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Structural analysis of the Malay Basin

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Abstract: The structural patterns within the Malay Basin are divided into fold and fault systems. Three main fold domains are demarcated based on fold geometry and characteristics of associated faults: Basin Hinge; Basin Axis; and Basin Ramp. As for fault systems, high density and low density fault domains are identified. Gravity and magnetic anomalies tend to have better correlation with faults than with folds. Based on fold and fault domains, two structural domains are demarcated: Eastern and Western structural domains. The Western domain comprises northerly trending structures. The Eastern domain comprises east-west trending structures. This domain can be further divided based on fold openness and presence of northerly faults. The northern sub-domain has northerly faults and more open folds whereas the southern sub-domain has less-open folds with different fold styles. The two sub-domains may be two separate structural units during the Tertiary structural development of the Malay Basin.

INTRODUCTION

Mazlan Madon (1993) provided an overview of the structural evolution of the Malay Basin. Through literature review, he found conflicting hypotheses regarding the formation of the Malay Basin. The formation of the Malay Basin can be explained by crustal extension model (caused by high heat flow) or by a more popular, extrusion model (e.g. Tapponier *et al.*, 1982). He suggested that the extrusion model cannot satisfactorily explain the structural trends of Penyu and West Natuna basins. Tjia (1994) provided an explanation for the structural relationship between Malay-Penyu-West Natuna basins. He suggested that these three basins are aulacogens of a late Cretaceous hot spot. Bulging by heating and expansion, this hot spot hypothesis explains the present high heat flow within these basins.

The Tertiary tectonic evolution of the Malay Basin has been widely accepted to comprise three main phases. The three main phases are crustal rifting, followed by basin subsidence (thermal subsidence), and compression (structural inversion). The EPIC (1994) study concluded that the first phase occurred before 30 Ma (probably as old as late Cretaceous), basin subsidence was from 30 Ma to 14 Ma and the third phase lasted from 14 Ma till the present.

N, NNW-NW, and E-striking faults are the major fault trends within the pre-Tertiary basement of the Malay Basin (Khalid Ngah *et al.*, 1991). The N-striking faults are pervasive within Sundaland and are interpreted to be the earliest regional fractures (?Jurassic). The NNW-NW trend is the main tectonic grain within the Malay Basin and was established in late Triassic-early Jurassic time. The E-striking faults are secondary extensional fractures that resulted from left-lateral strike-slip motions along NNW-NW faults during the initiation of the Malay Basin (pre-Oligocene). These E-striking faults are confined to the pre-Tertiary basement and exerted strong influence on the structural development of the Malay Basin during Tertiary (Tjia and Liew, 1996).

Tjia (1993) divided the Tertiary Malay Basin proper into four structural domains by three major north-south fracture zones. The fracture zones, from west to east, are Kapal-Bergading tectonic line, Dulang fault zone, and Laba-Mesah fault zone. The two later fault zones are interpreted to have initially moved sinistrally with later dextral movement. Five main fracture directions have been mapped in the Malay Basin: North, NW, NNW, NNE and East (Tjia and Liew, 1996). The fracture trends are found to be associated with different parts of the basin. The western margin of the Malay Basin is straddled by a major curvilinear fault system: Hinge fault system (Liew, 1993a; 1993b; 1995). This Hinge fault system is believed to have experienced right-lateral motion in the pre-Oligocene with subsequent reversal in the Middle Miocene.

A broad framework regarding the structural elements within the Malay Basin has been established by previous researchers. As a continuation from previous studies, this paper attempts to provide a refined structural framework of the Malay Basin by examining the characteristics of its structural domains.

FOLD SYSTEM

Based on fold geometry and characteristics of associated faults, three main fold domains within the Malay Basin are demarcated (Table 1). These fold domains are elongated parallel to the basin axis; that is, NW-SE. From southwest to northeast, the fold domains are basin hinge, basin axis, and basin ramp (Fig. 1). The basin hinge domain is bounded by the Hinge fault zone in the southwest and toward northwest grades into the basin axis domain. The basin axis domain is separated from the basin ramp domain by the Selambau fault zone and the Belumut Arch. The eastern boundary of the basin ramp domain is unknown.

Basin Hinge Fold Domain

This fold domain (Fig. 1) seems to be a buffer zone for the Hinge fault system (see Liew, 1995) and the Axial Malay fault zone (see Tjia, 1993). The fold axes orientations within this domain change from north to south. The lengths of the folds ranged from 30 km to 70 km and the half wave lengths are circa 10 km (see Table 1). The fold axes of this domain are northerly to north-westerly in the northern part and north-westerly in the southern part. The northern most folds are the Pilong-Gajah and Ular-Damar folds. Their shapes are elliptical with north-south axes. These folds are situated within the area of north-striking faults. South of these folds is the Bintang-Lawit

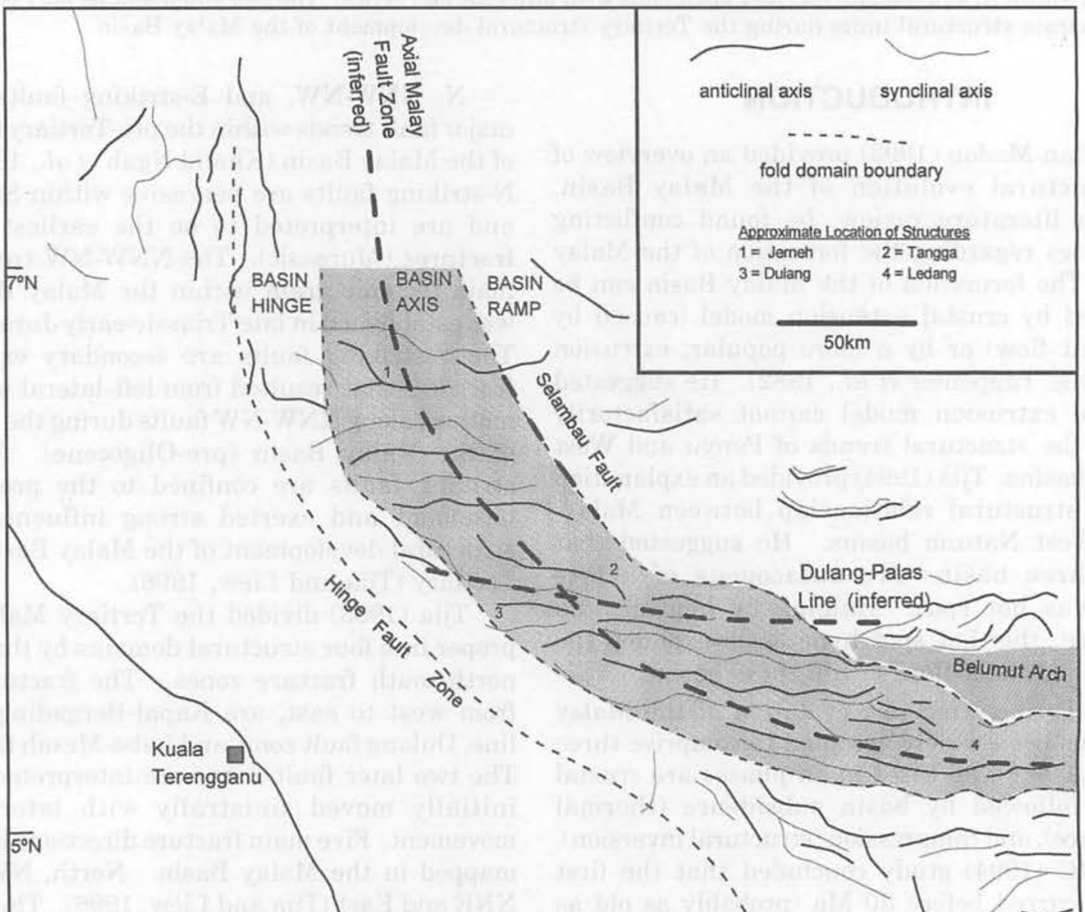

Figure 1. Fold domains and major structural features within the Malay Basin. Orientation of fold axes adapted from EPIC (1994).

Table 1. Summary of the characteristics of the folds and their associated faults within each fold domain.

FOLD DOMAIN	FOLD PATTERN		FOLD GEOMETRY			ASSOCIATED FAULTS			STRUCTURE (West to East)	Notes
			Length (km)	*Width* (km)	*Axis*	*Trend*	*Angle*[1]	*Intensity*		
BASIN AXIS	A	A1	45	30	E-W	NNE-NE	60-90	Low	Jerneh Barat -**Jerneh**	Jerneh -Tangga sub-domain
		A2	60	20		N-NNE			**Noring** -Sepat -**Laho**	
		A3	55	20					**Guling** -Inas -**Melor**	
		A4	60	20	ESE-WNW	NNW-NNE		Medium	**Bujang** -Tangga Barat -**Tangga**	
	B	B1	140	10		NNW-N	60-90	High	**Dulang** -Semangkok -Semangkok Timur -Ridan -Serok -Telok Barat -Telok -Tabu- Guntong -**Palas**	Dulang - Ledang sub-domain
		B2	120	15					**Jambu** -Irong Barat -Irong -Tapis -Tiong Barat -Tiong -Kepong, -Bekok, -Pendera -Seligi, -**Pulai**	
		B3	80	15				Medium	**Berantai**, -Ophir -Gayong -Ledang Barat -**Ledang**	
BASIN HINGE	C	C1	70	12	NW-SE	NW-NNW	60	Medium	**Angsi** -Besar -**Duyong**	
	D	D1	60	10	N-S	N-S	0	Low	Ular -Damar	
		D2	30	10					Pilong -Gajah	
		D3	30	20	E-W	NNE-NE	60-90		Bintang-Lawit	
		D4	30	10	NW-SE	N-NNE	0-30		Bedong -Tujuh	
BASIN RAMP	E	E1	30	>10	E-W	E-W, N-S	0, 90	?Medium	**Duri**, -South Bundi -**Bundi**	
		E2	35						**Larut-Liku** -Larut -East Larut - **North Larut**	Selanchar sub-basin
		E3	20						North Lukut	Abu-Bubu sub-basin
		E4	50						**Penara**, - Abu - Abu Kecil, -Bubu - **Diwangsa**	
		E5	45						**Serudon** - Lawang - Pantai -Paluh - **Beruang**	Peta sub-graben
		E6	50						**Yong**, Peta Kiri - Peta, Cahaya - **Chermingat**	
		E7	40		NW-SE				**Bunga Raya**	Bunga Raya sub-basin

