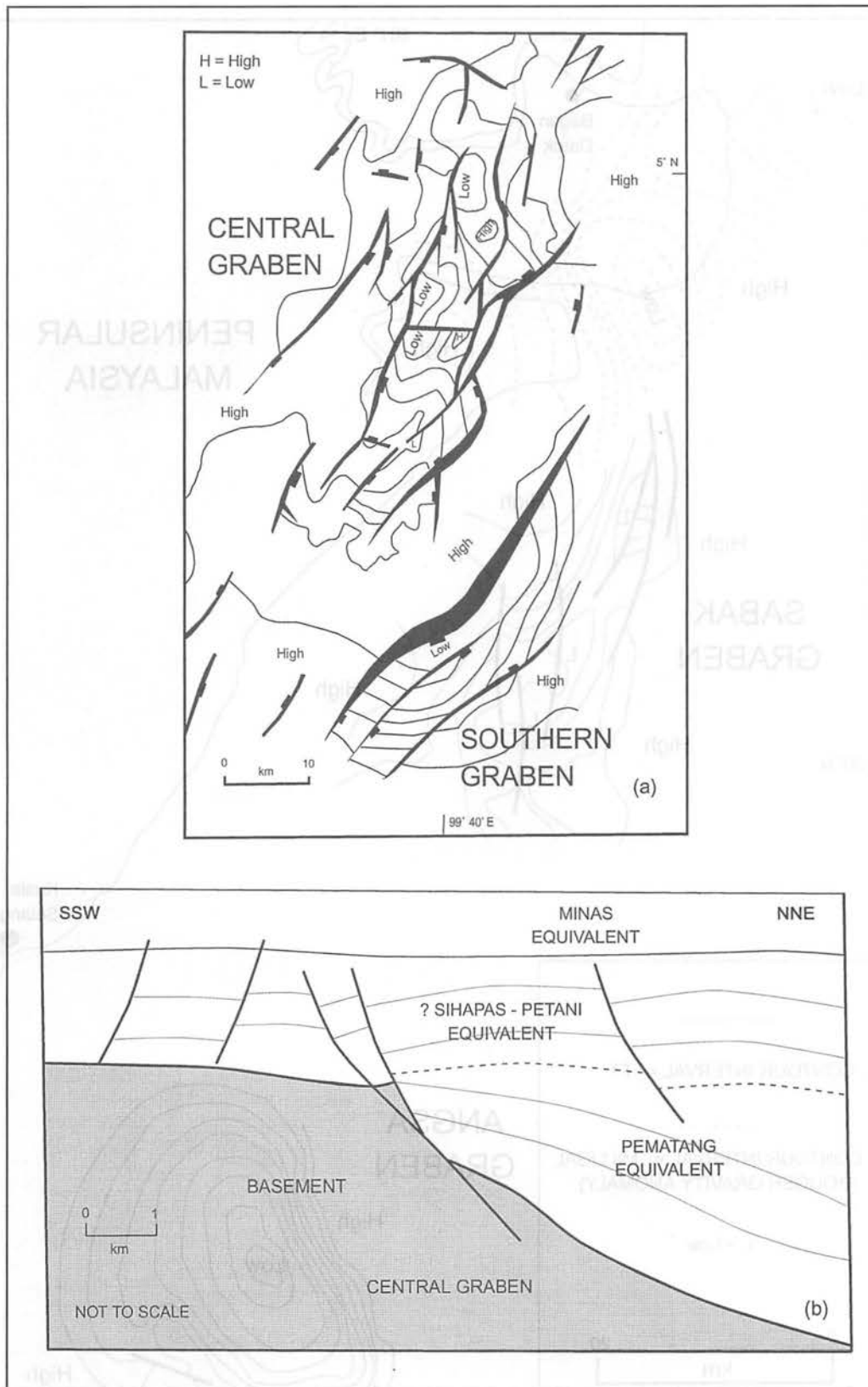


Figure 7. (a) Central and Southern Graben. The basement of Central Graben has variable topography. NE-SW elongation of numerous depocentres. Major faults demarcating the limit of the graben are NE-SW trending. Faults within the graben are north-south trending. Southern Graben has a major bounding fault on the western margin. Extracted and simplified from basement time structure map of Sun Malaysia Petroleum Co. (1989). (b) Simplified geoseismic cross section of the southern part of Central Graben. Basement topography is altered by later structural modification. Simplified from Dyer *et al.* (1991).

