Tertiary tectonics and sedimentation history of the Sarawak basin, east Malaysia

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TERTIARY TECTONICS AND SEDIMENTATION HISTORY OF THE SARAWAK BASIN, EAST MALAYSIA.

by

Ismail Che Mat Zin

A thesis submitted in partial fulfilment of the degree of Doctor of Philosophy

Department of Geological Sciences
University of Durham

1996

This thesis is dedicated
to
my wife Zaitun
and
my children
Fadhil, Ida and Helmi

Declaration

The content of this thesis is the original work of the author and has not been previously published for a degree at this university or any other institution. The work of others is acknowledged throughout this thesis by reference.

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ABSTRACT

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A seismic stratigraphic study of the regional lines for the offshore Sarawak area was undertaken with the aim of understanding the tectonics and sedimentation history of the hydrocarbon prolific Sarawak Basin. The aim here is to develop a workable stratigraphic scheme, a model of the sedimentation history of the basin, a model for Tertiary tectonics, and an analysis of the subsidence history of the basin. Six unconformities have been identified within the Tertiary sedimentary succession, based on seismic reflection and well data. Some unconformities coincide with eustatic sea-level falls; others are probably tectonic in origin. An alternative stratigraphic scheme for the Sarawak Basin was developed by subdividing the whole Tertiary succession into seven sequences. Palaeoenvironment maps of the basin document the interaction of tectonics and sedimentation commencing in late Oligocene times. Deposition started with a NW-SE coastline and a broad coastal plain, almost perpendicular to the present-day coastline (NE-SW) developed during late Miocene times. The maps illustrate the likely distribution of Sarawak Basin source and reservoir rocks which will help in effective planning for future exploration in the area.

The Sarawak Basin formed as a result of NW-SE trending right lateral fault movement during late Oligocene to Pliocene times. This dextral movement was responsible for creating the NW-SE coastline and divided the offshore Sarawak area into two sub-basins. Deposition and preservation of coastal plain and shallow-marine sediments continued in the eastern area while the western area remained as a 'high' until late Miocene times and subsided during late Early to Middle Miocene. The dextral strike-slip movement which controlled the evolution of the Sarawak Basin is sub-parallel to a number of lineaments elsewhere in Sarawak. The timing of movement suggests a progressive younging in an eastward direction.

Basin modelling suggests that the Sarawak Basin was characterised by rapid subsidence in the early stage of basin formation with a high stretching factor and episodic movements. This suggests that the basin did not form as a foreland basin nor as a typical rift basin, but indicates a strike-slip origin. Supplementary evidence for this is provided by the findings of the regional seismic stratigraphic study, which suggests that the whole onshore area of Sarawak and northern Borneo was subjected to strike-slip tectonism during Tertiary times. The driving force may have been initiated by the lateral movement between the Sundaland and South China Continental blocks, probably due to collision between Indian and Asian plates during the Middle Tertiary, continuing with the opening of the South China Sea during the Oligocene. The end result of tectonism in the region, however, is believed to be the combination of strike-slip movements and the counter-clockwise rotation of Borneo during the Oligo-Miocene. The superiority of the proposed strike-slip tectonic model over the present subduction model is the capability to explain most of the geological phenomena, including the absence of evidence for any subduction taking place in the area. The findings of this study should contribute towards a better understanding of the tectonics of the area which will be able to provide information on the development of structural traps for hydrocarbon plays that are believed to have formed by strike-slip tectonism.

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Chapter 1

INTRODUCTION TO PETROLEUM GEOLOGY AND TECTONIC EVOLUTION OF THE SARAWAK BASIN

1.1. About this thesis.

This thesis describes the present understanding and the alternatives offered for the Tertiary stratigraphic framework and tectonic evolution of the Sarawak Basin of Northern Borneo (Sarawak, Sabah and northern Kalimantan, Figure 1.1). This thesis also discusses the history of sedimentation in the basin. The findings of the study are derived mainly from the interpretation of 2,370 km of basinwide regional seismic lines and some 1,780 km of regional lines from two exploration blocks (SK5 and SK12, Figure 1.2). These lines cover an area of 200 km by 300 km of a large Tertiary sedimentary basin located both in onshore and offshore Sarawak, East Malaysia (Figure 1.1). All the seismic lines were used with the permission of PETRONAS, the national oil company of Malaysia.

No similar study has been carried out before as the basin-wide regional lines were reprocessed and/or redisplayed by PETRONAS Carigali commencing in 1992/93 and completed in 1993/94. The 1,780 km of seismic lines confined to the two exploration blocks may have been interpreted by the operators of the respective blocks. Although these data have been interpreted by oil industry staff, this study has carried out a fresh interpretation of the lines and it is totally independent of any other previous study. This study has also made use of forty-five composite well logs for wells drilled throughout the study area. The interpretations on the gravity, magnetic and synthetic aperture radar by previous workers were also used in deriving the conclusions of this study.

The aim of this study is to acquire a better understanding of the tectonic and sedimentation history of Sarawak Basin. An objective is also to develop alternative tectonic and stratigraphic models. This is very much needed, since the existing geological models for the Sarawak Basin are no longer adequate to explain the new findings and observations derived from more sophisticated geoscientific tools, i.e. deep penetration 2D and 3D seismics and the data from the new exploration wells. These expensive tools could be under utilised and high capital investments could not be remunerative if the geological framework of the basin is not well understood.

Figure 1.1. Map of South East Asia showing the location of the study area.

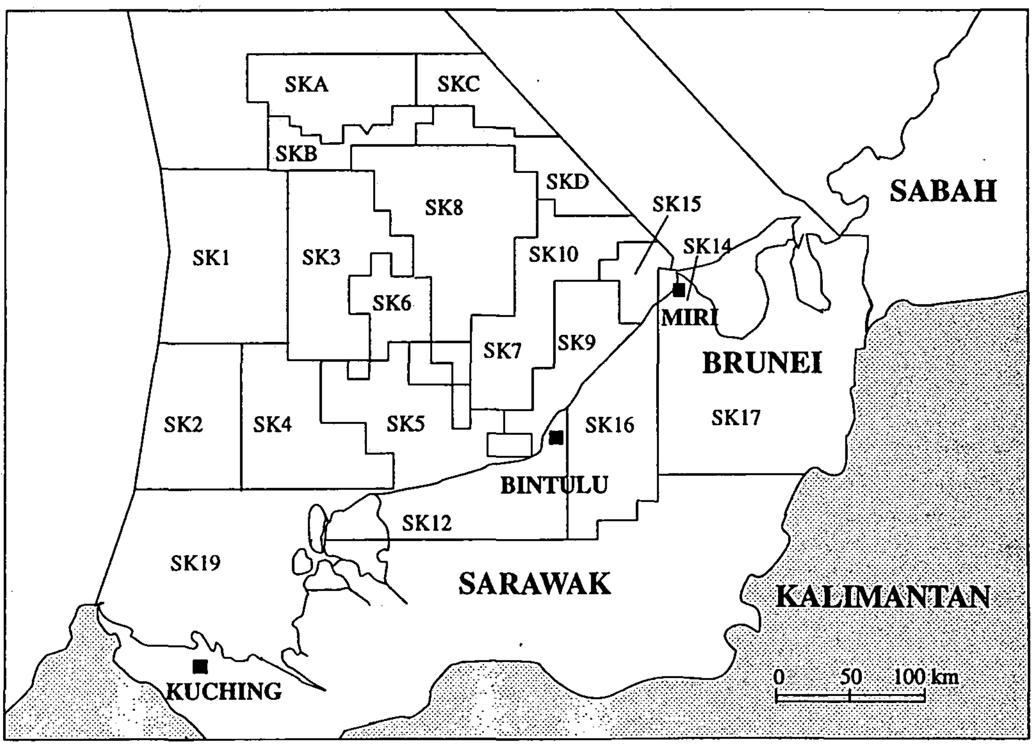


Figure 1.2 Current exploration sub blocks in Sarawak.

This chapter describes the history of petroleum exploration in Sarawak, the geology of the onshore area and the present understanding of the stratigraphic and tectonic frameworks of the Sarawak Basin. The **second chapter** describes in more detail the present stratigraphic framework and an alternative is offered. The **third** chapter describes the depositional history of the Sarawak Basin and the **fourth chapter** outlines the Tertiary tectonic evolution of the Sarawak Basin that is the main part of this study. The **fifth chapte**r describes how the basin modelling has been carried out and discusses the results. The **sixth chapter** discusses the Tertiary tectonic evolution of northern Borneo and the **final chapter** outlines the conclusions of this study.

1.2 History of Petroleum Exploration in Sarawak

The exploration for oil in Sarawak began more than a century ago when the first known report of the presence of oil in Sarawak was written in 1882, and the first onshore discovery well, Miri-1 was drilled in 1910 (Nagtegaal, 1989). Since then, there has been extensive exploration for oil in the onshore Balingian and Miri Provinces with exploration of the offshore area since the 1950s. The initial production of the Miri field was 83 bbl/d and peak of production reached 15,000 bbl/d in 1929/30 (Tan, 1994). Today, the Sarawak Basin is one of the three contributors besides the Sabah and Malay basins for a total of more than 600,000 bbl/d of oil and 2,500 million cubic feet of gas per day of the total hydrocarbon production of Malaysia (PETRONAS, 1994).

The whole of Sarawak (Figure 1.1) was concessioned to Shell for exploration until 1976. In 1974, PETRONAS was formed and through the Petroleum Act, it holds the entire ownership and control of all Malaysian hydrocarbon resources. The first Production Sharing Contract (PSC) was implemented in 1976 with Esso and Shell for the Malay Basin and Sarawak Basin respectively. In 1985 a new PSC was introduced and currently the Sarawak Basin has been divided into nineteen exploration sub-blocks (Figure 1.2).

To date, more than three hundred exploration and appraisal wells have been drilled in the Sarawak Basin. This has resulted in a total of 39 oil fields and 76 gas discoveries. Twelve oil fields and three gas fields are currently producing. In addition, eleven gas fields are dedicated to the liquefied natural gas project (PETRONAS 1994). The producing fields are located in the Balingian and Luconia Provinces that are located in the study area, and Baram Delta Province that is situated to the east of the study area.

1.3. Geology of onshore Sarawak

A sketch map based on the most recent geological map of Sarawak published by the Geological Survey of Malaysia is shown in Figure 1.3. Based on the map, onshore Sarawak can be subdivided geologically into four major areas:

1. *Eocene-Pliocene sediments*
2. *Cretaceous -Eocene Belaga Formation*
3. *Pre-Cretaceous basement complex and*
4. *Tectonic mélange*
5. *Eocene-Pleistocene igneous body.*

1.3.1 Eocene-Pliocene sediments

The Eocene-Pliocene sediments in central and eastern Sarawak include the Tatau, Buan, Tubau, Nyalau, Setap, Tanggap, Sibuti, Lambir, Belait, Balingian, Begrih and Liang Formations (Figure 1.4). However, only several Eocene-Pliocene geological formations are located in the study area (Figure 1.5) namely the Tatau, Buan, Nyalau, Setap, Begrih and Liang Formations. These formations and their subsurface equivalents are prolific for hydrocarbon reservoirs in both the offshore area and onshore sub-basins. The descriptions of the Eocene-Pliocene geological formations in the onshore Mukah-Bintulu areas are outlined below; mainly based on the work of Liechti et al. (1960). A stratigraphic summary of these geological formations with the main lithology, thickness and the depositional environments are shown in Table 1.1.

The Tatau Formation consists of a succession of sandstone, siltstone and shales with intercalations of marls, limestones and locally developed conglomerates. The sediments of this formation are interpreted to be deposited as submarine fan and slope deposits during the late Eocene-Oligocene times. The total thickness at the type locality (Arip-Pelagau Anticline) is 600-700 m. The formation is moderately to intensely deformed.

The Buan Formation is essentially made up of shales alternating with argillaceous siltstones and thin sandstones and measures 500-700 m thick in the Bukit Buan area. The formation lies conformably on the Tatau Formation and it is interpreted to be deposited in the shallow marine environment during early Oligocene times. The formation is moderately folded.

The Balingian Formation consists of sandstones and shales with abundant lignite. The total

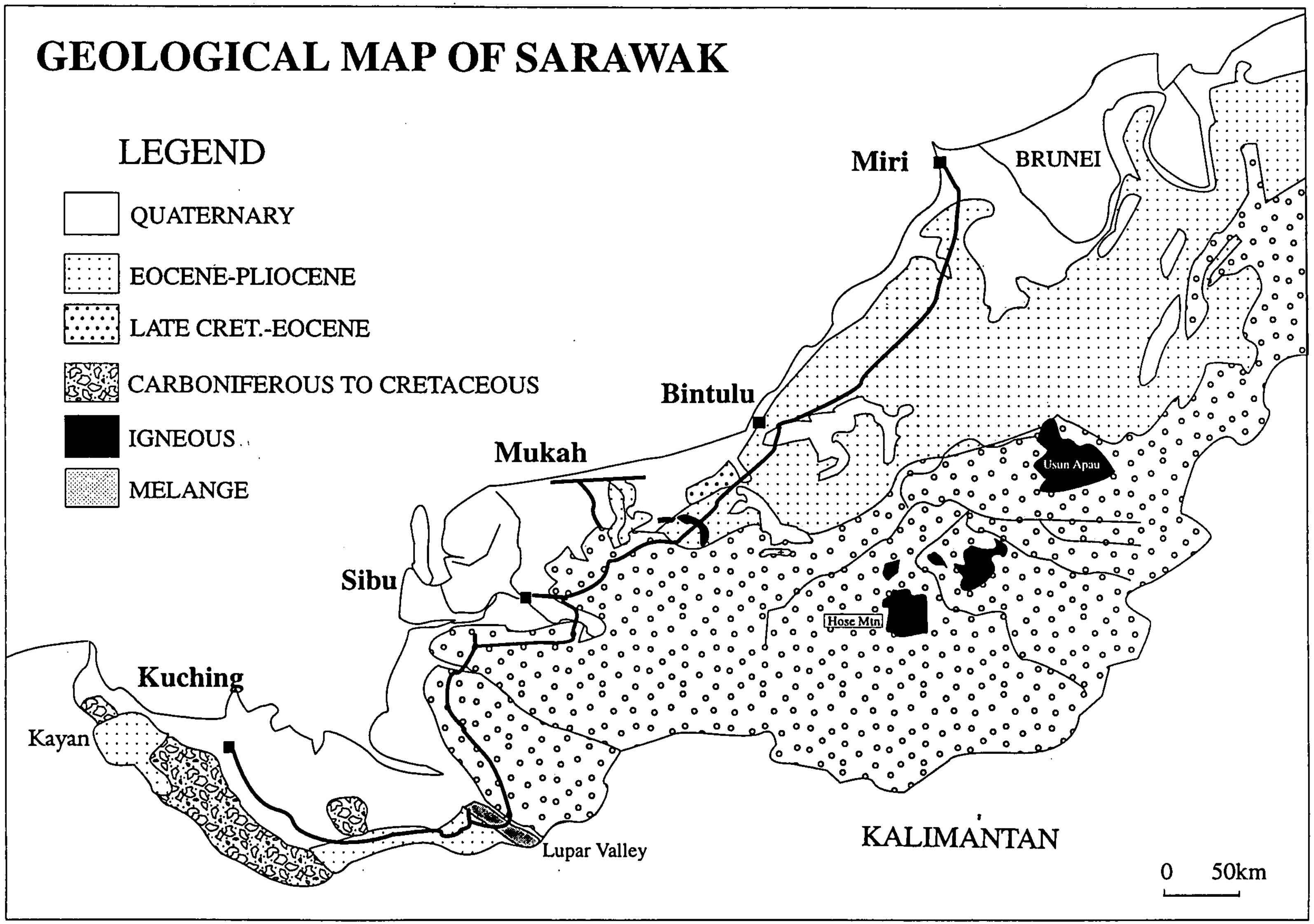


Figure 1.3. Geological map of Sarawak based on Heng (1992).

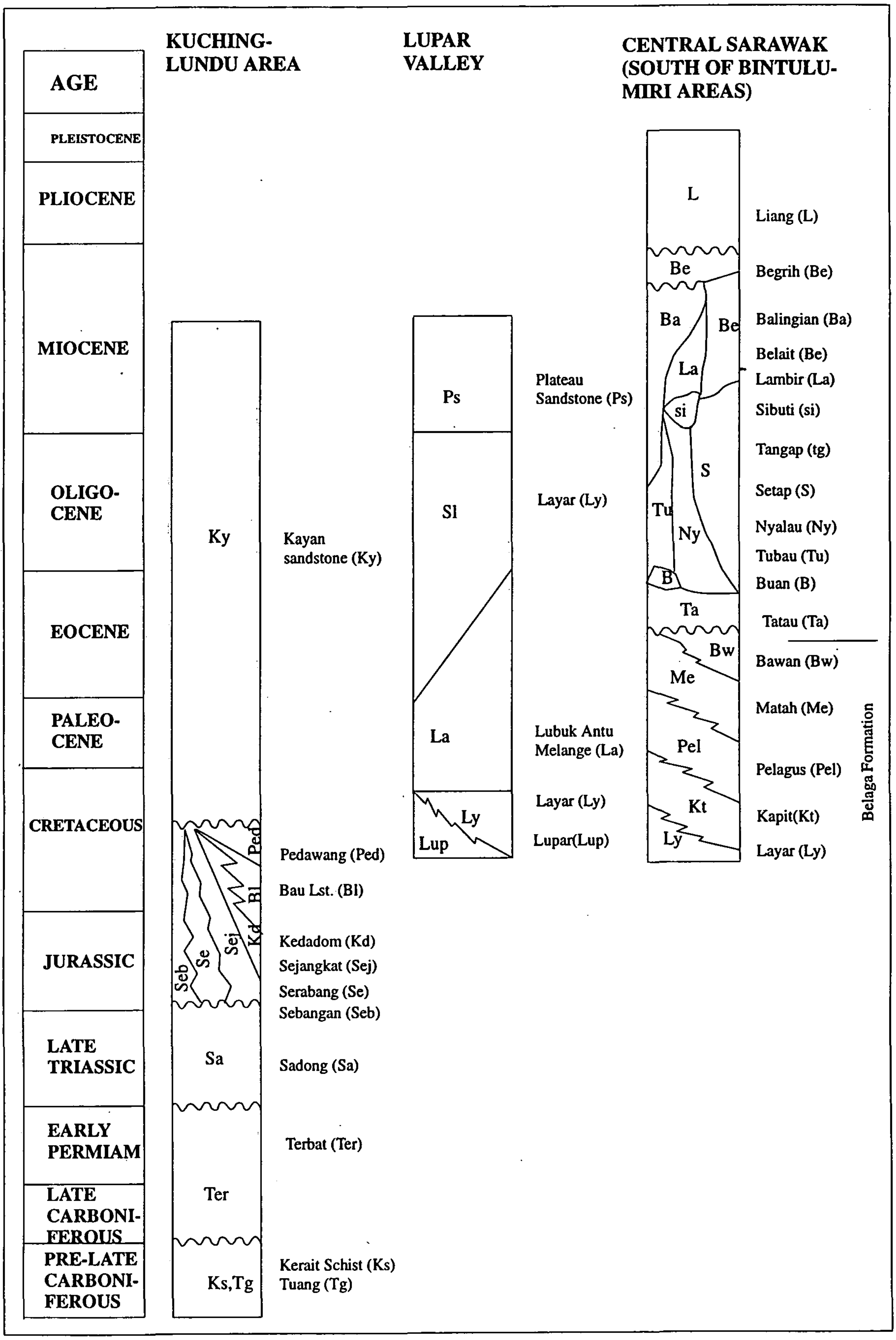


Figure 1.4. Generalised stratigraphy of Sarawak for the Kuching, Lupar Valley and the areas to the south of Bintulu and Miri, extracted from the Geological Map of Sarawak by Heng (1992).

thickness appears to exceed 3500-4000 m thick. The top boundary with the Begrih Formation is represented by a minor unconformity. The Balingian Formation is probably a lateral equivalent to the youngest Nyalau Formation but forms a separate area of outcrops . Outcrops only occur in the Block SK12 (Figure 1.2).

The Nyalau Formation consists of a succession of fine to medium-grained sandstones alternating with shales. Coals are present in the middle and upper parts of the formation that was deposited during the Oligocene to early Miocene times. The Nyalau Formation lies conformably on the Buan Formation and locally it lies unconformably on the Tatau and the Belaga Formations. The total thickness is 5200-6000 m . The sediments are moderately folded.

The Begrih Formation consists of a succession of clays, sandstones and very coarse to pebbly sandstone with local, boulder conglomerates at the base. The thickness of the formation varies in the surface outcrops from 600-750 m. The base of the formation is unconformable on the Balingian Formation and the top is also unconformable with the Liang Formation. The sediments were mainly deposited in the coastal plain environment during middle Miocene times and the sediments are gently folded. Outcrops only occur in the Block SK-12.

The Liang Formation consists of shales, sandstones, conglomerates and abundant lignite. The base of the formation is unconformable with the Begrih and Belaga Formations. The sediments were deposited during middle Miocene to upper Miocene times in the environment of predominantly coastal plain with some influences of shallow marine in the northern part of the outcrops. The thickness of approximately 520 m of this formation was encountered in the well Balingian-3 (Liechti et al., 1960). The sediments are gently folded.

1.3.2. Cretaceous-Eocene Belaga Formation

The Belaga Formation is a semi-metamorphosed shale succession of apparent huge thickness (5000-8000 m, Haile, 1957, quoted in Liechti et al., 1960). This formation is the basement to the Tertiary sediments in the offshore area. The formation could be described as "steeply dipping and highly deformed flysh deposits". It is commonly metamorphosed to greenschist facies slate and phyllite containing quartz veins (Hutchinson, 1988).

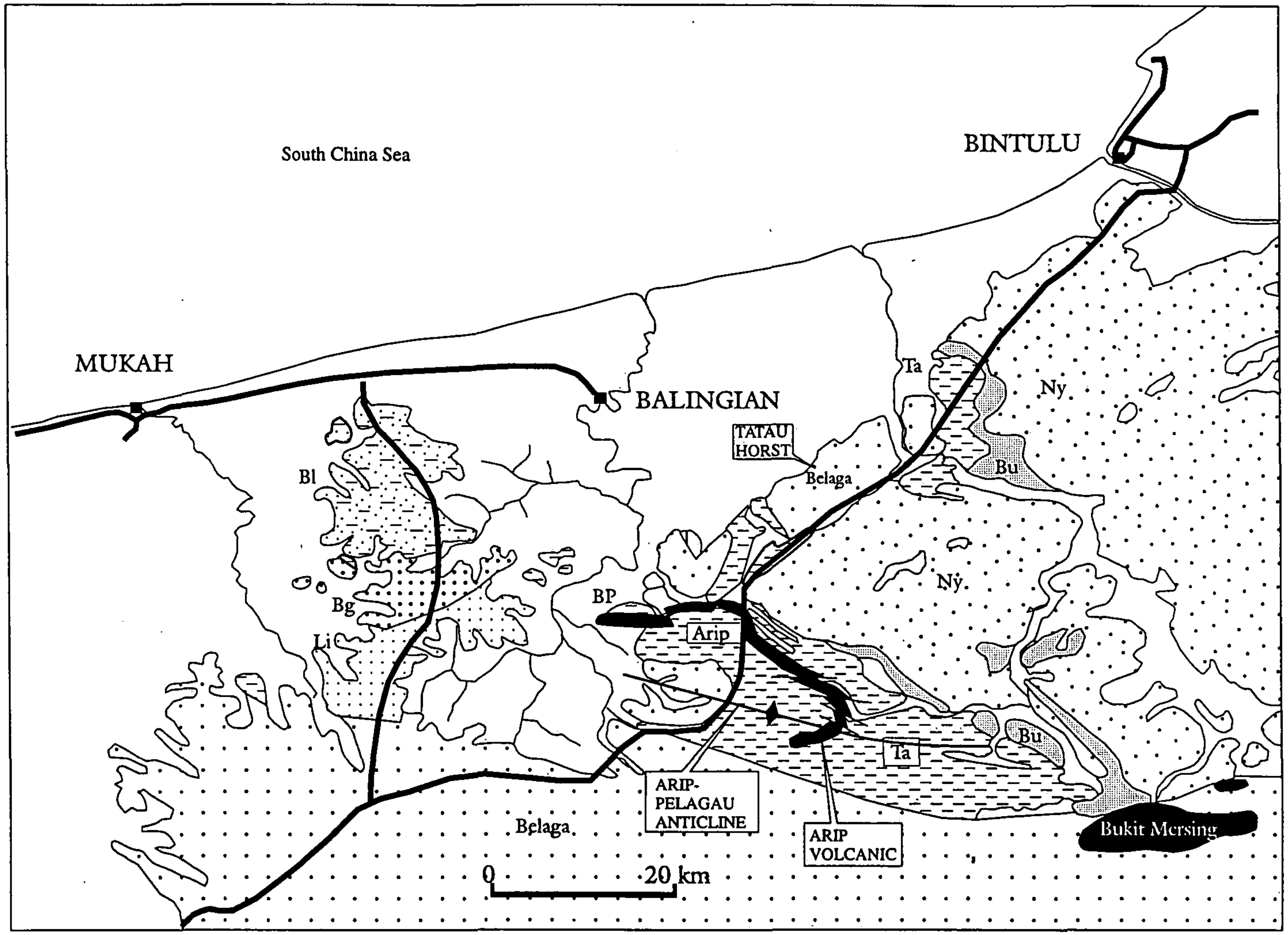


Figure 1.5, Geological map of Mukah- Bintulu area. Sketch based on Hing (1992). The map shows the distribution and lateral extent of the Tertiary formations in the area. The abbreviations used are: Ta=Tatau, Bu=Buan, Bl= Balingian, Ny= Nyalau, Bg=Begrih, Li=Liang formations. Black is granodiorite at Bukit Piring (BP), andesite and rhyolite lavas at Arip and andesite at Bukit Mersing.

Wolfenden (1960) divided the Belaga Formation into four stages based on paleontological evidence, largely on the basis of arenaceous smaller foraminifera. Earlier, Leichti et al. (1960, p 58) re-interpreted the four stages as members on the basis of the lithological differences, even though "their identification of lithology is only very approximately possible" (Wolfenden, 1960). Based on both larger and pelagic foraminifera, the approximate correlation of the four stages is:

Stage IV: Upper Eocene
Stage III: Middle to Lower Eocene
Stage II: Lower Eocene to Palaeocene
Stage I: Upper Cretaceous.

The oldest stage of the Belaga Formation (Stage I) is situated in the southernmost part of Sarawak, towards the Sarawak-Kalimantan border. It is progressively younger to the north with the Stage IV outcropping in the Tatau Horst area (Figure 1.5).

In terms of tectonic overprints seen on the formation, Wolfenden (1960) described the formation as intensely folded, although several major anticlinal and synclinal structures have been recognised on palaentological and photogeological evidence, the detailed structure is unknown. The rocks commonly show intense small-scale folding. The highly deformed and intensely folded nature of this turbiditic formation was reported by several workers including Haile (1994). Hutchinson (1994) described the formation as "compressed into a steeply-dipping isoclinally-folded quartz-veined phyllitic complex, peneplained in the northwest and unconformably overlain by the Nyalau Formation".

The Belaga Formation has been included together with the Crocker Formation and other deep-water formations in Sabah by Haile (in Hutchinson, 1988). Despite being grouped together, the Belaga and the Crocker Formations have some clear differences. This includes the age and the nature of the rock deformations. The West Crocker Formation in Sabah is Eocene to mid-Tertiary in age and consists mostly of flysch (Brown, 1987). The Crocker Formation was deposited mainly as proximal sandy turbidites throughout the Oligocene (Hutchinson,1994). The Belaga Formation (Rajang Group) in Eastern Borneo is not metamorphosed and the deformation style is different (Hutchinson, 1988). The grouping, therefore, seems to be over-simplified and it is believed that the differences warrant further detailed investigation and explanation. A possible explanation of why the age of the Belaga Formation changes as it goes farther to the north and northeast towards Sabah is discussed further in Section 6.4 of Chapter 6 that formed as part of the major findings of this thesis.

Table 1.1. Stratigraphic summary on the geological formations in onshore Sarawak (SK12 area) with the main lithology, thickness and depositional environments based on Liechti et al. (1960).

Age	***Geological formation***	***Lithology***	***Thickness (metres)***	***Depositional Environment***
Middle-later Miocene	*Liang Formation*	Alternating shales, sandstones, conglomerate and abundant lignite.	*app. 520*	Coastal plain
Middle Miocene	*Begrih Formation*	Succession of clays and pebbly sandstones	*600-750*	Coastal plain
Oligocene-early Miocene	*Nyalau Formation* *Balingian Formation*	Alternating sandstones and shales with occasional coal beds. Sandstones and shales with abundant lignite	*5,200-6,000* *3,500-4,000*	Coastal plain to shallow marine
Early Oligocene	*Buan Formation*	Essentially shale with thin silts and sandstones.	*500-700*	Shallow marine
Eocene-Oligocene	*Tatau Formation*	Succession of sandstones, siltstones and shales with intercalation of marls, limestones and conglomerate.	*600-700*	Submarine fan and slope.
Upper Cretaceous to Upper Eocene	*Belaga Formation*	Thick shale with thin intercalations of sandstones.	*5,000-8,000*	Deep marine.

1.3.3. Pre-Cretaceous Basement complex.

The Pre-Cretaceous basement complex situated to the south and southwest of Kuching, the capital of Sarawak, is the area with the oldest rock unit in Sarawak. In places, this basement complex is overlain by Tertiary sediments known as the Kayan Sandstone and Silantik Formation (Figure 1.4). The rock stratigraphic column of Sarawak by Heng (1992) recorded the oldest rock in the complex as pre-Late Carboniferous and known as the Kerait Schist Formation. The stratigraphy of the Kuching area is shown in Figure 1.4.

Among the geological formations in the Pre-Cretaceous complex outcropping in the Kuching area are Kerait Schist, Terbat, Sadong, Serabang, Sejingkat, Pendawan and Kedadom

Formations, including Sebangan Hornstone and Bau Limestone. The descriptions of the geological formations in Kuching area, mainly based on Heng (1992) are outlined below. The stratigraphic summary of these geological formations with the main lithology, thickness and the depositional environments (when available) based on Tate (1991) and Heng (1992) are shown in Table 1.2.

The Sadong Formation is Late Triassic age and the formation is made up feldspathic sandstone, shale, arkose with subordinate conglomerate, limestone, chert and tuff. The Serabang, Sejingkat and Sebangan Hornstone Formations are Jurassic to Cretaceous in age and the formations consist of shale, slaty shale, slate, phyllite, metagreywacke, chert, conglomerate and bouldery slate with some conglomerate, hornfels, and marble associated with metamorphosed gabbro, diabase, basalt and spilite with strong regional metamorphism. The Kedadom, Pendawan and Bau Limestone Formations are Late Jurassic to Late Cretaceous in age. The formations contain shale, mudstone, sandstone and conglomerate with lenses of chert, acid to intermediate lavas and associated tuffs, massive limestone with thin beds of calcareous sandstone and conglomerate (Heng,1992).

1.3.4. Tectonic mélange rocks.

The mélange rocks in the Lupar Valley (known as the Lupar Mélange, Figure 1.3) have been interpreted by Tan (1982) as the demarcation line between the Pre-Cretaceous basement complex and the Belaga Formation. This suture zone was interpreted as a Tertiary subduction zone in Sarawak. The zone is composed of fragments and blocks, ranging from a few centimetres to a few kilometres in maximum dimension of mudstone, sandstone, hornfels, chert, conglomerate, basalt and gabbro (Tan, 1982).

1.3.5. Eocene-Pleistocene igneous bodies.

Sarawak has a very small proportion of igneous rocks to sedimentary and metamorphic rocks. According to the Geological Map of Sarawak by Heng (1992), the biggest igneous body is at Usun Apau Plateau with dimensions of about 30km by 30km (Figure 1.3). The Usun Apau Plateau and Hose Mountain rocks have not been dated radiometrically but they are speculated to be equivalent of Pliocene explosive vulcanicity in Kalimantan (Tate, 1991). According to the Geological Map of Sarawak by Heng (1992), the rocks are mapped as basalt lava of Pliocene to Pleistocene age. Among the smaller igneous bodies are granodiorite intrusions at Bukit Piring, andesite and rhyolite lavas at Arip and basalt and andesite at Bukit Mersing. These igneous bodies are interpreted to be of Eocene to Oligocene age (Heng, 1992).

Table 1.2. Stratigraphic summary of the Pre-Tertiary geological formations in West Sarawak (Kuching area) with the main lithology of the formations, thickness and the depositional environments based on Tate (1991) and Heng (1992).

Age	***Geological formation***	***Lithology***	***Thickness (metres)***	***Depositional Environment***
Late Cretaceous	*Layar Member of Belaga Formation*	Rhythmically interbedded shale, mudstone, slate and greywacke with some conglomerate lenses. Strong regional metamorphism.		Deep marine
	Lupar Formation	More arenaceous than the Layar Member.		
Late Jurassic to late Cretaceous	*Pendawan Formation*	Thick marine shale, mudstone and sandstone with subordinate beds of conglomerate, limestone, chert and andesite to rhyolitic lavas and tuffs.	*2,000-4,500*	Shallow marine
	Bau Limestone	Massive, poorly to moderately fossiliferous limestone with thin calcareous shales and conglomerate.	*up to 600*	
	Kedadom Formation	Shale, mudstone, sandstone, conglomerate with lenses of chert, acid to intermediate lavas and associated tuff.	*400*	Shallow marine
Jurassic to Cretaceous	*Serabang, Sijangkat and Sebangan Hornstone Formations*	Shale, slaty shale, metagreywacke, chert, conglomerate and bouldery slate, with some conglomerate, hornfels, marble associated with metamorphosed gabbro, diabase, basalt and spilite. Strong regional metamorphism.	-	-
Late Triassic	*Sadong Formation*	Feldspathic sandstone, conglomerate and tuffaceous sediments with thin beds of coal, chert, tuff and limestone.	-	Shallow marine
Late Carboniferous to early Permiam	*Terbat Formation*	Massive limestone, recrystallised, silicified and dolomitised, and chert with subordinate shales.	-	Shallow marine
Pre-Late Carboniferous	*Kerait Schist* *Tuang Formation*	Muscovite and tremolite schists. Greenschist grade metamorphic rocks comprising basic rock with boudinage sandstones.	-	Turbiditic/ Oceanic environments

1.4 Stratigraphic framework of offshore Sarawak

The lithostratigraphic nomenclature of the rock succession of onshore Sarawak remains essentially unchanged since it was originally outlined by Liechti et al. (1960) and Wolfenden (1960). The limitations of using the formation names became apparent when attempts were made to correlate the subsurface sedimentary succession of the offshore area to the equivalent outcrops due to rapid facies changes and the diachroneity.

A scheme based on the genetic sedimentary cycle concept was developed by Shell (Ho, 1978). Eight sedimentary cycles have been recognised for the entire Tertiary sedimentary succession of offshore Sarawak. Each cycle starts with a transgressive basal part followed by a regressive unit which in turn is overlain by the basal transgressive unit of the next cycle. Most of the transgressions spread over a wide area within a short time and therefore the cycle boundaries closely follow time-lines. The cycles thus defined are approximately time units, with distinctive fossil biota and lithologies. The cycle concept is therefore chronostratigraphic in nature and this enables correlation across facies boundaries which neither biostratigraphy nor lithostratigraphy alone could provide.

By using the scheme, Ho (1978) was able to correlate between the onshore formations and their cycle equivalents in the offshore area (Figure 1.6). The cycle concept is widely accepted. With some modification the concept is still in use today, more than fifteen years from the time it was originally published.

1.4.1. Statement of problems.

The cycle concept means that one should look for the marine transgressive unit to identify the cycle boundaries. The sedimentary succession between two marine pulses or their correlatable boundaries is defined as a cycle. The cycle is mostly composed of a regressive unit of sediments.