[1] angle between fault trend and fold axis

fold. The geometry of this fold is more like rounded dome. The axis is almost east-west. The shape of the fold suggests the interaction of the Hinge fault system and Axial Malay fault zone as the mechanism for its formation. In the central part of this domain, folds are observed on its margins. The Bedong-Tujuh fold is situated near the eastern margin. The fold axis is NW-SE. Formation of this fold is controlled by the Axial Malay fault zone. Tjia (1993) documented the existence of north-striking drag folds within nine pull-apart depressions that straddle the central part of this fold domain. Lateral movements within the Hinge fault system is responsible for the creation of these structures. In the southern part, the fold geometry is elongated (e.g. Angsi and Besar) with NW-SE axes. The fold axes of Angsi-Duyong are arranged in a left stepping *en echelon* pattern. The Angsi-Duyong folds were interpreted as part of the Hinge fault system (Liew, 1995).

Basin Axis Fold Domain

Based on the openess of the fold, trend of fold axis, and abundance of crestal faults, this domain is divided into two sub-domains. The northern sub-domain is named Jerneh-Tangga sub-domain and the southern sub-domain is the Dulang-Ledang sub-domain. The names reflect the areal extent of these sub-domains. Petronas Carigali (1994) classified the approximate areal extent of the northern and southern sub-domains as Jerneh sub-basin and Dulang-Seligi fold zone respectively.

There seems to a major east-west ?tectonic/structural line that separates the northern and southern sub-domain. The author named this line the Dulang-Palas line (new name). The existence of this line is based on the drastic changes in fold characteristics across this line. North of this line, the length of the Bujang-Tangga fold axis is 60 km whilst the Dulang-Palas fold axis is 140 km long. The widths of the folds also changed circa two-fold. The widths of Bujang-Tangga fold and Dulang-Palas fold are is 20 km and 10 km respectively. The density of associated faults also changes: medium for Bujang-Tangga fold; and high for Dulang-Palas fold (see Table 1).

The shapes of both sub-domains are rhombic. The northern and southern boundaries are approximately east-west trending whereas the eastern and western boundaries are approximately NW-SE trending. The difference is that the Jerneh-Tangga sub-domain is elongated in north-south direction whilst Dulang-Ledang sub-domain is elongated in east-west direction. The northern sub-domain is bounded by the Selambau fault zone and Kapal-Kuda-Damar fault zone on the east and west respectively. These two fault zones trend NW-SE. The characteristics of both fault zones are similar: (i) numerous minor curvilinear faults merging into a major fault zone, and (ii) fault-bounded rhomboid-like depressions.

Comparatively, the southern sub-domain has less-open fold of higher asymmetry and more northerly crestal faults than the northern sub-domain (see Table 1). The fold axes in the northern and southern sub-domains are east-west and WNW-ESE, respectively. Within the southern sub-domains, the southern flanks of the folds are steeper. Structures in the southern sub-domain seem smaller than their northern counterparts but their fold axes are longer. In most parts, synclinal axes, which are trending east-west within this fold domain, gradually change into NW-SE trend near the western boundary of this domain. Collectively, the folds within this fold domain are arranged in a right stepping *en echelon* pattern. Tjia (1993) postulated that right lateral movement of the Axial Malay fault during late Middle Miocene was responsible for the formation of these folds.

Basin Ramp Fold Domain

The folds in this domain are situated in four east-west syn-rift depressions (Peta sub-graben, Abu-Bubu sub-basin, Simpur sub-basin and Selanchar sub-basin) and one NW-SE syn-rift depression (Bunga Raya sub-basin). The fold axes mimic the southern flank of the syn-rift depressions, and are approximately east-west, except the fold in Bunga Raya sub-basin (NW-SE). The length of the syn-rift depressions restricts the length of the fold. As the geometry of the fold is controlled by the size of the depressions, the width (> 10 km) of the folds in this domain is comparatively smaller than the rest of the fold domains. The major faults associated with the folds are parallel with the axes of the folds. Minor faults are represented by small extensional crestal faults. Comparatively, folds in Peta sub-graben have more crestal faults than those in other sub-basins. The sub-grabens and sub-basins are arranged in a right stepping *en echelon* pattern. This pattern was resulted from left lateral slip on the Axial Malay fault (Tjia, 1994).

FAULT SYSTEM

Based on the abundance of major faults within an area, two types of fault domain can be recognised in the Malay Basin: high density fault domain and low density fault domain. The determination of fault intensity is a qualitative assessment. The high density fault domains are the sites of major fault systems in the Malay Basin. Northerly crestal faults populate the low density fault domains. The fault domains are oriented north-south and are arranged alternately east-west. The southward extension of these fault domains are limited by the NW trending Hinge fault system (Fig. 2).

The most visible faults in the Tertiary sequences of the Malay Basin belongs to the curvilinear Hinge fault system that straddles the western margin of the Malay Basin (see Liew, 1995) and northerly striking faults that exist within the basin (see Tjia and Liew, 1996). The major northerly faults, from west to east, are Ular-Kuda segment of the Hinge fault system, Kapal-Bergading, Dulang, Bundi, and Mesah fault zones. There are three prominent NW-SE trending fault zones in the Malay Basin: Kuda-Beranang fault zone, Tenggol fault zone (or Sotong fault segment) and Selambau fault zone. The first two fault zones are associated with the Hinge fault system whilst the last fault zone is within the Central Malay fault system.

High Density Fault Domain

The northerly fault zones form two areas with high density of faults: western and central region. The area between the Ular-Kuda segment and the Kapal Bergading fault zone (western region) is populated by long curvilinear faults. This region extends southwards and meet the Hinge fault system. The region between Dulang and Mesah fault zone (with Bundi and the NW trending Selambau fault zones) forms another area of high fault density (central region). These bundles of fault zones form the Central Malay fault system (new name). Faults in this region are also curvilinear but are shorter compared to those in the western region. Minor faults are interconnected to form major fault zones.

Within the Central Malay fault system, the Mesah fault zone is the most eastern fault. EPIC (1994) referred to this fault zone informally as the "hinge zone" and emphasised it as an important facies demarcator. The sediments of ages D, E, and H are buried deeper in the west than in the east. This "hinge zone" is a north-south zone of weakness that extends from Serok to near Larut. It was found that subsidence increased rapidly westward from this zone. Therefore, large vertical movement on this fault zone is implied.

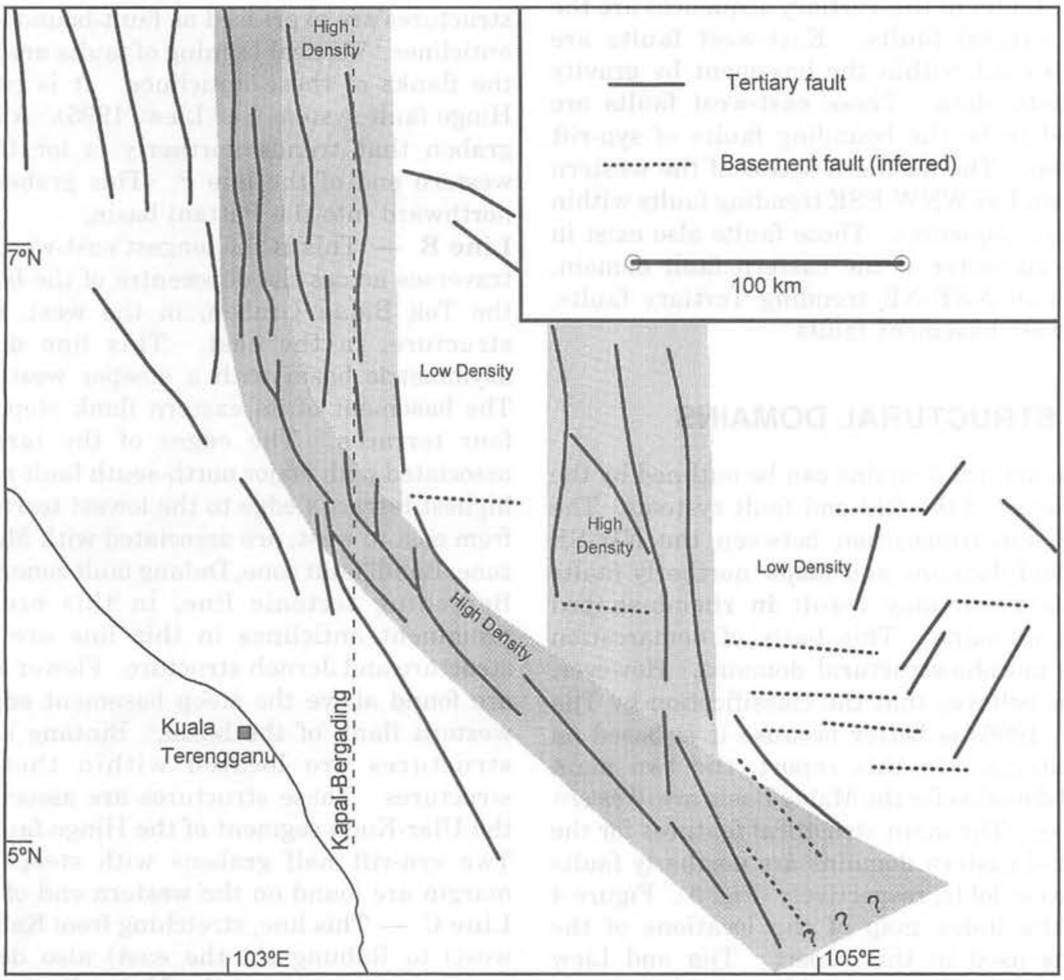

Figure 2. Fault domains within the Malay Basin. Adapted from Tjia and Liew (1996).