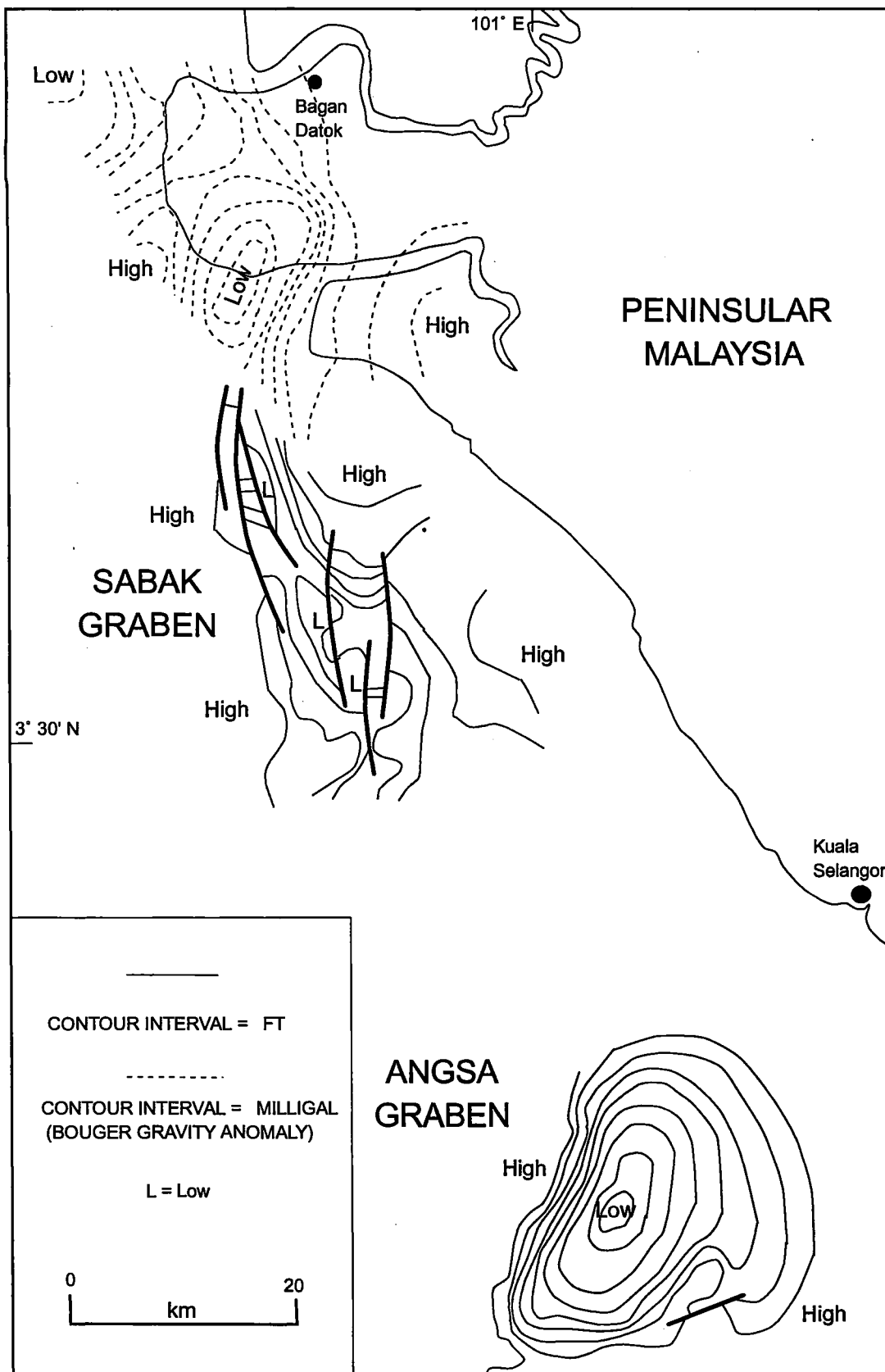


Figure 8. Simplified basement outline of Sabak Graben. The basement outline is curvilinear. The southern part of the graben is defined by seismic whilst the northern part is defined by Bouguer gravity anomaly. The oval Angsa Graben is south of Sabak Graben. Note the difference in graben geometry between these two grabens. Extracted and simplified from basement map of Wong (1990).

ANGSA GRABEN

Angsa Graben is oval in shape with a NNE trending fault bounding its western margin. This graben is situated between the Sabak Graben (see Fig. 8) and the Port Klang Graben (see Fig. 9a). It is located 20 km west of Pulau Ketam. Contours on western margin are aligned in NNE direction whereas contours on the eastern margin are convex towards ENE. This graben deepens towards west. The depth of the basement is estimated to be 3,600 metres. Diameter of this graben is approximately 25 km. Offshore gravity data indicate a possible extension of the Angsa Graben into the Angsa Bank area. Basement has tilted to the west after the deposition of ?Petani Formation (Plio-Pleistocene) (Fig. 9b).