The question of general applicability of the scheme arises when one tries to identify the marine surfaces or their correlatable strata within the sediments that were deposited in non-marine environments. This is critical for the Late Oligocene-Miocene sediments that form the most important hydrocarbon reservoirs in the nearshore and onshore Sarawak. These sediments were predominantly deposited within the lower coastal plain to upper coastal plain environments, normally barren of foraminifera. As for the non-marine strata, Ho (1978) suggested that palynology provided the only means of dating the fluvial sediments. In view of the rather uniform climatic conditions since Oligocene time, few changes occur in the overall

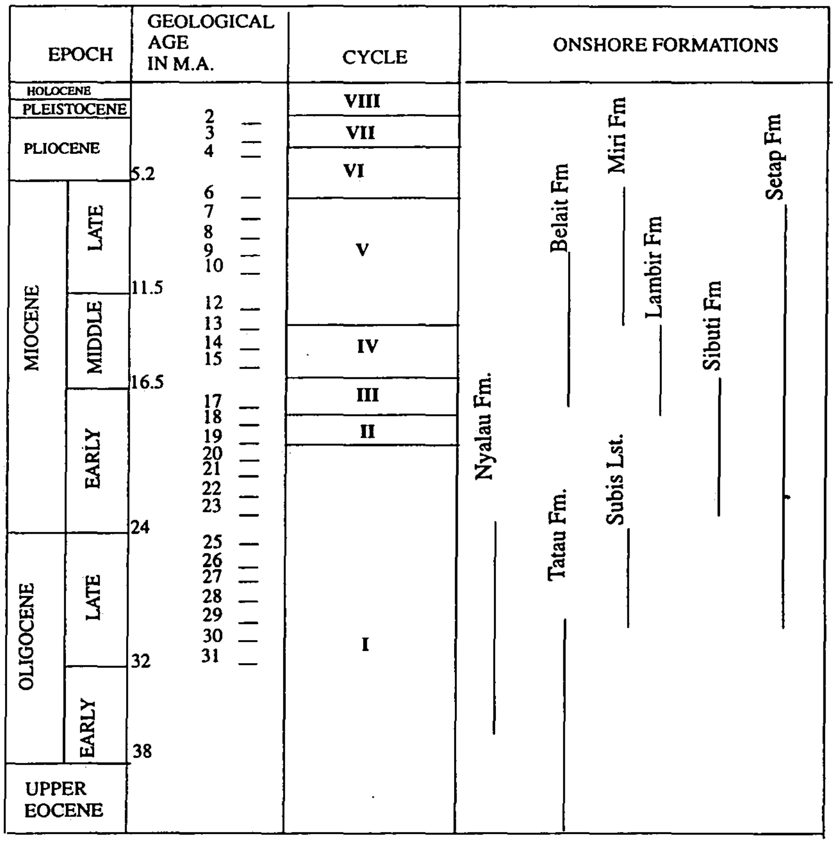


Figure 1.6. Correlation between the offshore sedimentary cycles and the geological formations in onshore Sarawak. Based on Ho (1978).

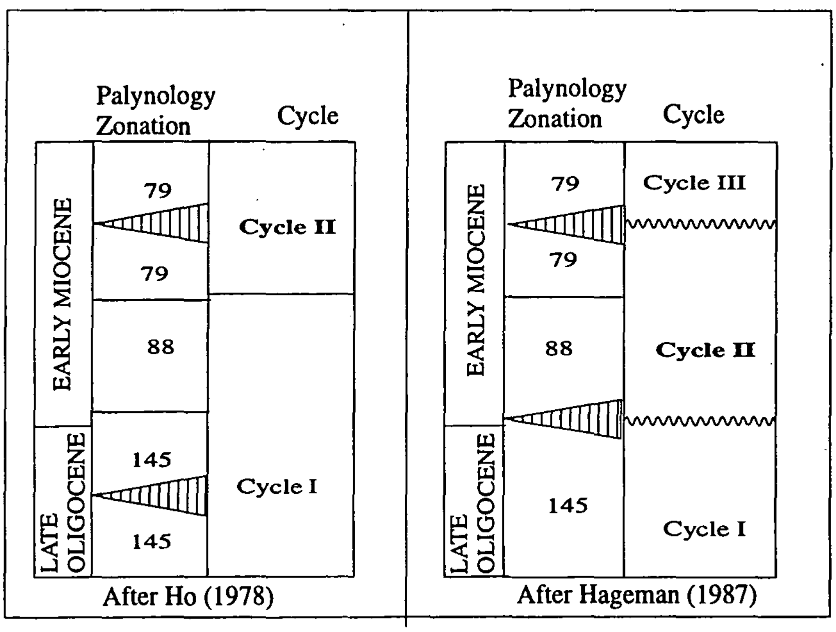


Figure 1.7. Figure shows how the cycle boundaries have been moved from the original positions to the new cycle boundaries.

flora and as a result only a broad palynological zonation can be established for regional correlation.

In reality, the use of pollen is very difficult. When the attempts were made to correlate the wells in Block SK5 using the cycle boundaries picked on the composite well logs, cycle boundaries were not picked consistently and others could be differentiated. A similar situation was experienced by Levesque and Ooi (1989) who found that only the base of Cycle II has a clear pollen break but that often this does not agree with the seismic pick, even where detailed field studies have been completed. They noted that the cycle boundaries are often unprecise both in seismic and well logs. This is due to the fact that the cycle concept was originally intended to be used only in the Baram delta area, where indeed there is little or no physical evidence of boundaries.

In summary, it is not feasible to correlate the cycle boundaries for the wells in the nearshore and onshore areas by only using the pollen zonations. This is even more difficult for non-Shell workers since the pollen zonations on the well logs are coded.

By adopting the concept of global sea-level changes, Hageman (1987) modified the stratigraphic scheme of the Sarawak basin that was introduced by Ho (1978). Figure 1.7 shows how the position of the original cycle boundaries for Cycles I, II and III were moved to the new cycle boundaries. Hageman (1987) compared the Sarawak palaeobathymetrical curve with the global sea-level curve and suggested that from Middle Miocene to Pliocene times changes in bathymetry were largely controlled by eustasy, while during the Late Oligocene to Early Miocene the effect of global sea-level changes was largely masked by important tectonic movements.

Some of the "new cycles" are bounded by unconformities. Thus the new stratigraphic scheme introduced by Hageman (1987) forms a hybrid of the cycle concept and the concept of sequence stratigraphy. The definition of a sequence by Mitchum (1977) is a relatively conformable succession of genetically-related strata bounded by unconformities or their correlative conformities. However, Hageman (1987) continued to call the sedimentary unit in the new stratigraphic scheme a "*Cycle*" despite the changes in the datum used. The present stratigraphic scheme for Sarawak Basin used by PETRONAS, mainly based on the new approach is shown in Figure 1.8.

The *new cycle* is different from the definition of cycle as defined by Ho (1978). The difficulties of recognising the cycle boundaries coupled with the new changes leads to great confusion and results in a serious problem in mapping and well correlation. The situation is

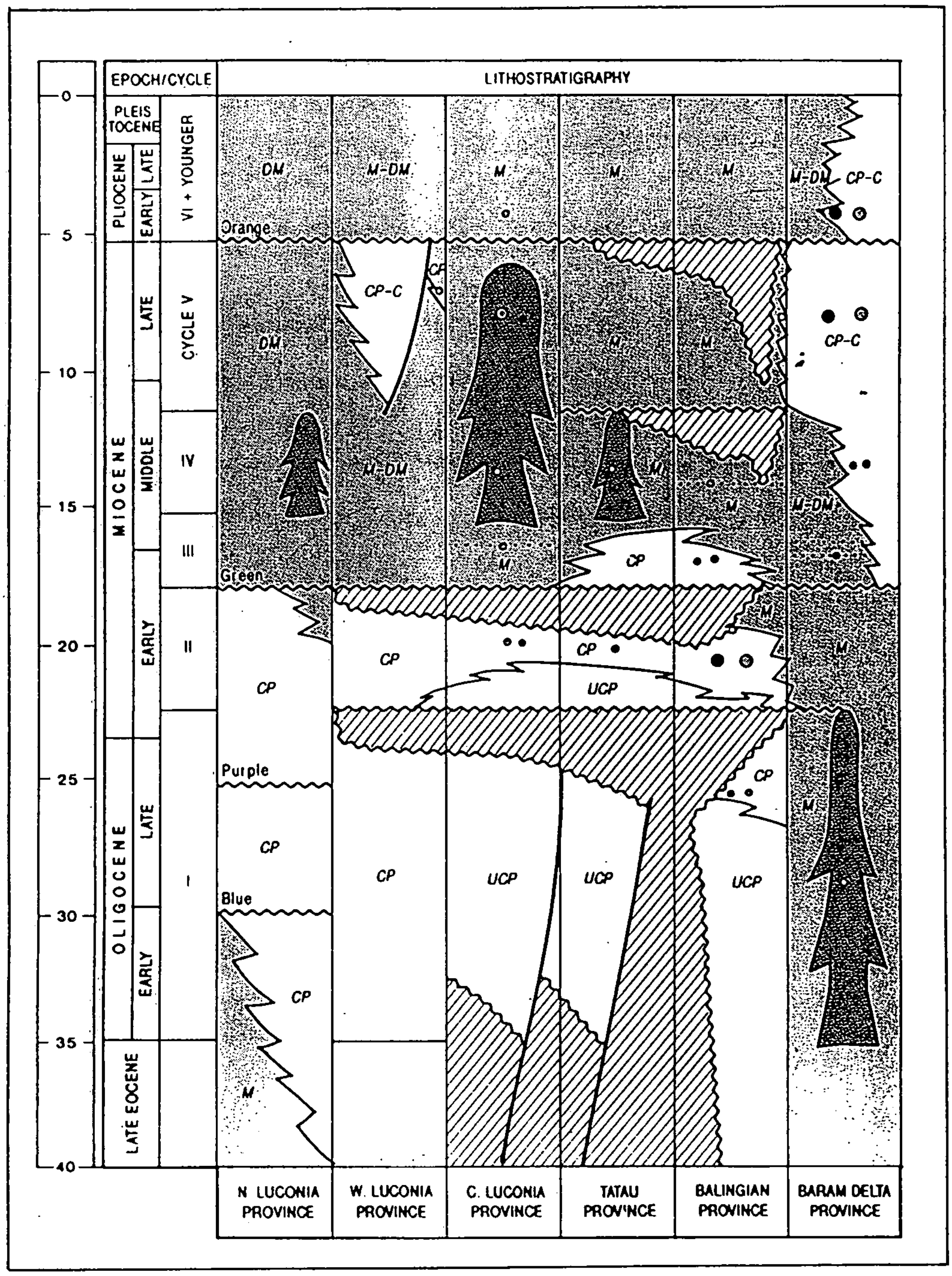


Figure 1.8. Stratigraphic scheme of Sarawak Basin. After PETRONAS (1994). The abbreviations used are: DM=deep marine, M= Marine, C=Coastal CP=Coastal Plain, UCP=Upper coastal plain

even more serious since the Sarawak Basin has been subdivided into several exploration blocks and they have been awarded to different operators. Almost all the well logs that were made available for the new operators, including PETRONAS Carigali, are based on the old coded palynological zonation with the old stratigraphic scheme. Nobody outside Shell is supposed to know the scientific names of the coded species! During the late 1980's Shell changed their codes for pollen zonation that is different from the names used by Ho (1978) and Hageman (1987), making both schemes more difficult to comprehend. It appears that PETRONAS has adopted the stratigraphic scheme by Hageman (1987) for the present stratigraphy of Sarawak (Figure 1.8).

The seismic mapping calibrated with the well data conducted in this study observed that the cycle is not associated with any pollen zonation as proposed by Hageman's (1987) stratigraphic scheme. The findings of this study also disagree with Hageman's (1987) interpretation whereby a number of unconformities in the Sarawak Basin were not controlled by eustasy but rather more related to the major tectonic movement in the area that will further be discussed in Section 2.6 of Chapter 2.

1.4.2. The goal

The aim of this study is to document properly the cycle concept and to devise a more open stratigraphic scheme. More importantly there is a need to develop a more conventional, multidisciplinary approach to the stratigraphic scheme that can be understood and appreciated not only by the palaeontologists but by all disciplines in the exploration and production teams. The scheme should be able to facilitate the need to predict the stratigraphic level, not only after the well has been drilled but also prior to drilling.

1.5. Depositional history of the Sarawak Basin

The subdivision of depositional environments for the Sarawak Basin is essentially unchanged since it was originally proposed by Ho (1978). The subdivision is based on foraminiferal assemblages and to a lesser degree, on the lithological descriptions and gamma ray or spontaneous potential log responses. The faunal and sedimentological criteria have been derived from study of Recent sediments of the Sarawak shelf. The self-explanatory subdivision of the depositional environment by Ho (1978), taken from Besems (1993), is shown in Figure 3.20.

Maps of the palaeogeography of the Sarawak Basin are mainly based on well data from Jalal (1987) and a series of maps from the Exploration Data Books of Sarawak Shell. However, none of these maps have been published to date. Several workers have published palaeogeographic maps of local areas for certain stratigraphic horizons. These include Agostinelli et al. (1989) who published maps showing the Miocene-Pliocene palaeogeographic evolution of Block SK9 and Ismail and Jaafar (1993a) who published maps showing the interpreted palaeogeographic environments for Cycle I and Cycle II of the Sarawak Basin.

Based on the previous studies mentioned above, the evolution of the depositional environments in the Sarawak Basin can be described as follows:

A. The coastline of the Sarawak Basin during Early to Late Oligocene until Early Miocene was almost in the NW-SE orientation with a narrow coastal area located to the east of SK6 and SK5 (refer Figure 1.2 for the location of exploration blocks). The area to the east of SK8 and SK7 is characterised by the marine environment while the area farther west was located within a broad coastal plain area.

B. The coastline shifted to an almost E-W orientation during Middle Miocene. The areas closer to the present-day coastline including the whole part of SK5 and the southern part of SK6, SK7 and SK9 were located within the shallow-marine environment whilst SK8 and the areas farther northward were situated within the marine environment.

C. The orientation of the coastline shifted close to the orientation of the present-day coastline (NE-SW) during late Middle Miocene when the Baram delta started to prograde northward in the Miri area. The environment has basically remained unchanged since then.

There has been no explanation as to why the orientation of the coast-line changed. Most of the articles including Almond (1990) and Shell (1993) indirectly relate the phenomenon to the changes in sea-level and the effect of tectonic rejuvenation in the hinterland area.

1.5.1. Statement of problems

Maps of the depositional environments have also been changed following the changes of the stratigraphic schemes for the Sarawak Basin, as discussed in Section 1.5 and discussed further in Chapter 2. Consequently, any palaeo-depositional environment maps for the Sarawak Basin cannot be utilised unless the stratigraphic scheme used for the construction of the maps is known.

All the available maps of the depositional environments for the Sarawak Basin were based on well data. Therefore, the lateral extent and the thickness of a particular sedimentary interval or cycle is not known unless the wells were already drilled in the area. For example, by referring to the map by Jalal (1987), the lateral extent of Cycles I and II to the western part of offshore Sarawak are not known, mainly because the wells in the area are sparse and most of the wells did not penetrate Cycles I and II. Furthermore, the maps cannot provide information about the thickness of a particular zone between the data points, which is important for the prediction of the thickness of the particular zones for planning a well, because of the discrete nature of the well data.

1.5.2. The goals.

It is the aim of the study to:

1. construct a palaeoenvironment map of each sequence in the Sarawak Basin from the well data, using the new proposed sequence stratigraphy combined with the depositional environment subdivision of Ho (1978). The aim is to understand the evolution of the depositional environments of the Sarawak Basin through time and to study the relationship between the environments and the tectonic history of the basin.

2. generate an isochore map (the sedimentary thickness map in two-way time) and lateral extent map of each sequence based on the seismic interpretations. This will provide the information on both vertical and lateral extents of every sedimentary sequence throughout the basin.

3. compare the wireline log responses for particular depositional environments in the literature to help relate the subdivision of depositional environments by Ho (1978) to a conventional subdivision of depositional environments. The aim here is to understand the associated sedimentary facies and depositional mechanisms with the depositional environment and ultimately, to understand the relationship between the reservoir geology, including their geometry and physical properties with the depositional environments.

1.6 Tectonic evolution of Sarawak and northwest Borneo

The tectonic evolution models that have been proposed by previous workers for the Sarawak Basin have evolved simultaneously with contemporaneous doctrines in geoscience. Therefore, in discussing the tectonic evolution of Sarawak, it is more appropriate to discuss these models in the context of the respective era of geoscience doctrines. Sarawak has always been considered as part of the north-west Borneo region and the discussion can therefore be linked to the periods of:

1. ***Geosyncline theory***
2. ***Plate tectonic and subduction theory***
3. ***Other tectonic model and observations.***

1.6.1 Geosyncline theory.

A major compilation of the geology of Northwest Borneo, which is largely factual and descriptive, was published by Leichti et al. (1960). Haile (1968), based primarily on the work of Leichti et al. (1960) and his own observations, was among the first workers to make an attempt to outline the geological history of Sarawak and to fit it into a wider geological tectonic framework. The term "North-west Borneo Geosyncline" was introduced and thirty-two formations were classified as eugeosynclinal, miogeosynclinal and isolated basin formations.

To make the old geological terminology easier to understand, the definition of geosyncline and miogeosyncline as outlined by Whitten and Brooks (1972) are as below:

Geosyncline is a major structural and sedimentation unit of the Earth's crust. It consists of an elongated basin that was filled with a very great thickness of sediments and intercalation of volcanic rocks. The basin floor progressively subsides and the accumulated pile of sediments is subsequently strongly deformed by orogenic forces into a fold-mountain chain. During the process, the lower portion of the sedimentary pile may become highly metamorphosed and granite emplacement may take place.

Eugeosyncline is the basin that has thick sediments with an abundance of volcanic rocks, forming some distance from the craton.

Miogeosyncline is the basin that has thinner development of sediment and no volcanic rock, forming adjacent to the craton.

Haile (1968) subdivided all the geological formations in North-west Borneo into four groups namely: Brunei Group, Plateau Group, Baram Group and Rajang Group.

The Rajang Group (which is also known as the Belaga Formation) was interpreted to have been deposited within the *Eugeosynclinal furrow*. The miogeosyclinal ridge was represented by the Bukit Mersing spilitic pillow lavas, spilite and radiolarian chert at Usun Apau Plateau and limestones in the upper Baram Valley. The Baram Group (which is also known as the Tertiary sediments), was interpreted to be deposited within the *Miogeosynclinal furrow*.

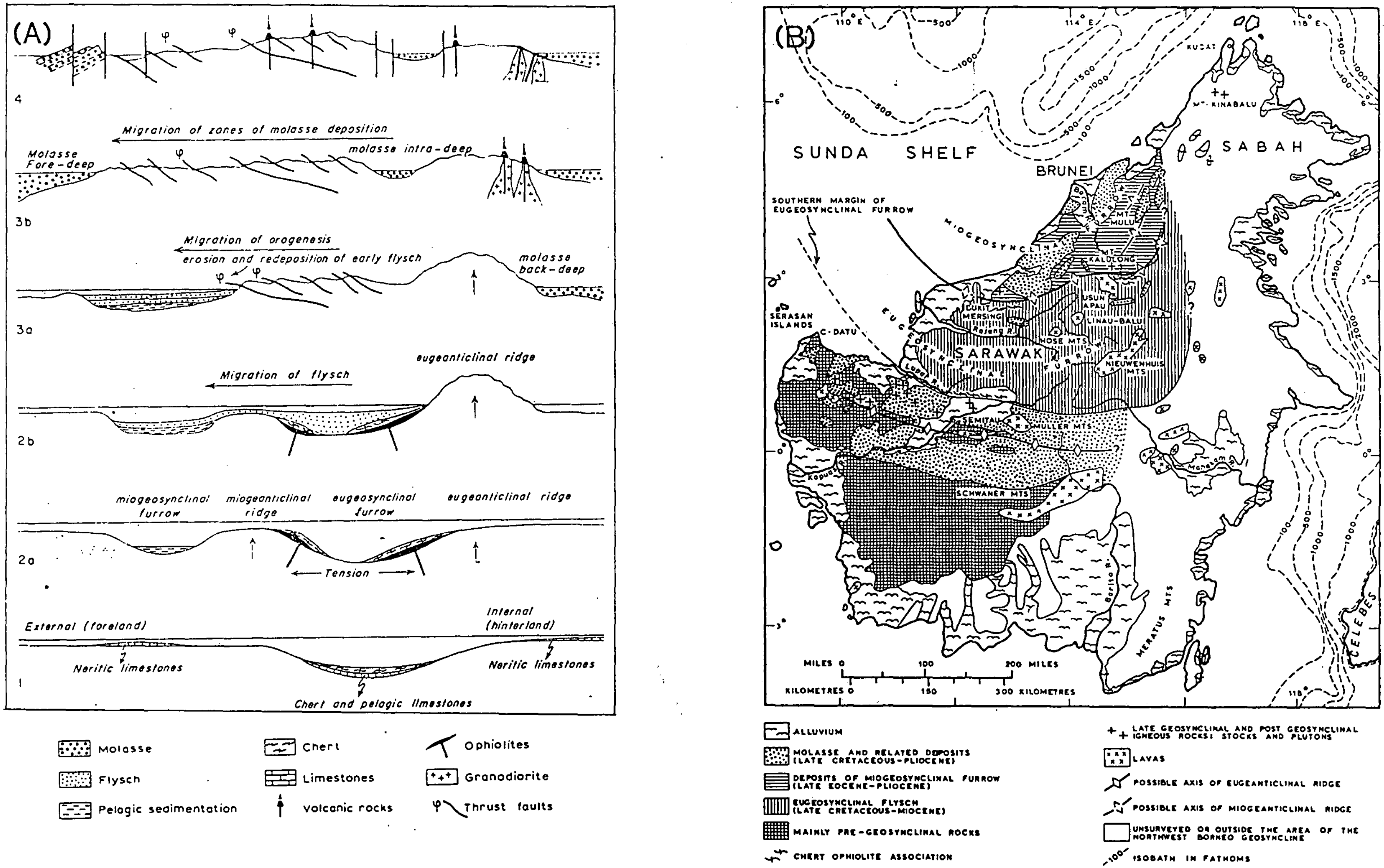


Figure 1.9. Figures showing (A) Evolutionary pattern of elementary geosyncline.
B) Organizational pattern of the North-west Borneo Geosyncline, After Haile (1969).

The evolution and the organisation of the Northwest Borneo Geosyncline are shown in Figure 1.9A. The stages of evolution shown in Figure 1.9B are:

1. Generative stage.
2. Development stage.
    - 2a Ophiolite-chert formation.
    - 2b Flysh-filling of eugeosyncline and then miogeosynclinal furrow.
3. Terminal stage of orogeny involving uplift, buckling and thrusting of eugeosynclinal deposits and then the miogeosyncline.
4. Post-geosynclinal period, with positive and negative vertical movement and terminal volcanic basalt activity.

1.6.2 Plate tectonic and subduction theory

The geological history of Sarawak was re-interpreted following the application of "Plate Tectonics" to the Northwest Borneo region by James (1984) who divided the North Borneo area into eight tectonic domains, whereby the whole of Sarawak was subdivided into seven provinces:

1) SW Sarawak Province
2) Rajang accretional prism
3) Tatau Province
4) Tinjar and Balingian Provinces
5) Luconia platform
6) Baram delta province
7) Crocker accretional prism (in Sabah).

James (1984) did not elaborate in detail about the tectonic evolution of Northwest Borneo but rather illustrated the evolutionary model using the figures, as attached in Figure 1.10. Based on the figure, it could be deduced that James's model commenced with subduction of the South China Sea plate beneath the Borneo continental plate during the Oligocene. This subduction activity resulted in deformation of the Belaga Formation which was interpreted to have formed as the accretionary prism. The area between the accretionary prism and the Luconia Platform, which was interpreted to be a drifted micro-continent from the South China sea area, formed as the basin for the deposition of sediments eroded in the hinterland area to the south. The Oligocene sedimentary basin was referred to as the Balingian and Tinjar Provinces, which is the main study area of this thesis.

At present the terminal collision between the Luconia platform and the Rajang accretionary

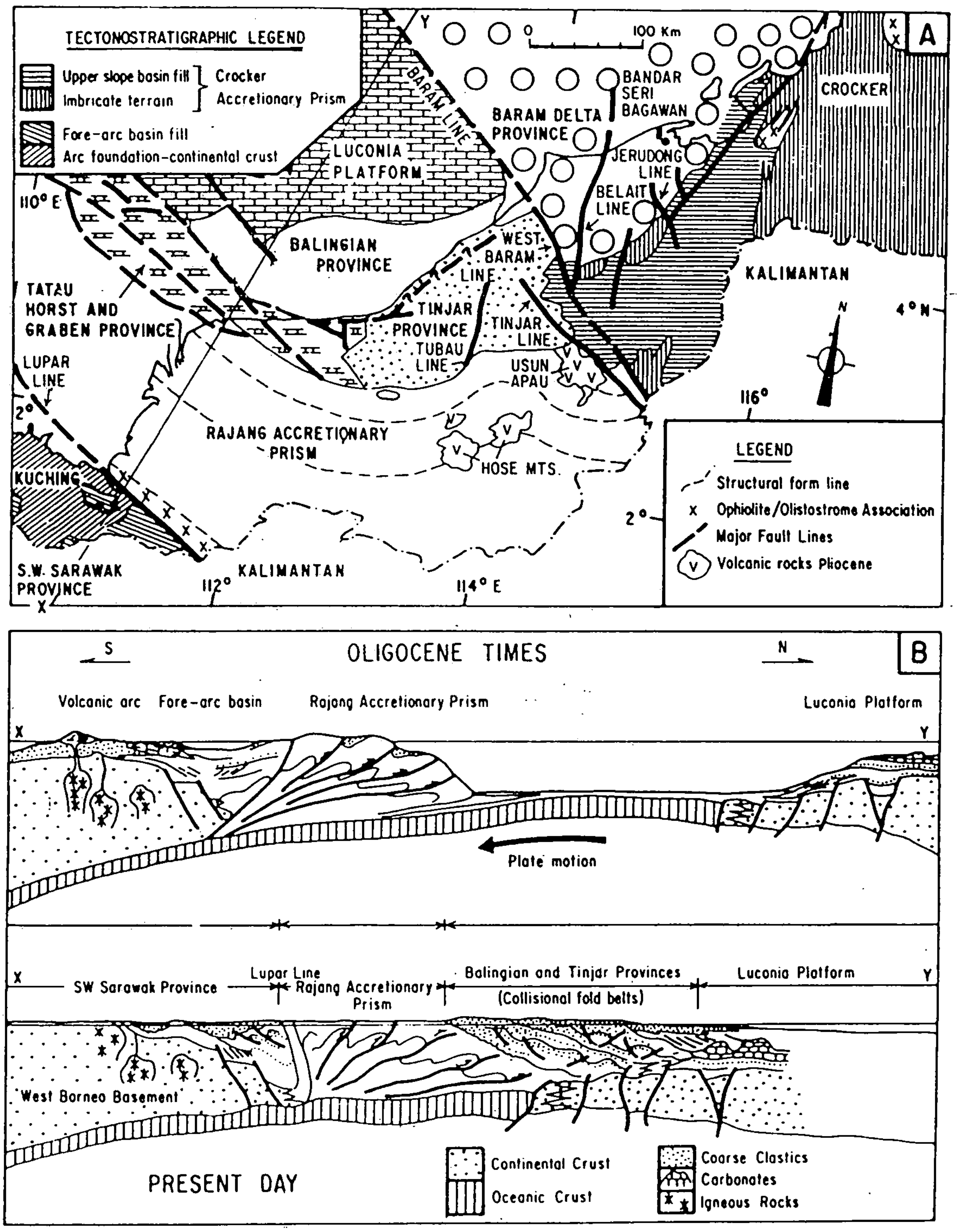


Figure 1.10. (A) Tectono-stratigraphic provinces of Northwest Borneo.

B) Diagrammatic cross section across central Sarawak; reconstructions for Oligocene and configuration at the present day. After James (1984).

prism has been reached and the Balingian and Tinjar provinces that were deposited in the basin during the Oligocene, were interpreted to be the collisional fold belts between the two tectonic plates whilst the Luconia province marked the northern limit of the Sarawak Basin.

Several workers in later years have added other new findings and observations to strengthen further the James model, including Hutchinson (1988) with the interpretation about the occurrence of ophiolite at the Bukit Mersing Line. Hutchinson (1988) wrote: "The Neogene collision orogeny was caused by the arrival of the Luconia micro-plate and during the orogeny, some pillow basalts from the basement of the Sibu Zone (Belaga Formation) were uplifted along the Bukit Mersing line. There basalts were interpreted as volcanic arc products associated with the final stage of subduction. Tectonic complexities along the Bukit Mersing line in the Tatau area between Sibu and Bintulu, and granophyre and ignimbrite occurring at Bukit Piring and Sungai Arip, suggest very active tectonics".

There are several weaknesses in the plate tectonic model proposed by James (1984). The model still needs other data to support it, notably deep crustal studies using both reflection and refraction seismic and also palaeomagnetism (James, 1984). However, James's model is widely used by workers in the region especially by Sarawak Shell. This is evident from the most recent paper on the Tertiary tectonic evolution of the Northwest Borneo continental margin by Hazebroek and Tan (1993) and Hazebroek et al. (1994).

By having a detailed look at the James's tectonic model and by comparing it with a broader area of Sarawak, including Borneo as a whole, coupled with new seismic data from the Sarawak Basin, it is soon obvious that the model is lacking some supporting evidence and the new information for the Sarawak Basin from this study disagrees with the model. Among the weakness of the model are:

1. *Absence of a trench and no preserved oceanic plate.*
2. *No volcanic arc*
3. *Age of Luconia sediments does not suggest Luconia as a drifted microplate.*

1.6.2.1. Absence of a trench and no preserved oceanic plate.

The idea of subduction was mainly based on field observations, that is, the nature and tectonic overprints of the Belaga Formation. Hutchinson wrote in 1988, "Subduction activities along the margin of the west Borneo block is indicated by deformation of the Belaga Formation". However, the interpretation was not supported by other data such as magnetic, gravity or deep penetration seismic or any other scientific evidence.

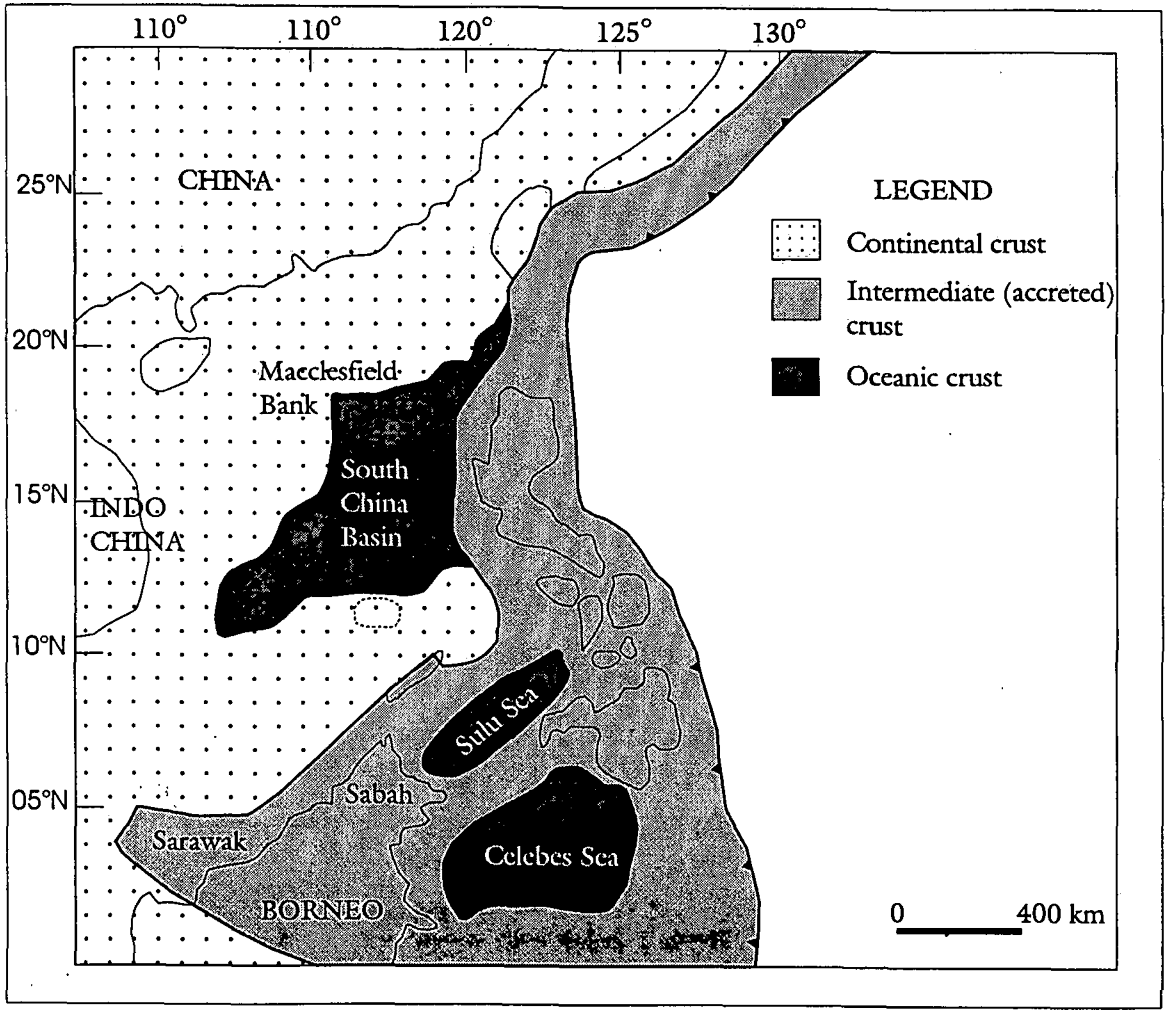


Figure 1.11. South China Sea area: geography, tectonics and crustal distribution. After Holloway (1982)

The subduction is interpreted to have taken place during Oligocene times (38-26 Ma), which may coincide with the initial opening of the South China Sea that began about 32 Ma ago. At the time of opening of the South China Sea new oceanic crust was confined to the Macclesfield Bank area (see Briais et al., 1993). By the termination of sea-floor spreading at 17 Ma ago, oceanic crust is estimated to be only present to the east of 115.5 degrees East and to the north of 10 degrees North. (Figure 1.9). Therefore, the origin of the subducting plate in James's (1984) model is questionable.

1.6.2.2. No volcanic arc

The subduction model above interprets the SW Sarawak Province (Figure 1.8) as the volcanic arc and the forearc areas. The model also suggests that the later phases of subduction transferred from the Lupar line farther northeast (i.e.Bukit Mesing line). Onset of subduction in the Oligocene should have led to the development of a post-Oligocene volcanic arc.

It is known that the volcanic rocks in the SW Sarawak Province and in the Sarawak-Kalimantan border are mainly of Cretaceous age. Therefore, these volcanics are not appropriate to represent the volcanic arc of Oligocene subduction. Furthermore, the volcanic rocks in Usun Apau and Hose Mountain areas are mainly of Pliocene -Pleistocene age (Pietiers and Supriatna, 1990 and Heng, 1992). If there is any evidence for subduction during Pliocene times in the Sarawak Basin, the trench that is associated with subduction should be visible on the exploration seismic data passing through the Balingian Province. To date no such evidence has been reported.

Hutchinson (1994), in disagreeing with the model and illustrating that the model is unworkable wrote: "Tectonic models based on the Sibu zone as the accretionary prism and the wholly continental Ketungau basin as forearc are difficult to accept. The accretionary prism would be required to have a perfect barrier to the sea from its inception, and there is no volcanic arc". However, no better, conclusive and sound tectonic model was offered by Hutchinson.

1.6.2.3. Age of Luconia sediments does not suggest Luconia as a drifted subcontinent.

The interpretation that the Luconia Province drifted southwards from the South China Sea was mainly based on the occurrence of carbonate platforms and the deduction that the Luconia Province was a stable continental crustal block. Similar to the interpretation of the subducting oceanic plate above, there is no scientific evidence to support this interpretation.

To fit his model, James (1984) required that the Luconia carbonates started to grow earlier than their documented age, i.e. since the late Oligocene (James, 1984). Drilling for exploration and gas producing wells in the Luconia Province, however, has confirmed that the Luconia carbonates only started to grow during Cycle III and IV times which is Middle Miocene (see also Epting, 1980). Based on the well data and seismic correlation, it is shown later in this thesis that the Oligocene-early Miocene sediments in the Luconia Province are clastics which are also present in the Balingian Province and other areas closer to shore.