The present day bathymetry map of the Malay Basin reveals a 100 kilometres long north-south trench that is located on the Dulang fault zone (western most fault in the Central Malay fault system). This trench is 75 metres below sea level and is the deepest part of the Malay Basin. The superimposition of this trench with the Dulang fault zone may suggest that vertical movement of the Dulang fault zone is active till present day.

Based on the arrangement of the oil fields within the axis of the Malay Basin, it has been proposed that the northerly faults of the Central Malay fault system has produced large dextral movement (Tjia and Liew, 1996). The fault zones have collectively produced 30 kilometres of dextral separation. The Central Malay fault system with large vertical and lateral movements has proved its importance in the structural evolution of the basin.

Low Density Fault Domain

There are two low density fault domains which are separated by the Central Malay fault system: western and eastern fault domain. These fault domains can be subdivided into northern and southern sectors. Within the southern sectors, the prominent faults in the Tertiary sequences are the northerly crestal faults. East-west faults are inferred to exist within the basement by gravity and magnetic data. These east-west faults are interpreted to be the bounding faults of syn-rift half grabens. The northern sector of the western fault domain has WNW-ESE trending faults within the Tertiary sequences. These faults also exist in the northern sector of the eastern fault domain, together with NNE-NE trending Tertiary faults, and east-west basement faults.

STRUCTURAL DOMAINS

The structural domains can be outlined by the characteristics of the fold and fault systems. The structural superimposition between the NW-SE trending fold domains and major northerly faults within the basin may result in rhomb-shaped structural domains. This basis of demarcation results in morpho-structural domains. However, the author believes that the classification by Tjia and Liew (1996) is better because it is based on stress systems. In this report, the two main structural domains for the Malay Basin are *Western* and *Eastern*. The main structural features for the western and eastern domains are northerly faults and east-west folds, respectively (Fig. 3). Figure 4 provides the index map of the locations of the geosections used in this report. Tjia and Liew (1996) named the Western and Eastern domains as north and south domain, respectively.

Eastern Structural Domain

This domain is separated from the western domain by the Kapal-Bergading tectonic line. The eastern domain can be subdivided into northern and southern, with a Dulang-Palas line as their transition boundary.

(1) Northern sub-domain

The structural characteristic of the northern sub-domain can be seen from seismic lines A, B, and C (Fig. 5).

Line A and F — These two northern most east-west lines run across Ular, in the west, to Bunga Raya, in the east. The basement and Tertiary sequences generally dip westward. Two half-grabens, with major west bounding faults, are located at the eastern end of this section. The Bunga Raya structure is a drape anticline that is situated above the horst of the two adjacent half grabens. This asymmetric anticline has numerous crestal faults and a steeper eastern flank. The Kapal-Bergading tectonic line is not well expressed in this section. The only structural indication of this line is the flexuring of the Tertiary sequences in the vicinity of this line. The Kuda and Gajah structures are expressed as fault-bounded box-like anticlines. Vertical fanning of faults are located at the flanks of these anticlines. It is part of the Hinge fault system (see Liew, 1995). A large half graben that trends northerly is located in the western end of the line F. This graben extends northward into the Pattani basin.

Line B — This is the longest east-west line that traverses across the depocentre of the basin, from the Tok Bidan Graben, in the west, to Mesah structure, in the east. This line depicts an asymmetric basin with a steeper western flank. The basement of its eastern flank steps down in four terraces. The edges of the terraces are associated with major north-south fault zones. The highest terrace's edge to the lowest terrace's edge, from east to west, are associated with Mesah fault zone, Bundi fault zone, Dulang fault zone and Kapal Bergading tectonic line, in this order. The prominent anticlines in this line are the Duri structure and Jerneh structure. Flower structures are found above the steep basement edge on the western flank of the basin. Bintang and Lawit structures are located within these flower structures. These structures are associated with the Ular-Kuda segment of the Hinge fault system. Two syn-rift half grabens with steeper eastern margin are found on the western end of this line.

Line C — This line, stretching from Kabut (in the west) to Rabung (in the east) also depicts the asymmetric nature of the Malay Basin. Syn-rift sequences are mapped from the eastern flank to

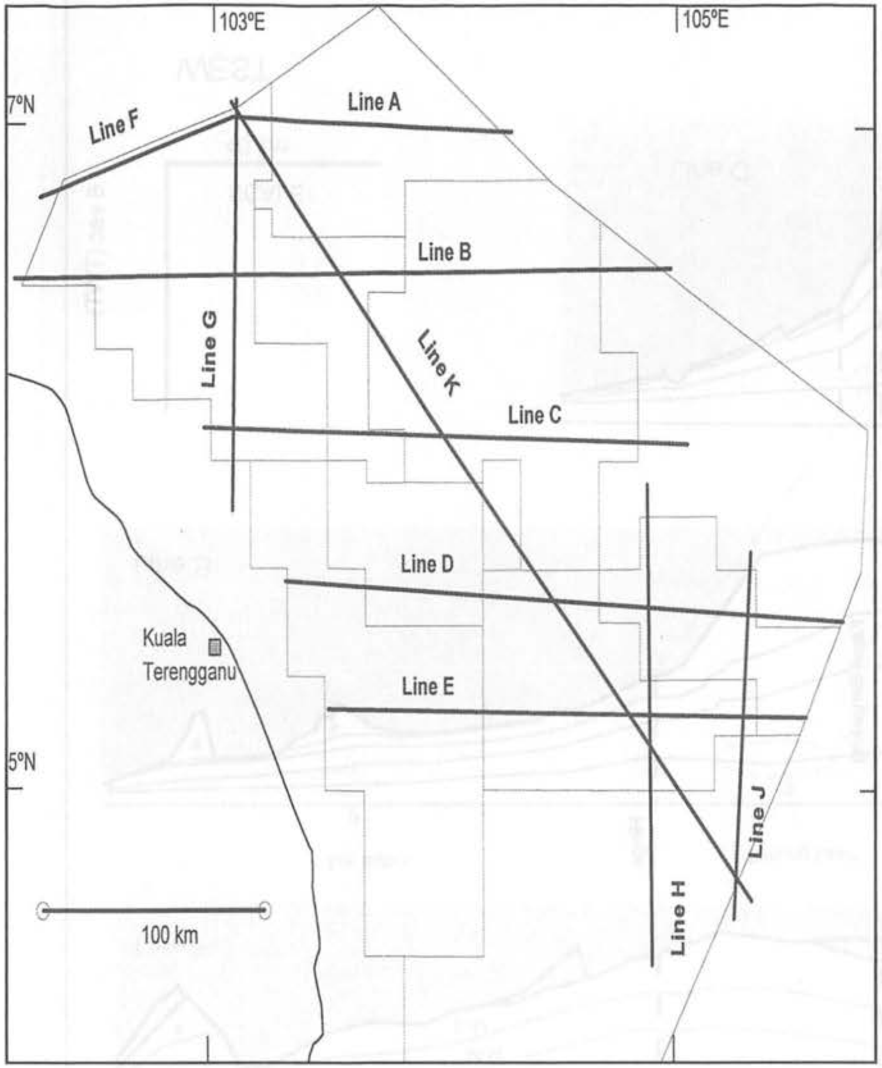

Figure 3. Comparison of tectonic elements within the Malay Basin (adapted from Carigali, 1994) and structural domains in this study. The shaded areas represent depocentres.

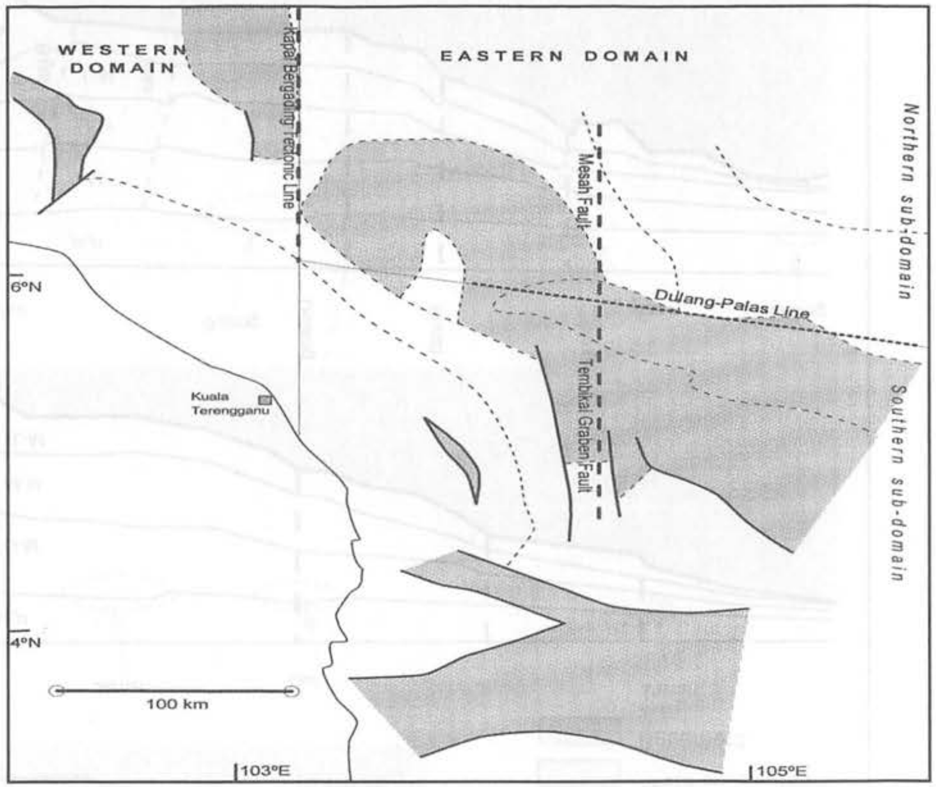

Figure 4. Index map of geosections.