PORT KLANG GRABEN

This NNW-SSE elongated graben is situated approximately 25 km west of Bukit Jugra. The axis of this graben extended across the Malaysia/Indonesia international boundary, reaching a length of approximately 80 km. The average width of this graben is 15 km. The NNW-SSE elongated depocentre is approximately 3,600 metres deep. N-S faults have transected the depocentre of this graben. Normal faults have been mapped on the eastern and western flanks of the graben. The eastern flank of this graben is steeper than the western flank. Higher curvature is observed on contours of the western flank of the graben. The higher linearity of the contour on the eastern flank suggest that a major fault has bounded the eastern margin of this graben and the graben deepens towards east (Fig. 10a). Offshore gravity data suggest that the Port Klang Graben may extend in northeast direction into the islands offshore Kuala Selangor. Basement topography is altered by later structural events. Wrench faulting with flower structure is observed in this graben (Fig. 10b).

Separated by a N-S elongated basement high on the western margin of Port Klang graben, is a NNE-SSE oriented depression. This depression is also bounded by a major fault on the east margin. This depression deepens towards east, reaching a depth of 1,700 msec. This depression and Port Klang graben could be structurally related. These two structural features are located on the eastern flank of Kepulauan Aruah Nose, a regional basement high (Fig. 10a).

JOHOR GRABEN

The Johor Graben is situated approximately 20 km west of Pulau Pisang. This graben is elongated

in NNE-SSW direction and is bounded by curvilinear faults which progressively change northward from NNE to N. The graben deepens towards ESE, reaching a depth of 3,300 metres (Fig. 11a). Numerous curvilinear step faults have been mapped on the western boundary of this graben. Seismically, this graben is approximately 15 km wide along its axis and 10 km wide across its bounding faults. Bouguer gravity suggests that the deposition area of this graben could be extended landward into the Batu Pahat-Air Hitam area. On land, the probable extension of the Johor Graben is elongated in NW-SE direction and is parallel to the axis of the granite bodies in Johor. Flower structures and folded younger sedimentary sequences within this graben indicate a structural overprint on the basement topography (Fig. 11b).

East of the Johor Graben, in the vicinity of Pulau Kukup, Kukup Graben is mapped. This graben represents a N-S half graben with a major fault on the eastern side of the graben. Geometrically, this graben could be structurally related to the Johor Graben (Fig. 11a).

DISCUSSION

Based on the spatial relationship between the grabens and regional elements, these grabens are grouped as follow: (1) Bengkalis Trough related grabens, (2) Pematang-Balam Trough related grabens, (3) Asahan Arch-Kepulauan Aruah Nose related grabens and (4) Tamiang-Yang Besar High related grabens.

Bengkalis Trough related grabens include Johor Graben and Kukup Graben. These grabens are situated about 60 km east of the N-S trending Bengkalis Trough. Both grabens are aligned to the NNE direction (Fig. 12b). Tjia (1988, 1989) suggested that in late Cretaceous-early Tertiary time, the Bengkalis segment of the Bentong-Bengkalis suture experienced normal faulting that created the depression. Lateral faulting occurred in the Oligocene (?) and the Miocene. Pleistocene NW striking reverse faults are superimposed upon earlier trends. Wong (1990) believed that the Johor Graben is genetically related to the Bengkalis Trough in Central Sumatra. This graben could have developed as a side graben of the Bengkalis Depression (see Moulds, 1989).

Pematang-Balam Trough related grabens are Port Klang Graben, Angsa Graben and Sabak Graben. These grabens are situated north of the N-S trending Balam Trough and Pematang Trough and could be the northern extension of the Troughs. Kepulauan Aruah Nose is situated west of these grabens. These grabens are aligned in NNW direction. Port Klang Graben and Sabak Graben