1.6.3. Other tectonic models and observations.

1.6.3.1. Southward thrusting model.

The southward thrusting model for the Belaga Formation in the Sarawak-Kalimantan area was proposed by Untung (1990). The model suggests that the Belaga Formation formed an allochthonous block thrusted southward over the authochthonous continental basement. The Lupar Line and Boyan mélanges are interpreted to represent oceanic crust that was upthrusted to the surface. The thrusting direction of the Belaga Formation is in the opposite direction to the subduction model. The proposed model together with gravity data are shown in Figure 1.12.

The Untung (1990) model treated the Lupar and Boyan mélanges as similar in origin, since these mélanges are similar in lithological composition as reported by several workers. The Lupar mélange was reported to be made up of chert, basalt, gabbro, and serpentine in a highly sheared mud matrix (Tan, 1975). In Kalimantan, the Kapuas Complex which is disrupted and contains chert appears to be the same as the Lupar mélange (Tate, 1991). The high Bouger values for the Boyan and Lupar mélanges may be due to the occurrence of basaltic rock in the formations.

Despite some true facts about the model, it seems that the model has over-simplified the tectonic history of the Belaga Formation and has not taken the structural pattern of the Belaga Formation into consideration. This includes the different structural style between the Belaga Formation in Sarawak and Eastern Borneo as described by Hutchinson (1988) and the complexity of the structure as described by several workers including Haile (1994).

Boyer and Elliot (1982) described thrust repeats the size and shape of the neighbouring thrust sheet so that they overlap each other like roof tiles, all dipping in the same general direction, (i.e., an imbricate system). Each thrust sheet is an upward-opening crescentic slice,

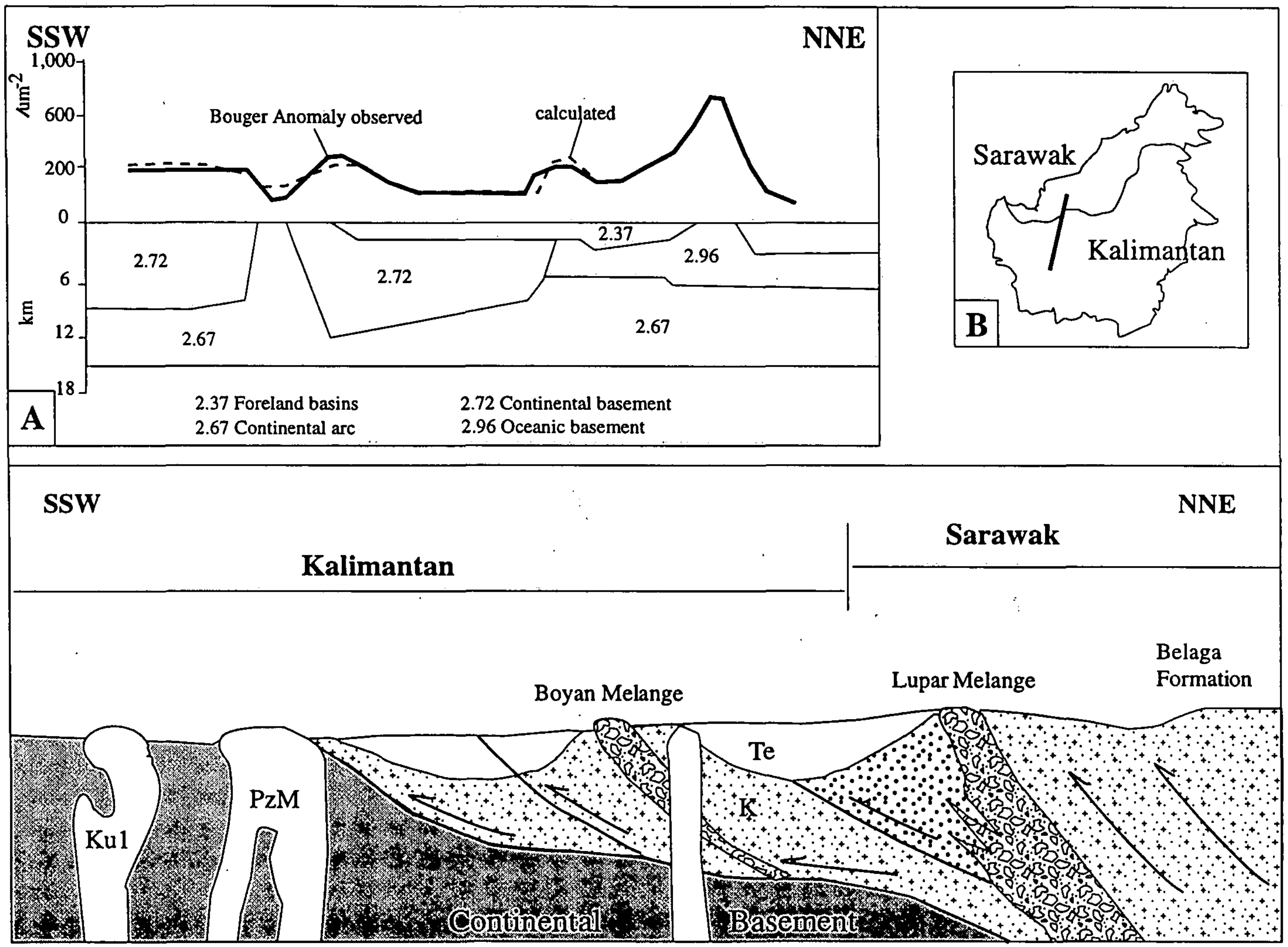


Figure 1.12. Geological cross section from Sarawak to Kalimantan. (A) Gravity section for the same cross section. (B) The location and orientation of the cross section. After Untung (1990).

and all curve asympotically downward to a common basal sole thrust. The pattern for an imbricate thrust system does not occur in the Belaga Formation. It is therefore difficult to accept that the deformation of the Belaga Formation could solely be explained by the thrust system.

The thrusting model also seems to adopt the concept of thin-skinned tectonics and it looks similar to the cross-section through the Alpine-Carpathian chain (Figure 6 in Royden, 1985). If this comparison is true, the Sarawak Basin could be assumed to have formed as a pull-apart basin. However, the formation of the Tertiary sedimentary basin and driving force responsible for the thrusting and the timing of the event are not shown in the model.

Due to the weakness of the model as discussed above and possibly for other reasons, the model was not accepted in the region and it was not discussed in the latest conferences on regional tectonics.

1.6.3.2. Strike-slip tectonism

The occurrences of the Tinjar Line, West Baram Line and other tectonic lines have been recognised for a long time. Among the workers who have discussed the lines are James (1984), Hutchinson (1988), Tan and Lamy (1990), Agostinelli et al. (1990), Posehn et al. (1992), Hazebroek and Tan (1993), Tjia (1994), and several other workers who worked in the Sarawak area.

The occurrence of the Tinjar and West Baram Line as interpreted by James (1984) and later used by Hutchinson (1988) could be seen in Figure 1.9. Tan and Lamy (1990) showed the location of both West Baram Line and the West Balingian Line in Figure 3 of his paper. Agostenelli (1990) recognised the occurrence of the West Baram Line by the presence of an escarpment, abrupt changes in water depth to the east of the line and the line marking the south-western termination of the NW Borneo-Palawan trough. Posehn et al. (1992) believed that the SAR data were able to identify major transform fault zones corresponding to major boundaries of known tectonic provinces in the Baram delta or greater Sarawak Basin.

Hazebroek et al. (1993) also show the location of the West Balingian Line and West Baram Line in figure 2 of their paper. Tjia (1994) described the Tinjar Line as the line marked by the NW striking fault along a similar named river which is parallel to the Dulit Range. The Geological Map of Sarawak by Heng (1992) shows a similar location and orientation to the Tinjar Fault. Most of the above mentioned workers interpreted the Tinjar/West Baram lines as dextral strike-slip faults.

Although the above-mentioned workers have called the tectonic lines by the same names, in some instances they were actually referring to different lines. For example, most of the recent publications except by James, 1984 (Figure 1.9) interpreted the Tinjar Line to be the continuation of the West Baram Line in the offshore Baram area. This is including Tjia (1994) and Tan and Lamy (1990). Tjia wrote: "It is common to extend the Tinjar fault into NW Borneo's offshore as the West Baram Line". Tan and Lamy (1990) in Figure 3 of their paper, extended the West Baram Line from the offshore as the Tinjar Line in the onshore.

The occurrence of strike-slip related structural configuration in the nearshore area deduced from seismic interpretations has also been discussed in recent years. Among them are Levesque and Ooi (1989) and Swinburn (1993), both are Shell staff.

Levesque and Ooi (1989) wrote: "The West Balingian Line coincides with a marked regional gravity trend along which occurs a discontinuous line of narrow elongated graben of post-Cycle II age, including the South West Luconia Graben, and along which major basement offset as well as severe tectonisation of Cycle I sequence is noted locally on seismic data. The line may represent old boundary transform faults. The zones appear to have had a history of right lateral movement".

Swinburn (1993) who referred to the nearshore area as the Balingian Province wrote that the Balingian Province can be sub-divided into three sub-Provinces, each with different structural trends and timing:

i) The East Balingian Sub-Province is an area of strong, late Miocene to Pliocene wrench-related deformation with structural axes oriented NE-SW. Individual structures are typically large, high amplitude folds, bounded by reverse faults which converge at depth and can be related to oblique strike-slip movements;

ii) The SW Balingian sub-Province is an area of Oligocene to early Miocene wrench-related deformation of varying intensity. Structural axes trend NW-SE. The dominant fault trend is NE-SW and characterised by basement faulting in the west and growth faults on the flanks of the Balingian Basin to the southeast;

iii) The NW Balingian sub-province was subjected to several phases of strong deformation from Oligocene to Pliocene and is characterised by en-echelon NW-SE trending folds with complex patterns.

1.6.4 The recent understanding on regional tectonic of Sarawak

It is difficult to determine which tectonics model is the most acceptable for Sarawak. However, judging from the amount of data and involvement towards an understanding of the tectonics of the basin, it is believed that Sarawak Shell is due for credit. This is because most of the geological framework including the stratigraphic scheme by Ho (1978), Hageman (1987) and the tectonic framework by James (1984) are examples of Shell's contribution to the geological understanding of Sarawak, and particularly the Sarawak Basin.

On the above basis, it is believed to be appropriate to assume that the current understanding and the geological concepts adopted by Sarawak Shell give the more acceptable tectonic model of Sarawak. Therefore, the most accepted tectonic model for the Sarawak Basin is that of James (1984). This is because the same tectonic concept was presented by the two highest ranked Shell geologists during recent years, namely Tan, who is the head of regional geological studies and Hazebroek, who is currently the chief geologist of Sarawak Shell.

Tan and Lamy (1990) wrote: "The tectonic evolution of Northwest Borneo commenced in the late Cretaceous with the rifting of South China Sea basin. The late Cretaceous and Palaeocene rifting and subsequent sea-floor spreading from Palaeocene to late Eocene resulted in south-westward subduction of pre-existing South China Sea oceanic crust beneath the Sunda Shield at a subduction front marked by the Lupar line. This resulting imbricated terrain forms the Rajang Accretionary Prism which became uplifted and eroded, forming the major sediment source for the younger sequences deposited to the north and northwest".

Hazebroek et al. (1993) wrote: "The Luconia block has been interpreted as a continental fragment originally attached to the South China Sea continental margin, that has been transported by the opening of China Sea. This stable platform is characterised by a large number of gas accumulations. The Luconia is bounded by major NW-SE, WNW-ESE trending faults (SW Luconia-Mukah line and West Baram line). Deformation characterised by wrench-induced folding and thrusting, is present along the southern margin of Luconia Block, the Balingian belt. This belt has been interpreted as a collisional margin where the Luconia Block has impinged upon the Rajang Group fold-thrust belt. However, many feature's characteristic of sinistral wrenching are present".

1.6.5. Statement of problems

Even though the tectonic model of James (1984) could be regarded as the most recent, the model has a number of weaknesses as discussed in Section 1.6.2. This is also true for the other models including the southward-thrusting model proposed by Untung (1990). The full-proof tectonic model for the Sarawak Basin is therefore not yet available and the tectonic setting of Sarawak is not fully understood to date.

1.6.6. The goals.

It is the aim of this study is to acquire a better understanding of the tectonic evolution of the Sarawak Basin. The study is carried out using the regional and prospect lines of seismics together with the well data and other supporting information including the geological map of Sarawak.

1.7. Summary

Sarawak Basin is a proven prolific hydrocarbon basin and it has been explored for more than a century. At present the Sarawak Basin is producing a substantial amount of oil and gas, and it forms one of the main contributors to the hydrocarbon production of Malaysia. Sarawak Shell, which is the pioneer in the area, has made a tremendous contribution to the understanding of the geology of Sarawak in past years, i.e. the tectonic model by James (1984) and the stratigraphic scheme by Ho (1976). However, the tectonic model and the stratigraphic scheme need to be revised and upgraded as more new and sophisticated data have become available in recent years.

Despite the long history of oil exploration, the tectonics and evolution of the basin are not well understood. Most of the regional studies which lead to the creation of tectonic and stratigraphic models were conducted more than ten years ago. No new studies or findings on the Sarawak basin have been reported more recently. Among the factors that might hinder the regional study of the Sarawak Basin is that the exploration area has been subdivided into smaller block areas compared to the past and therefore, no single oil company has a complete dataset covering the whole basin.

PETRONAS Carigali has an advantage since the company is granted an interest in all blocks. This study has made use of all the latest PETRONAS data on Sarawak, from which a thorough reappraisal of the Tertiary tectonic and stratigraphic evolution of Sarawak Basin has been conducted and is presented in this thesis.

It is the aim of this study to develop a workable **Stratigraphic Scheme** and **Sedimentation History** for the Sarawak Basin. It is also the aim of this research to generate a **Tertiary**

tectonic model for both the Sarawak Basin and Northern Borneo areas. This will help in generating a better understanding of the geology of the basin and also help in maximising the success ratio in exploring the rich natural resources of the Sarawak Basin.

Chapter 2

TERTIARY STRATIGRAPHIC SCHEME OF THE SARAWAK BASIN.

2.1 Introduction

Although the Shell stratigraphic scheme for Sarawak was introduced by Ho (1978) and modified by Hageman (1987), the scheme was not adopted by all exploration teams. This could be due to several reasons. It is believed that the exploration teams who prepared the well summary reports and the biostratigraphers who determined the stratigraphic zonations in the wells were having difficulty in recognising the stratigraphic boundaries. The inconsistencies in identifying the cycle boundaries can be seen in Figure 2.1. Several cycle boundaries were picked at different horizons in different wells. In some cases the boundary between cycles could not be differentiated.

There are several reasons for the difficulties in recognising the cycle boundaries. The main reason, as experienced by this author, is that the cycle boundaries proposed by Ho (1978) are based predominantly on the foram zonations. The palynological zonation does not correlate exactly with the cycles. Since the succession of the study area is dominated by non-marine sediments, subdivision could not be based on foram zonation. The only alternative for the stratigraphic subdivision is to use the palynological zonation.

Shell changed the stratigraphic subdivision for the wells drilled from 1989 and used a new coded palynological zonation (Figure 2.1). Based on the new stratigraphic subdivision, four of the original cycle boundaries have been reclassified as unconformities. This is similar to the stratigraphic subdivision of Hageman (1987). However, Hageman used the earlier palynological zonation that is similar to the zonation used by Shell for the wells drilled before 1989 (Figure 2.1), for his stratigraphic subdivision. There is no clue as to how the new palynological zonation was created. Therefore the correlation between the original cycle concept and the new scheme by Shell is not easy to understand.

There is no indication that seismic reflection profiles were used by Hageman (1987) in identifying the cycle boundaries. This assumption is made based on two factors. Firstly, the study was carried out using the data from 88 wells to unravel the palaoebathymetrical history of NW Sarawak and to correlate with the global sea-level curve of Haq et al. (1987). Secondly, there is no cycle boundary that corresponds with the seismic surfaces of Levesque and Ooi (1989). Therefore it is not

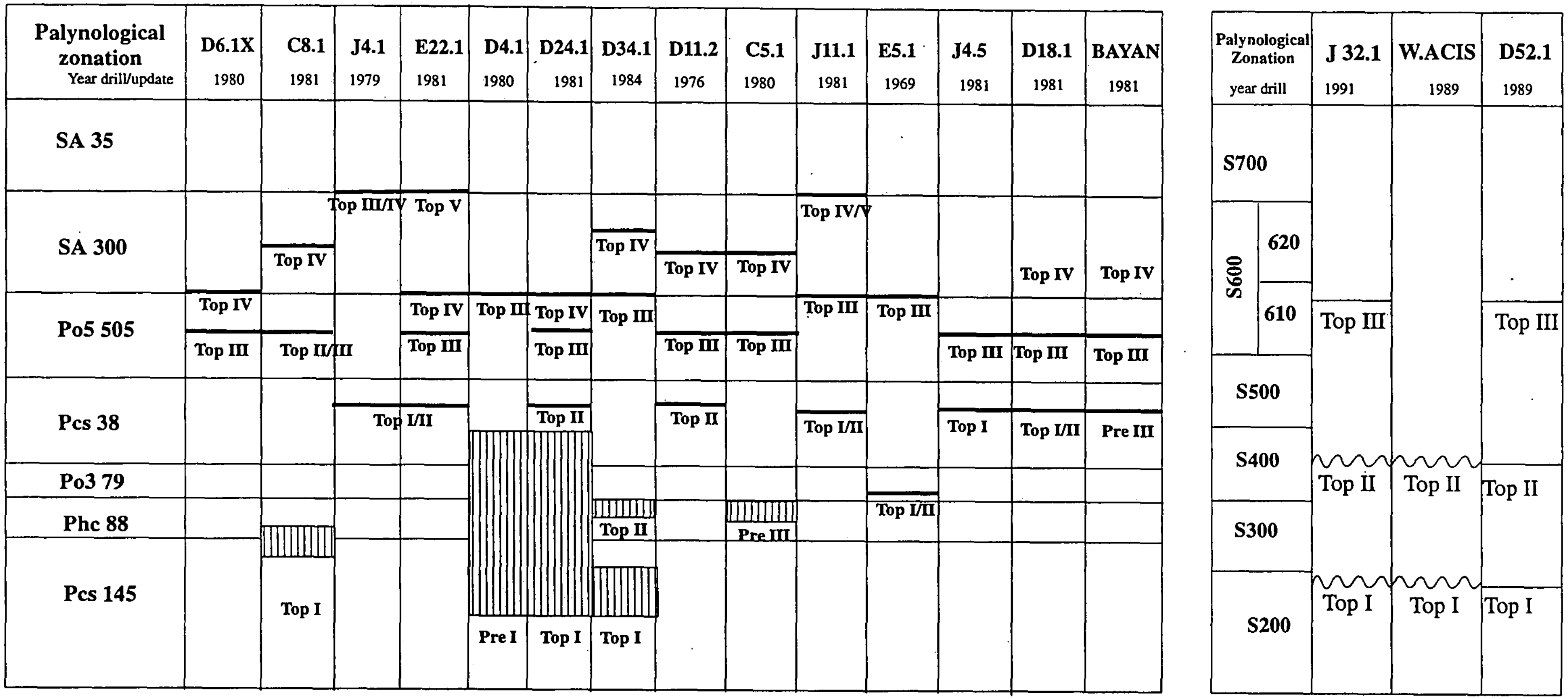


Figure 2.1 Location of cycle boundaries in respect to palynological zones obtained from the wells drilled by Sarawak Shell.

understood how and why Hageman (1987) changed four of the original cycle boundaries to the unconformity boundaries.

This situation as described above created problems for the non-Shell workers who took over the area surrounding Block SK5. This is important because the old wells were left with a scheme that was almost obsolete. A rough count of the number of exploration and appraisal wells shows that out of more than 300 wells drilled in Sarawak to date, about 90% of the wells were drilled before 1990. The question now is to have a consistent stratigraphy for all old and new wells.

This chapter discusses the techniques used in the stratigraphic scheme by Shell and a new stratigraphy for the Sarawak Basin is offered. It is believed that the new scheme could be understood and appreciated not only by palaeontologists but by all disciplines in the exploration and production teams. The scheme will allow the prediction of the stratigraphic level not only after the well has been drilled but also before the drilling.

2.2. Data and Techniques

2.2.1 Data

The data used in this study include a total of 4,170 kilometres of seismic lines and forty-five composite-logs drilled throughout the Sarawak Basin. The stratigraphic charts of Sarawak Shell (from Shell, 1992), the palynological zonation chart of the International Stratigraphic Consultancy, the stratigraphic chart of Simon-Robertson Research (from Simon-Robertson, 1992), and the stratigraphic schemes of Ho (1978) and Hageman (1987) are also used to understand the previous stratigraphic scheme.

2.2.1.1 Seismic Lines

The seismic lines used in this study come from three different areas. The lines that are regional in nature cover the whole offshore area, the shorter regional lines for the nearshore area and mainly prospect lines for the onshore area. The lines are different in scale, depth of penetration and vintages and use different processing parameters. The orientations of the lines are shown in the Figures 2.2, 2.3 and 2.4.

Seismic lines for the onshore area were acquired by the Overseas Petroleum and Investigation Corp. (OPIC) during 1989 and 1991 seismic acquisition programme for Block SK12. All the lines are displayed in 10 cm sec^{-1} vertical scale and 1:25,000 horizontal scale. The 1990 and

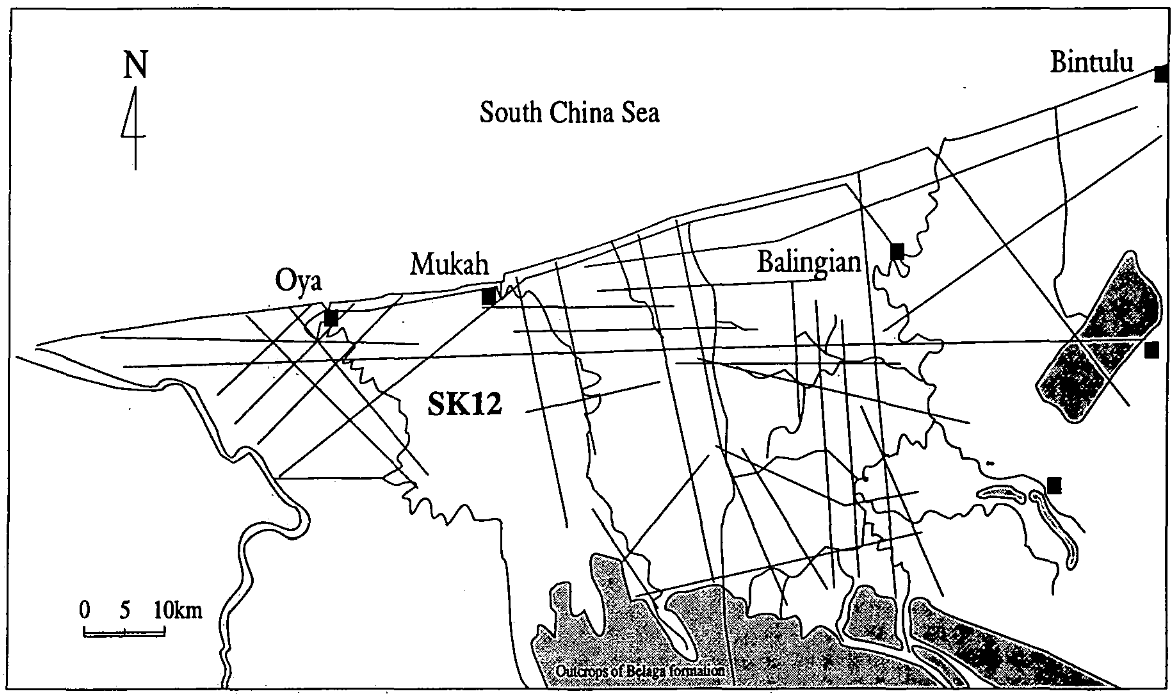


Figure 2.2 Map showing the orientation of the seismic lines in the onshore area.

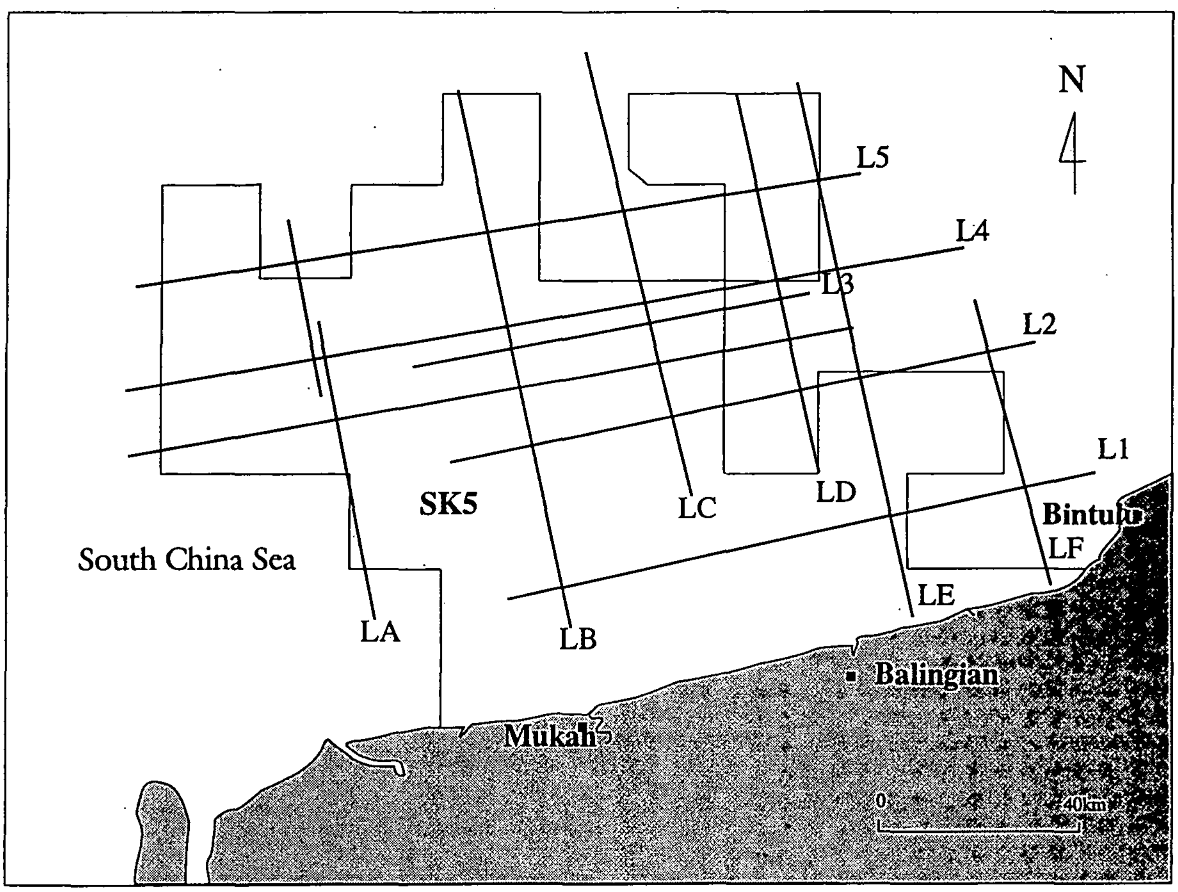


Figure 2.3 Map showing the orientation of the seismic lines in the nearshore area.

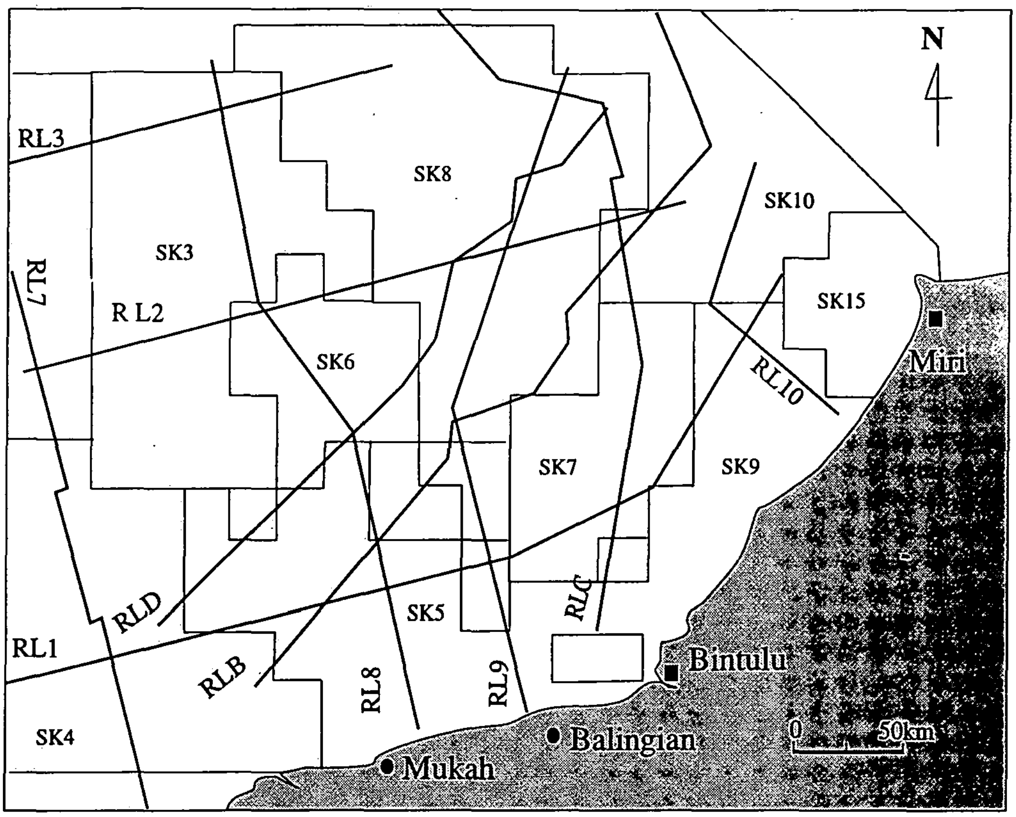


Figure 2.4. Map showing the location and the orientation of the seismic lines in the regional offshore area.

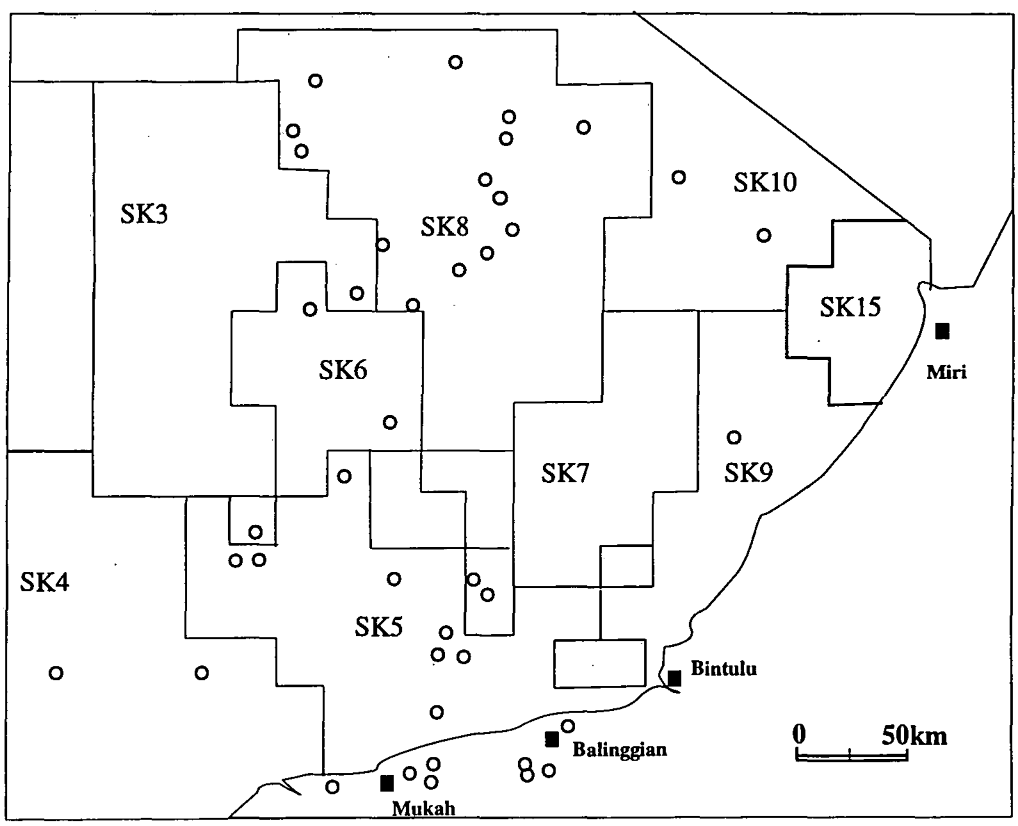


Figure 2.5 Map showing the location of the wells used in the study.

1991 lines have been processed by Digicon and Teknosif /CGG Data Processing Services respectively. A total of 730 kilometres of seismic lines used in the study are mainly of good quality. Figure 2.2. shows the orientation and the location of the lines .

For the nearshore area, the reprocessed lines for Block SK-5 by Sarawak Shell were used. The lines are marked as L1, L2, L3, L4, L5, LA, LB, LC and LD (Figure 2.3). All the lines are regional lines with each made up of several short prospect lines which were acquired from the year 1971 to 1979. The reprocessed lines are displayed from sea-level to 5 seconds in Two Way Time (TWT). The vertical scale is 5 cm sec^{-1} and horizontal scale is 1:100,000. The lines were reprocessed by Digicon in 1987.

Eight regional seismic lines cover several exploration blocks in the offshore area. Five of the lines marked as RL1, RL2, RL3, RL7, RL8 and RL10 have been reprocessed by PETRONAS Carigali in 1993/94 using the services of Teknosif / CGG Data Processing Centre in Kuala Lumpur (Figure 2.4). The lines are displayed from sea-level to 4 or 5 seconds in Two Way Time (TWT). The vertical scale is 5 cm sec^{-1} and the horizontal scale is 1:200,000. Similar to the nearshore lines, several short prospect lines acquired between 1968 to 1991 were reprocessed and displayed as a single regional line. All the lines are of good to very good quality, except RL3 which is poor.

Three other lines, namely RLB, RLC and RLD were reprocessed by Shell in 1990 using the Seismograph Service Company. The lines are displayed from sea-level to 5 or 6 seconds in Two Way Time (TWT). The vertical scale is 5 cm sec^{-1} and the horizontal scale is 1:200,000. These regional lines are also the combination of several prospect lines that were acquired between 1971 and 1990. All the lines are of very good to excellent quality.

2.2.1.2 Composite Well Logs

The study used a total of forty-five composite well logs, for the wells drilled by the operating companies in the Sarawak Basin including Sarawak Shell, OPIC, PETRONAS Carigali, Agip and Occidental. The logs consist of well co-ordinates, spud date, logging suits, gamma ray, hydrocarbon intervals, resistivity, sonic, porosity values, dipmeter, lithology, environment of deposition, palynological zonations, depth, cycle boundaries, geologic age and depth. The approximate locations of the wells are shown in Figure 2.5.

2.2.2. Study Techniques

The stratigraphic nomenclature of the Sarawak Basin is complicated. It evolved from the sedimentary cyclicity concept and the role of eustatic sea-level changes to the recognition of strong tectonic influences on sedimentation. The original scheme has been modified to suit the need of the particular area, data and the particular time. The techniques used to produce a stratigraphy for the Sarawak Basin include:

1). Reconstruction of a comprehensive stratigraphic chart by integrating all the previous stratigraphic schemes used for the Sarawak Basin. This enables comparison and correlations between the schemes. This is also to check whether any of the schemes share the same stratigraphic boundaries.

2). Selection of the most suitable scheme that can be used for regional seismic mapping. The stratigraphic scheme by Hageman (1987) seems to be more suitable. However, a series of regional unconformities identified on the regional seismic lines by this author were not recognised by Hageman (1987) and other previous schemes.

3). Use of a new stratigraphic approach for the regional seismic mapping of the Sarawak Basin. This study applied the ***seismic sequence stratigraphy technique*** for the mapping project. The technique involves the recognition of sequence boundaries including erosional unconformities and other types of reflection terminations.

4). Determination of the ages of the unconformities and their correlatable conformities based on the age of the bounding sediments from the well data. The ages of all the sequence boundaries were compared with the previous schemes from the comprehensive stratigraphic chart for the Sarawak Basin.

5). Correlation of the sequence boundaries for the Sarawak Basin with the 'global eustatic curve' of Haq et al. (1987,\1988) to determine whether the identified sequence boundaries are global or regional in extent.