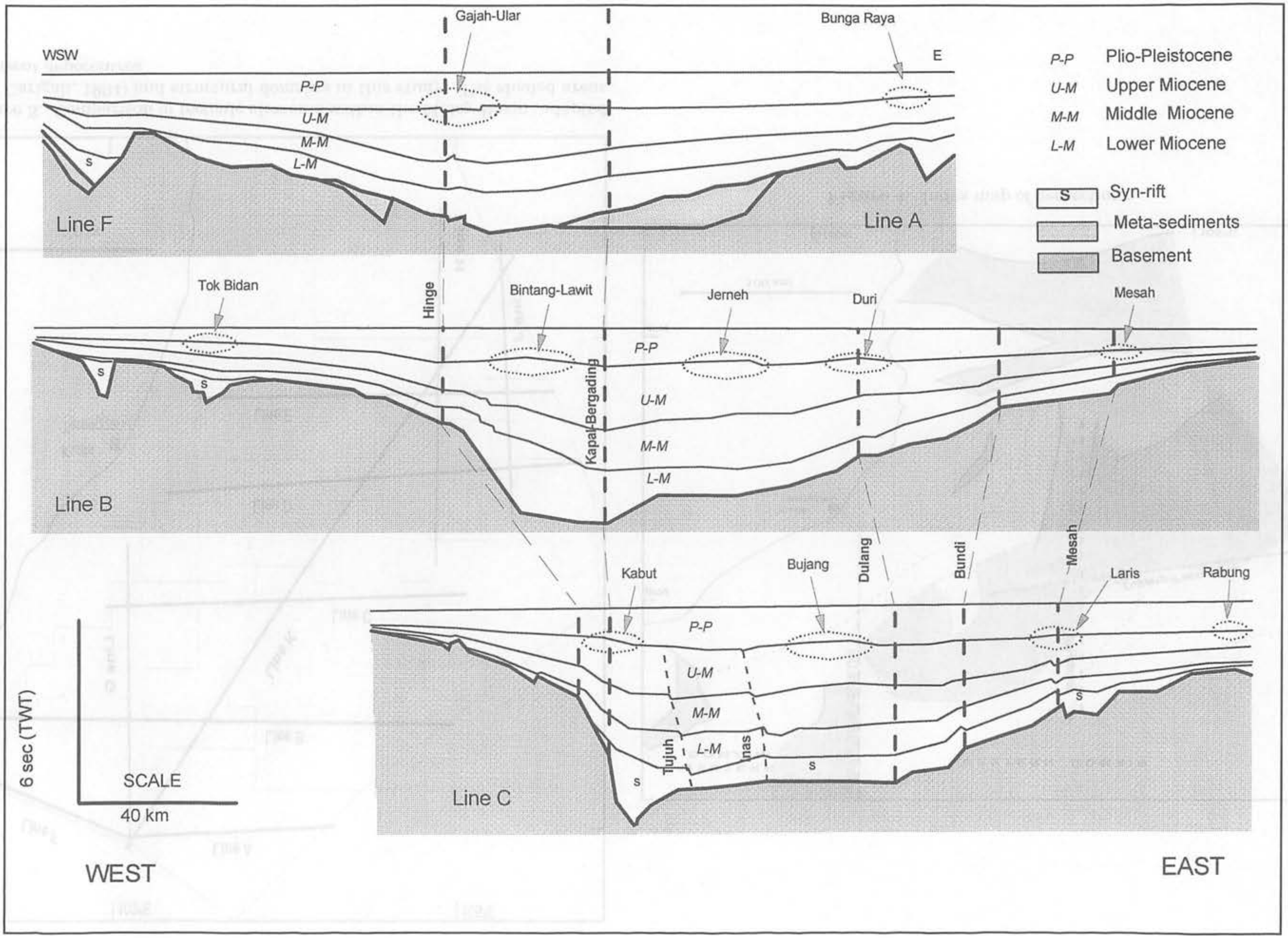

Figure 5. Geosections showing major structural features in the northern sub-domain of the Eastern structural domain.

the depocentre of the basin. The terraced basement features of the eastern flank are not as pronounced as in line B but the terrace edges correspond to three northerly regional faults. The three north-trending fault zones display flower structures. The steep basement of the western flank is the site of the Kabut-Tembikai segment of the Hinge fault system and ?Kapal-Bergading tectonic line. Flower structures are observed in this location. Two other faults are observed near the depocentre of the basin: Inas fault (new name) and Tujuh fault (new name). Bujang structure forms the largest anticlinal closure in this line. Other anticlinal closures are related to the fault zones.

The most prominent structural features within the northern sub-domain are the major north-south faults. They also form the west and east boundaries of the sub-domain. These faults can be traced to the Tertiary basement and controlled the differential subsidence within the sub-domain. This part of the basin, due to differential subsidence by north-south faults, resembles a north-south trough. The wrenching nature of the north-south faults has yet to be confirmed. The fold styles are characterised by fault-induced folds (box-like) which are associated with flower structures. Open gentle folds are found within the faults.

(2) Southern sub-domain

The structural characteristic of the southern sub-domain can be seen from seismic lines D, E, H, and J (Fig. 6).

Line D — The asymmetry of the basin is less prominently shown than in lines B and C. Syn-rift sequences are found on both flanks of the basin. The base B unconformity is evident at both ends of this line. This line runs from Resak (west) to Belumut (east). The most prominent anticlinal closure is the Jambu-Liang structure. Numerous faults and chimney effect are observed in the centre of this structure. The eastern flank depicts a series of gentle undulating anticlines with numerous crestal faults. The crests of these anticlines have been eroded. These anticlines are situated in the synclinal axis between Dulang-Palas fold and Jambu-Seligi fold. Pronounced flexuring of the Tertiary sequences occurs west of the Jambu structure. A flower structure (Resak) on the western flank is the site of the Kabut-Tembikai segment of the Hinge fault system.

Line E — The prominent structural features are the unconformity and the moderate westward dipping strata in the eastern end of this line (Payung to Ledang). Three fault zones are observed between Rajah and Angsi. The presence of the Hinge fault system may be indicated by the occurrence of a small anticline below Tembikai. Syn-rift sequences are located mostly on the eastern part of this line. The Angsi structure is the largest anticlinal closure.

Line H — This is one of the north-south lines that traverses the southeast margin of the Malay Basin. The Tertiary basement generally slopes northward. There are two distinct types of basement topography: the southern part is more undulating than the northern part. The transition between these two types of topography is the site of the Angsi-Duyong fault zone. Syn-rift sediments are interpreted to have been deposited across the width of this line. Structural styles of Tertiary sequences seem to be related to the types of basement topography. The southern part has Tertiary sequences of almost horizontal strata. However, folding is prominent in the northern part. Fold styles vary across the northern part. The southern most fold is the ?Besar structures. This anticline has a steeper northern flank with numerous crestal faults. North of the Besar structure is the Berantai anticline. This anticline is almost symmetrical in the younger Tertiary sequences, but has a steeper southern flank in the older Tertiary sequences. A vertical curvilinear fault separates the Besar and Berantai anticlines in the older Tertiary sequences. The asymmetry of these two anticlines may be attributed to the influence of this fault. Further northward is the Irong-Tapis anticline. This anticline has the highest amplitude and is almost symmetrical. The southern flank is only marginally steeper. The younger Tertiary sequences in the crest of this anticline is eroded. The northern-most anticline in this line is the Tabu structure. Structural similarity is observed between Tabu anticline and Berantai anticline. The difference is that Tabu anticline has a steeper northern flank.

Line J — This north-south line is east of line H. Two different fold styles are observed. In the southern part, there is one major anticline (Duyong) with two small undulating anticlines on its southern flank. Crestal faults are prominent. The northern part comprises three asymmetric anticlines with steeper southern flanks. They are, from south to north, the Ophir, the ?Bekok, and North Seligi structures. The steepness of the southern flank seems to increase northward. The crests of the anticlines are eroded in the younger Tertiary sequences. However, crestal erosion is more pronounced in the three anticlines in the northern part. Between the anticlines in the northern and southern part is a broad syncline with a steeper northern flank.