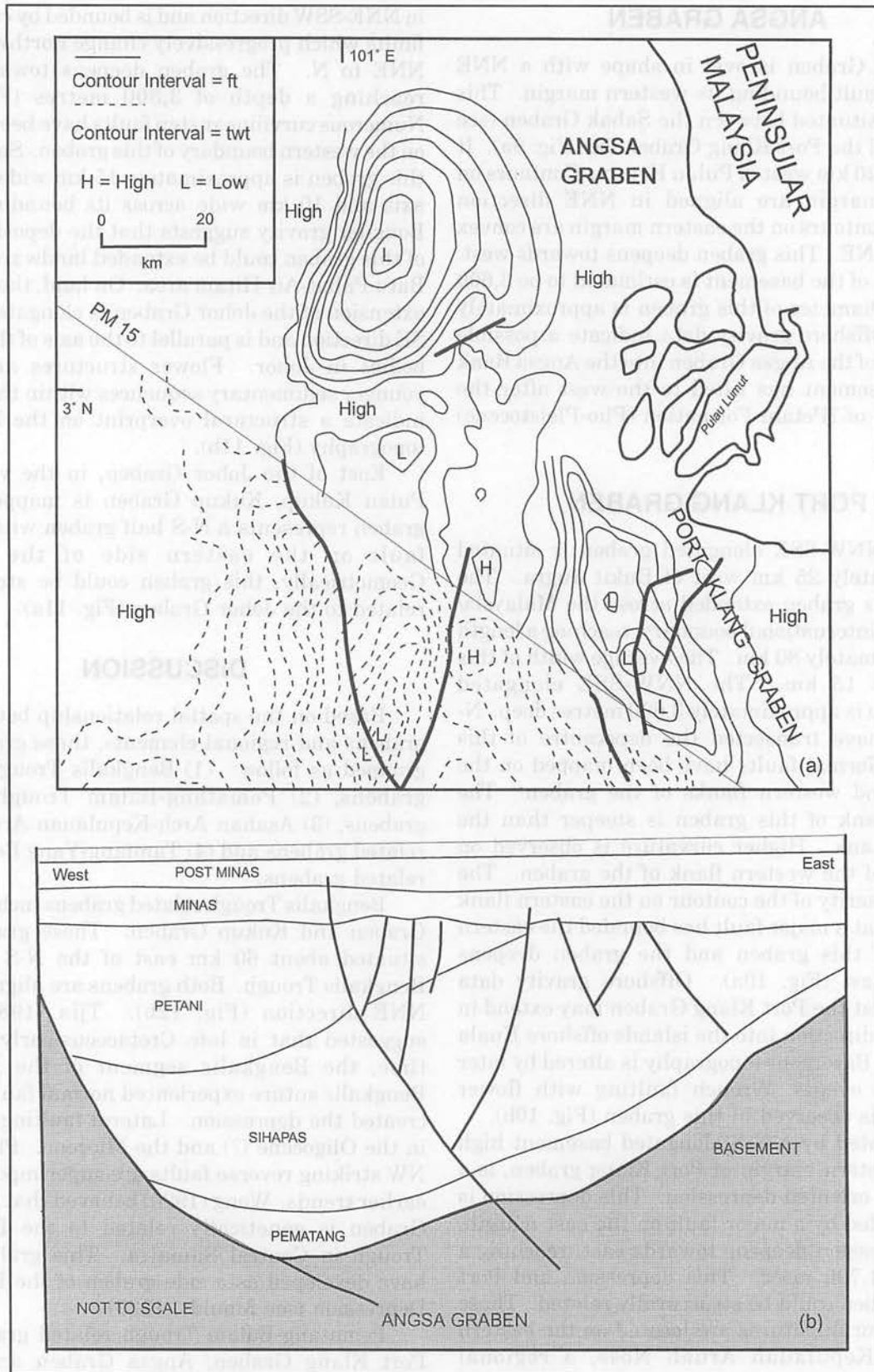


Figure 9. (a) Simplified basement outline of the oval Angsa Graben. The steep contour on the western margin suggest a major bounding fault. Port Klang Graben is south of Angsa Graben. Note the difference in graben geometry between these two grabens. Extracted and simplified from basement map of Wong (1990). (b) Simplified geoseismic cross section of the Angsa Graben. Basement tilted westward after deposition of Petani Formation. Major faults dip east with smaller antithetic faults dip west. Simplified from Wong (1991).