6). Correlation of the sequences with the petrophysical characteristics, sedimentary facies and palaeontological zonations.

2.3. Stratigraphic Subdivision and Proposed Scheme for the Sarawak Basin

This section discusses how all the previous stratigraphic schemes for the Sarawak Basin were placed into a single stratigraphic table. This enables a comparison and correlation between existing schemes and with the proposed new stratigraphic scheme. Among the previous schemes used are the cycle concept by Ho (1978), Hageman (1987), and the stratigraphic boundaries recognised by Simon-Robertson (1992), and by the International Stratigraphic Consultancy (in Simon-Robertson, 1992).

2.3.1. Steps in generating the Stratigraphic Table.

1. The correlation of the cycle boundaries of Ho (1978) with the planktonic foraminifera zonations and the old coded palynological zonations of Shell. This was done because the cycle boundaries of Ho (1978) were predominantly based on the foraminifera zonation. The cycle boundaries on the well logs, however, are based on the palynological zonations. The correlation between the old palynological zonations and the foraminifera zonations are from Simon-Robertson (1992). The correlations are as follows:

Cycle Boundaries Ho (1978)	Planktonic Foraminiferal Zonation	Old Palynological Zonation of Shell
Cycle VIII	*Globorotalia truncatulinoides*	Pv2 581
Cycle VII	*Globorotalia tosaensis*	Pv2 483
Base Cycle VI	Base *Globorotalia margaritae*	Sa 35 (Upper)
Base Cycle V	Base *Globorotalia lobata /robusta*	Sa 300 (Basal)
Base Cycle IV	Base *Globorotalia barosanensis*	Po5 505 (Middle)
Cycle III	*Globogerinatella insueta*	PCs 38 (Basal)
Cycle II	*Catapsydrax dissimilis*	Po3 79 (Basal)
Base Cycle I	within *Globogerinopsis semiinvolata*	Basal Po3 79 to Po5 462

2. Correlation of the cycle boundaries of Hageman (1987) with the new coded palynological zonations of Shell. This is important because the new cycle boundaries of Hageman (1987) are based on the old palynological zonation and the new cycle boundaries on the well logs use the new coded palynological zonation of Shell. The correlation is done by matching the calcareous nannoplankton zonation with the old palynological zonation of Simon-Robertson (1992) and the calcareous nannoplankton zonations with Shell's new palynological zonations. The correlation is shown in the Stratigraphic Subdivision table (Figure 2.6).

Other information that helps in the reconstruction of the stratigraphic chart is the palynological zonation of the International Stratigraphic Consultant (from Simon-Robertson, 1992). The table provides the scientific palynological names for the old coded palynological zonation of Shell. This helps to understand better the palynological zonation used for the cycle subdivisions. On the basis of personal communication with Ho Kiam Fui, who introduced the cycle concept for Sarawak, the relationship shown in the table below is *correct for a general correlation* in the Sarawak Basin.

Palynological Zonations	**Old Coded Palynological Zonation by Shell**
Stenoclaenidites papuanus	Sa 35
Florschuetzia meridionalis	Sa 300 Po5 505
Florschuetzia levipoli	Pcs 38 upper Po3 79
Florschuetzia semilobata	basal Po3 79
Psilatricolporites	Phc 88
Cicatricosisporites	upper Pcs 145
Cyclophorus	basal Pcs 145

3. Determination of the Epoch and the Geochronometry. It is possible to do this when all the stratigraphic boundaries are confirmed by reference to the age scale in millions of years.

4. Incorporation of the stratigraphic datums proposed in this study with the sequence boundaries recognised elsewhere in the form of unconformities and conformities. The ages of the new boundaries are discussed further in Section 2.3.2.

2.3.2. The age of the new sequence boundaries.

The age of the sequence boundaries is based on the age of the bounding sediments to the particular unconformity or the correlatable conformity. However, the ages of four out of the six unconformities recognised within the Tertiary sediments in the Sarawak Basin have been determined by Shell (1992) for the nearshore area and by Simon-Robertson (1992) for the onshore area. The differences between the timing of the identified unconformities seem to be very small. The ages of the unconformities are as follows:

Sequence Boundaries	Age Ma (Shell)	Age Ma (Simon-Robertson)
Base T 5 S	5.3	5.2
Base T 4 S	11.0	13.00
Base T 3 S	18.0	18.5
Base T 2 S	22.5	23

The ages of the Base T6S and T7S are not known. However, it is interpreted that the ages of the two sequence boundaries are very close to the base of Cycle VII and VIII of Ho (1978) respectively.

The timing of the sequence boundaries as given above is believed to represent the shortest time in the history of the particular unconformity. In other words, it represents the time when the unconformity is almost conformable and where the break in sedimentation is minimal. Based on the mapping experience in the Sarawak Basin it shows that almost all the identified sequence boundaries are diachronous. Often one unconformity is truncated by the younger unconformity. The intensity and the timing of all the identified unconformities in the basin are discussed in Section 2.5.

2.3.3 Proposed New Stratigraphic Scheme for the Sarawak Basin

The proposed stratigraphic scheme for the basin is based on sequence stratigraphic concepts with the utilisation of unconformity or conformity as the stratigraphic boundary. Each regional unconformity in the Sarawak Basin formed at intervals of about six million years during Late Oligocene to Late Miocene times. During the Pliocene to Pleistocene the intervals were about one million years.

The sequence boundaries are shown in terms of duration rather than as a single representative line to show the different interpretation of the time for the particular sequence boundary

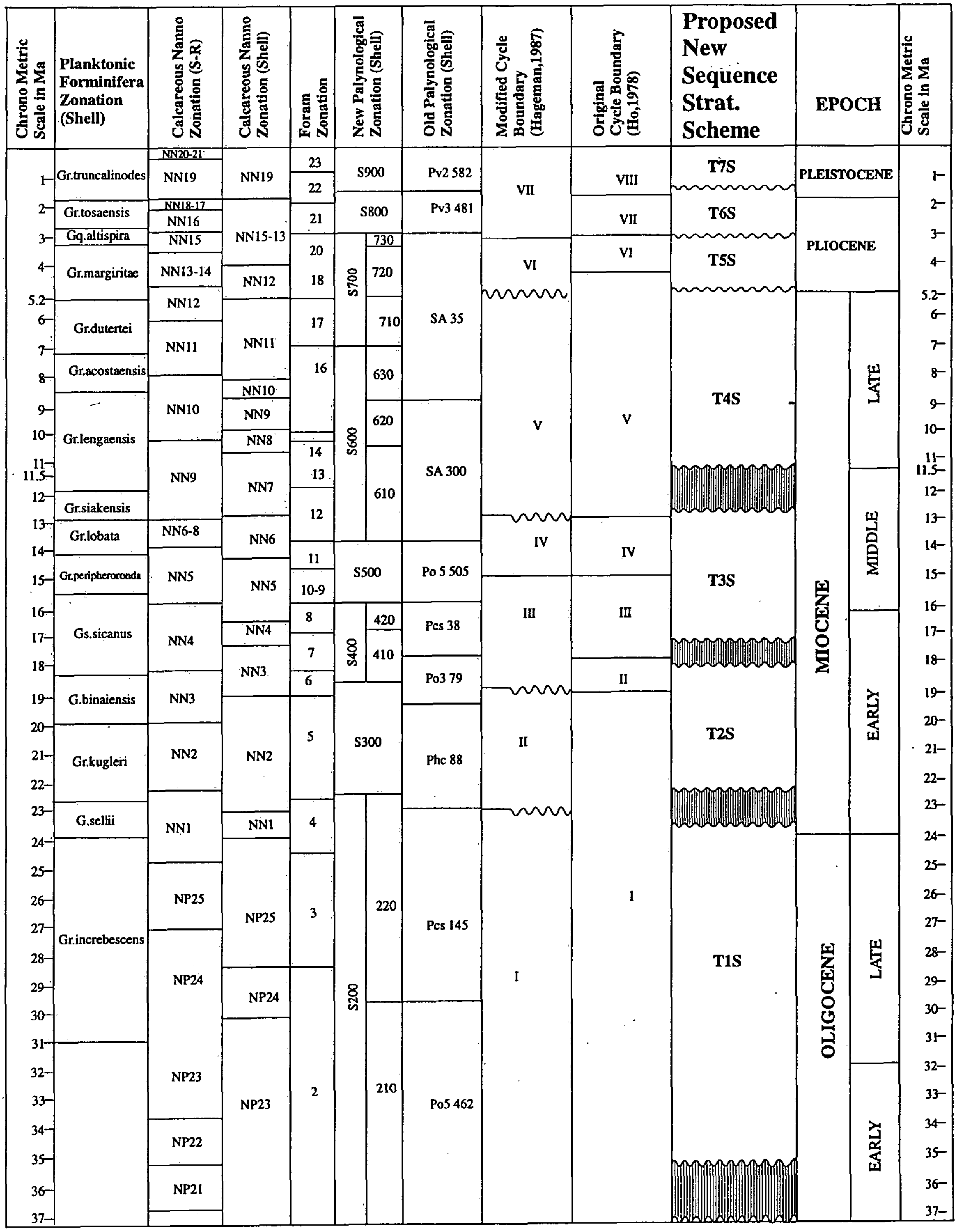


Figure 2.6 Composite stratigraphic table with the previous schemes used for the Sarawak Basin and the proposed new Sequence Stratigraphic Scheme.

(Figure 2.6). This is also done to suit the biostratigraphic zonation. For example the base T2S was interpreted to be between 2.5-3.0 million years which coincides with the top of Pcs 145 zone. However, most of the well data in the study area show that this unconformity occurs within the upper part of the Pcs 145 zone.

The sedimentary units between the unconformities can be recognised as ***Sequences*** as defined by Mitchum (1977). The oldest unconformity is that between the basement (Belaga Formation, late Cretaceous to late Eocene) and the overlying Tertiary sediments that are mainly of Late Oligocene age. Since the sediments in the basin are mainly of Tertiary age, the older unit of the succession is referred to as the **Tertiary One Sequence**, with the abbreviation of **T1S**. The next younger sequence is called **Tertiary Two Sequence** with abbreviation of **T2S** and so on.

Seven sequences have been identified throughout the basin. The age of the Tertiary sequences are as follows:

TERTIARY SEQUENCES	Abbreviation	AGE
Tertiary Seven Sequence	(T7S)	Pleistocene-Recent
Tertiary Six Sequence	(T6S)	Pliocene-Pleistocene
Tertiary Five Sequence	(T5S)	mainly Pliocene
Tertiary Four Sequence	(T4S)	mainly Late Miocene
Tertiary Three Sequence	(T3S)	mainly Middle Miocene
Tertiary Two Sequence	(T2S)	mainly Early Miocene
Tertiary One Sequence	(T1S)	mainly Late Oligocene

2.4 Application of seismic sequence stratigraphy techniques

The techniques involved are the identification of sequence boundaries, correlation of the boundaries and mapping of the sedimentary units to generate a three dimensional map of each sequence. Mapping has been carried out for the whole area in the Sarawak Basin by using the seismic lines in Figure 2.4. The steps in applying the techniques in this study are discussed in the next section.

2.4.1 Picking the sequence boundaries

It is a seismic sequence stratigraphy procedure to pick the unconformities that bound units and thus isolate them. The angular pattern of reflections at sequence boundaries is the key to

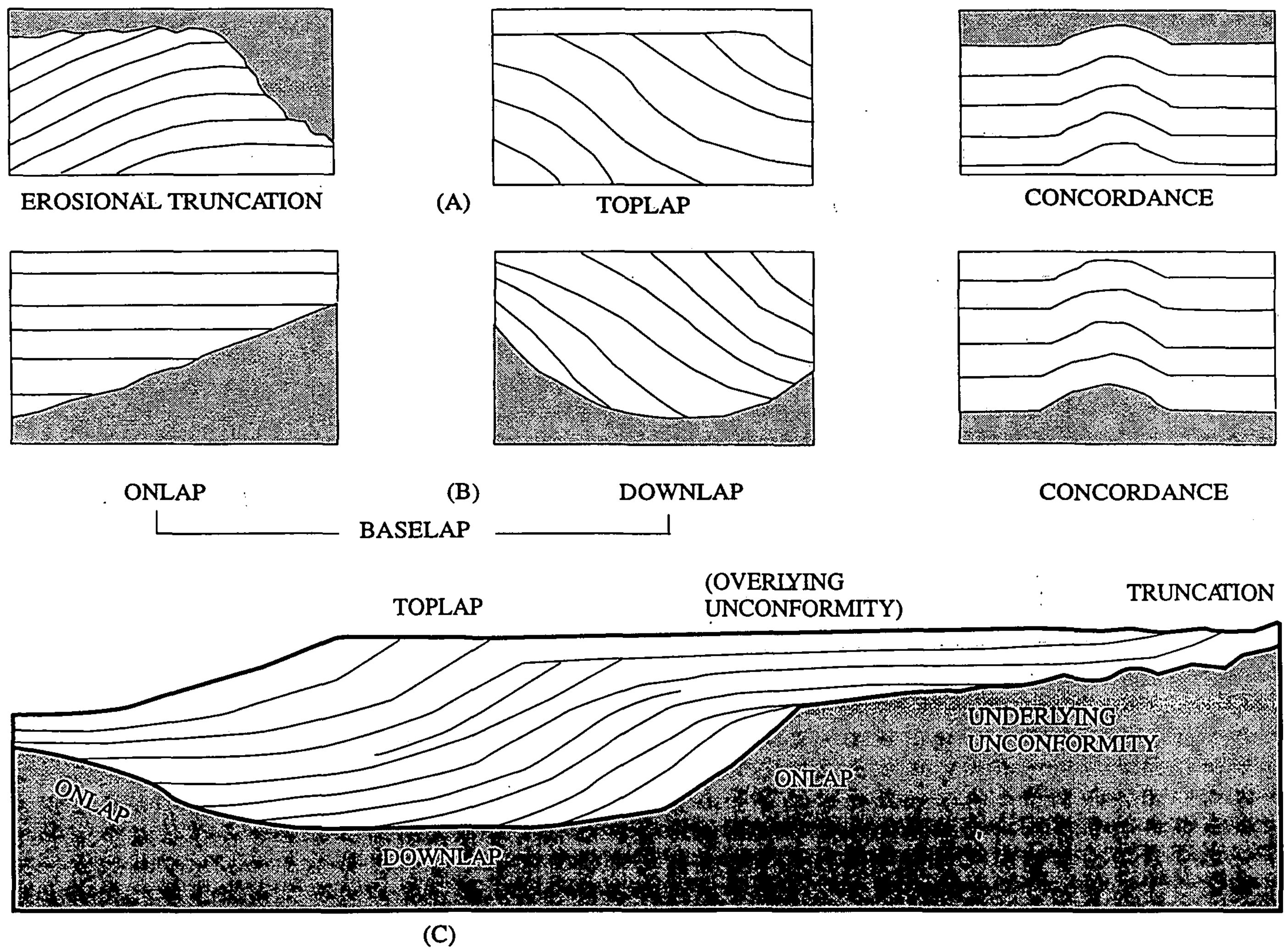


Figure 2.7. Relations of reflections within a sequence unit to the unit boundaries.(A) Relation at the top of sequence unit, (B) Relation at the base sequence unit and (C) Reflection terminations within an idealised unit (from Mitchum et al.,1977).

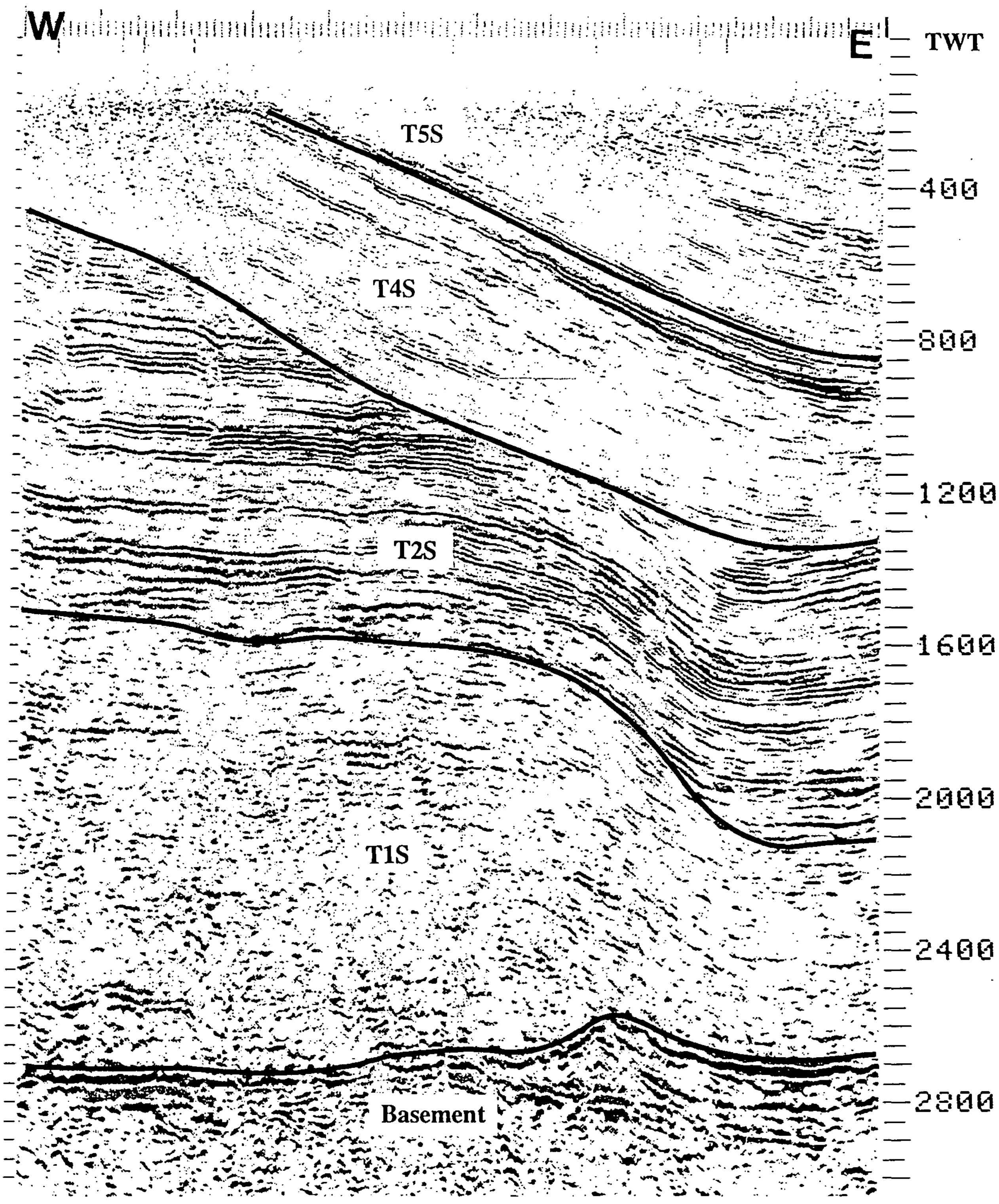


Figure 2.8 Seismic section showing examples of sequence boundaries for the base T1S, base T2S, base T4S and base T5S. The unconformity between T1S and T2S is almost concordant in nature to the west and characterised by onlaps to the east. However, the two sequences are represented by different seismic facies. In places, base T2S is also erosive in nature.

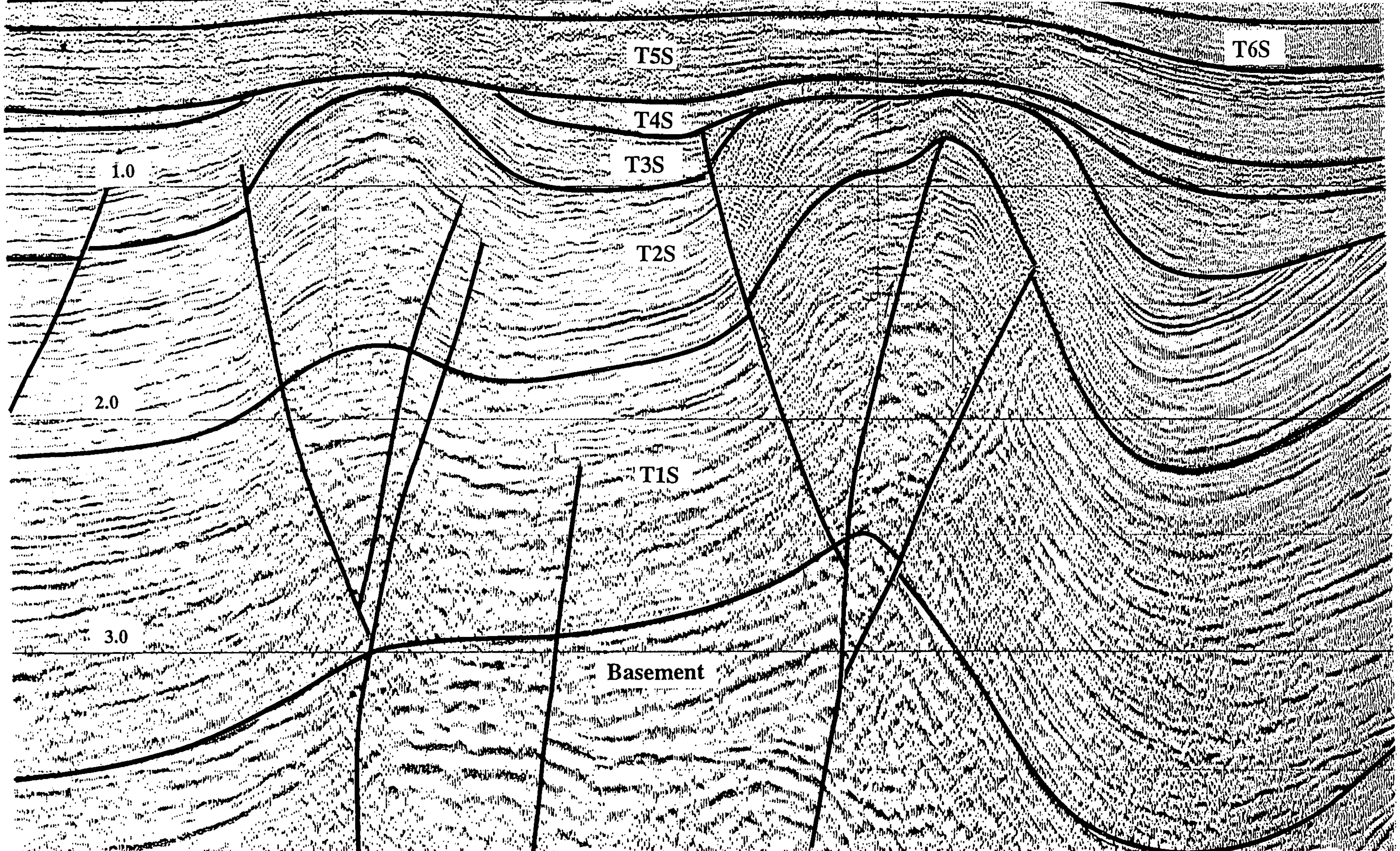


Figure 2.9 Seismic section showing examples of unconformable sequence boundaries for the base T3S, T4S and T5S. The bases of the sequences are characterised by erosional unconformities.

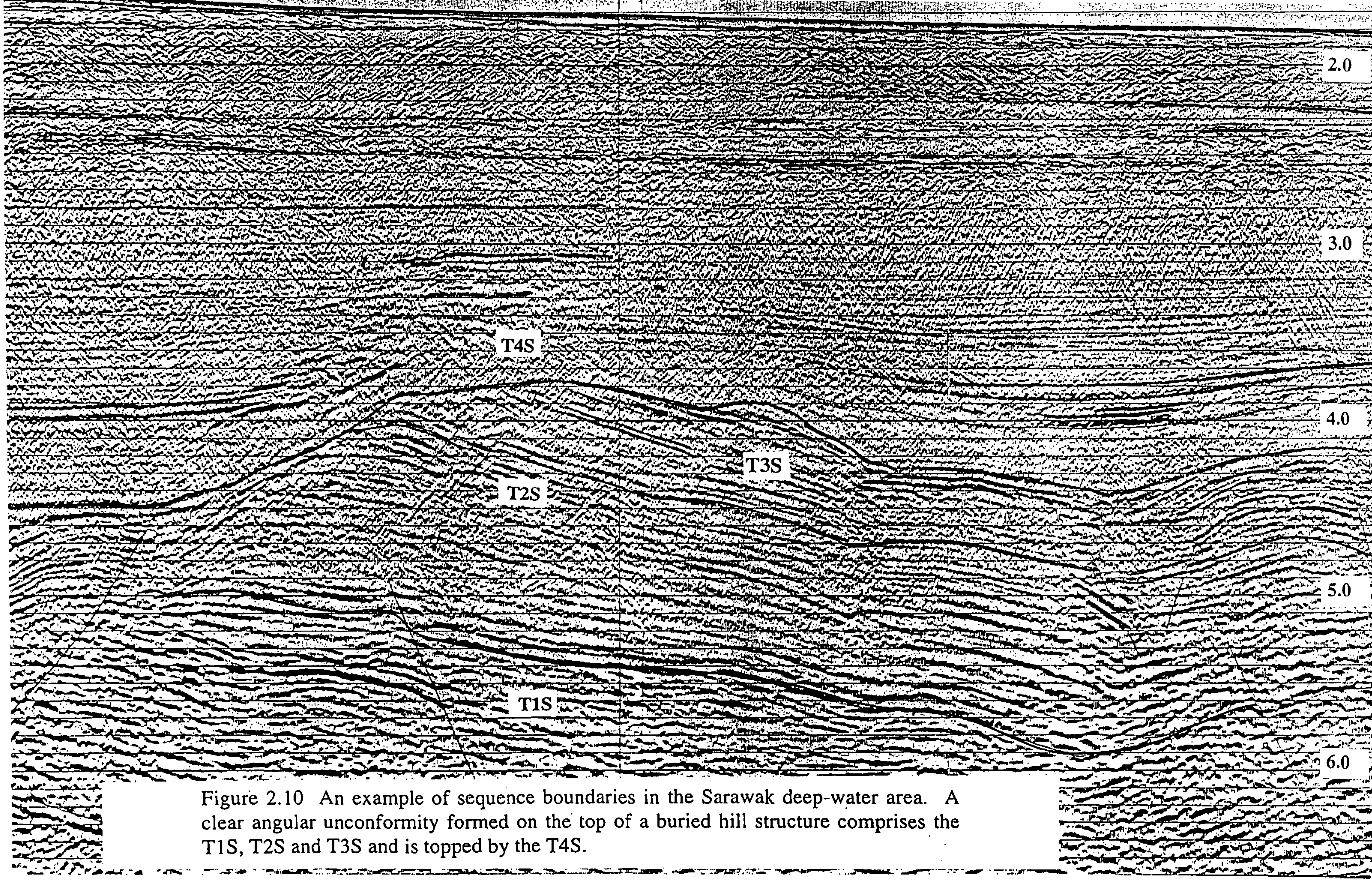


Figure 2.10 An example of sequence boundaries in the Sarawak deep-water area. A clear angular unconformity formed on the top of a buried hill structure comprises the T1S, T2S and T3S and is topped by the T4S.

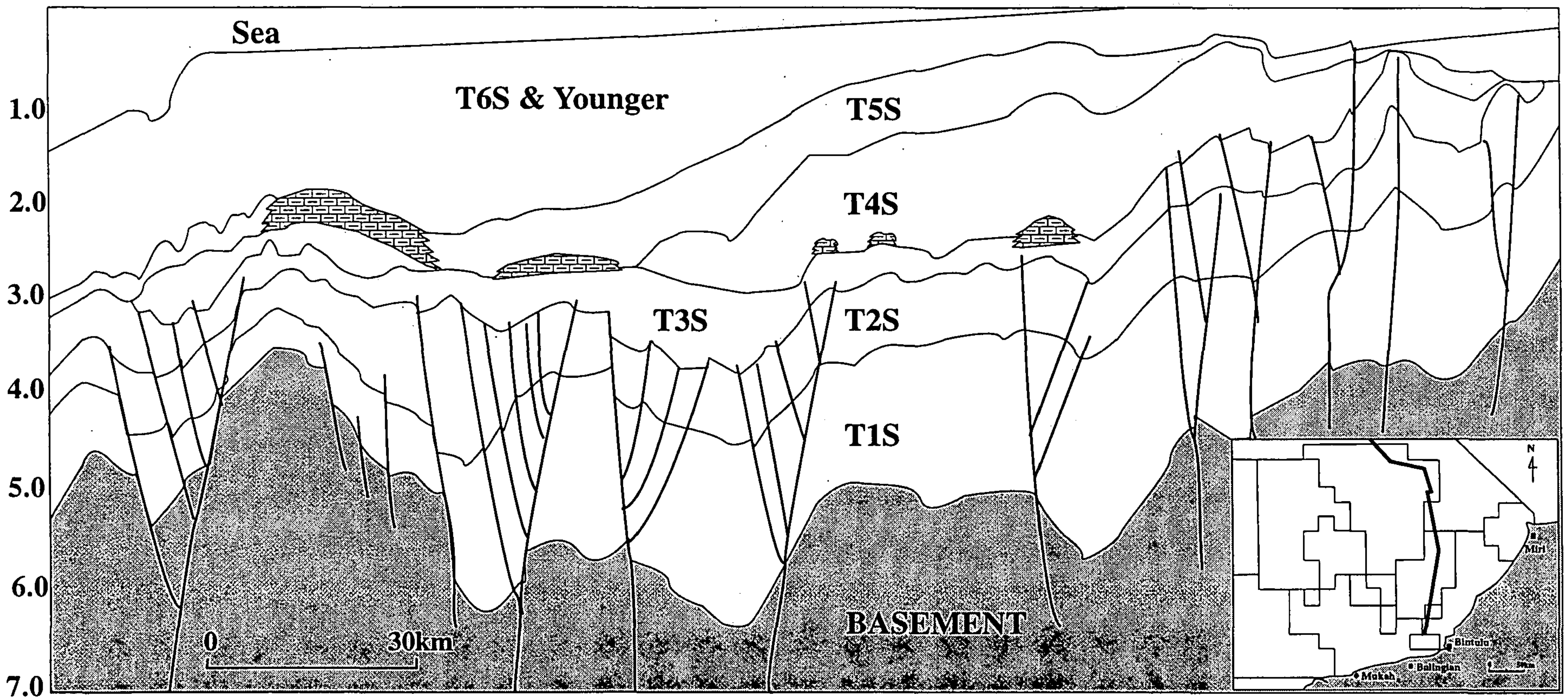


Figure 2.11 Geoseismic correlation from the nearshore to the deep-water area shows how the seismic mapping was conducted using the sequence boundaries as the marker for correlation.The orientation of the line is shown in the inset figure.

identifying sequence units (Sherif, 1980). Examples of reflection terminations based on Vail et al. (1977) are shown in Figure 2.7. Examples of sequence boundaries identified in the study area in the onshore, nearshore and deep-water areas are shown in Figures 2.8, 2.9 and 2.10.

In the study area, the sequence boundaries for the younger sequences, that is the Base Tertiary 3, 4, 5 and 6 Sequences, are relatively easy to identify. The boundaries are angular unconformities and widespread (Figure 2.9). In contrast, the sequence boundaries for the older sequences, that is the Base Tertiary 1 and 2 Sequences, are more difficult to pick. This is because the angular nature of these unconformities are only limited to a certain area, mostly in the onshore area. In other places, these unconformities are almost conformable. In the onshore area, the Base Tertiary 1 and 2 boundaries appear to be irregular erosional surfaces, with an abrupt seismic facies change between the two bounding sequences (Figure 2.8).

2.4.2 Mapping the sequence boundaries.

An unconformity becomes a conformity in an area where there was no exposure and/or erosion or where the area was not tectonically deformed during the formation of the unconformity. The well data were used, whenever available, to locate the equivalent or correlatable conformity. Generally, where an unconformity cannot be seen on seismic, it could be picked from the well data. This was done by using dipmeter variations, shift in sonic and shale density trends, abrupt facies changes and/or biostratigraphic gaps.

In the case where the equivalent conformity could not be clearly identified on seismic, the mapped datum was projected (*push* or *phantom* of Sherif, 1980) through the area to complete the mapping of the bounding surface. This was done carefully so that the correlated datum is situated within the same biostratigraphic zone with its equivalent unconformity. The age and the biostratigraphic zonation for all the sequence boundaries will be discussed in the next section. Another way to check the correlation, especially when there is no well control in the area, is by a looping process. This is achieved by tracing the datum on several lines and correlating the datum back to the original intersection where the datum had already been determined.

2.5 Regional Mapping

By adopting seismic sequence stratigraphy techniques, the seismic mapping has been carried out using both the regional and prospect lines. It was found that this technique is suitable for the Sarawak Basin primarily because of the presence of several prominent unconformities. The unconformities used as the seismic markers could be seen clearly throughout the whole basin, including the onshore and the deepwater area. The selected digitised seismic sections from the nearshore to the deepwater areas are shown in Figures 2.11 and 2.12.

In the onshore area, the erosional intensity of the unconformities and the period of non-deposition are generally longer than in the nearshore area. In some areas, a whole sequence is missing, e.g. the Tertiary Three Sequence (T3S) is only preserved in half-graben structures. Elsewhere, the T2S is overlain by the T4S instead of T3S.

In the nearshore area (SK5), all the unconformities are present and all the Tertiary sequences are preserved without a complete succession; the intensity of the unconformities is reduced compared to the onshore area. In some places, carbonate buildups developed during T2S, whereas in other areas the carbonate formed during T4S times (Figure 2.13).

In the Luconia area (SK 8 and SK6) most of the sequence boundaries are conformable. However, the seismic reflectors below the carbonates are reasonably good for correlation. Although there are some pull-up effects in the area due to the faster seismic velocities within the carbonate, it is believed to be minimal since all the regional lines were reprocessed to image the deeper intervals. The correlation across the area could further be confirmed by looping through areas without carbonates. The carbonates started to grow in the area during the Middle Miocene (T3S) and most carbonate deposition ceased during the Late Miocene (T4S) except in the area towards the present-day deepwater (Figure 2.13).

The deep-water area is the area that was tectonically active until Late Miocene times. Almost all the identified unconformities in other areas could be traced into the deeper-water area. The unconformities are clear with a certain degree of angularity. In some areas the Base T3S is dominant and in other places, the Base T2S formed as a prominent unconformity. This created the erosional remnant structures termed "buried hills" by Smith (1994). The whole deep-water area was fully submerged during the Pliocene (T5S) where the Base T5S unconformity is absent and a great thickness of the sequence is preserved in the western part (Figure 2.12).

A stratigraphic scheme for the Sarawak Basin (Figure 2.13) summarises the information about the intensity of the unconformities and the amount of preserved sedimentary units in the various areas within the location of the region.