The prominent features of the structural styles in the southern sub-domain are the occurrence of an unconformity, eroded anticline crests, and two different fold styles. The unconformity is more clearly shown in the east-west seismic lines. The

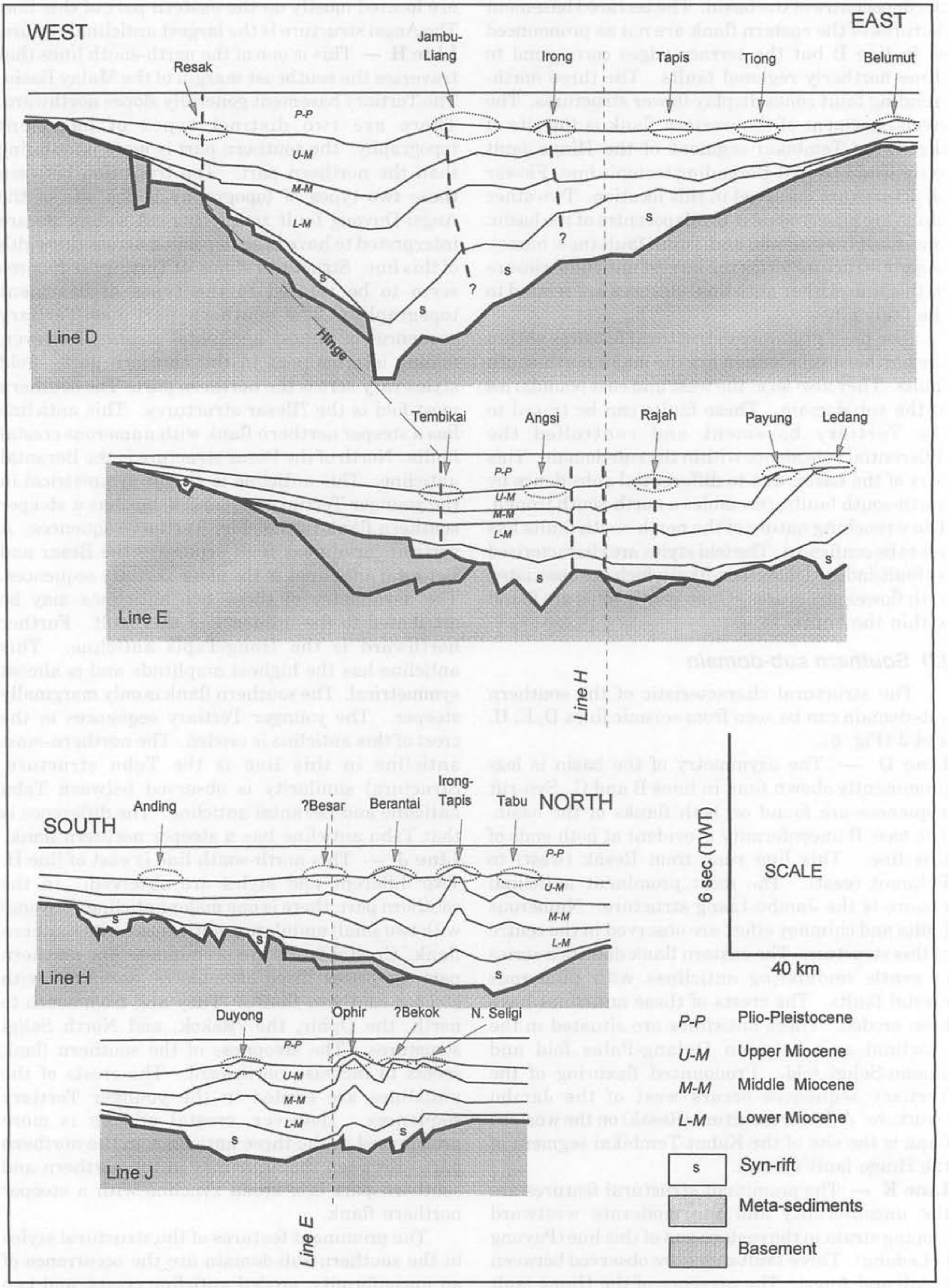

Figure 6. Geosections showing major structural features in the southern sub-domain of the Eastern structural domain.

effect of the unconformity is more pronounced in the eastern part than the western part of the basin. Compared to north-south seismic lines, the crestal erosion features are less prominently shown in the east-west seismic lines. This is because the east-west seismic lines traversed through the synclinal areas of the folds. The north-south seismic lines clearly depict the presence of two types of folding style. Folds in the southern part are more open (Besar and Duyong) and are within the basin-hinge fold domain. The northern folds (Berantai to Tabu, and Ophir to North Seligi) are less open and represent folds in the basin axis fold domain.

(3) Relationship Between Northern and Southern Sub-Domains

The relationship between the two sub-domains is best depicted by seismic line K (Fig. 7). This is the longest line of the Carigali regional seismic survey. It traverses along the axis of the Malay Basin, from Delah (approximate) in the south to Gajah-Ular in the north. There are three distinct depths within the Tertiary basement. The shallowest Tertiary basement lies in the south and runs from Duyong Barat to Jambu (average of 3.5 seconds TWT), whilst the deepest Tertiary basement is from Jambu to Dulang (average of 6 seconds TWT). The basement depth from Dulang to Gajah averages 5.5 seconds TWT. The structural styles within the Tertiary strata is closely related to the depth of the Tertiary basement. From Duyong to Jambu, the Tertiary strata is almost horizontal, except for areas of faulting. Faults can be traced to the half-grabens below. Anticlines are found above the half grabens, suggesting structural inversion. The least open folds along this line, is from Jambu to Dulang, correspond to the deepest parts of the Tertiary basement. Chimney? effects and faults are observed in the crestal areas of these asymmetrical anticlines. Between Dulang and Sepat, the three anticlines (Bujang, Inas and Sepat) are broad and asymmetrical. Chimney? effect is seen in the Bujang structure. Westward of Sepat, the strata are almost horizontal, except where faulting occurred. The Kapal-Bergading tectonic line is represented by a bundle of faults. Box-like anticlines, where Gajah and Ular are situated, are observed at the northwest end of this line.

Western Structural Domain

This domain is situated west of the Kapal-Bergading tectonic line. The prominent structural feature is that northerly faults are aligned with their drag folds. This domain can extend eastward into the northerly Pattani basin. The western part of seismic lines F, B and C and the north-south seismic line G show the structural characteristics of this domain (Fig. 8). The major feature in this domain is a basement high that plunges northward. Northerly faults are the dominant faults. A north-south graben is observed at the eastern end of line F and B. Syn-rift deposits are found in local depressions and half-grabens.

Line G — This north-south line is situated at the northwest margin of the Malay Basin. The north-south Kapal-Bergading tectonic line is situated east of this line. The Tertiary basement slopes northwards. Three basement terraces are observed. Syn-rift sediments are deposited above the middle and lower terraces. The transitions between the terraces correspond to the inflexion of the Tertiary sequences. Faulting is more pronounced in the Tertiary sequences above the lower terrace. The northern end of this line is the Gajah structure.

RELATIONSHIP BETWEEN STRUCTURES AND GRAVITY AND MAGNETIC ANOMALIES

The Bouguer gravity anomaly, residual Bouguer gravity anomaly, aeromagnetic anomaly and residual aeromagnetic anomaly reduced-to-equator maps are superimposed onto the structural map of the Malay Basin. The objective is to establish, if any, the relationships between the structural patterns (folds and faults) and gravity and magnetic anomaly within the Malay Basin. The gravity and magnetic anomaly maps have been produced by Geophysical Consultants (1994).

Bouguer Gravity Anomalies

Figure 9 shows the variation in gravity anomaly that is due to free air gravity variations. The anomalies range from –10 to + 40 mGal. The lows are areas with values less than –3.2 mGal and the highs are areas with values higher than 8.7 mGal. The areal extent of lows clearly show northerly elongations. Highs are also trending northerly, except on the southwest flank of the Malay Basin. The lows correspond to the high density fault domain. East-west folds seem not be related to any anomaly pattern.

Residual Bouguer Gravity Anomalies

The residual separation of the gravity anomaly was made at a cut-off of 180 km wavelength (see Geophysical Consultants (1994) for technical details). The distribution of highs and lows seems random (Fig. 10). The highs are areas with values greater than 1.0 mGal and lows are areas with values less than –1.77 mGal. Most of the anomalies showed north-south elongation. However, if the lows represent local depocentres, then the formation