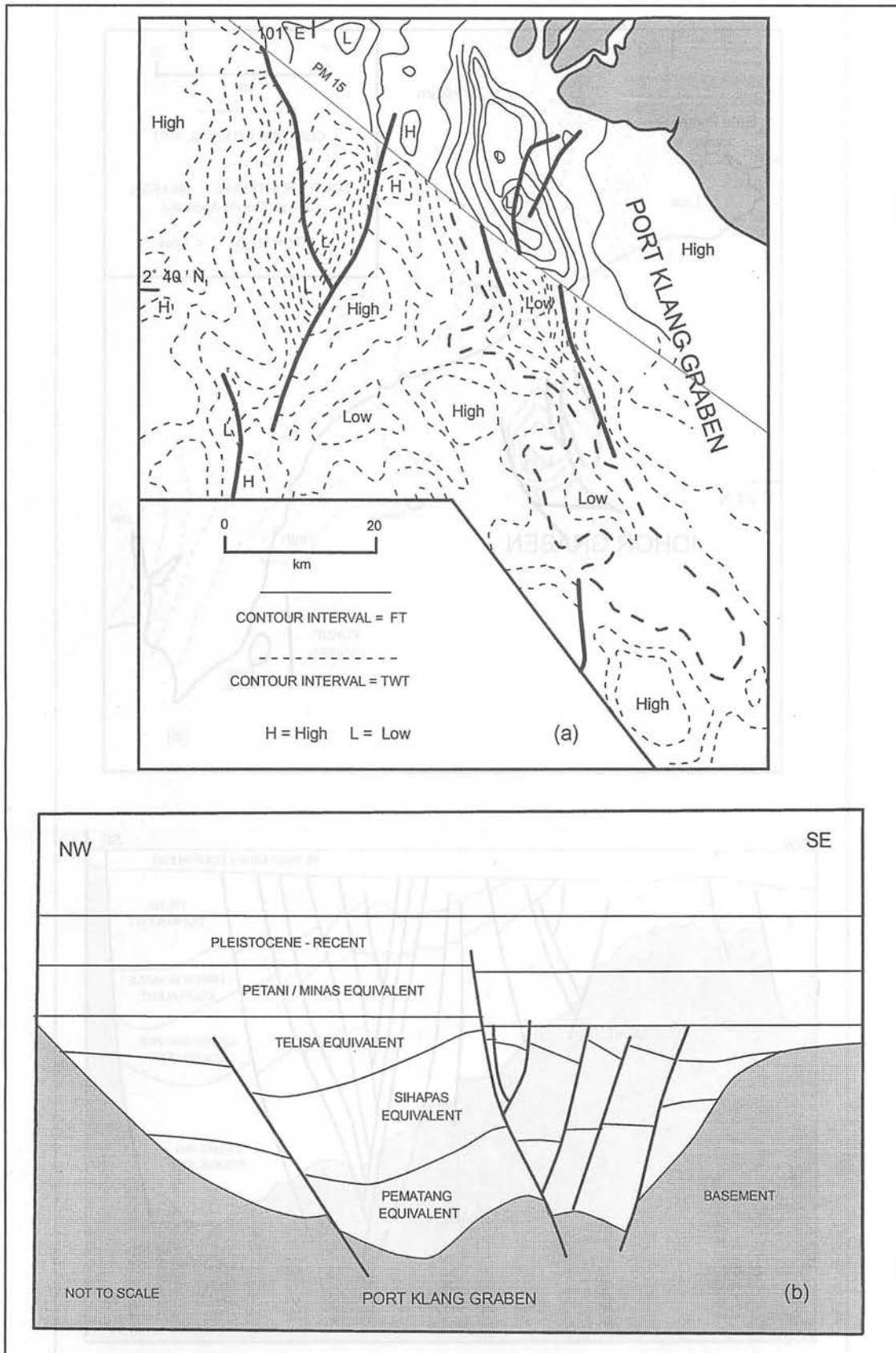


Figure 10. (a) Simplified basement outline of Port Klang Graben. The steep contour on the eastern margin suggest a major bounding fault. To the west is a similar elongated graben. Extracted and simplified from basement map of Wong (1990). (b) Generalised cross section of Port Klang Graben. Negative flower structures and folded younger sedimentary sequences indicated later structural overprint on the basement topography. Simplified from Wong (1991).