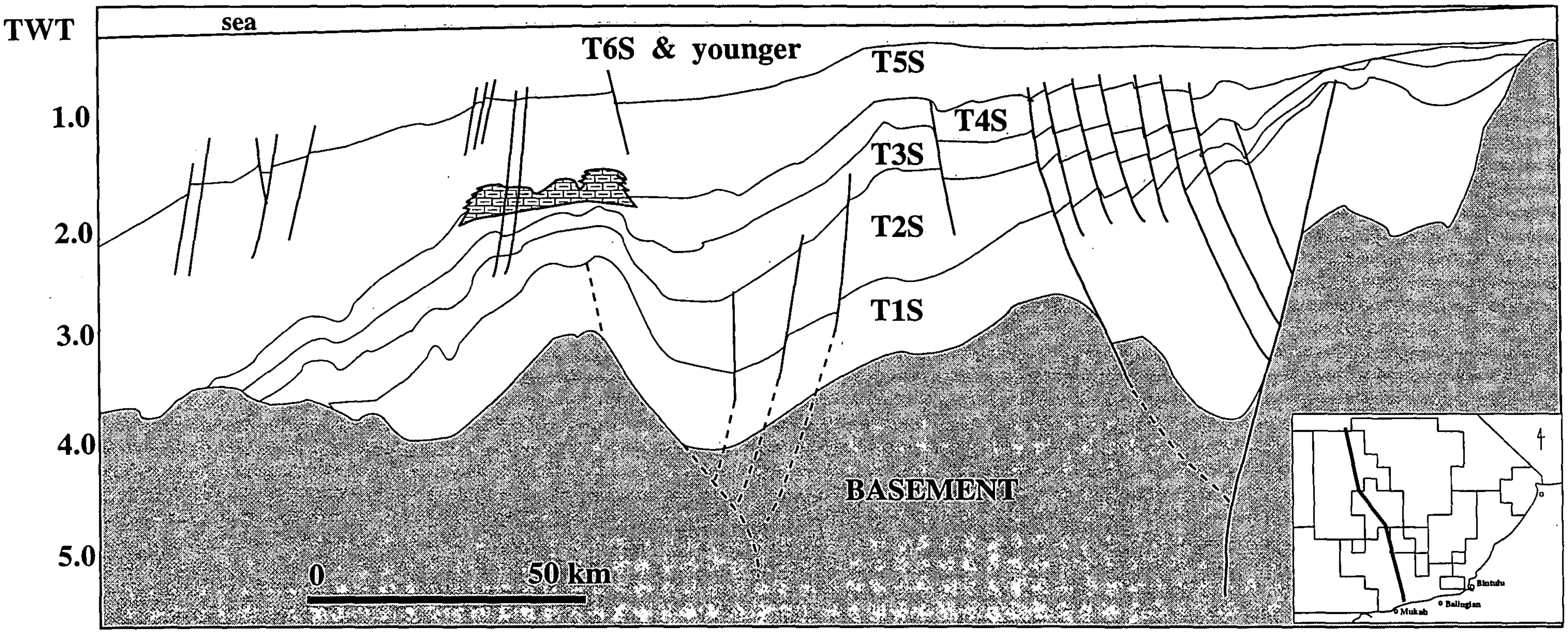
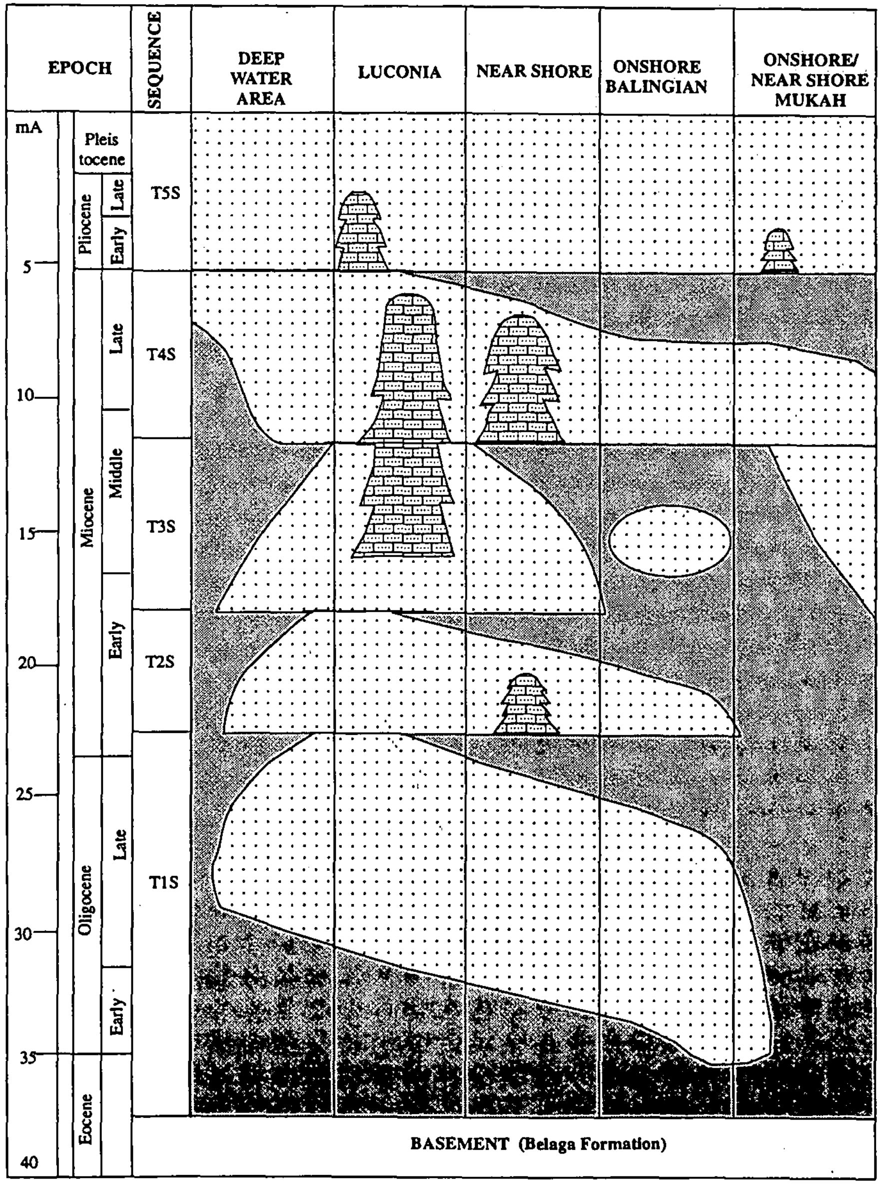


Figure 2.12 Geoseismic correlation showing that the sediments of T1S to T4S were deposited only in the limited area in the present day shallow-water area. The whole area to the west of present-day deep water area is mainly covered by the T5S and the younger sequences. This suggest the area subsided during the Pliocene (T5S).



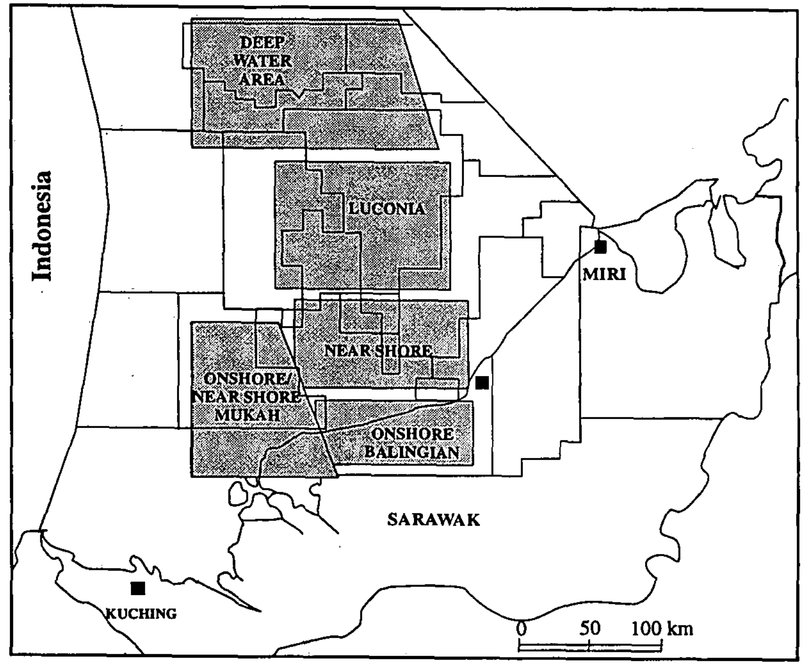


Figure 2.13 Stratigraphic column for the Sarawak Basin shows the non preserved section (in grey), preserved clastic section (dots) and carbonates. The map to the right shows the location of the respective area.

2.6. Comparison between the Cycle and Sequence Stratigraphic concepts

This section discusses the original idea behind the two concepts and then considers the possible driving mechanisms for the cycle and sequence evolution.

2.6.1. Stratigraphic Concepts.

The basic idea of stratigraphy is to subdivide the rock succession according to the age of the formations. This subdivision is important for the purpose of both time and space correlations, especially for the sedimentary rocks. This will help in understanding the similarities and differences of the lithologies between the same and different age groups. Sedimentary rocks even of the same age may be different in sedimentary facies and lithology because of deposition in different depositional environments. Variation in diagenesis and compaction history may also be important. A good stratigraphic understanding of a particular basin will facilitate the interpretation of the sedimentary record.

2.6.1.1. Cycle Concept

The original cycle concept was based on the idea that sedimentation took place as a regressive wedge in between two periods of high sea-level. A thick succession was deposited in the long regressive period. By way of contrast, the sediment deposited during the shorter transgressive interval is relatively thin but widespread. This unit could be used as a time line and defines the base of a cycle according to the definition by Ho (1978). The base of the next cycle is at the next maximum transgressive unit.

The idea of sea-level rising relatively rapidly, followed by sedimentation building up to sea-level during a relatively long period of base-level stability has also been applied to other successions, such as the Devonian cycles in eastern USA (Goodwin and Anderson, 1985) for which they introduced the term punctuated aggradational cycle. In contrast, Vail et al. (1977) suggested that eustatic sea-level changes are frequent, with rapid falls and gradual rises. However, Ho (1978) did not discuss the driving mechanism that resulted in the cyclic nature of the sedimentation in Sarawak.

The modified cycle scheme of Hageman (1987), later adopted by Sarawak Shell, does not seem to agree with any known established stratigraphic concept. For example, all the cycle boundaries were moved to the unconformity boundaries of a similar age. However, in the case where this was not possible the scheme maintained the original cycle boundaries. By moving the cycle boundary to the unconformity boundary, it no longer agreed with the original definition of a cycle. This means that the sediment within the new cycle no longer represents a transgressive-regressive sedimentary package. Therefore, the biostratigraphic assemblage from the original cycle will not be suitable for the new cycle. The application of the new cycle scheme will cripple the ability to identify the transgressive unit that is recognised by the occurrence of plankton-rich and deeper-marine benthic-zone sediments.

The only reason that can be seen for changing the cycle boundary is to suit the request of geophysicists. This happened when Vail et al. (1977) introduced the seismic stratigraphy concept and workers started to use unconformities for correlation. All those unconformities were named as "near top cycle I unconformity, or near top Cycle II unconformity" and so on in the old Shell reports. This means that those unconformities did not coincide with the cycle boundaries. Therefore the modification to the stratigraphic scheme by Hageman (1987) should not be encouraged unless a new definition of the cycle concept is put forward. Without a new definition it will not give any improvement to the stratigraphy, but just add confusion for the later workers (which included this author) and Levesque and Ooi (1989).

2.6.1.2. Sequence Concept

The sequence concept that is proposed in this study is developed from the idea that the unconformity and its correlatable conformity formed as a time line in the preserved stratigraphic column. This simply means that the sediment below the unconformity must be older than the sediment above the unconformity. By this reason the unconformity surface itself is the time line and it could be used for correlation purposes. For the case of the Sarawak Basin, a sequence is defined in a similar way to the definition of Mitchum (1977): "a stratigraphic unit composed of a relatively conformable succession of genetically-related strata and bounded at its top and base by unconformities or their correlative conformities".

As discussed by Wagoner (1990), the idea of using the sequence as an unconformity-bounded stratal unit is not as it was originally proposed by Sloss in 1948. The next major development in the evolution of sequence stratigraphy happened when Vail et al. (1977) published the concept of seismic sequence stratigraphy and they modified Sloss's 1948 use of sequence in two important ways. Firstly, the sequence of Vail et al. (1977) encompassed a much smaller amount of time than the sequence of Sloss (1963). Secondly, they proposed eustasy as the prominent driving mechanism for sequence evolution. In the 1980's the application of seismic stratigraphy was broadened by new accommodation models developed by Jervey (1988) to explain seismically-resolvable stratal patterns.

2.6.2 The driving mechanisms for the evolution of cycles and sequences.

The most important mechanisms for the evolution of cycles and sequences are eustatic sea-level changes and tectonics besides the other minor controlling factors which include sediment supply and production rate and compaction. Since the tectonic and sedimentation history of the Sarawak Basin will be discussed in the following Chapters, this section will only discuss whether there is a relationship between the ***cycle*** boundaries and the proposed ***sequence*** boundaries with the global sea-level curves of Haq et al. (1987,1988).

2.6.2.1 Global Eustatic Sea-Level changes

The subject of eustatic control that involves changes in ocean level on a global scale has been discussed by several workers including Tucker and Wright (1990). Ocean level is controlled by both tectonics and climate. The concept of plate tectonics explains many features of sedimentary geology, but particularly those of a large-scale or long time-scale. The first-order cycles of the global sea-level curve, for example, are explained through opening and closing oceans, and the second-order cycles through passive-margin subsidence. However, plate tectonics is a global continuum, in space and time, so that plate tectonic process will operate on the small scale and short time-scale. One mechanism supposedly able to cause rapid sea-level changes is in-plane stress (Cloetingh et al., 1985 in Tucker and Wright 1990).

One of the popular mechanisms for global sea-level fluctuations is glacio-eustasy driven by orbital perturbations (Milankovitch rhythms), on a time-scale of tens to hundreds of thousands of years. The rationale is that the astronomical cycles of precession of the equinoxes (periodicity 23,000 and 19,000 years), obliquity of the ecliptic (41,000 years) and eccentricity (100,000 and 400,000 years) control the position of sea-level through variation in solar radiation causing changes in the size of the polar ice caps..

Sea-level cycles are classified by Vail et al. (1977) according to their duration:

third-order cycles, defined from fall to fall, have a duration of 0.5-3.0 million years,
fourth-order cycles have a duration of hundreds of thousands of years.
fifth-order cycles were assigned by Wagoner (1990), following Vail et al.(1977) and have a duration of tens of thousands of years.

A composite eustatic curve (Wagoner,1990) is the product of interference of third-order cycles (approximately one million years), fourth-order cycles (approximately 120,000 years) and fifth-order cycles (approximately 50,000 years).

One of the most popularly-used supposed eustatic sea-level curves is that of Haq et al. (1987). The chart is used in this study to determine whether there is a relationship between the cycle boundaries and the global sea-level changes.

2.6.2.2 Relationship between Cycle Boundaries and Eustatic Sea-Level Changes.

The cycle boundaries of Ho (1978) in the Sarawak Basin can be correlated to the Haq et al. (1987) chart as follows:

Cycle Boundaries	Third-Order Cycle Number
Base Cycle 2	near top of 2.1
Base Cycle 3	middle of 2.2
Base Cycle 4	near top 2.3
Base Cycle 5	middle of 2.4
Base Cycle 6	near top of 3.3
Base Cycle 7	near base of 3.6
Base Cycle 8	near top of 3.8

Based on this one could see that all the seven cycle boundaries roughly coincide with third-order cycles of global sea-level change and sequences in the Haq et al. (1987). The conclusion that could be derived from this is that all the cycle boundaries in Sarawak and the cycles themselves are most likely controlled by global sea-level changes.

2.6.2.3 Relationship between Sequence Boundaries and Eustatic Sea-Level changes.

In correlating the sequence boundaries to the global sea-level curve, it can be seen that the bases of T2S and T3S do not correlate with the sea-level falls. However, the bases T4S, T5S and T6S do coincide with eustatic sea-level falls. However, no firm conclusions can be drawn at this stage for several reasons.

Firstly, the intervals between the sea-level fall and rise during this period are very short (approximately one in every million year, during late Miocene, Pliocene and Pleistocene times). This short interval is beyond the resolution of foram or pollen zonation that is about 0.5- 4.0 Ma (Hageman,1987).

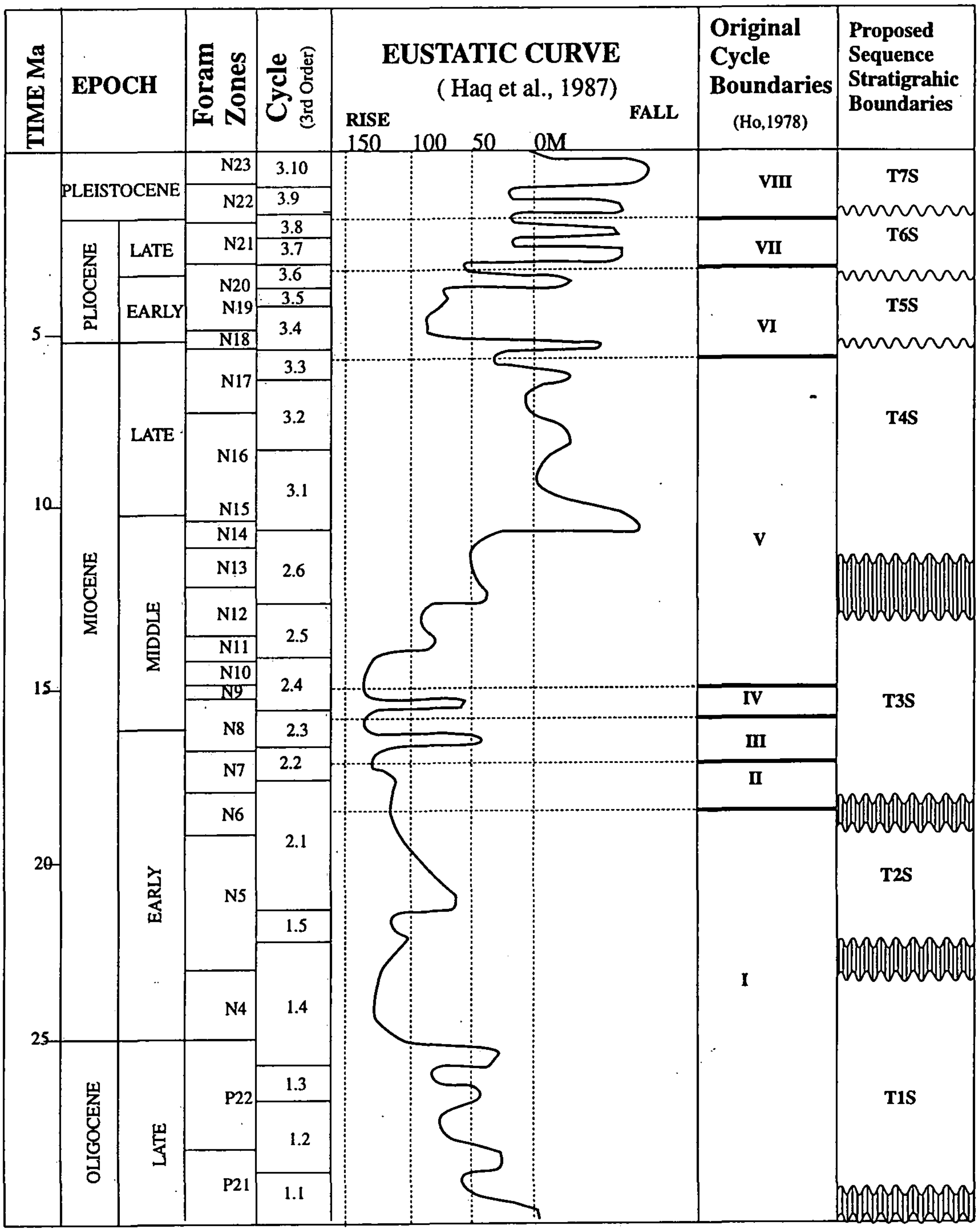


Figure 2.14 The relationship between eustatic sea-level changes and cycle boundaries and the comparison with the sequence boundaries. The base of all the cycles correspond to eustatic sea-level rise. The sequence boundaries in contrast do not normally coincide with the sea-level fall. It is interpreted that most of the sequence boundaries are tectonically originated rather than eustatic.

Secondly, the ditch cutting sampling for biostratigraphic investigation is mostly in a broad interval because the Pliocene-Pleistocene sediments are not the prospective reservoirs for hydrocarbons in the area.

Thirdly, base T4S that coincides with the sea-level fall between the third-order cycle 2.4 and 2.5 also coincides with a major tectonic event in the onshore area (Figure 2.8) and base T5S that coincides with the sea-level fall between the third-order 3.3 and 3.4 is also coincident with a major phase of subsidence in the western part of the deep water-area (Figure 2.14).

It could be concluded that all the boundaries for the Miocene sequences are not related to global eustatic sea-level falls. Other boundaries do coincide with eustatic sea-level falls but the boundaries in the Tertiary succession of the Sarawak Basin are most likely controlled by the tectonics instead of eustasy.

2.7. Recognition of the sequence boundaries.

As has been discussed in Sections 2.4 and 2.5, the most conventional way to identify the sequence boundaries in the study area is through seismic sections. The information then can be transferred to the well-logs by converting the time interval into depth. However, it is possible to identify the sequence boundary from well data alone, if the unconformity cannot be defined on the seismic or the workers have no knowledge of seismic. This section discusses how to identify the sequence boundaries during the various stages of exploration.

Figure 2.15 shows an example of how correlation between five wells in Block SK5 was made when the seismic lines passing through the wells were not available. Other material such as conventional cores were not available for the identification of sequence boundaries. Among the data used to identify the sequence boundary are the sonic and dipmeter logs, together with biostratigraphic data. The correlations show that all the sequence boundaries can be recognised and the well correlation was successfully made by integrating all the above-mentioned data.

2.7.1 Compaction Trend.

An unconformity is a break in the sedimentary and stratigraphic record and one of the many ways to recognise the unconformity is by analysing the compaction trend. The effect of compaction is obvious on a sonic log where over a thick shale interval, there is a regular increase in velocity downwards due to compaction. Compaction is normally accompanied by diagenetic effects which are irreversible and stay 'frozen' during uplift (Rider, 1986). The 'jump' in compaction reflects the amount of section missing.

The effect of compaction can also be studied by measuring the shale porosity which in turn can be correlated with sonic transit times. Quantitatively, this can be expressed as shale porosity (Magara, 1978; Rider, 1986). Several different computerised methods for compaction trend prediction have been developed by mud-logging companies, i.e. D-Exponent by Analyst Schlumberger and Shale Density Log by EXLOG Company.

The compaction trend is one of the most convenient methods to use for the drilling engineer, the wellsite geologist and mud-logging engineer to identify the sequence boundaries during the course of drilling the well. The sequence boundary can be confirmed after the wireline log is run.

2.7.2 Other wireline logs.

Among the wireline data that could be used for picking the sequence boundary are dipmeter, gamma ray, neutron and density logs. Since it is likely that all or some of the sequence boundaries in the study area are tectonically induced, one would expect that each sequence has undergone a different tectonic history. This will produce a different strike and dip for each sequence which should be detectable from the dipmeter logs.

The gamma ray, neutron and density logs are used for the interpretation of the sedimentary facies that will be discussed further in Chapter 3. However, the data from those logs can be used to interpret whether there is an abrupt change in the depositional facies that is normally associated with the presence of an unconformity. All the interpretations can be done immediately when the complete suite of wireline logs is available.

2.7.3 Biostratigraphy data

Biostratigraphic data are one of the most useful tools for the determination of the sequence boundaries. It is vital since that is the only conventional way to determine both the ages of the sedimentary succession and the presence of an unconformity. The unconformity can be identified by an abrupt change in depositional environment and by the break in stratigraphy. The depositional environment can be interpreted from benthonic foraminifera for the marine sediments and the age can be determined by diagnostic planktonic foraminifera and other palaeontological data. In the drilling operation, however, the biostratigraphic interpretation will only be available long after the well has been terminated.

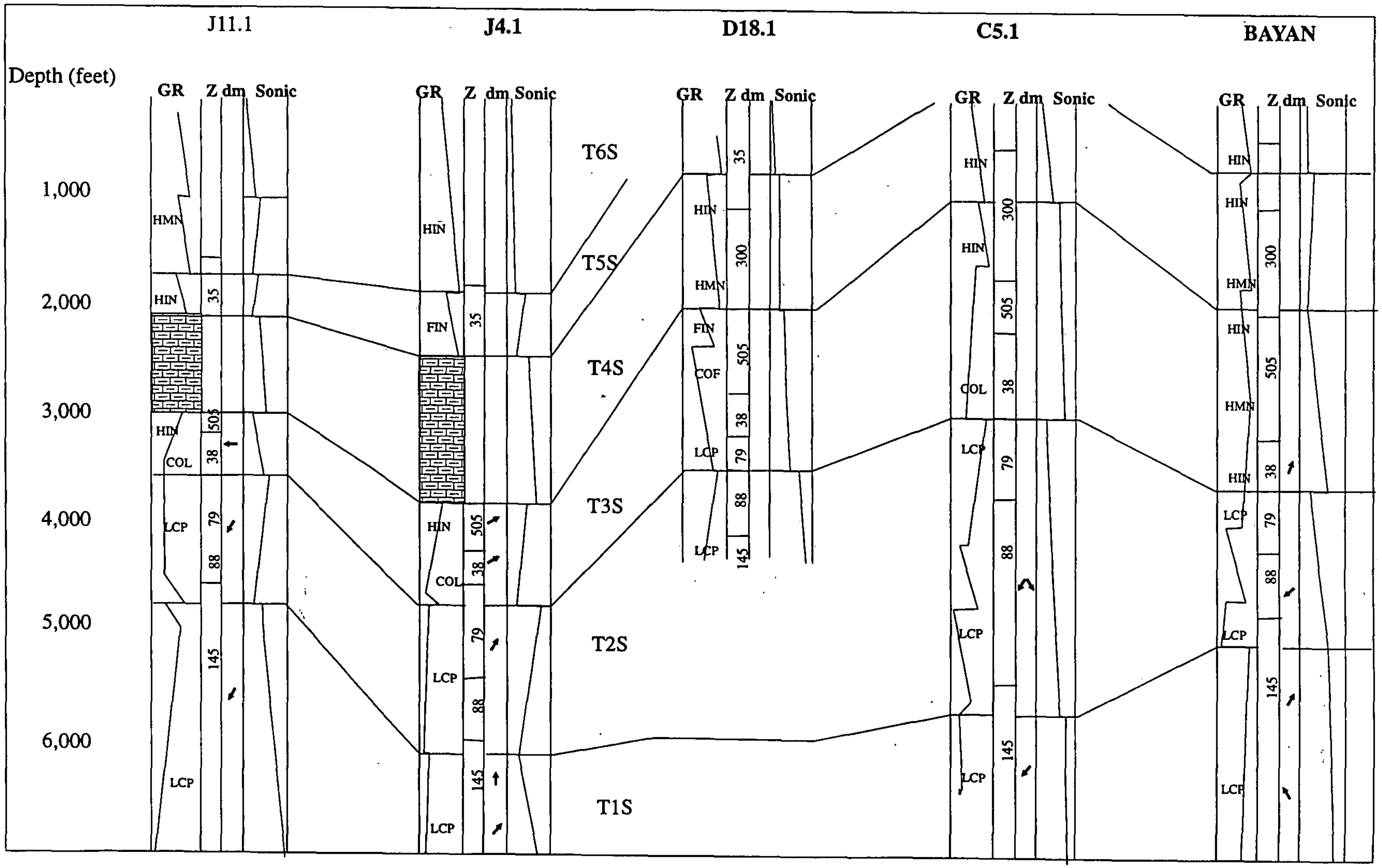


Figure 2.15 Correlation between five wells in Block SK5. The distance between J 1 1.1 and Bayan is about 80 kilometres. The correlation was made based predominantly on the changes in the sonic trend. The correlation is believed to be conclusive since all the sequence boundaries fall in the pollen zonation according to the proposed scheme in Figure 2.6 and agreed with other data, i.e. dipmeter and variation in the depositional facies.

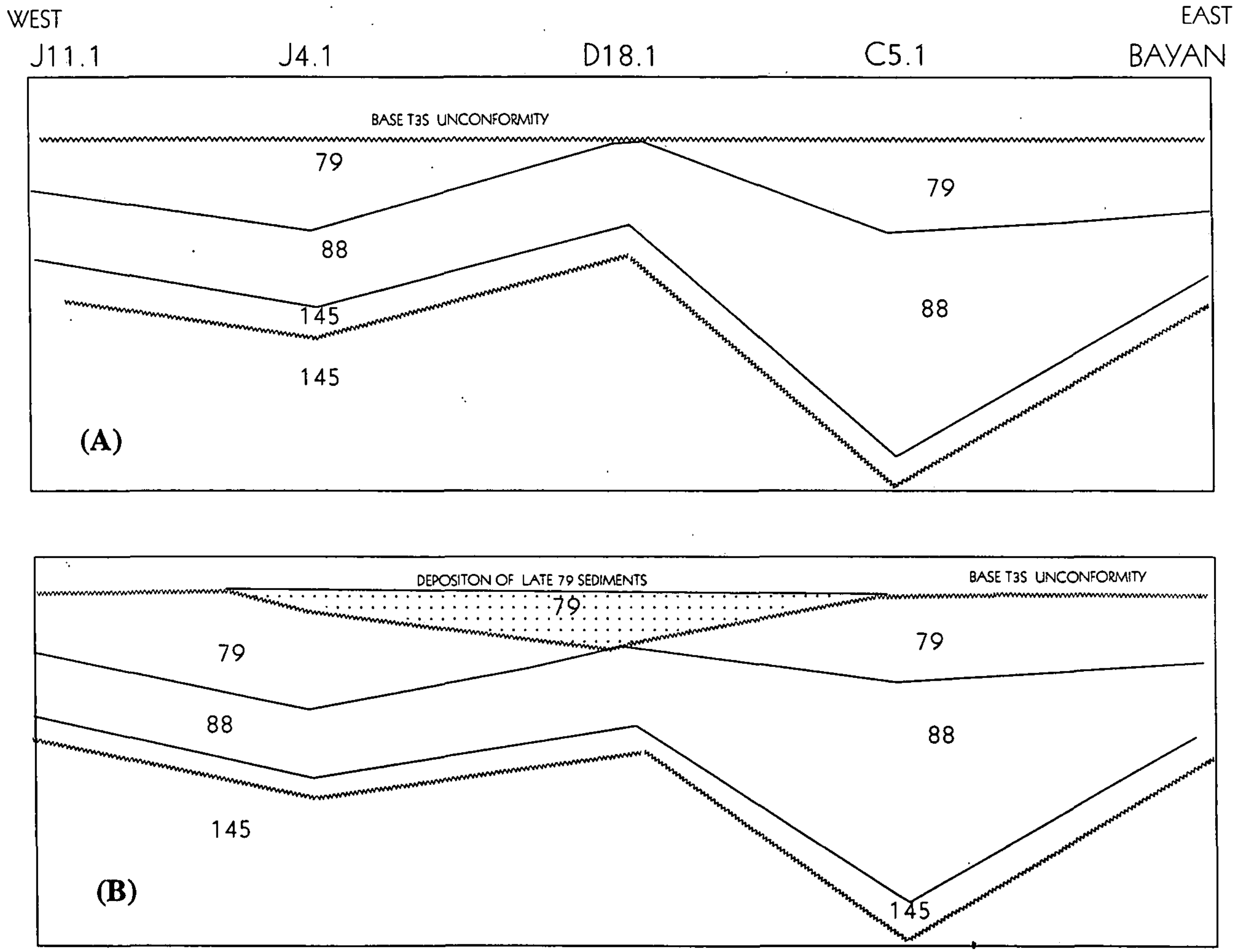


Figure 2.16 Back stripping for the period during the erosion by the base T3S unconformity in (A) and during the deposition of the younger unit of the 79 sediments in (B). The area in the vicinity of C5.1, Bayan and J1 1.1 wells remained exposed during the time while deposition took place in the depression at the location of J4.1 and D18.1 wells. Model suggests that the younger unit of 79 sediments is likely to be recycled from the older unit.

As for the correlation of the five wells in Figure 2.15, it cannot be based solely on the palynological zonation because that is very broad. For example, the Base T3S unconformity falls at the base of Pcs 38 for Bayan and C5.1, at the base of Pcs 79 at D18.1 and in between Pcs 79 at J4.1 (Figure 2.16). By flattening the Base T3S unconformity, that is by assuming that the unconformity surface is flat during the time of erosion, it shows that the upper part of the Pcs 79 unit in the D18.1 and J4.1 was deposited later than the time of formation of the unconformity. Figure 2.11b shows the situation after the deposition of the upper part of the Pcs 79 sediments.

The two figures (Figures 2.16a and 2.16b) suggest that the upper part of the Pcs 79 sediments at D18.1 and J4.1 are younger than those in Bayan and C5.1 wells. This unit is recycled sediments containing pollen similar to the older sequences and deposited when the area subsided in T3S times. Based on this observation it was realised that the current palynological zonation for the study area needed to be refined for a more accurate biostratigraphic zonation.

2.8. Summary and conclusions.

1. The regional seismic mapping in the Sarawak Basin leads to the identification of seven regional unconformities. From these, it was decided to apply a seismic sequence stratigraphic interpretation for the Sarawak Basin.

2. All the Late Oligocene to Late Miocene sequence boundaries are probably tectonically induced rather than related to global eustatic sea-level falls. The sequence boundaries in the Pliocene-Pleistocene sediments in contrast may be derived from the eustatic sea-level changes or a combination of eustasy and tectonics.

3. The proposed stratigraphic scheme is superior to the cycle concept in several aspects including:

a) The sequence boundary can be identified on seismic and the stratigraphic subdivision can be made before drilling. The cycle boundary in contrast can only be established after the biostratigraphic study is completed.

b) The sequence boundary can be recognised by workers from other disciplines by using the information from logging tools. Cycle boundaries in comparison need to be confirmed by the biostratigrapher.

c) By using sequence stratigraphy, mapping can be carried out in all areas irrespective of the sedimentary facies. In contrast, mapping the cycle boundary is only accurate for marine and marine-influenced environments.

4. The main interval for the study area, i.e. the Late Oligocene-Middle Miocene sequences, are predominantly made up of non-marine sediments. Therefore the stratigraphic subdivision using sequence stratigraphy is more appropriate.

5. In correlating between the proposed stratigraphic scheme and the original cycle zonation, several cycles occur within one sequence, i.e. the upper part of Cycle II, the whole Cycle III and Cycle IV occur within the T3S.

6. All the cycle boundaries in the original cycle stratigraphy (Ho,1978) coincide with the third-order cycles of global sea-level rise.

7. The modified cycle scheme (Hageman,1987) that was later adopted by Sarawak Shell, should not be used unless the meaning of the cycle is redefined. Without it, the scheme will overshadow a powerful concept of stratigraphy, that is the original cycle concept of Ho (1978).

Chapter 3

SEDIMENTATION HISTORY OF THE SARAWAK BASIN

3.1. Introduction

This chapter discusses the facies variations in thickness, changes in depocentre and the lateral extent of all the Tertiary sedimentary sequences in the Sarawak Basin. This is based on the isochore maps derived from regional seismic mapping in the whole study area covering both the onshore, nearshore and the offshore areas. The discussion will also emphasise the controlling factors for deposition in the study area. This chapter describes the evolution of the depositional environments in the Sarawak Basin based on reconstructed palaeoenvironment maps derived from the well data using the proposed sequence stratigraphic scheme.

Since the model for deposition used in the study of Ho (1978) is mainly based on the biostratigraphic subdivision, this chapter will also describe the sedimentary facies and depositional mechanisms that were associated with each particular depositional unit. In this way it is easier to understand the distribution of reservoirs, sources and seals for hydrocarbons in respect to the depositional environments.

The discussion of the variation in thickness and lateral extent of the sedimentary sequences is separate for the offshore, nearshore and the onshore areas. This is due to several reasons but mainly because the seismic lines used for the three areas are different in scale, grid and vintages. For example, the study in the offshore area is based on the sparse grid of regional seismic lines (Figure 2.4) and well data. Only a general picture of the factors controlling the sedimentation in the Sarawak Basin can be obtained from interpretation of the regional seismic lines. This was then refined by conducting a more detailed study of the closer-spaced seismic in the nearshore and onshore areas.

Since the data sets used are different, the accuracy of the maps generated from these data are also different. Often different contour intervals were used in the isochore maps for the different areas. In addition, the onshore area experienced a different history of sedimentation compared to the nearshore and the offshore areas, and this needs further explanation. Therefore, similar to the tectonic history that is covered in Chapter 4, the discussion of the sedimentation history of the Sarawak Basin will be made in separate sections for the onshore, nearshore and the offshore areas.

3.1.1 The onshore area

This area, also known as Block SK12 in Sarawak, is a lowland area mostly covered by tropical swamp except in the south and southwest. In the subsurface, the area is characterised by several sub-basins that are named after the present river flowing in that particular sub-basin (Figure 3.1). From the work of several petroleum companies, four sub-basins have been identified, namely the Igan-Oya Half-Graben, Mukah Half-Graben, Lemai Sub-Basin and Balingian Sub-Basin (Figure 3.2).

The Igan-Oya and Mukah sub-basins are termed half-graben because they were interpreted to be formed by extensional tectonic movements, which is the characteristic features of the Tatau Horst and Graben Provinces (see James, 1984). Shell (1992) demonstrated that rift-related tectonism is most dominant in these provinces. Hydrocarbon exploration in the area commenced in the 1940s and resulted in minor discoveries. The area is a proven oil and gas province with wells producing small to moderate quantities of oil. Among the recent discoveries is gas in the Igan-Oya Half-Graben.