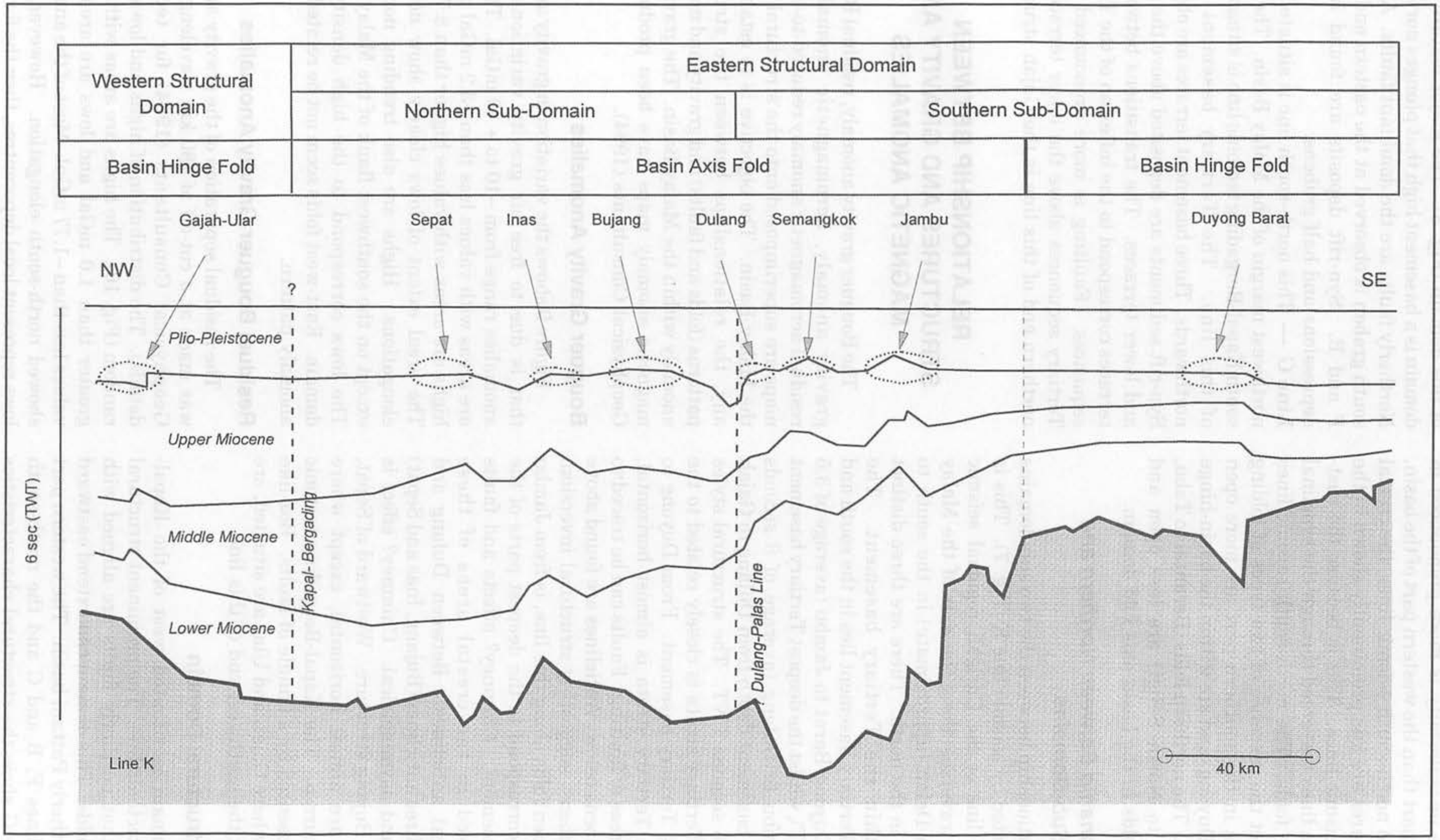

Figure 7. Geosection that shows the structural changes from the northern sub-domain to the southern sub-domain of the Eastern structural domain.

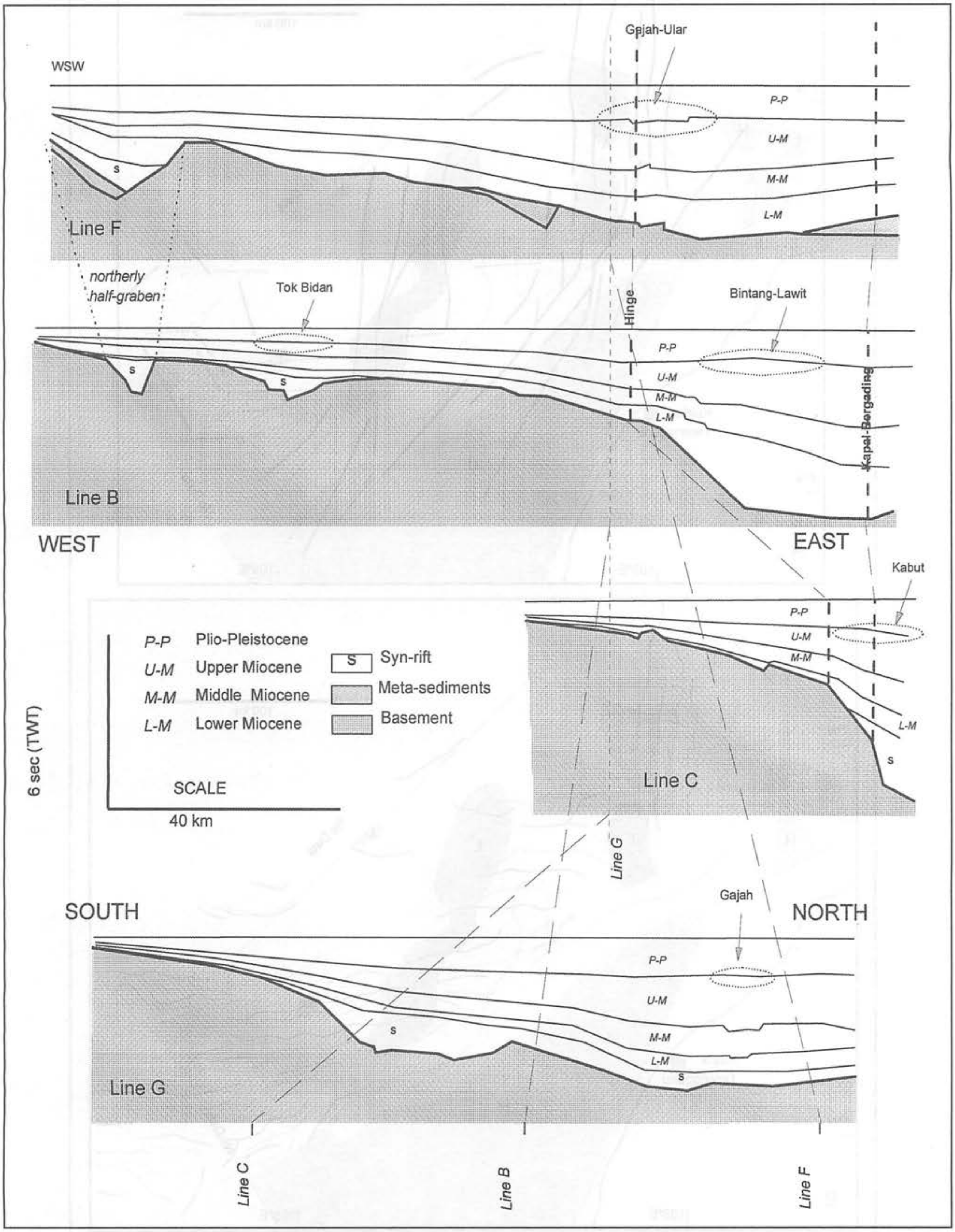

Figure 8. Geosections showing the major structural features in the Western structural domain.

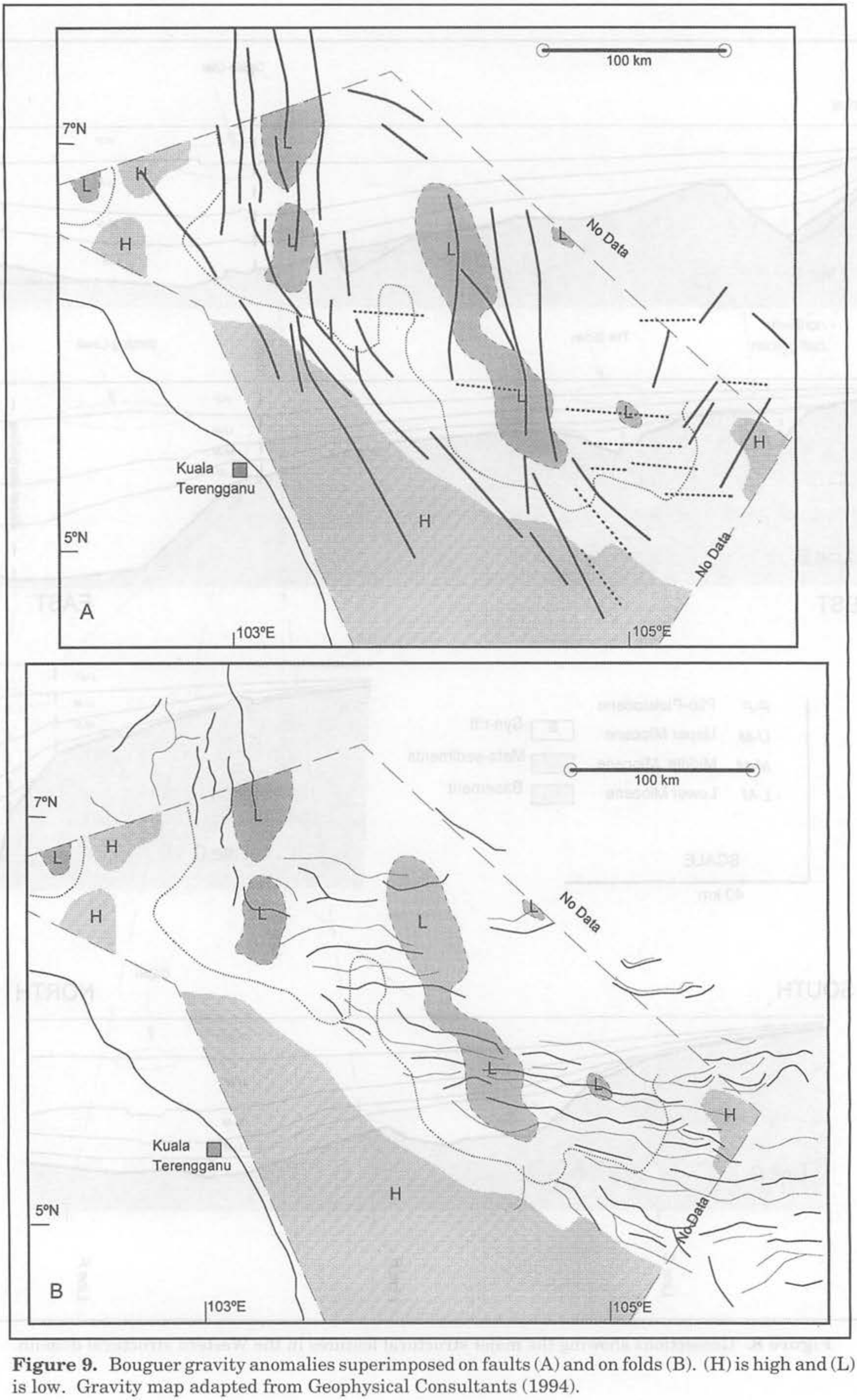

Figure 9. Bouguer gravity anomalies superimposed on faults (A) and on folds (B). (H) is high and (L) is low. Gravity map adapted from Geophysical Consultants (1994).