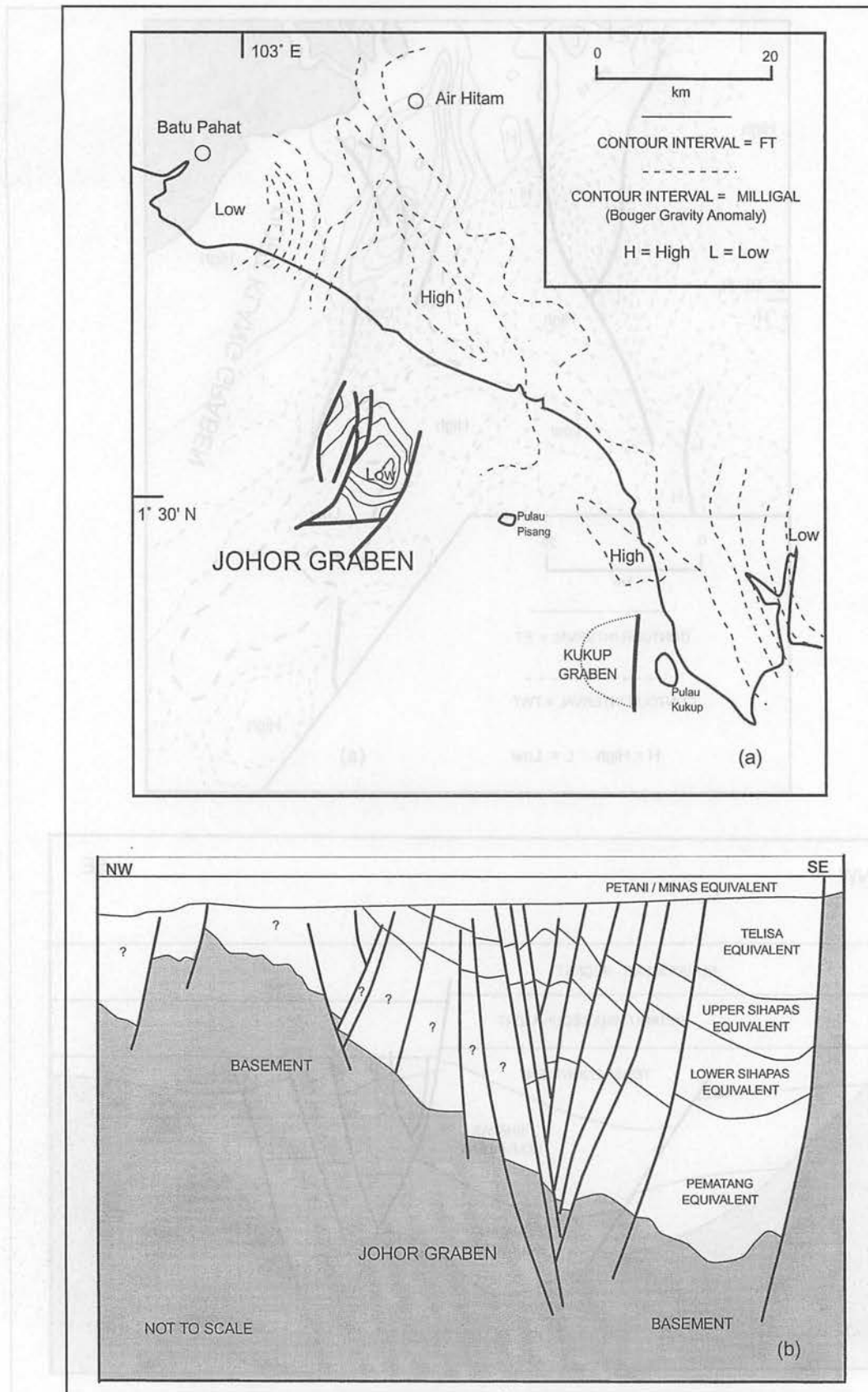


Figure 11. (a) Simplified basement outline of Johor Graben. Graben may extend onshore into the Batu Pahat-Air Hitam area. Extracted and simplified from basement map of Wong (1990). (b) Simplified geoseismic cross section of the Johor Graben. Basement slopes east. Flower structures and folded younger sedimentary sequences indicated modification of basement topography by later structural event. Simplified from Wong (1990).