The Balingian Sub-Basin has also been studied in detail, especially for the offshore part of the basin as this is interpreted to be the kitchen area for the oil-producing fields in the nearshore area. In contrast, there is little published on the Lemai Sub-Basin. To date, the Lemai Sub-Basin is regarded as a small unprospective depression in the southernmost part of the study area.

3.1.2 The nearshore area

This area is also known as Block SK5 and is currently operated by Sarawak Shell. The study area covers both the exploration block and the production sub-blocks within and adjacent to the exploration blocks. The oil-producing fields in the area include Temana, D18, and Patricia (Almond, 1990). The main producing reservoir sequences are T1S and T2S. These two sequences are the thickest sedimentary units in the area, although T3S is also reasonably thick in certain places. The younger sequences were not mapped and will not be discussed herein as they are thin and only occur in the very shallow subsurface.

Geologically, the nearshore area can be subdivided into two areas based on the basement topography and presence of the reservoir sequences. The area to the west of the block is characterised by shallow basement and it is only covered by thin Middle Miocene and younger sediments. The eastern area has the thick hydrocarbon-bearing sequences of Oligocene to Pliocene age.

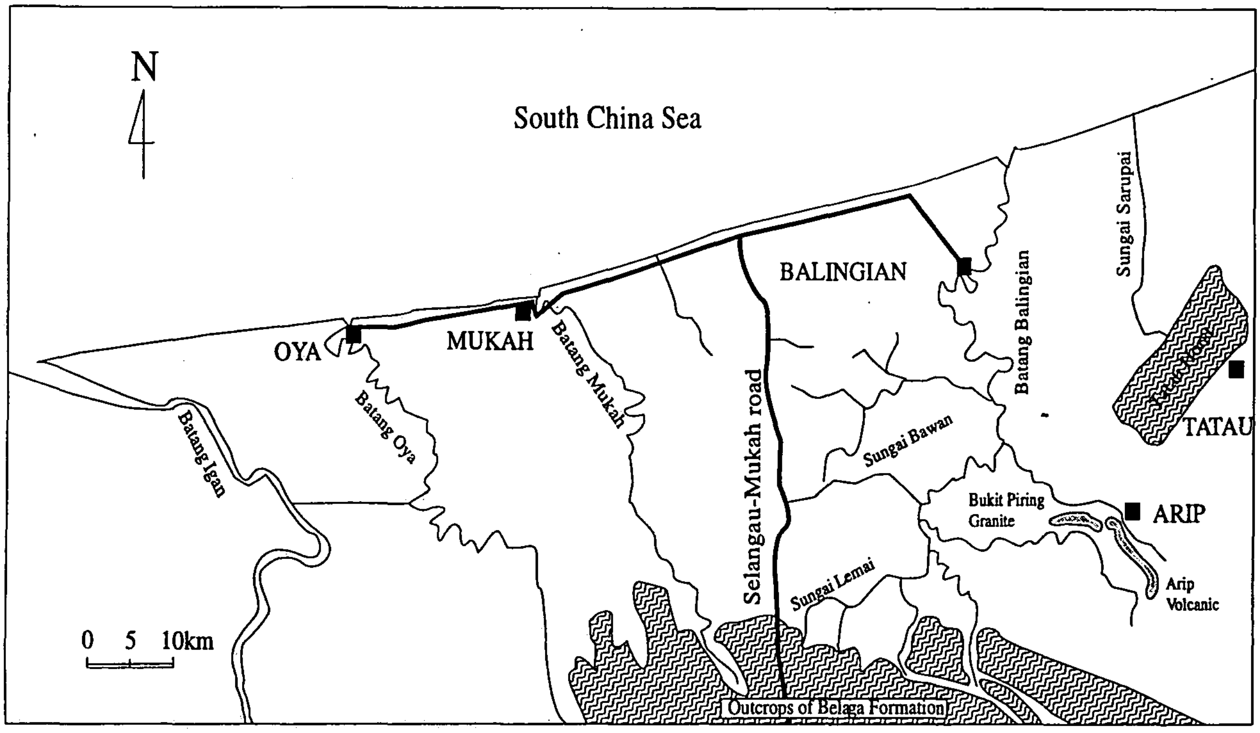


Figure 3.1. Location map of the onshore area. Note: Sungai and Batang are local words for river, with Batang normally for a bigger river than Sungai.

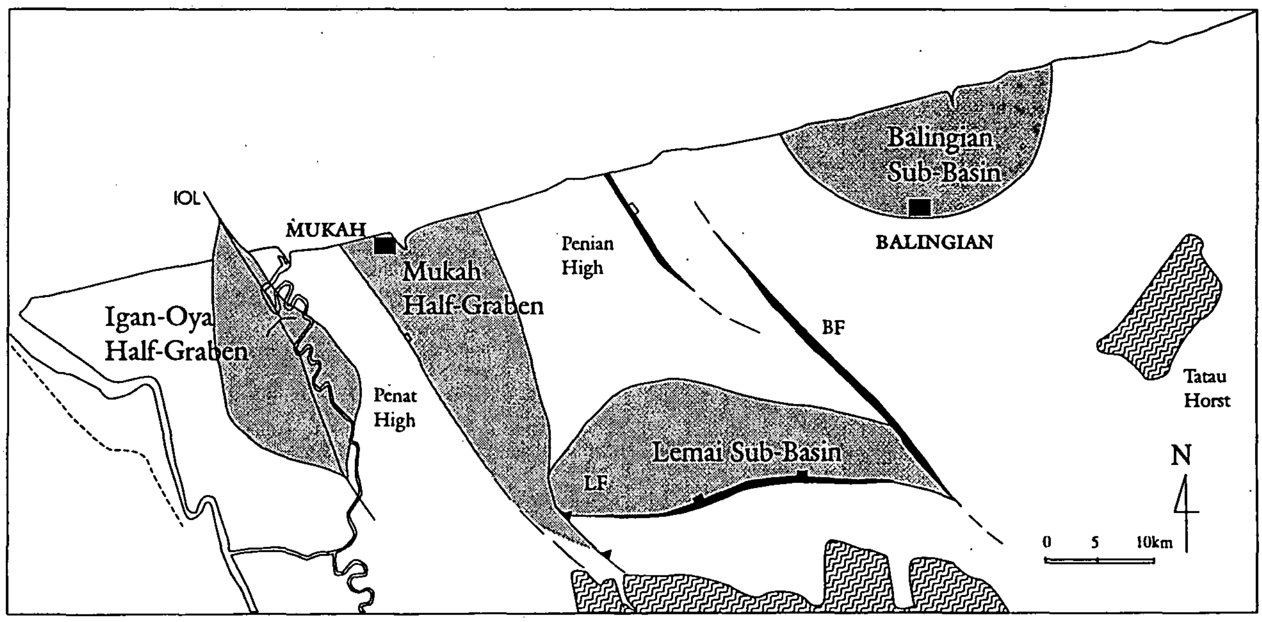


Figure 3.2. Map showing the location of four sub-basins and major faults in the area. BF-Bawan Fault, LF -Lemai Fault, IOL- Igan-Oya Fault.

The discussion of the sedimentation history in the nearshore area will relate the thickness of the preserved sediments to the present-day basement topography and the topography of each sequence. The discussion of the sedimentation history of the area will also emphasise the significance of certain faults in controlling the deposition of the Tertiary sediments in the area.

3.1.3 The offshore area.

The offshore area covers most of the exploration blocks in the Sarawak Basin including all the blocks in the shallow-water area, the Luconia Province (Block SK8 and SK6) and the southern part of the deep-water blocks. However, the study area does not cover the Baram Delta (offshore Miri) which is the major oil-producing area in Sarawak, and the area towards the Indonesian waters (Figure 2.13) around Natuna Island.

In the shallow-water area, the exploration is mainly targeting the coastal plain and shallow-water deposits of T1S, T2S and T3S. The Luconia Province is one of the most important areas for the gas exploration and production. The history of exploration in Luconia started in early 1960's (Ramli, 1982). Major gas fields have been discovered, mostly in the early 1970's. However, exploration for hydrocarbons in the area continues with a high rate of success.

Out of 76 gas discoveries in Sarawak, more than half of the fields are from the Luconia Province (PETRONAS, 1994). The prospective sequence for the gas is the reefal Miocene carbonate which grew mainly during T4S times. In some places, the growth started as early as T3S times (Figure 2.13). Some 200 carbonate structures have been mapped (Epting, 1980 and Ng, 1994).

Some sub-commercial discoveries have been made from the sedimentary sequences beneath the carbonate but no production from these zones has been made to date. The nature of the sedimentary sequences beneath the carbonates, the structure and trap style are not well understood. This is mainly because most of the wells drilled in the area were total-depthed within the carbonates.

The Sarawak deep-water area is the frontier area for exploration. The area was concessioned to Mobil. There are many uncertainties in dealing with the geology of the deep-water area. To date, there have only been four wells drilled in the Sarawak deep-water area, with two recent wells targeting the clastic sequences and two older wells targeting the carbonates. No discoveries have been made to date.

3.2. Data and techniques

3.2.1. Data

This study of the sedimentation history of the basin uses all the seismic lines and composite well logs as listed in Sections 2.2.1.1 and 2.2.1.2.

3.2.2. Study techniques

A) In generating the isochore and lateral extent maps, the following steps were conducted. The seismic interpretation for the whole study area was first carried out using the regional and prospect seismic lines. Upon completion of the seismic interpretation, the thicknesses (in two-way times) between the sequence boundaries were measured and these transferred to the base map. The next step was to contour the values on the base map, to give an isochore map. This process was repeated for all the sequences.

B) The information on the depositional environments was obtained from the composite well logs following the interpretation of the depositional environments made earlier by the petroleum companies who drilled the wells (primarily Shell) based on the biostratigraphic data of Ho (1978). All the stratigraphic boundaries on the well logs were first adjusted to the new stratigraphic subdivision as discussed in Chapter 2. The depositional environment maps were then generated for each sedimentary sequence. Interpretations of the depositional environments for areas without well data were based on published information.

C) To understand the sedimentary facies associated with certain depositional environments, representative log intervals with interpreted depositional environments were selected and studied. This included studying the log responses for the particular environment and comparing with the log responses for sedimentary facies from published informations including Serra (1985), Rider (1986), Wagoner, (1990) and others. This needed to be done because the available composite logs normally only use two types of wireline log, namely sonic and gamma ray. Further, all the logs have been digitised and squeezed from the original scale. Therefore, by having only the squeezed logs without other logs that are normally used for lithological interpretation such as neutron and density logs, the interpretation of the depositional facies solely from the available wireline data could not be done.

3.3 Sedimentation history of the onshore area.

The Tertiary One and Two Sequences are the two thickest units preserved in the area, while all the younger sequences are thin (normally less than 1 Second TWT in thickness). From the well data, the sediments of T1S and T2S in the area are known to have been deposited mostly in lower coastal plain environments, as were the younger sequences. No evidence of a true marine influence is seen throughout the whole succession in the area.

3.3.1. Tertiary One Sequence (T1S)

The thickest part of the T1S is situated in the northeast part of the Lemai Sub-Basin and southwest part of the Balingian Sub-Basin. The maximum preserved thickness of the T1S is about 2.0 Sec TWT (Figure 3.3). The sequence is bounded by the Lemai Fault to the south, Tatau Horst to the south-east and by the western fault of the Mukah Half-Graben to the west. Figure 3.4 shows the cross section of the Lemai Sub-Basin.

3.3.2. Tertiary Two Sequence (T2S)

The isochore map of T2S shows that the centre of deposition for the T2S was situated in the area of the present Balingian Sub-Basin. The sequence thins towards the Lemai Fault to the south, towards the Tatau Horst to the southwest and Mukah Fault to the west. The sequence is not preserved over the Penian High suggesting that this area was already a positive structure during the Early Miocene. This leads to the interpretation that the T2S was not deposited in the Mukah Half-Graben. This observation also suggests that the Mukah and Tatau Horst blocks were uplifted while the Lemai Fault was inactive during the Early Miocene after the Lemai Sub-Basin was filled by the T1S sediments.

3.3.3. Tertiary Three Sequence (T3S)

In the whole onshore area, the T3S is only preserved in Mukah Half-Graben and Igan -Oya Half-Graben (Figure 3.5). This suggests that the whole onshore area was uplifted during this time and the formation of the Mukah and Igan-Oya Half-Grabens took place during late Early Middle Miocene. At that time, the two sub-basins formed two separate depressions.

As for the Igan-Oya Half-Graben, the oldest known sedimentary unit preserved in it is the T3S, as confirmed by drilling. Therefore, it is interpreted that the Igan-Oya Half-Graben was formed and terminated at the same time as the Mukah Half-Graben. However, the Igan-Oya Half-Graben may have been in existence during T1S times and reactivated during T3S times.

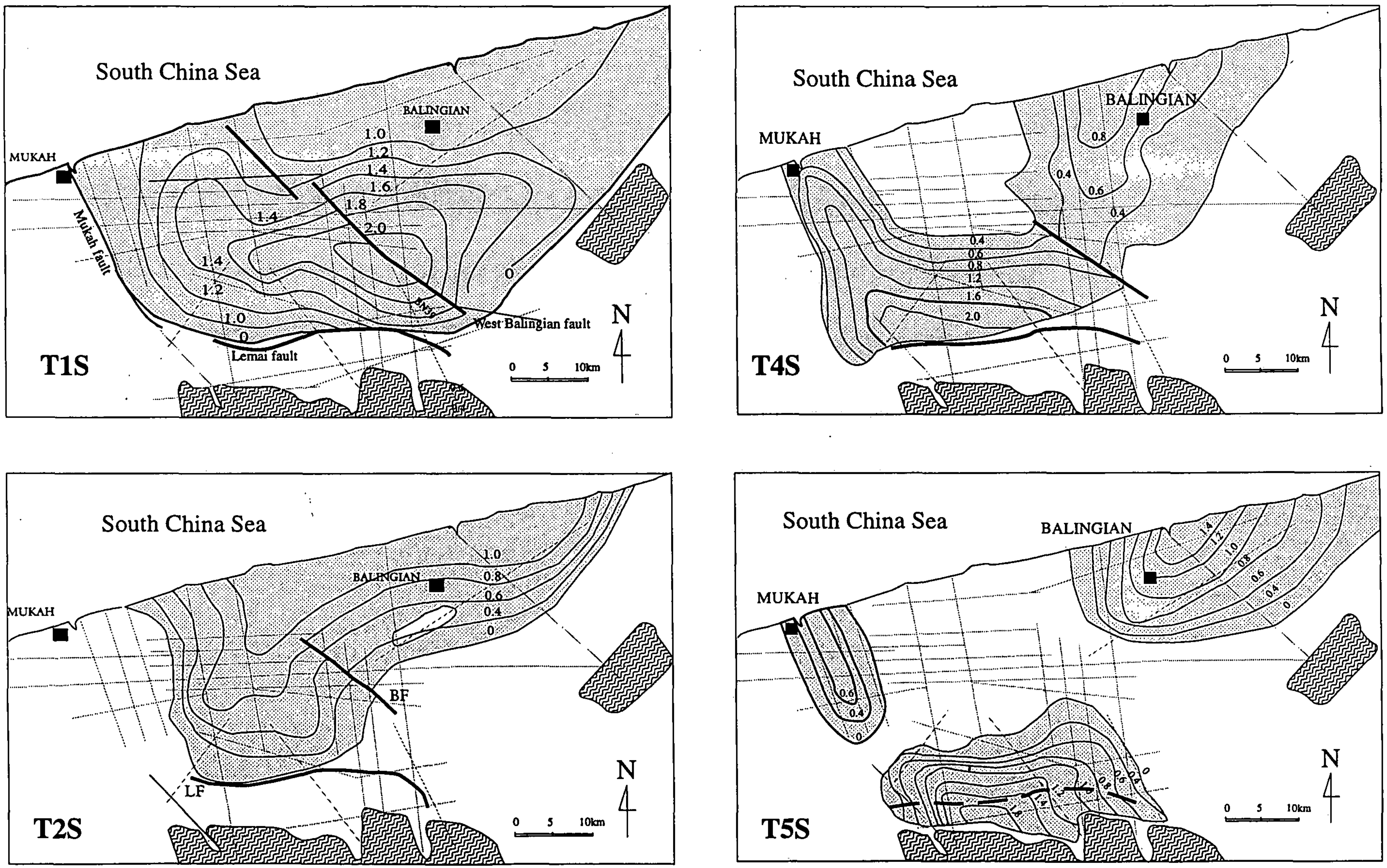


Figure 3.3. Isochore maps of T1S, T2S,T4S and T5S showing that the depocenter of the sedimentary sequences shifted from one area to another, throughout the history of deposition in the onshore area.

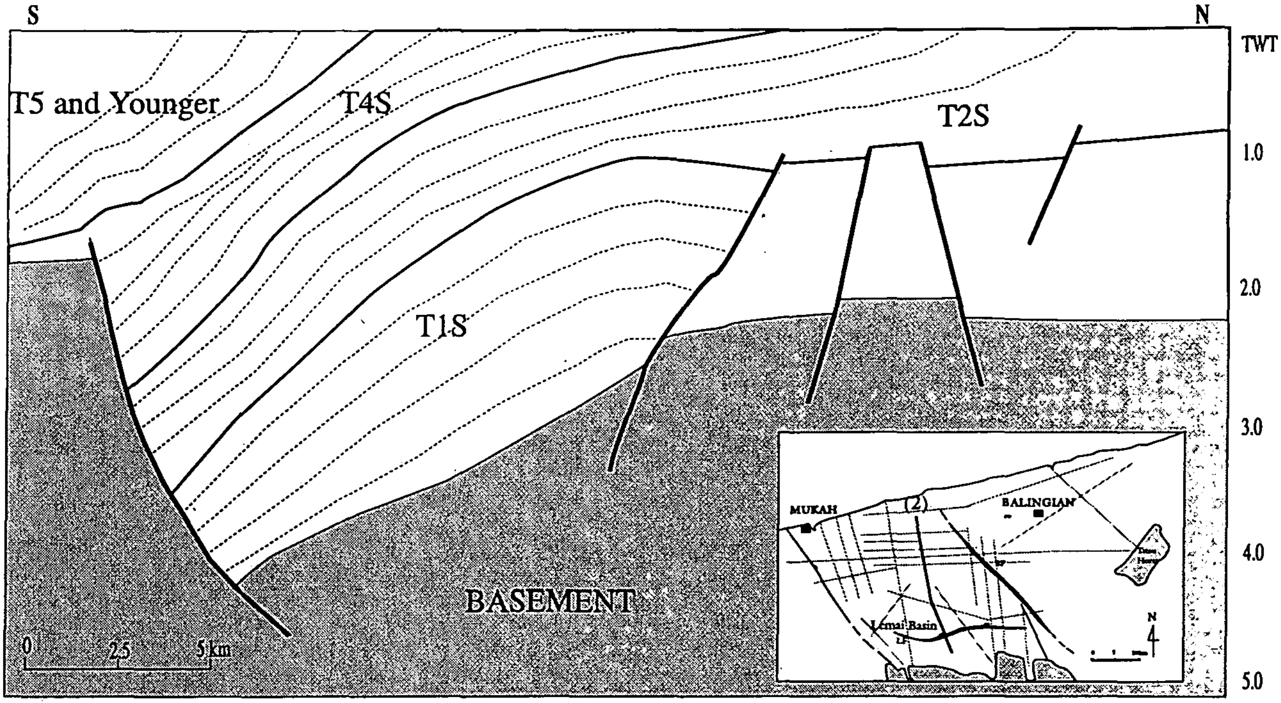


Figure 3.4. North-South geological cross section along seismic line (2), showing the nature of sedimentation in Lemai Sub-Basin. The inset figure shows the orientation of the line.

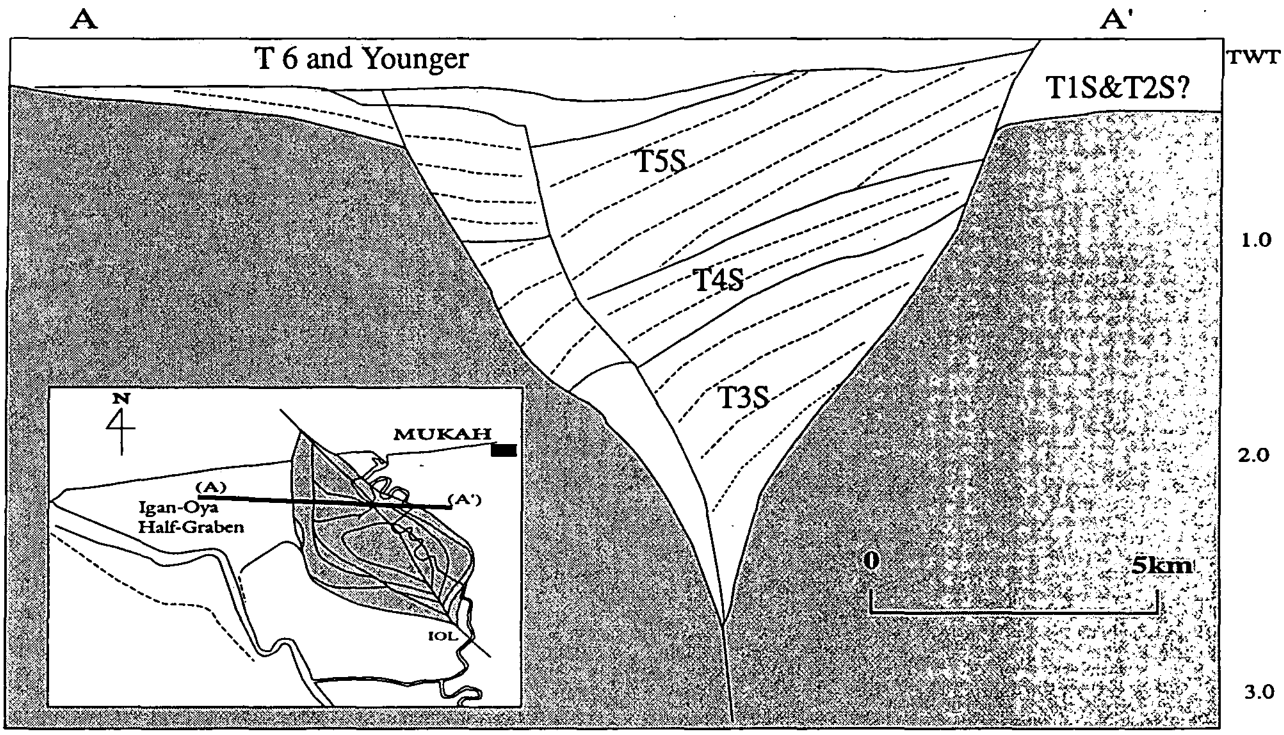


Figure 3.5. East-West geological cross section along seismic line A-A', showing the nature of sedimentation in Igan-Oya Half Graben. The inset figure shows the orientation of the line.

Based on very sparse seismic data, an older unit of sediments, probably of T1S age is present to the west of the Igan-Oya Half-Graben.

3.3.4. Tertiary Four Sequence (T4S)

The isochore map of the T4S shows a major shift in the depocentre from T2S. The Tertiary Four Sequence thickens to the western part of Lemai Sub-Basin and there was no deposition or preservation of the sequence in the Penian High area (Figure 3.3). This can be seen on seismic whereby the T4S was deposited in two different directions, to the southwest and northeast of the Penian High. This suggests that the Balingian Sub-Basin started to be isolated from the other sub-basins during this time.

3.3.5. Tertiary Five Sequence (T5S)

During T5S times (Pliocene), the three sub-basins in the onshore area are totally separated. Movement on the Lemai fault ceased and the T5S sediments were deposited in the area of the Lemai Sub-Basin as well as farther to the south of it. The Mukah Half-Graben was completely infilled during this time. Similar to the Lemai Sub-Basin, the Balingian Sub-Basin preserved about 1.4 to 1.8 Sec TWT thickness of the T5S (Figure 3.3)

3.4 Sedimentation history in the nearshore area.

3.4.1. Tertiary One Sequence (T1S)

The deposition of the T1S is believed to be controlled by two major lineaments. The first lineament to the west is here named the Mukah Line as its passes through Mukah village on the coast of Sarawak (Figure 3.6). The line to the east will be referred to as the West Balingian Line (WBL) as named by several Shell workers including Levesque and Ooi (1989). The same lineament is also called the West Luconia Line in the area farther to the north

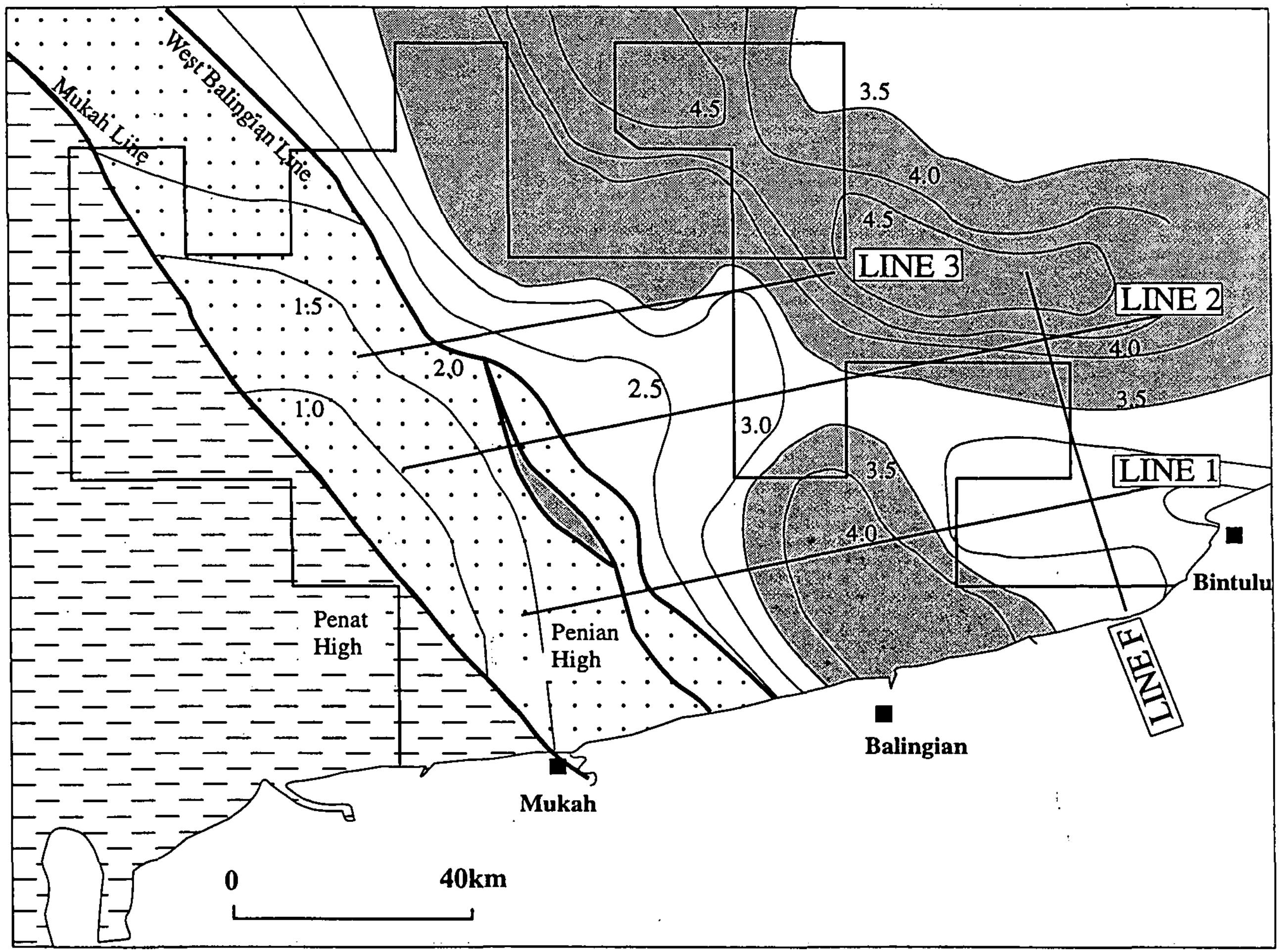


Figure 3.6. Basement topography map of the nearshore area. Contours in Two-way time. The map shows the orientation and the extent of the major lineaments, namely the West Balingian Line and Mukah Line. The lineaments separated the basement high that is the Penat and Penian Highs from the basin. The grey areas are depressions, the dotted area is shallow basement with preservation of thin T1S and the dashed area is the area without preservation of the T1S. The figure also shows the orientation of the seismic lines in Figures 3.7, 3.8 and 3.9.

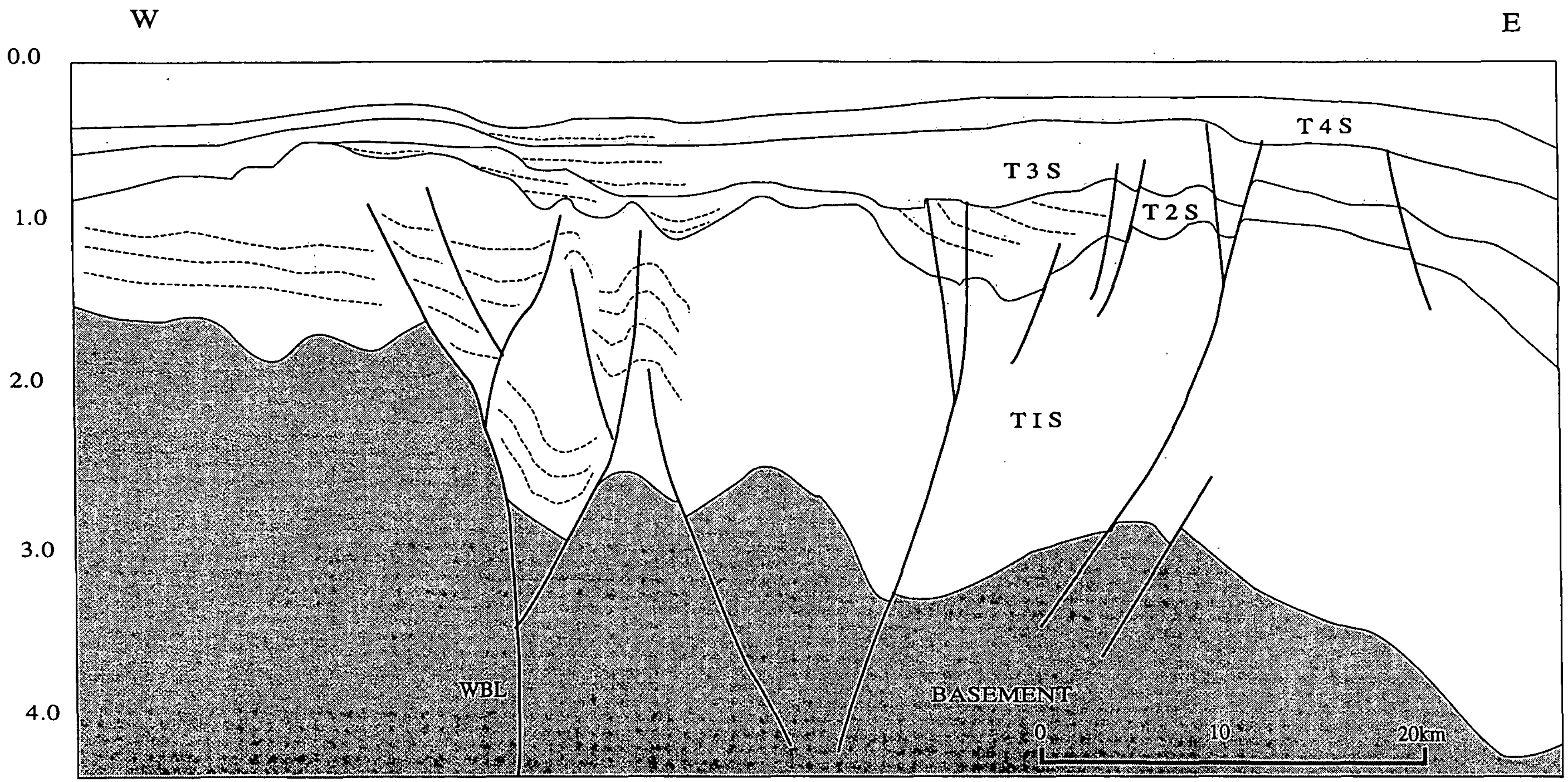


Figure 3.7. Geoseismic section along Line 3. Note the displacement and the thickness of T1S sediment on both sides of the fault that represents the West Balingian Line (WBL). The orientation of the seismic line can be seen in Figure 3.6.