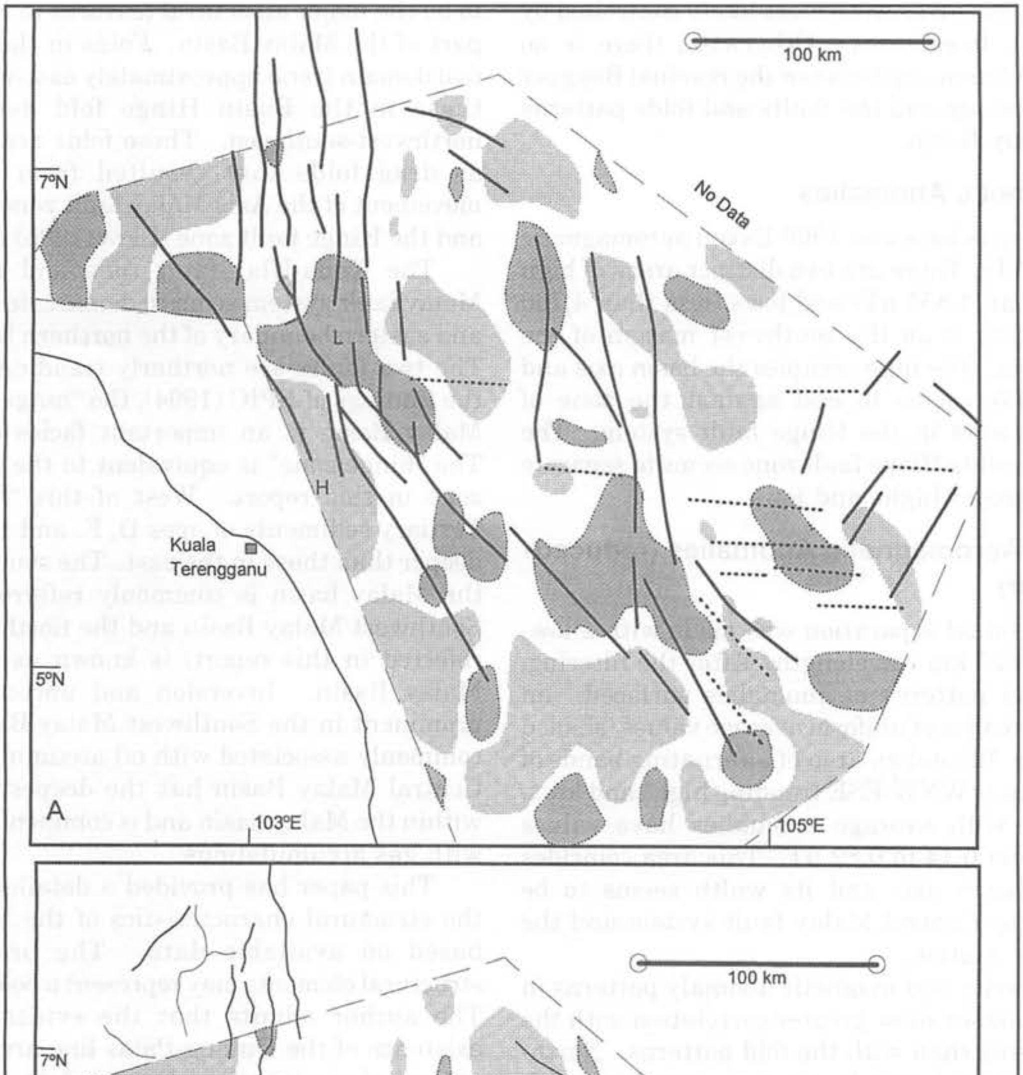

Figure 10. Residual bouguer gravity anomalies superimposed on faults (A) and on folds (B). (H) is high and (L) is low. Gravity map adapted from Geophysical Consultants (1994).

of these depocentres were most likely controlled by north-south lineaments. Otherwise, there is no apparent relationship between the residual Bouguer gravity anomaly and the faults and folds patterns in the Malay Basin.

Aeromagnetic Anomalies

The map is based on 1969 Exxon aeromagnetic data (Fig. 11). There are two distinct areas of high (greater than 4,855 nT) and lows (less than 4,760 nT). The low is on the southwest margin of the Malay Basin. The high occupies the basin axis and towards NW seems to end against the zone of northerly faults in the Hinge fault system. The NW-SE trending Hinge fault zone seems to separate these two major highs and lows.

Residual Aeromagnetic Anomalies (reduced-to-equator)

The residual separation was made with a low-cut filter of 25 km wavelength. After the filtering, two distinct patterns of anomalies surfaced: an area of anomalies of uniform average values (shaded dark in Fig. 12) and an area of alternating bands of approximately WNW-ESE trending highs and lows. The areas with average anomalies have values ranging from 0.14 to 0.82 nT. This area coincides with the basin axis and its width seems to be controlled by Central Malay fault system and the Hinge fault system.

The gravity and magnetic anomaly patterns in the Malay Basin show greater correlation with the fault patterns than with the fold patterns. North-south structural trends tend to correlate with gravity anomalies whereas the NW-SE structural trends with magnetic anomalies.

DISCUSSION

Fig. 13 provides a schematic diagram of the important structural features that have been discussed earlier. Table 2 summaries the characteristics of structural features in the Malay Basin. North-south lineaments seem to be more prominent in the northern part of the basin. Kapal-Bergading is a major north-south tectonic feature that separates the study area into two major structural domains. The Central Malay fault system, also a north-south structural feature, is located in the northern part of the basin (Fig. 13). The major north-south features seem to terminate in the vicinity of the east-west Dulang-Palas line. The Dulang-Palas line is interpreted as a gradual boundary between the northern sub-domain and the southern sub-domain in the Eastern structural domain (see Basin Axis Fold Domain). Folds seem to be the major structural features in the southern part of the Malay Basin. Folds in the Basin Axis fold domain trend approximately east-west whereas those in the Basin Hinge fold domain trend northwest-southeast. These folds are interpreted as drag folds that resulted from the lateral movement of the Axis Malay fault zone (Tjia, 1993) and the Hinge fault zone (Liew, 1995) respectively.

The Kuda-Ular fault zone and the Central Malay fault system seem to demarcate the western and eastern boundary of the northern Malay Basin. The two faults are northerly trending. Based on the findings of EPIC (1994), the "hinge zone" of the Malay Basin is an important facies demarcator. The "hinge zone" is equivalent to the Mesah fault zone in this report. West of this "hinge zone", Tertiary sediments of ages D, E, and H are buried deeper than those in the east. The southern part of the Malay basin is commonly referred to as the Southwest Malay Basin and the northern part (as referred in this report) is known as the Central Malay Basin. Inversion and unconformity are prominent in the Southwest Malay Basin and are commonly associated with oil accumulations. The Central Malay Basin has the deepest depocentre within the Malay basin and is commonly associated with gas accumulations.

This paper has provided a detailed account of the structural characteristics of the Malay Basin based on available data. The proposed new structural elements may represent a bold conjecture. The author admits that the evidences for the existence of the Dulang-Palas line are weak. The author also recognises the need to gather more evidences to strengthen or to disprove this conjecture.

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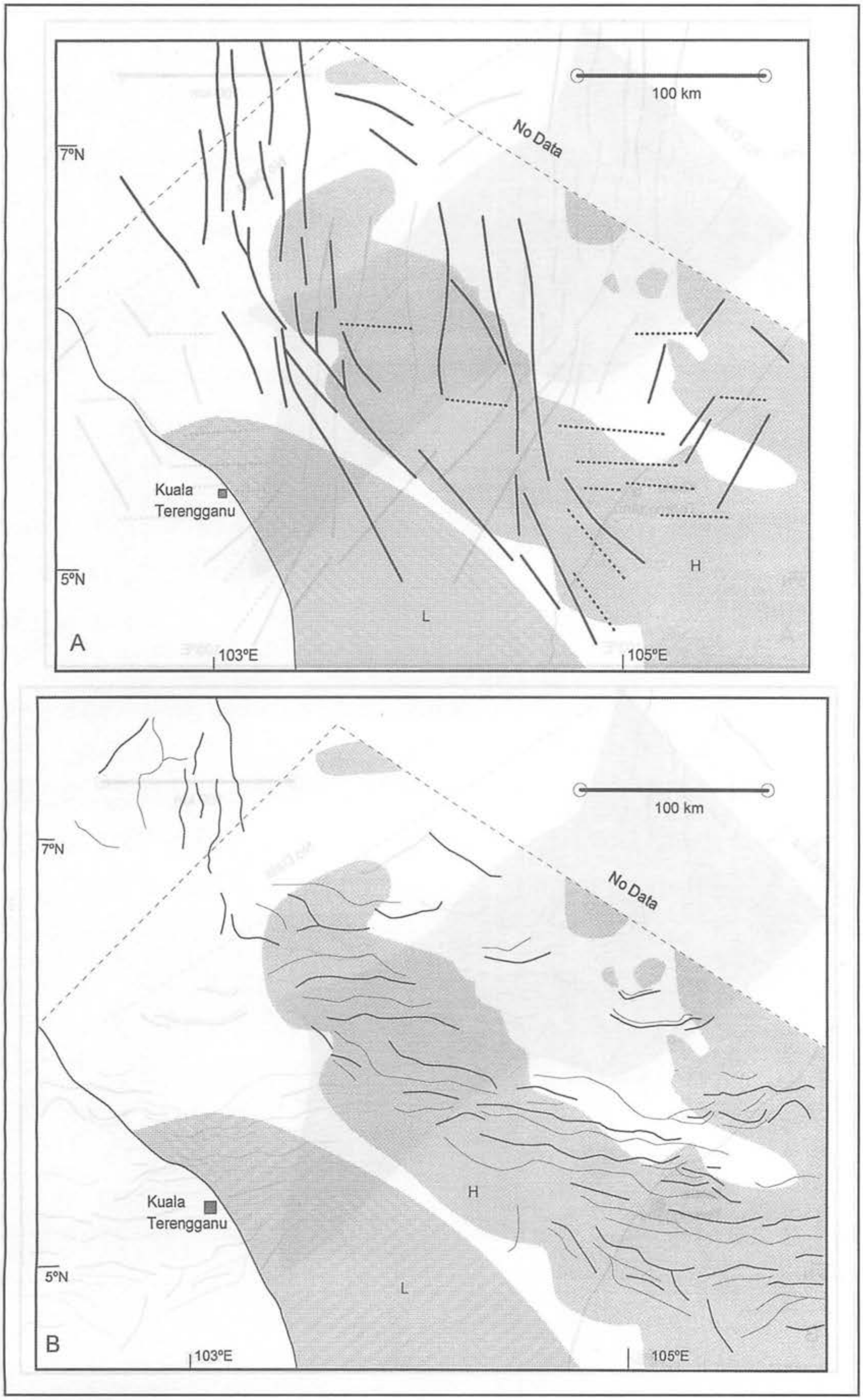

Figure 11. Aeromagnetic anomalies superimposed on faults (A) and on folds (B). (H) is high and (L) is low. Magnetic map adapted from Geophysical Consultants (1994).