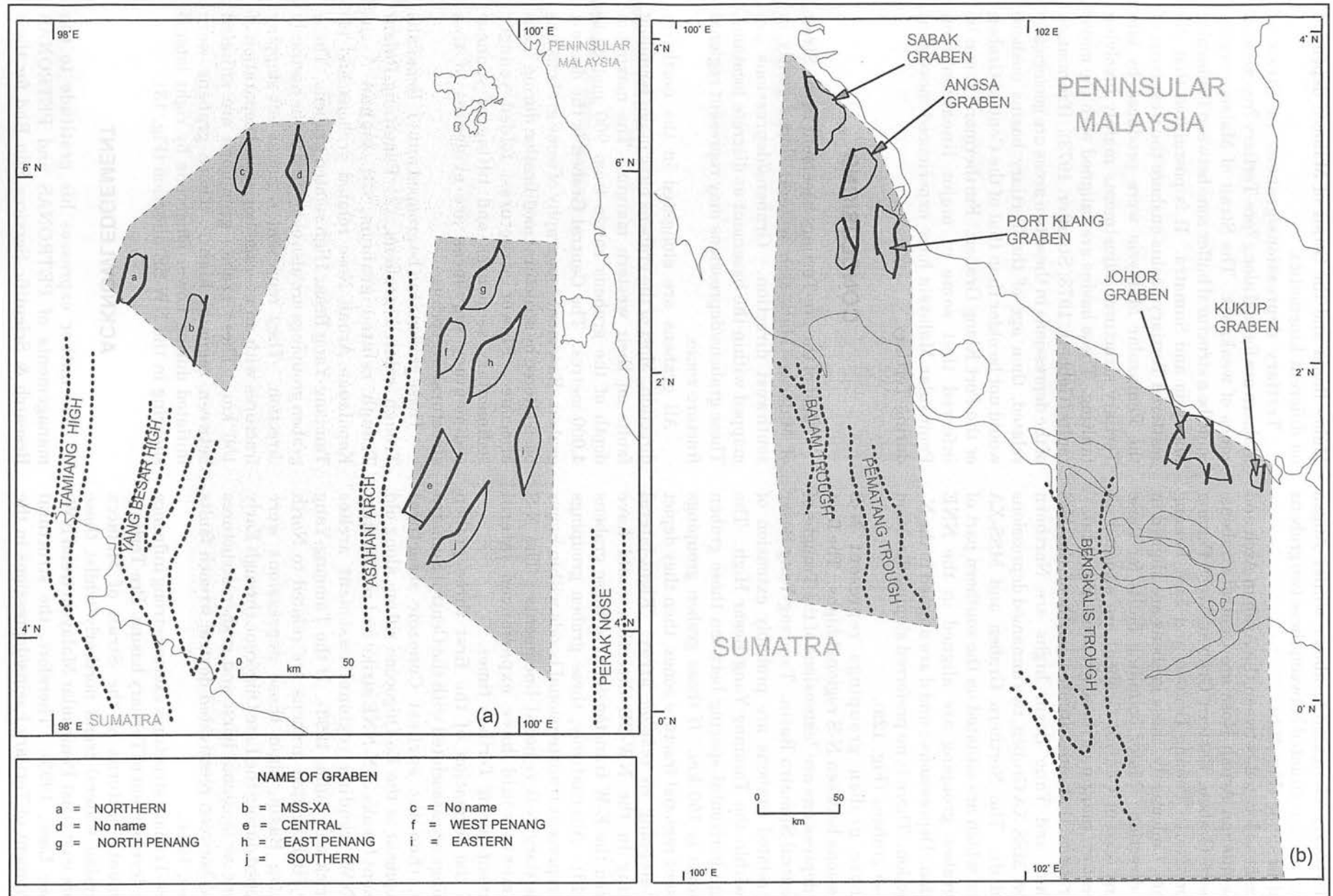


Figure 12. (a) Location of graben groupings with regional elements. Note the orientation of graben groupings with regional elements. Modified from Sosromihardjo (1988) and Dyer *et al.* (1991). (b) Location of graben groupings with regional elements. Note the alignment of the Balam-Pematang Trough related grabens with both Troughs. Johor Graben and Kukup are east of the Bengkalis Trough. Modified from Wong (1990).

are northerly elongated grabens whilst Angsa Graben which is situated between these two grabens is oval in shape (Fig. 12b).

Grabens located between the Asahan Arch and the Kepulauan Aruah Nose are Central Grabens, Southern Graben, Eastern Graben, West Penang Graben, North Penang Graben and East Penang Graben. Collectively, these grabens are aligned in NNE direction. Major bounding faults for these grabens (except Central Graben) are situated on the western margin of these grabens (Fig. 12a).

Grabens that are situated north of the N-S Tamiang and Yang Besar highs are Northern Graben, MSS-XA Graben, two unnamed depressions (c and d). The Northern Graben and MSS-XA Graben which are situated on the southern part of this graben grouping are aligned in the NNE direction. Depressions c and d are aligned in the N-S direction. There is no preferred sloping direction of these grabens (Fig. 12a).

These graben groupings represent N-S depressions between N-S regional highs. The first three depressions are ?extensions of the Troughs of the Central Sumatra Basin. Tamiang-Yang Besar High related grabens are probably extension of lows within the Tamiang-Yang Besar High. The average horizontal spacing between these graben groupings is 150 km. If these graben groupings represent regional fracture zones, then they depict a left-stepping *en echelon* array. Right-lateral shearing in the NW-SE direction could have initiated the E-W transtensional of these grabens (Fig. 13). Alternatively, these graben groupings could represent transtensional bends within major pre-Tertiary N-S regional lineaments. The N-S lineaments could have experienced lateral movement during Tertiary times.

If the formation of the first three graben groupings are associated with the Central Sumatra basin, then the earliest Cenozoic structural development is the Eo-Oligocene rifting along old basement breaks of N-NNE strike and reactivation of WNW trending regional basement arches (Heidrick and Aulia, 1993). If the Tamiang-Yang Besar High related grabens are related to North Sumatra Basin, then these depressions were developed during the Late Oligocene through Early Miocene as tensional horst and graben structures formed between reactivated dextral wrench faults (Davies, 1984).

Pre-Tertiary structures exerted strong influence on the development of Tertiary basins. Pre-Tertiary lineaments patterns of the Strait of Malacca (Malaysian waters) trend northerly whilst those offshore east coast Peninsular Malaysia trend NW-SE (see Liew, 1993). Therefore, the structural development of Tertiary basins/depressions in the

Malay Basin and the Strait of Malacca depended on different kinematics.

Tertiary depressions/grabens in Strait of Malacca are formed along ?pre-Tertiary ?reactivated zones of weakness. The Strait of Malacca region could be a structural buffer zone between Peninsular Malaysia and Sumatra. It is postulated that the scattered Tertiary basins onshore the west coast of the Peninsular Malaysia were produced by late Tertiary structural adjustments mainly involving faulting. These basins are ?aligned with the major faults (Gobbett, 1973; Stauffer, 1973). If formation of the depressions in these two areas are geologically related, then age of the Tertiary basins onshore would not be older than that of the Central Graben or the Port Klang Graben. Furthermore, it can be inferred that some of major lineaments on Peninsular Malaysia have experienced movement during Tertiary.

CONCLUSIONS

Most of the pre-Tertiary basement in the Strait of Malacca (Malaysian waters) slopes gently in southwest direction. Grabens/depressions are mapped within the basement at discrete locations. These grabens/depressions may represent regional fracture zones.