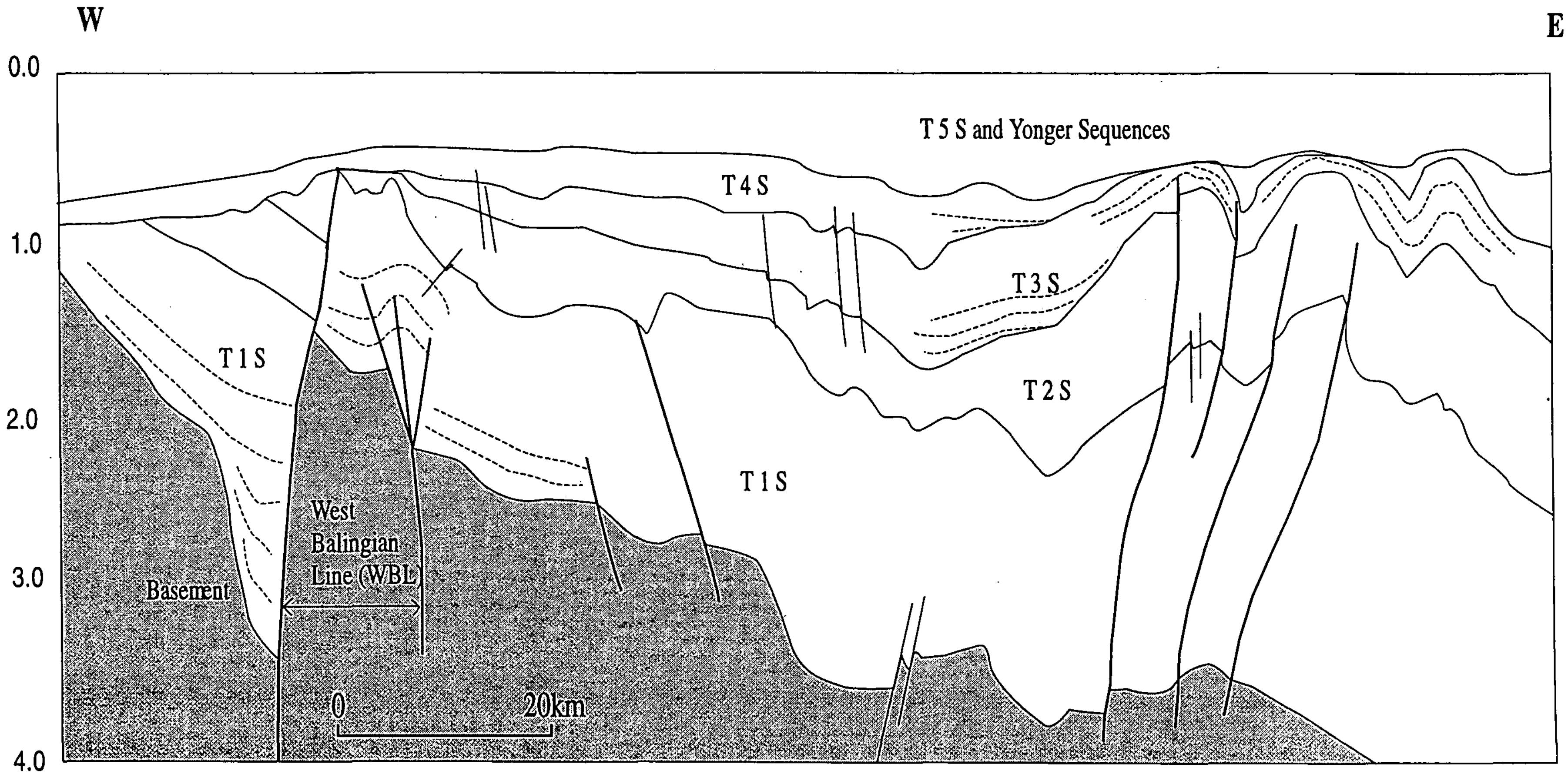


Figure 3.8. Geoseismic section along Line Two. Note the thickness of the T1S in a depression to the west of western fault of the West Balingian Line (WBL). The thickness of the T1S also increases to the east of eastern fault of the West Balingian Line (WBL). The orientation of the line can be seen in Figure 3.6

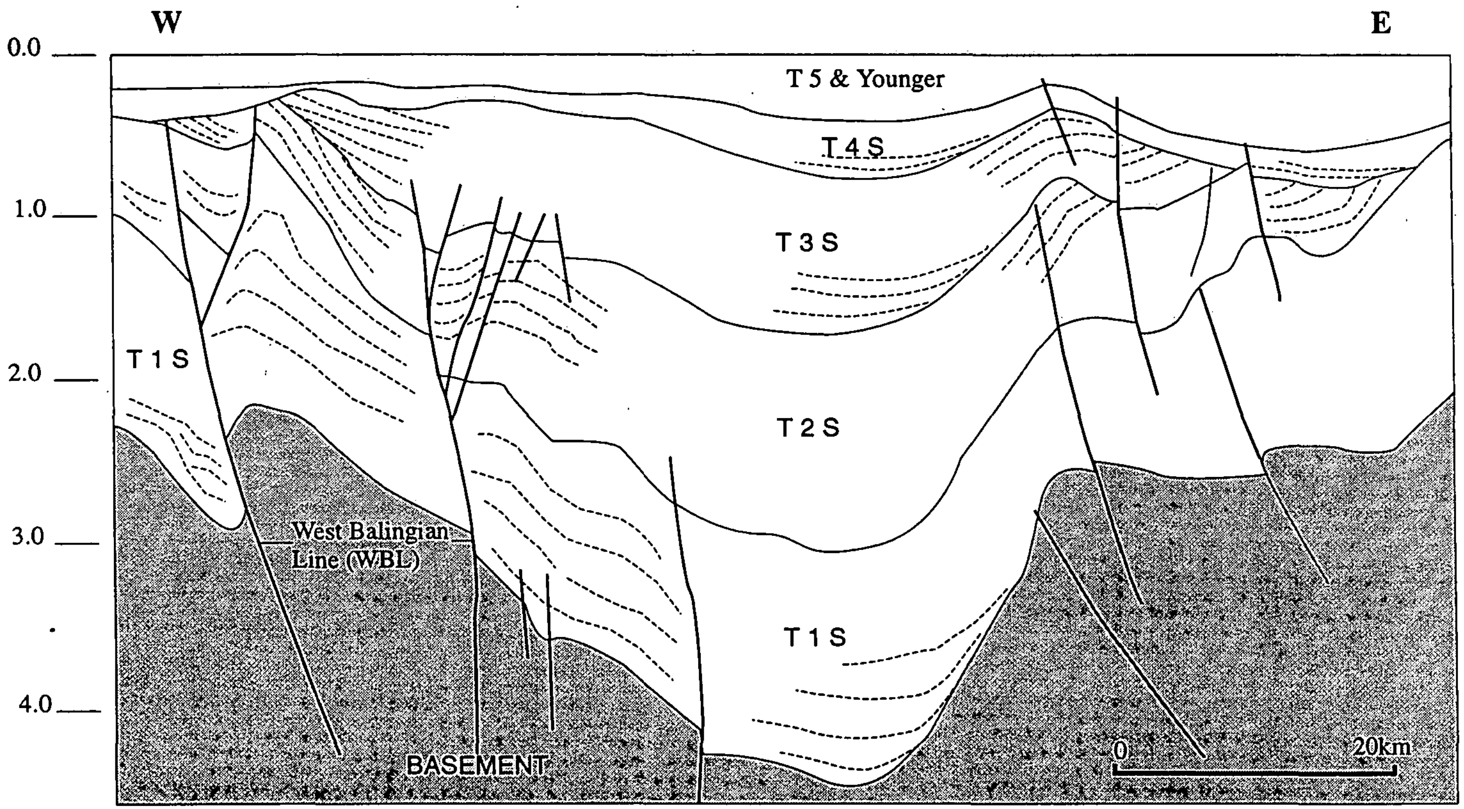


Figure 3.9. Geoseismic section along Line One. Note that the eastern fault of the West Balingian Line (WBL) does not control the deposition of the T1S since the thickness of the sequence on both sides of the fault is almost the same. However, the thickness of the T2S is different across the fault. The fault terminates within the T3S and it is believed the fault movement ceased during T3S times. The orientation of the line can be seen in Figure 3.6.

(Hazebroek, 1993). The Mukah Line marked the western limit of sequence T1S (Figure 3.6). To the east of this line, the basement is tilted to the east and increased further in the area to the east of West Balingian Line and the thickness of the T1S increases tremendously towards the east of the latter lineament (Figure 3.7). In places, where the narrow depression to the west of the western fault of the WBL is developed, the T1S reached a thickness of about 2.0 Sec TWT (Figures 3.8 and 3.9).

To the north, the thickness of the T1S to the east of WBL increased tremendously, from about 1.0 Sec to 2.0 Sec TWT (Figure 3.7). In contrast, there is no difference in the thickness of T1S in the south (Figure 3.9). This suggests that the WBL was already in existence in the north during the T1S times, but that the line started to extend to the south after the T1S times.

The present-day topography on the top of T1S shows that the deep area is located to the northeast and to the southeast. However, the depocentre for the T1S sediments is only seen in the northeast of the area where it also covers the mid-ridge area (Figures 3.10 and 3.11). The thickness of this sequence exceeds 2.5 Sec TWT, in some areas. Other than the basin area to the east, the T1S is also preserved in the Penian High area. The thickness of the sequence is less than 1.0 Sec TWT. There is no preservation of this sequence farther west than the inferred location of the Mukah Line.

3.4.2. Tertiary Two Sequence (T2S)

The deposition of the T2S is also believed to be controlled by the West Balingian Line which marked the western limit of the T2S (Figure 3.10). However, the T2S is also preserved in the small depressions to the west of the WBL (Figure 3.8). In the south, the T2S increased tremendously to the east of the eastern faults of the West Balingian Line (Figure 3.9) with the thickness reaching 1.0 Sec TWT across the fault.

Based on this observation, it is inferred that uplift took place in the mid-ridge area during and after the deposition of T2S (Figure 3.8). In contrast there was continuous deposition of the sequence to the south. This is evidently seen where the thickness of the sequence has increased to the east of the WBL. Furthermore, the sequence is almost conformable with the overlying sequence (Figure 3.9). Other than this area, the upper part of the T2S has been truncated in the eastern area. This suggests that the eastern part of the basin probably experienced uplift during T2S times.

The present-day topography on the top T2S shows that this sequence closely follows the topography of the basement and the T1S. The deep area was situated to the mid-north, northeast and to the southeast (Figure 3.11). However, the depocentre for the T2S sediments is seen in the southeast of the area and in a small area to the northeast (Figure 3.10). The preserved thickness of the sequence in the southeast depocentre is about 1.4 Sec TWT. There is no preservation of this sequence farther west of the West Balingian Line.

3.4.3. Tertiary Three Sequence (T3S)

The deposition of the T3S is believed to be controlled by major tectonic movements which post-dated the T2S deposition. The topography and the distribution of the T3S sediments suggest that there was an opening to the northwest, subsidence in the northern part of the basement high, uplift in the southeastern and southern area including the onshore region. This movement resulted in uplift and erosion of the older sequences, T2S and T1S, in the southern and eastern part of the nearshore area.

The present-day topography on the top of T3S shows that the morphology of this sequence is almost totally independent of the present-day basement morphology. The deep part of this sequence is situated to the north and northwest and in a small area to the southeast of the study area (Figure 3.11). Similarly, the depocentre for the T3S sediments is in the north and in a small area to the southeast (Figure 3.10). This situation is very different from the older sequences. The depocentre and the deep area for this sequence is situated in the area that used to be the basement high during the T1S and T2S times.

3.4.4. Tertiary Four (T4S) and younger sequences

The T4S and younger sequences are not important for hydrocarbon prospectivity. This is because these sequences normally occurred near the sea-floor and the sequences are generally very thin (Figures 3.7, 3.8 and 3.9). Furthermore, the distribution of these sequences is not extensive since most of the time these sequences were deposited in the small depressions between the older structures.

Based on the seismic data, these young sequences are found to be thicker in the north and northeast of the study area similar to the T3S. Other than this area, these young sequences started to develop eastward of the study area, accumulating a huge thickness of sediment in the area of the Baram delta, which is outside the study area.

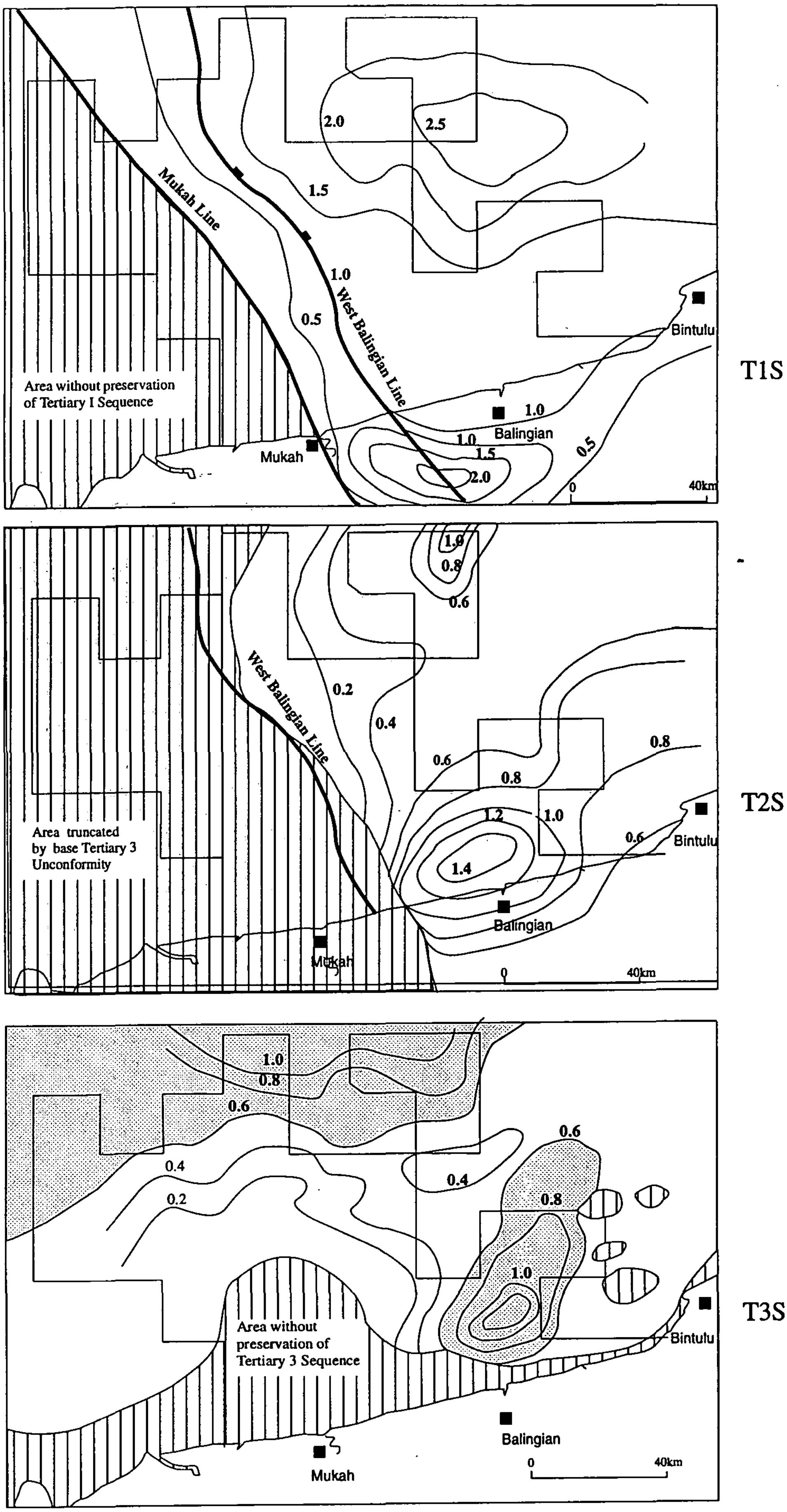


Figure 3.10. Isochore and lateral extent maps of T1S, T2S and T3S. The maps show how the depocenter of the sediments for each sequence changed. The area to the northwest remained as the basement high area until T2S times (Early Miocene). The northern part of the present-day basement high subsided and formed a depocenter further north during T3S times (Middle Miocene).

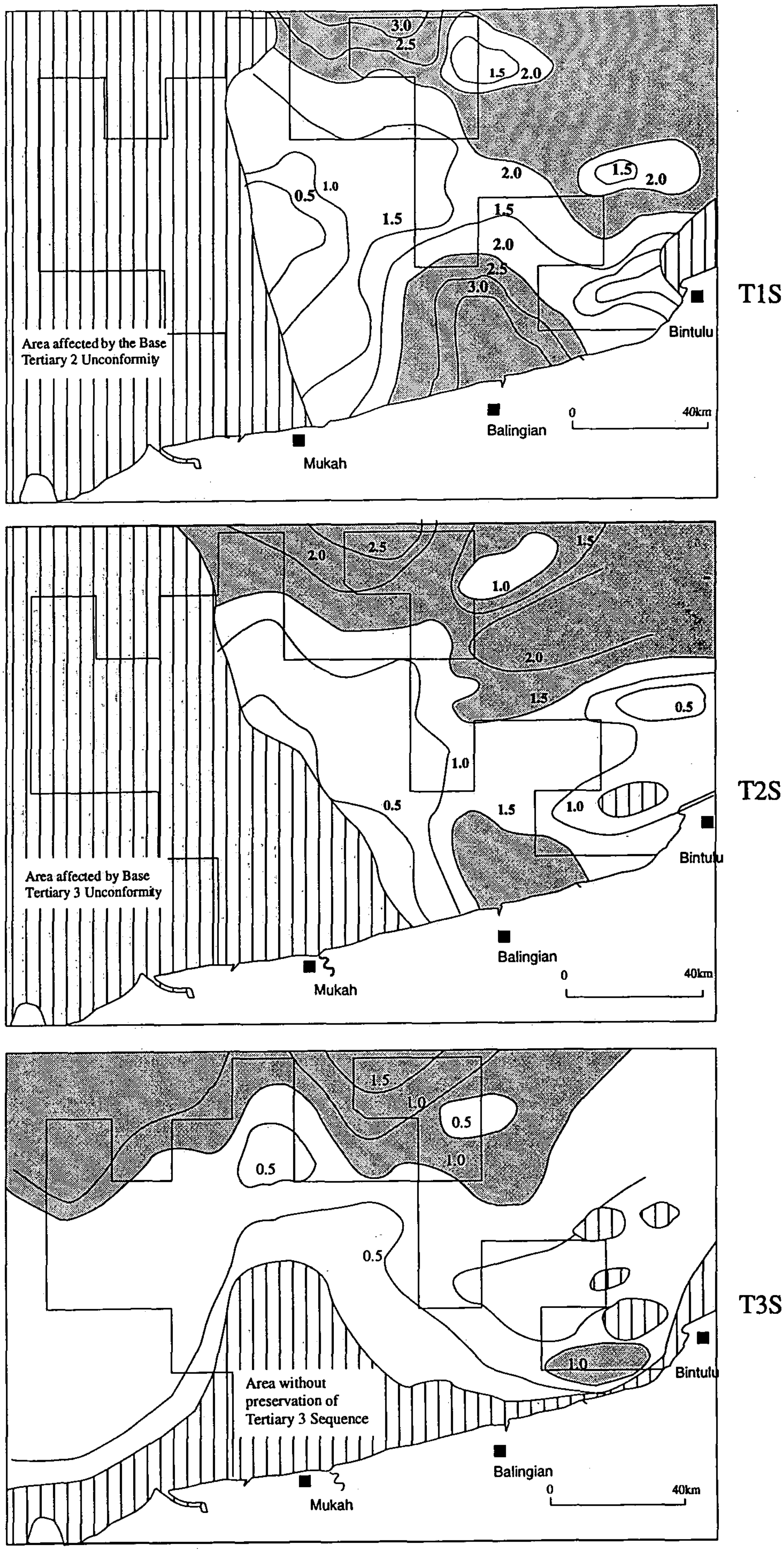


Figure 3.11 Topography map of top T1S, T2S and T3S. Note that the general topography of top T2S and T3S follows the basement topography. In contrast, the topography of top T3S is very different from the older sequences and basement topography.

3.5 Sedimentation history of the offshore area

Similar to the onshore and the nearshore areas, the offshore Sarawak Basin is also characterised by the shift in depocentre for every sequence. There is no direct relationship between the present-day basement topography and the distribution of the T1S and T2S. However, the distribution of the T3S closely follows the present basement topography. This leads to the interpretation that the present-day situation of the basement was reached only after the T2S times (Middle Miocene).

3.5.1. Tertiary One Sequence (T1S)

As it is understood from the observations in the nearshore area, the sedimentation of the T1S and T2S was controlled by the two major lineaments, namely the Mukah Line and the West Balingian Line. The same lineaments seem to control the deposition of the two sequences in the area farther north of the present-day basement high (Figure 3.12). In this area, although it is now characterised by a deep basement, the seismic information shows that the deposition of the T1S and T2S did not take place here (Figure 3.14). This suggests that this area subsided later, presumably during the T3S (Middle Miocene) time and then further subsided during the T5S time (Pliocene).

The isochore and lateral extent map of the T1S shows that deposition took place only in the eastern part of the Sarawak Basin. The areas to the west including the main part of SK3, the western part of the deep-water area and the western part of SK5, remained as a 'high' without preservation of the T1S (Figure 3.13). The thickest part of the sequence occurs in two places: to the east of SK8 and in the middle part of SK10. Another depocentre is in SK7 and SK5.

3.5.2. Tertiary Two Sequence (T2S)

Similar to the T1S, the T2S is only preserved in the eastern part of the Sarawak Basin. The depocentre for the sequence is oriented north-south covering the eastern part of SK8, through the middle part of SK7 and eastern part of SK5 (Figure 3.14). Another depocentre also formed in the area of SK9.

The two separate depressions of T1S times formed a single depression during T2S times. The thickness of the T2S in this depression exceeds 1.0 Sec TWT. The western boundary of the T2S in the Mukah area moved farther eastward to the area between Mukah and Balingian. The area to the west including the western part of SK3, SK5 and the western part of the deep-water area, remained a high during the T2S times.

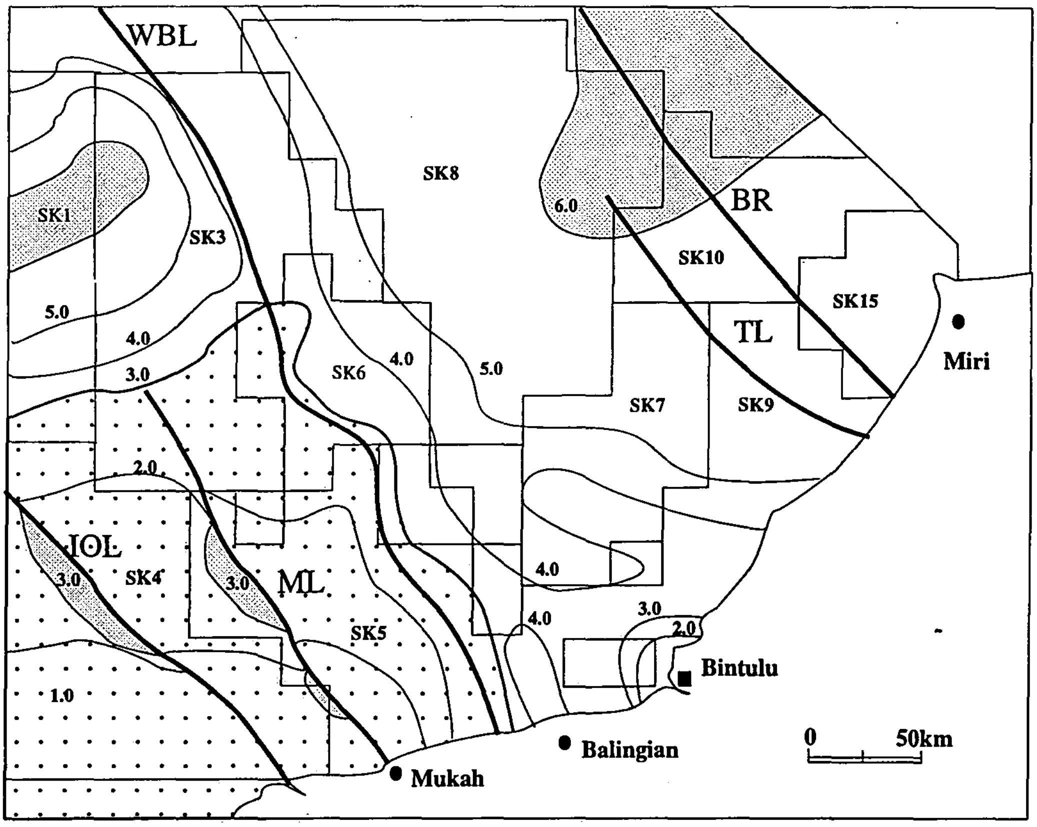


Figure 3.12 Basement topography map of the offshore Sarawak Basin. Contours in Two Way Time. The dotted areas are the shallow basement and the grey are the depressions. The thick lines are the major lineaments: IOL-Igan-Oya Line, ML-Mukah Line, WBL-West Baligian Line, TL-Tinjar Line and BR-West Baram Line.

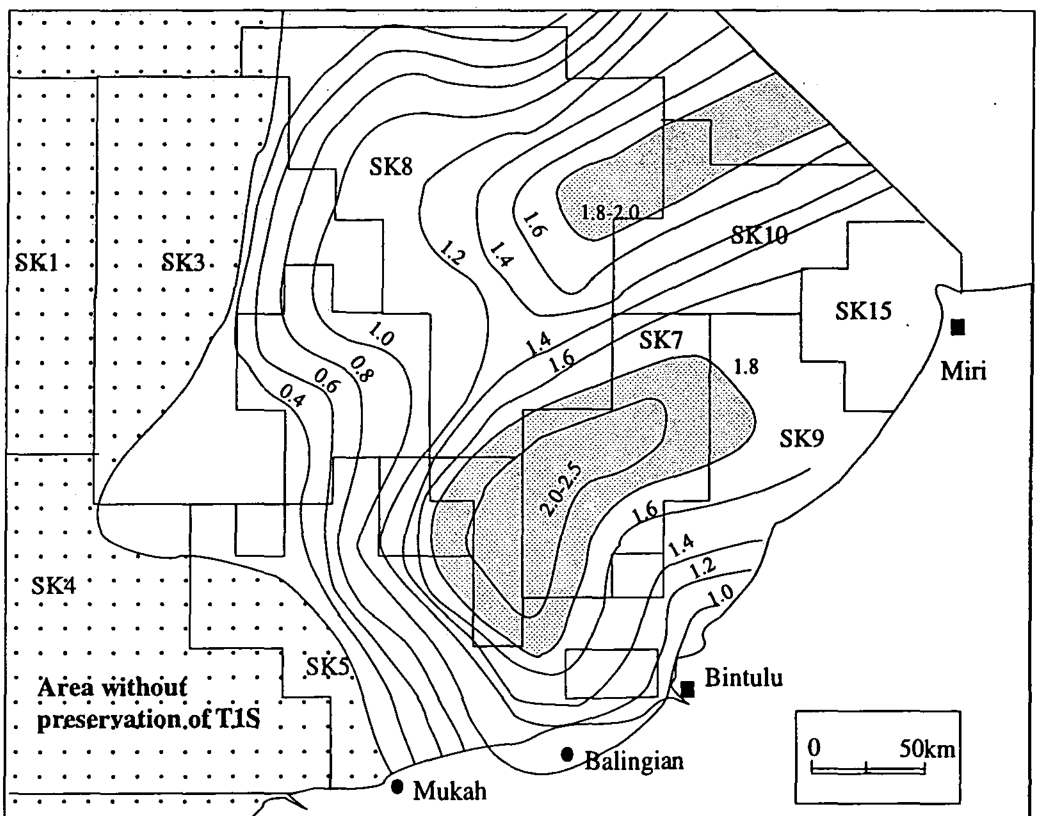


Figure 3.13 The lateral extent and isochore map of Tertiary One Sequence (T1S). The isochore values are in TWT. The dotted area is the area without preservation of the sequence and the grey areas are the thickest parts of the sequence.

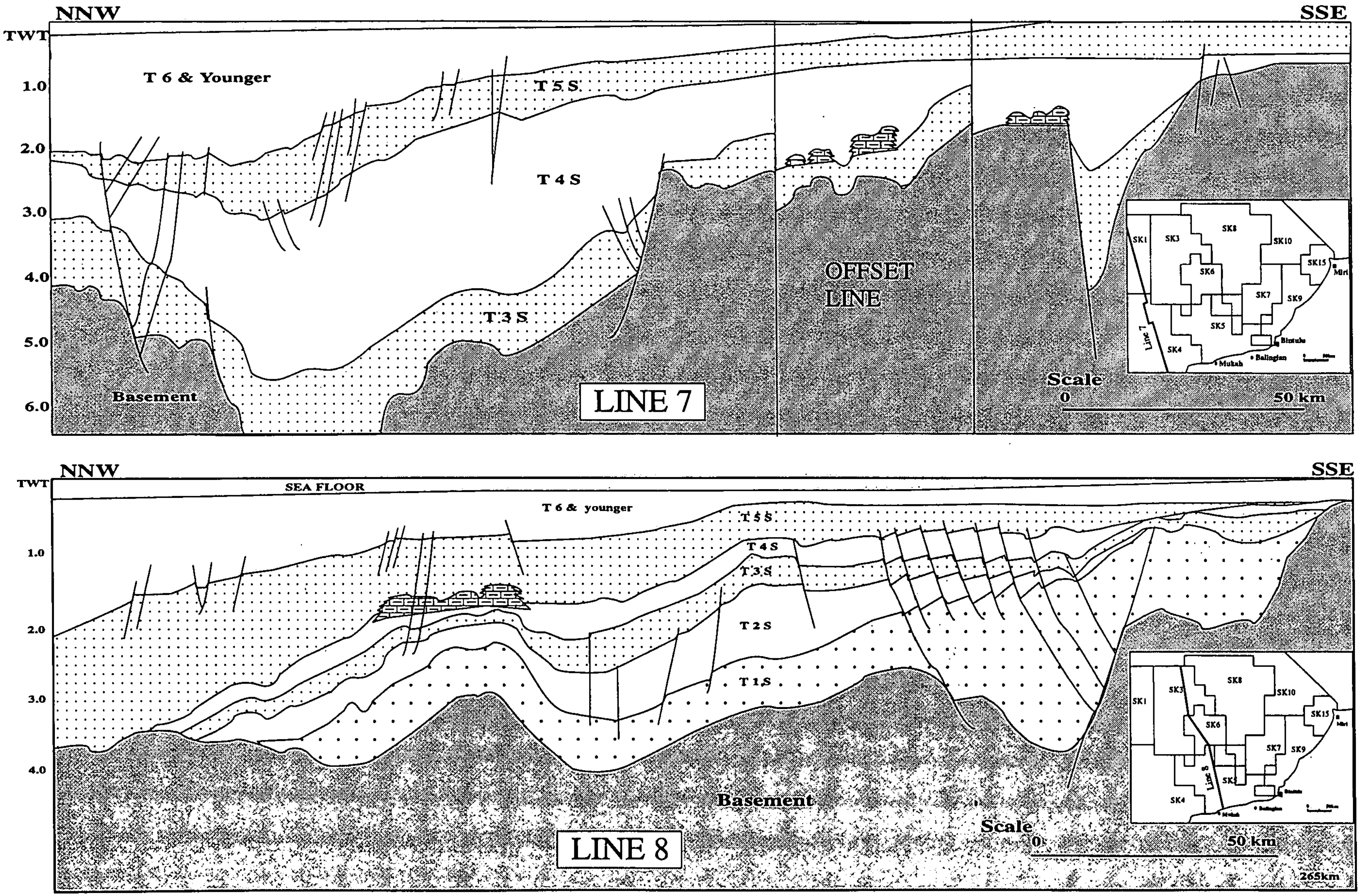


Figure 3.14 Geoseismic profile along Regional Lines 7 & 8. Line 7 shows the basement high to the South and the young depression area to the North. The depression was formed during T3S times. Line 8 shows that the northwestern part of the deep water area remained as a high until T5S time (Pliocene). The inset figures show the orientation of the lines.

3.5.3. Tertiary Three Sequence (T3S)

The area covered by the T3S is totally different from the area of the T2S and T3S. It is believed that the depositional history of T3S is also different from the depositional history of previous sequences. The depocentre for the T3S coincides with a depression in the present-day basement. This suggests that the formation of the depression to the west of SK3 took place during this time (Middle Miocene). The area to the west of SK3 and the middle part of SK4 formed a new depocentre with the preserved thickness exceeding 1.0 Sec TWT (Figure 3.16). The other area with thick preservation of T3S is the SK9 and SK15 areas. The sediment thickness, however, is less than the other two areas.

The T3S covered most of the area that formed as a high during the T1S and T2S times except the small area to the south and the onshore area. Other than this area, the area to the north of SK3 remained as a high during this time. This is evidently seen on seismic where sediment of this sequence onlaps onto the high in the deep-water area to the north of SK3 (Figure 3.14). This suggests that the northern part of the present-day basement high subsided leaving the southern part of the basement block and the onshore area as a high during this time. However, the T3S is preserved in the deep narrow depressions along the Mukah Line in the present-day basement high area and in the onshore area (Figure 3.17).

In correlating to the global sea-level changes, the T3S time (Early-Middle Miocene) represents a period of major sea-level rise (Figure 2.14). The observations on the distribution of the T3S sequence suggest otherwise, whereby the whole onshore area was emergent during this time. This leads to the interpretation that the distribution of the T3S is more likely to be controlled by tectonics rather than eustasy. From seismic evidence in Figure 3.17, one could suggest that the movement along the West Balingian and Mukah Lines ceased during the early period of the T3S times and this further indicates that this region acted as one tectonic unit from this time onward.

3.5.4. Tertiary Four Sequence (T4S)

During the T4S times (Late Miocene), the deposition of the T4S continued in the area to the west of SK3. Another depocentre was developed during this time in the area of SK10, SK15 and to the north of SK7 and SK9 (Figure 3.17). This suggests that another phase of subsidence had taken place. This could be the result of movement along the Tinjar Line and West Baram Line (Figure 3.12). A huge thickness of the T4S sediments is preserved in the area and was deposited by the northwest progradation of the Baram Delta during the Late Miocene.

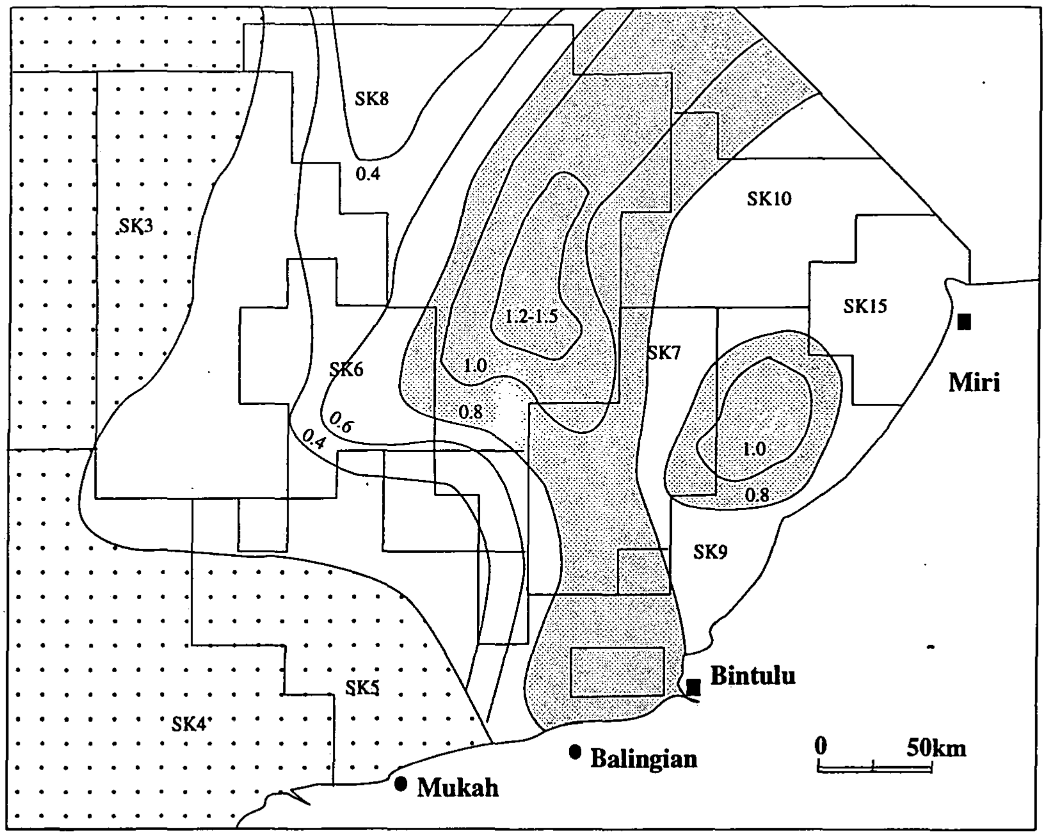


Figure 3.15. The lateral extent and isochore map of Tertiary Two Sequence (T2S). The isochore values are in TWT. The dotted area is the area without preservation of the sequence and the grey areas are where the sequence is the thickest.

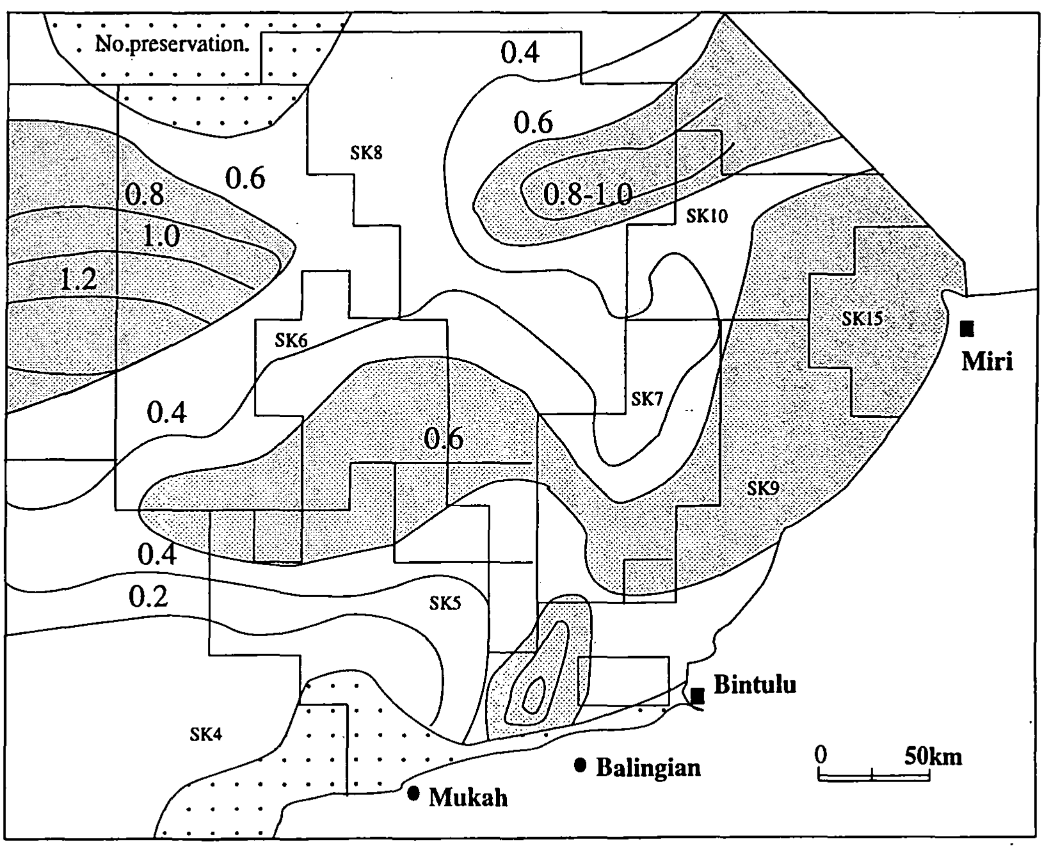


Figure 3.16. The lateral extent and isochore map of Tertiary Three Sequence (T3S).The dotted areas are the areas without preservation of the sequence and the grey areas are the thickest preservation of the sequence.