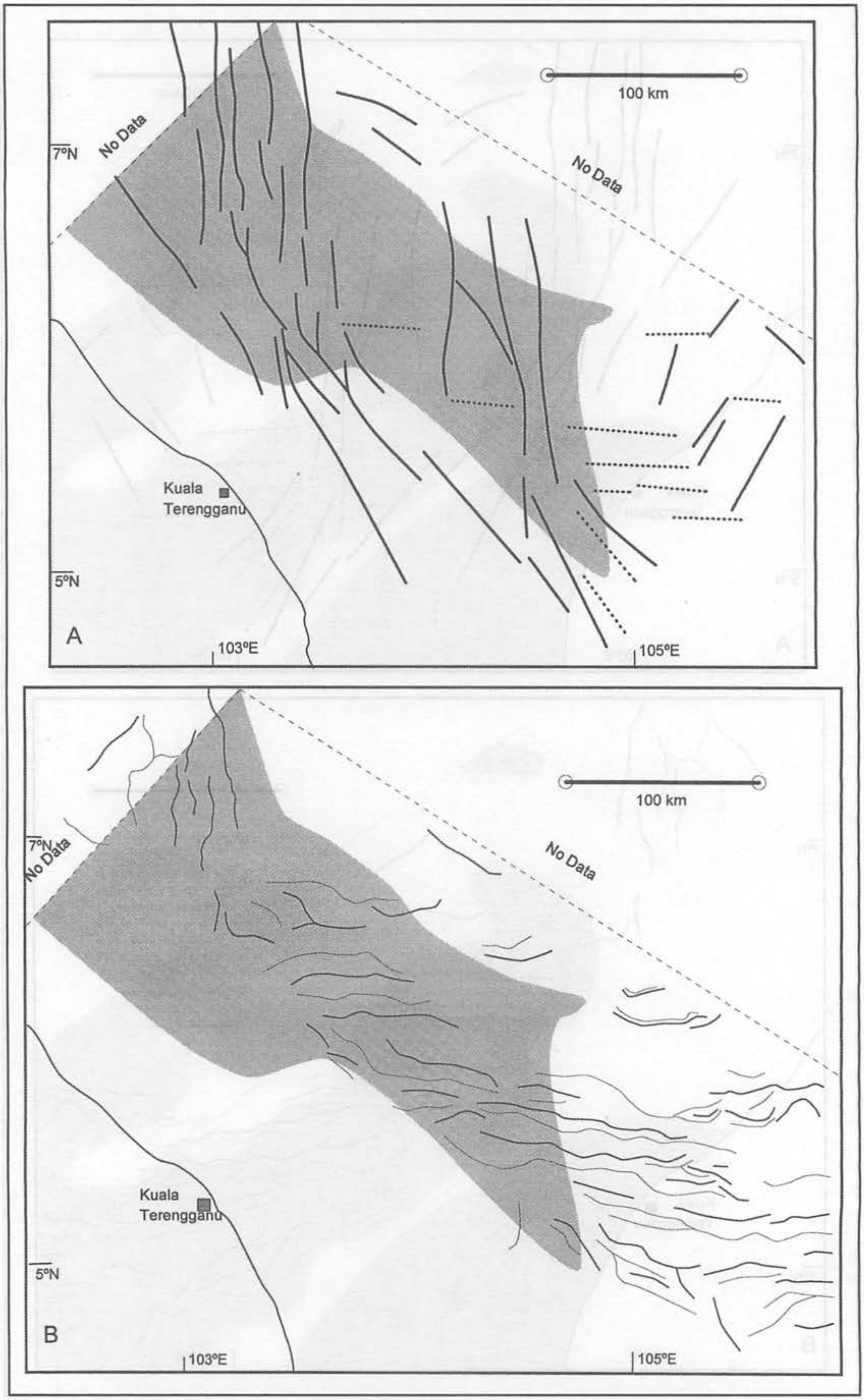

Figure 12. Residual aeromagnetic anomalies superimposed on faults (A) and on folds (B). Shaded area is area of average anomaly. Magnetic map adapted from Geophysical Consultants (1994).

Table 2. Summary of the characteristics of structural features in the Malay Basin.

STRUCTURAL FEATURES	CHARACTERISTICS
Western Structural Domain	Northerly trending structures.
Eastern Structural Domain	East-west folds; two sub-domains separated by Dulang-Palas line.
Northern Sub-domain	Northern part of Eastern structural domain; bounded by Kuda-Ular fault zone and Central Malay fault system; folds are more open and have shorter fold axis than Southern sub-domain; associated with gas.
Southern Sub-domain	Southern part of Eastern structural domain; folds are less open and have longer fold axis than Northern sub-domain; associated with gas.
Kapal-Bergading Tectonic Line	A north-south lineament that separates Western and Eastern structural domains.
Central Malay Fault System	Comprise Dulang, Mesah, Bundi and Selambau fault zones.
Dulang-Palas Line	A proposed east-west line that separates Northern sub-domain and Southern sub-domain.

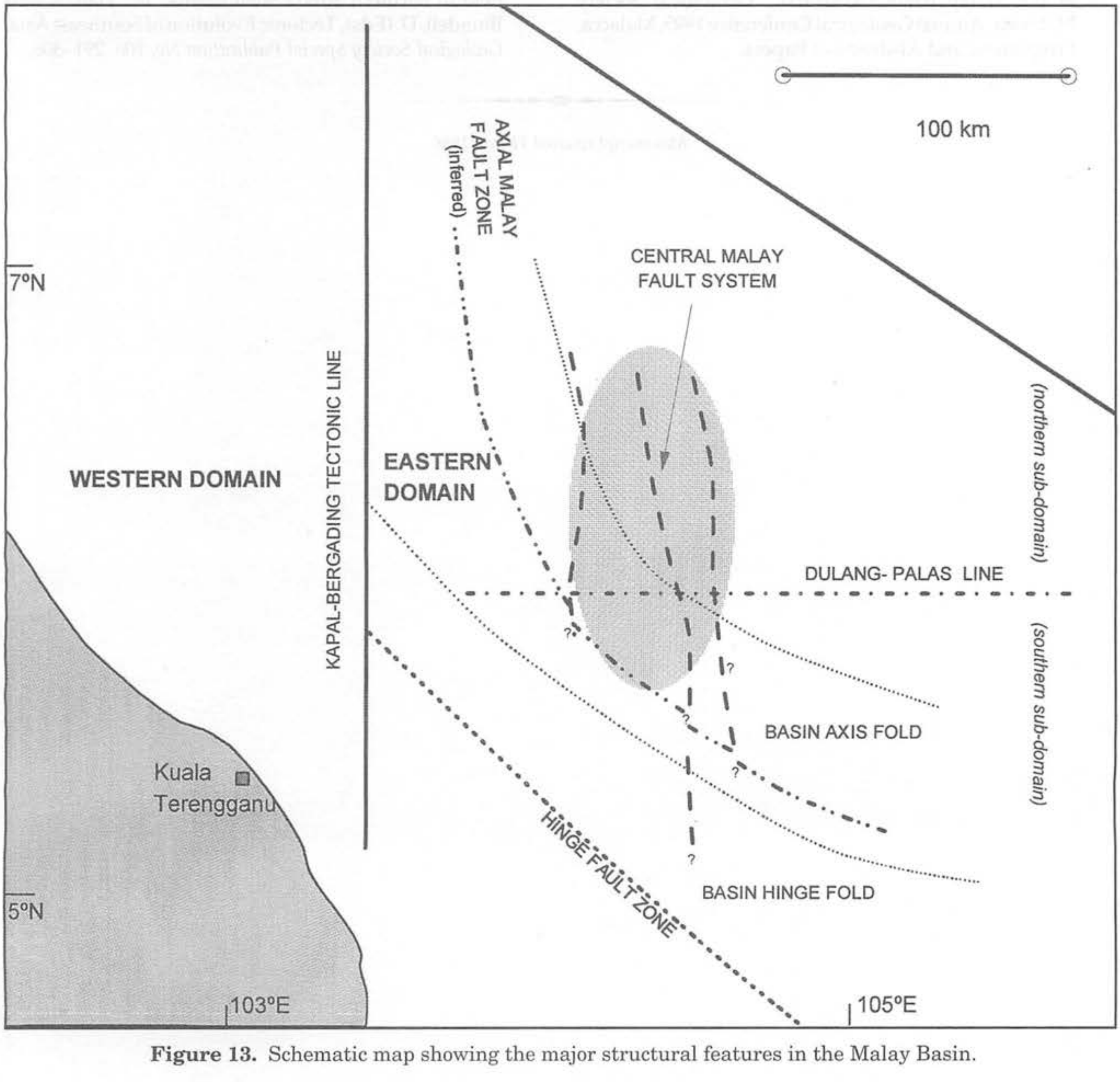

Figure 13. Schematic map showing the major structural features in the Malay Basin.

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