All grabens are elongated in the northerly direction. Most of the grabens have major bounding faults on their western margin. The maximum depth of the grabens range from 900 metres to 4,000 metres. The Central Graben is the deepest graben. Basement topography of some grabens has been altered by structural modification during ?Late Miocene. Flower structures, folded younger sedimentary sequences and tilting of younger sedimentary sequences are evidences of this structural overprint.

These grabens can be grouped into (1) Bengkalis Trough related grabens, (2) Pematang-Balam Trough related grabens, (3) Asahan Arch-Kepulauan Aruah Nose related grabens and (4) Tamiang-Yang Besar High related grabens. These graben groupings are also elongated in the northerly direction. They represent regional left-stepping fractures with an average horizontal separation of 150 km. These graben groupings are situated between regional highs. These grabens were initiated during Lower Oligocene by right lateral shearing in the NW-SE direction (Fig. 13).

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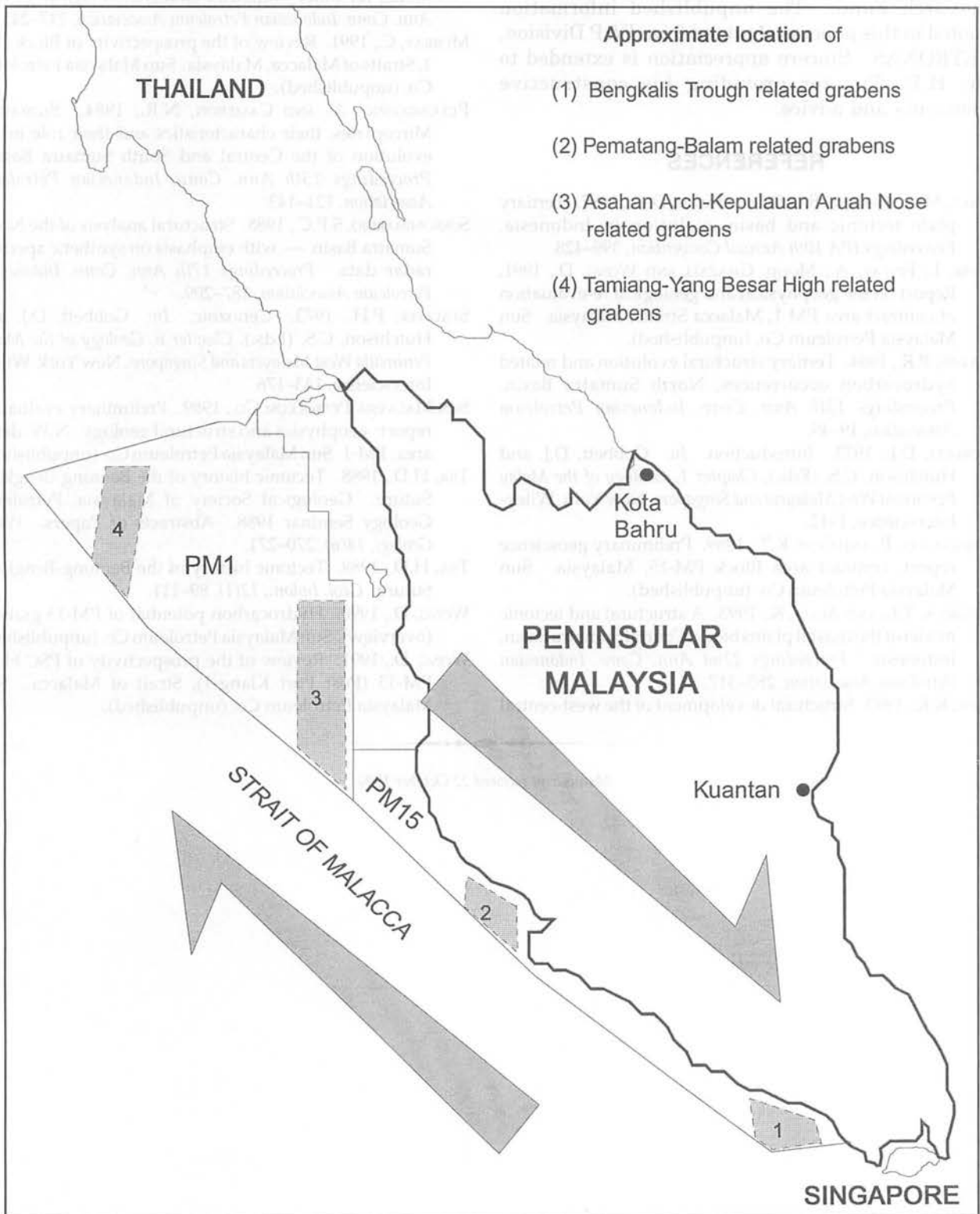


Figure 13. Summary map of graben groupings and its regional interpretation.

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