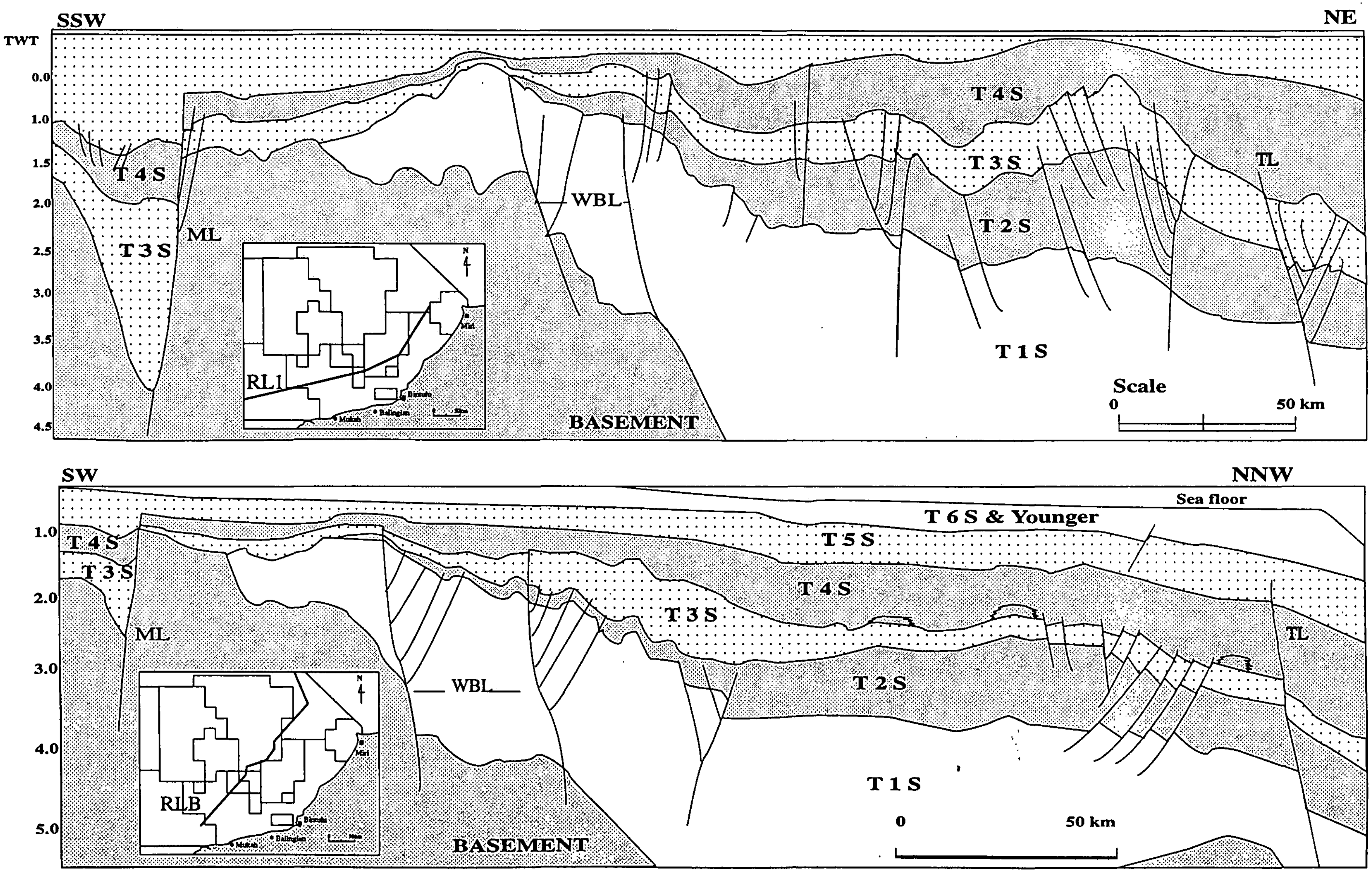


Figure 3.17. Geoseimic sections along Regional Line One (RL1) and Regional Line B (RLB) showing the sedimentation nature in the shallow basement area and within the half-graben structures. Among the major tectonic lineaments to be seen in the two lines are: ML-Mukah Line, WBL-West Balingian Line and TL- Tinjar Line.

The area to the west of SK3 formed another depocentre for the T4S. The area was not well studied before and similarly it could not be done in this study because of insufficient seismic data for the area. However, based on several unpublished in-house reports it is believed that the area to the west of SK3 is preserving the sediments transported by the palaeo Rajang River. This is based on the location of the depression that is situated in front of the present Rajang River. The Rajang River is the longest river in Sarawak and it flows over 400 kilometres across the Belaga Formation in the hinterland of Sarawak (Figure 6.3). Areas without preservation of the T4S are located in several places in the deep-water area, to the north of SK3 and SK8. However, the areas that formed basement highs in SK4 and SK5 during T3S times were no longer highs during this time.

The distribution of the T4S in the Sarawak Basin (Figure 3.18) provides some information about the tectonic movements and basin modification during this time. The evidence seen on seismic suggests that the Mukah Line and West Balingian Line were no longer active during this time. The compartment comprising the area to the east and the west of the West Balingian Line and Mukah Line moved as one unit and subsided, including the onshore area. It is also believed that the Tinjar Line and West Baram Line (Figure 3.17) started to be active during this time, resulting in a huge thickness of the T4S to the north of Miri (Figure 3.18).

The deep-water area, the area without preservation of T4S extended farther to the northeast suggesting that the area remained as high during T4S times (Figure 3.18). This phenomenon could be related tectonic uplift and/or sea-level fall as the T4S represents a major period of global sea-level fall (Figure 2.14). However, if this phenomenon is related to the sea-level fall, the deep-water area should be less affected as compared to the shallow-water area. Therefore, the most likely explanation for the observed situation is the effect of tectonism.

3.5.5. Tertiary Five Sequence (T5S)

The Rajang delta area shifted farther northward during the T5S times (Figure 3.19). The deposition of the sediment took place in the northern part of SK3 in the area that used to be a high during the T4S times. This suggests further opening in the area to the north of SK3. The broad area of T4S offshore from Miri was reduced during T5S times suggesting that the Baram delta shifted its progradation eastward during this time. The area to the east of SK8 has no T5S sediments preserved. The southern part of the present-day shallow basement area in SK4 and SK5 that was mainly covered by T4S was a high again during this time.

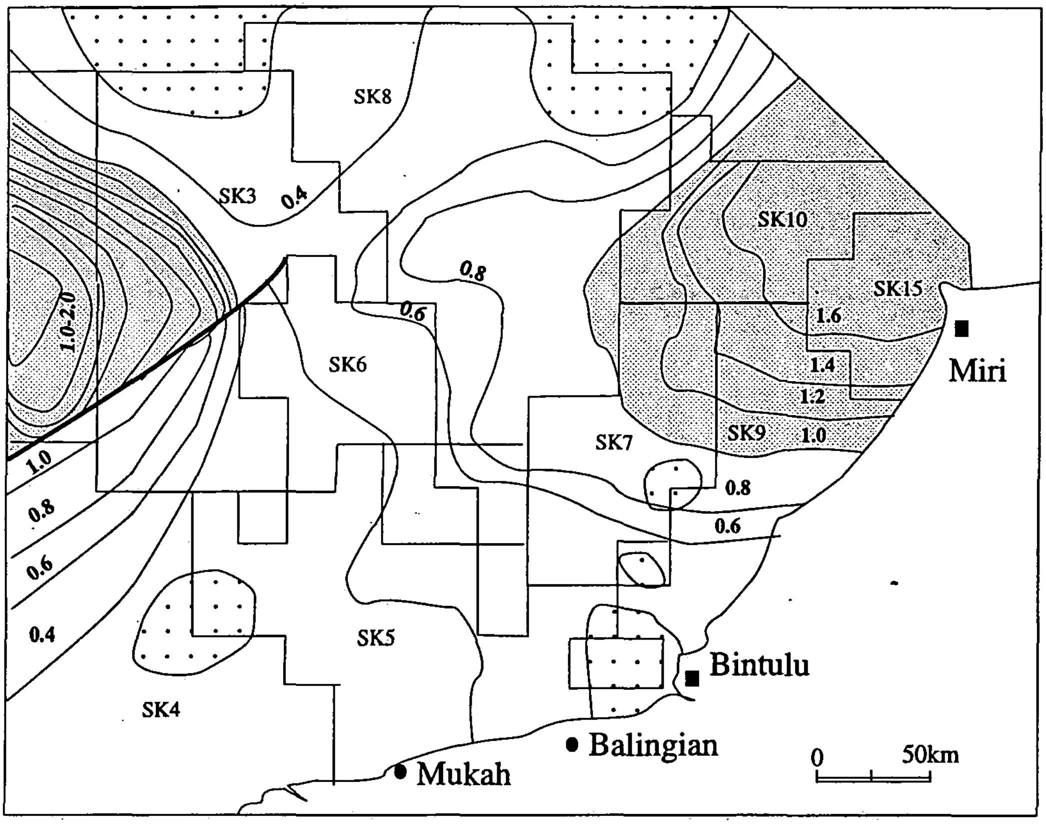


Figure 3.18. The lateral extent and isochore map of Tertiary Four Sequence (T4S). The dotted areas are the areas without preservation of the sequence and the grey areas are the thickest preservation of the sequence.

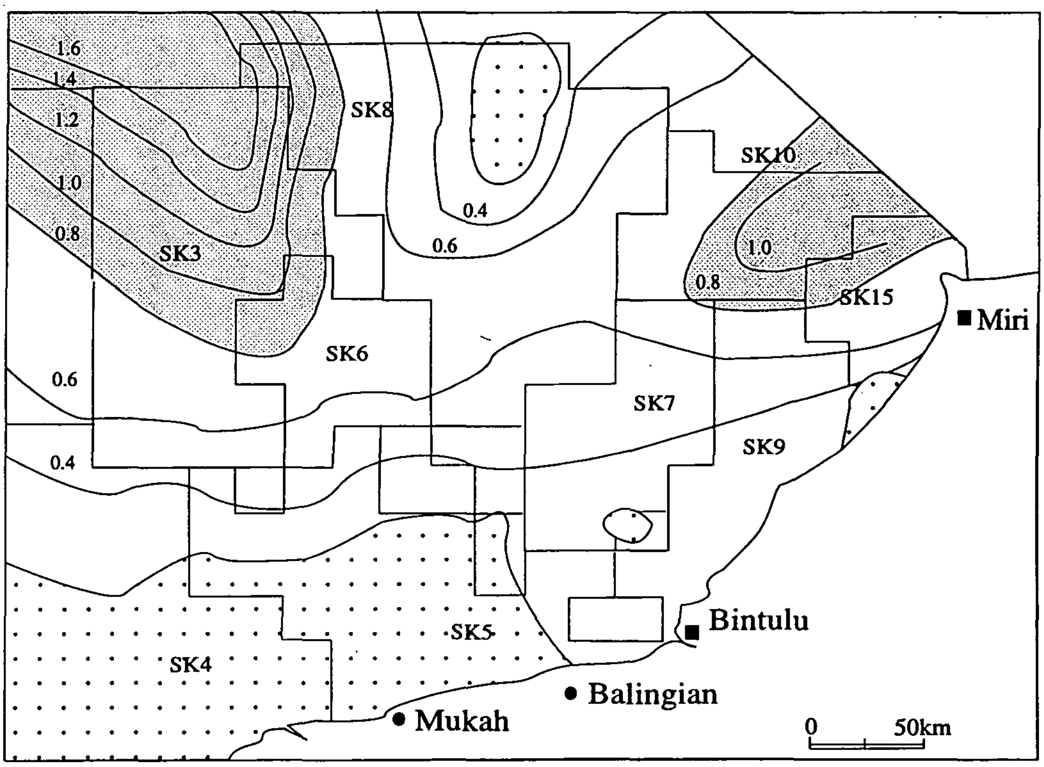


Figure 3.19. The lateral extent and isochore map of Tertiary Five Sequence (T5S). The dotted areas are the areas without preservation of the sequence and the grey areas are the thickest preservation of the sequence.

3.6 Palaeodepositional Environments of the Sarawak Basin

This section discusses the depositional environments in the Sarawak Basin and how they changed through time from Late Oligocene to Pliocene (T1S to T5S). The aim here is to gain an understanding of the distribution of reservoir, source rock and seal units in the basin that is vital for the purpose of hydrocarbon exploration.

A depositional environment can be defined in term of physical, biological, chemical or geomorphic variables (Reineck and Singh, 1980). However, to describe the evolution of the depositional environments in the Sarawak Basin, the depositional models for each Tertiary sequence were reconstructed using the depositional environment subdivision of Ho (1978). The environmental model (Figure 3.20) used in this study was developed from the present-day environments of the Baram delta region. The faunal and sedimentological criteria used have been derived from the study of the recent sediments on the Sarawak Shelf (Ho,1978). There are four major environments: **Continental, Coastal Plain, Coastal and Marine** environments. *Continental* is defined as the area upstream from the boundary between the brackish and fresh water. *Coastal Plain* is the area dominated by brackish water and characterised by mangrove swamp. The *Lower Coastal Plain* is the area located within the influence of normal tides and characterised mainly by mangrove swamp. The *Upper Coastal Plain* is the area farther upstream from the area normally influenced by tides but within the maximum reach of brackish water. It is characterised mainly by mangrove swamp.

Coastal includes the area along the shoreline. The *Coastal Fluvial* environment is the coastal area under the influence of fluvial activity. The *Marine* environment is subdivided firstly on whether the area is fully marine or partly fluvial (deltaic) and secondly based on the water depth. For example the area under the full marine influence located between the water depth of 40-100 metres is called *Holomarine Middle Neritic* (HMN) while the area within the same water depth under the deltaic influence is called *Fluvial Middle Neritic* (FMN). The subdivision of other marine environments based on the water depth can be seen in Figure 3.20.

3.6.1 Environments of deposition during Late Oligocene (T1S)

During the T1S times (Late Oligocene), there was no sediment deposited, or at least preserved, in the area to the west of the Sarawak Basin. The coastal plain belt developed with a north-south orientation in the offshore area and shifted to a NW-SE orientation towards to the present-day coastline. The coastal area was almost parallel to the coastal plain belt. The deeper water environments (HIN-HMN) occupied the whole area in the northeast of the

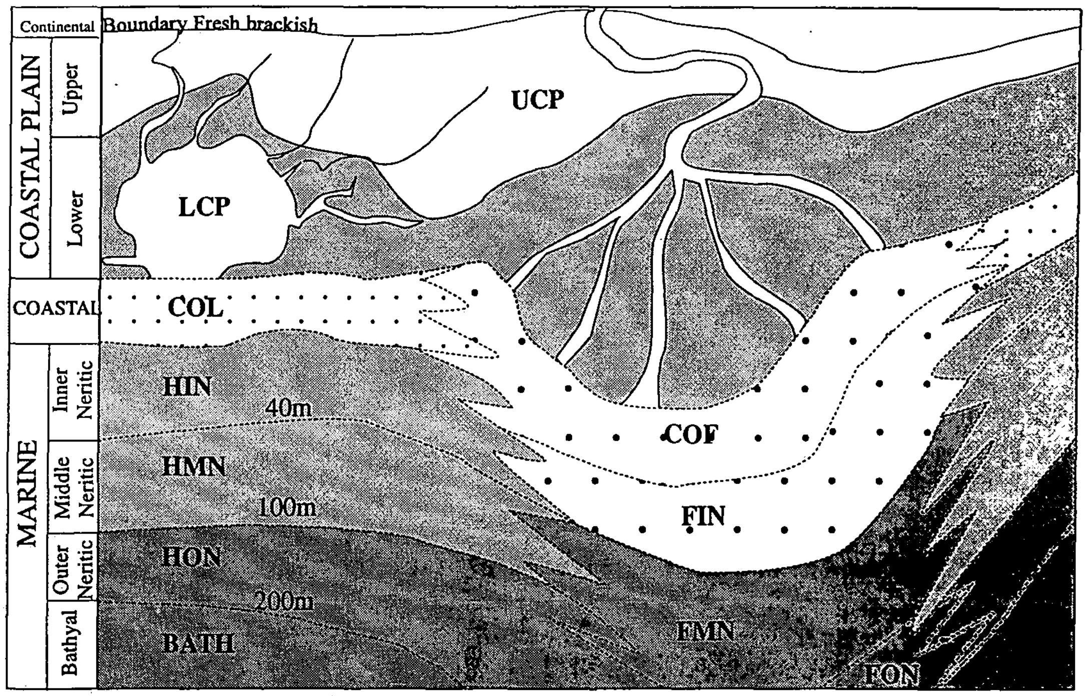


Figure 3.20. Depositional environments for the Sarawak Basin based on Ho (1978). The abbreviations used are: UCP- Upper Coastal Plain, LCP-Lower Coastal Plain, COF-Coastal Fluvial, FIN-Fluvial Inner Neritic, FMN-Fluvial Middle Neritic, FON, Fluvial Outer Neritic, COL-Coastal, HIN-Holomarine Inner Neritic, HMN-Holomarine Middle Neritic, HON-Holomarine Outer Neritic, BATH-Bathyal.

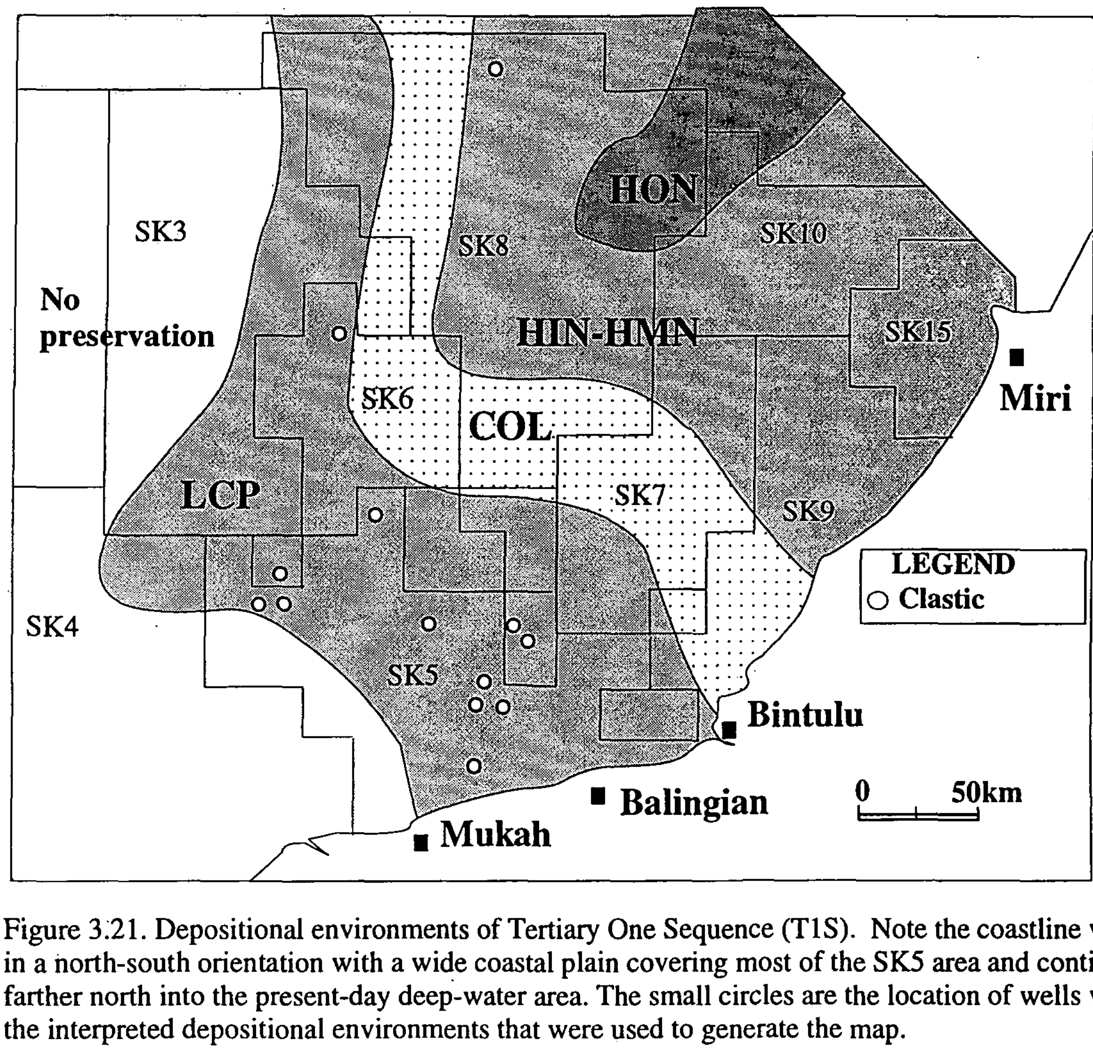


Figure 3.21. Depositional environments of Tertiary One Sequence (T1S). Note the coastline was in a north-south orientation with a wide coastal plain covering most of the SK5 area and continuing farther north into the present-day deep-water area. The small circles are the location of wells with the interpreted depositional environments that were used to generate the map.

Sarawak Basin with the HON environment to the northeast of SK8 (Figure 3.21).

The interpretation of the orientation of the coastal plain belt is supported by data from several wells. The area to the west represents the area without preservation of T1S sediments as seen on seismic lines (Figures 3.14 and 3.17). The interpretation of the width and orientation of the coastal area was based on the presence of one well with HIN facies in the northern part of SK8. Although no well penetrated the T1S with COL facies to support this interpretation, it agrees with the interpretation by Ismail and Jaafar (1993) and Agostinelli et al. (1989) for block SK9. This is also applicable for the area of HIN-HMN where the facies could only be confirmed by one well. The model of Agostinelli et al. (1989) interpreted the area to the north of SK9 to be situated within a similar environment during this time. The presence of deeper-water to the northeast of SK8 is based mainly on the preservation of thick T1S in the area (Figure 3.13). This, however, could not be confirmed by drilling as most of the wells in the area terminated within the younger sequence.

3.6.2 Environment of deposition during Early Miocene (T2S)

The environments of deposition during T2S were almost the same as in the T1S times. The area to the west still has no T2S sediments. The coastal plain belt formed in a north-south orientation in the present-day deeper-water area and shifted to a southeast orientation towards the present-day coast. The coastal area was also running in the same orientation, parallel to the coastal plain. The HIN-HMN environments similarly followed the orientation of the coastal environment. The area with the HON environment of deposition covered a wider area to the northeast of the Sarawak Basin, the northern part of SK9, east of SK8, the whole of SK10 and SK15 (Figure 3.22).

The interpretations on the orientation of the coastal plain, coastal and HIN-HMN are supported by well data. Similarly for the area to the west where there are no T2S sediments preserved, this is confirmed by seismic sections (Figures 3.14 and 3.17). Although no well penetrated the T2S in the northeast area, the interpretation that this area was located within the HON was based on the study of Agostinelli et al. (1989), suggesting that the northern part of SK9 was located within the HON environment of deposition during this time.

3.6.3 Environment of deposition during Early-Middle Miocene (T3S)

The orientation of the coastal plain and the coastal environments changed tremendously during the T3S time compared with the T1S and T2S times. The coastal plain belt during the T3S times has an east-west orientation similar to the coastal environment. These

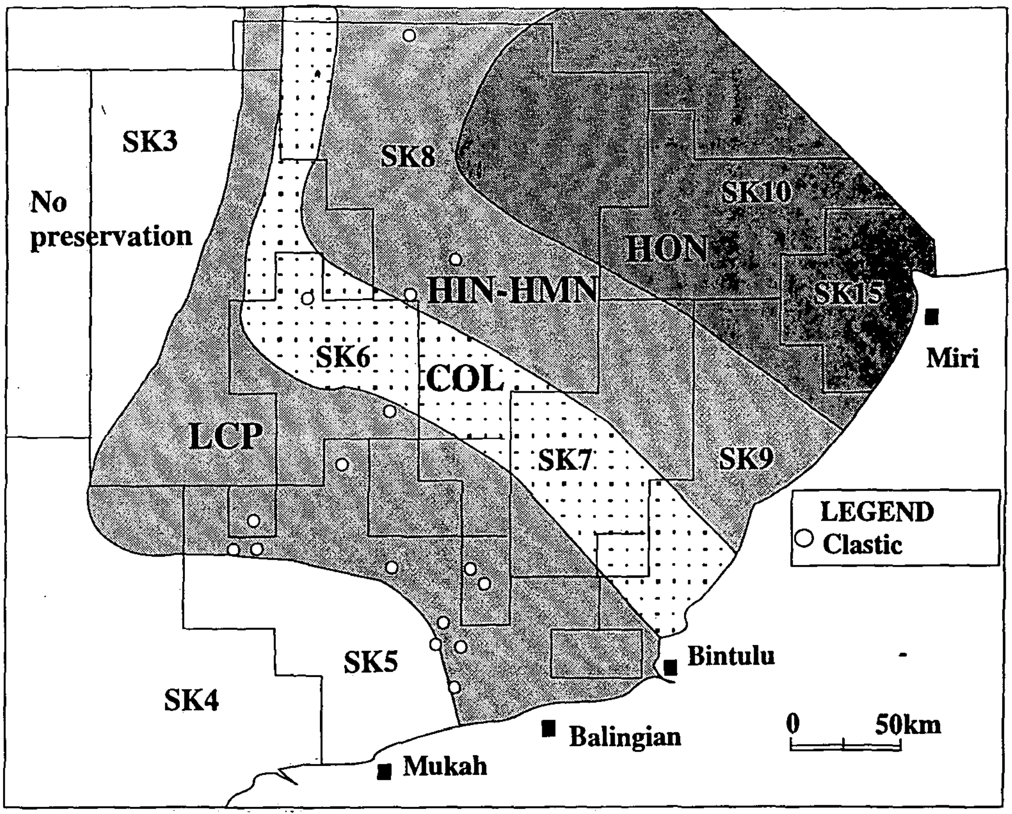


Figure 3.22 Depositional environments of Tertiary Two Sequence (T2S). Note the general shape and orientation of the coastline during this time is very similar to the T1S. The coastal plain belt is narrower and the outer neritic area is broader compared to the T1S times.

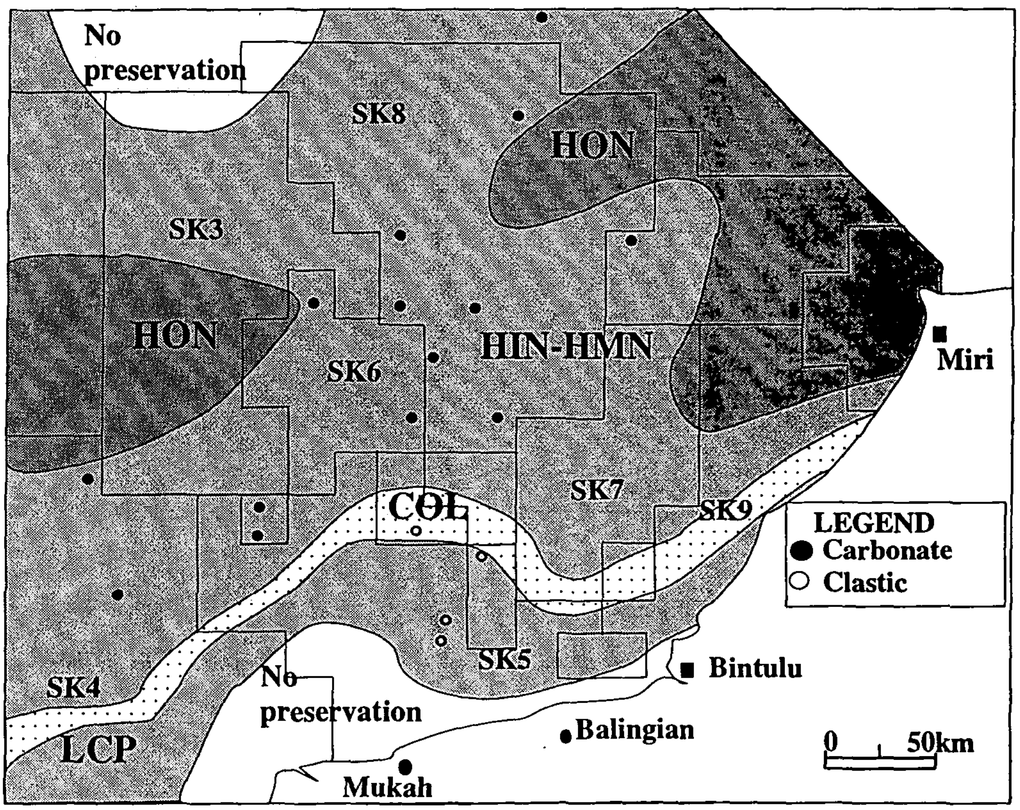


Figure 3.23 Depositional environments of Tertiary Three Sequence (T3S). Note the shape and orientation of the coastline during this time were very different compared to the T1S and T2S times. The coastline during this time changed to an east-west orientation with narrow coastal and coastal plain belts. The majority of the area was situated in holomarine environments. Note also that the carbonate production started during this time, mainly in the SK6 and SK8, with minor production in SK4, SK5 and SK10.

environments covered mainly the SK5 block and extended to SK4 to the west and SK9 to the east (Figure 3.23).

The whole area farther seaward to SK5 was situated within the environment of deposition primarily of HIN-HMN. The area to the northeast of the study area and the area in the middle part of SK3 were situated within the HON environment. The area to the north of SK3 and the area to the south of SK5 remained as high areas with no preservation of T3S sediments. Beside these areas, the whole of the present onshore area has no T3S sediments preserved.

The interpretation on the orientation of the coastal plain belt is supported by data from several wells. This is also true for the interpretation of the HIN-HMN environment. The interpretation of the HON environment was, however, based on seismic since no available well penetrated the sequence in the two areas. The interpretation on the HON environment is believed to be conclusive for several reasons. The environment of deposition during the T3S times was closely controlled by the basement topography and a similar topography remained until the present-day. Secondly the seismic reflectors suggest that the two areas represent a deeper-water area of deposition. The absence of T3S sediments to the north of SK3 is based on seismic interpretation (Figures 3.14).

Another major difference during the T3S times as compared to the older sequences is the development of the thick carbonates in SK8, SK6 and the northern part of SK5 and SK4. These areas were conducive for carbonate production on a broad shelf area, supplied by nutrient-rich waters away from terrigeneous influx as there was no major delta prograding into the basin at this time. Although the main environment of deposition of carbonate was within HIN-HMN, most of the carbonates in the wells of SK8 and SK5 appear to have developed within shallow-water.

The regional seismic lines passing through the Luconia Province show that most of the carbonate was associated with the basement highs. In some areas, the carbonate production took place in areas of inversion of the T2S and T3S (Figure 3.26). In these places, the basement is very deep, below seismic resolution. A question arises as whether the inversion structures seen on seismic are real or due to pull-up effects of the shorter seismic travelling time through carbonate. This would have resulted in the appearance of the sequences beneath the carbonate as a high. In this regard, it is believed that the inversion of the T2S and T3S is real as it can also be seen elsewhere including the area closer to the present-day coastline as on Regional Line One (Figure 3.17). This suggests that although the surrounding area to the carbonate buildups is within the HIN-HMN environment of deposition, the carbonates grew on elevated shallower-water environment.

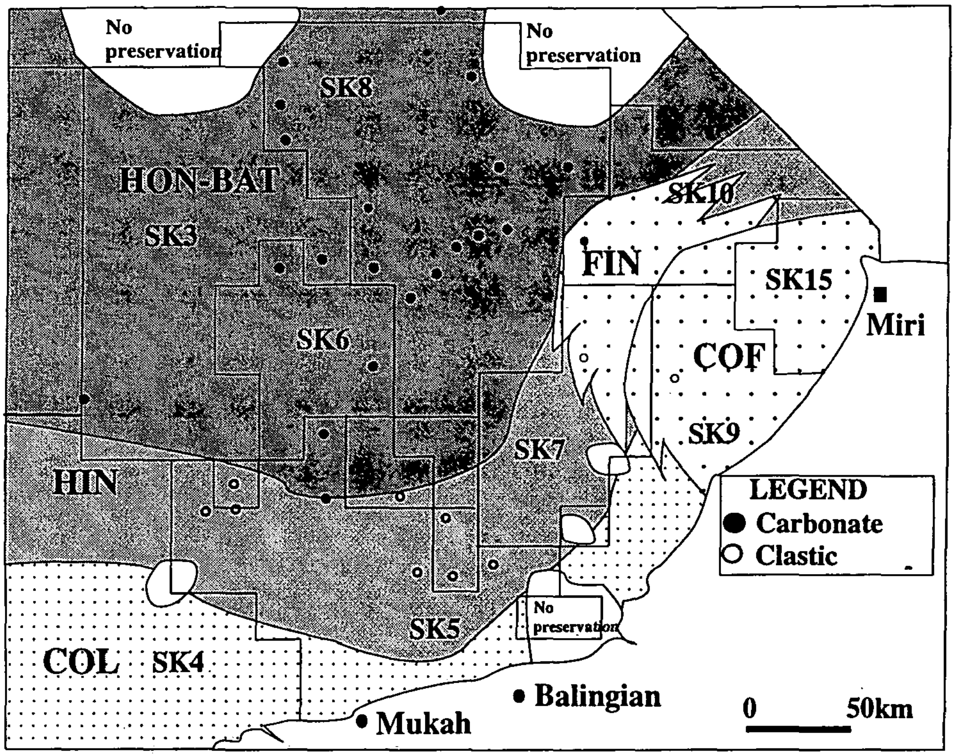


Figure 3.24 Depositional environments of Tertiary Four Sequence (T4S). Despite the increase in water depth the carbonate production continued mostly in the Luconia Province (SK6 and SK8). Some carbonate buildups were killed by the clastic influx from the Baram Delta that started to prograde to the northwest during this time.

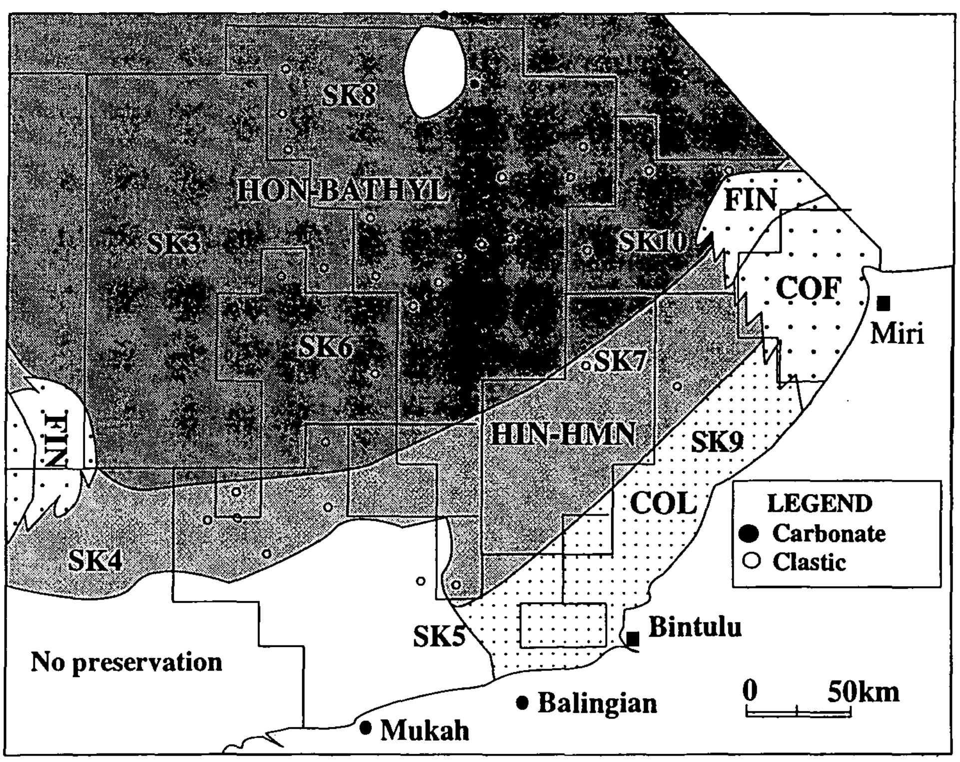


Figure 3.25 Depositional environments of Tertiary Five Sequence (T5S). Most of the carbonate production in the Luconia Province ceased during this time except in the area farther offshore. The termination of carbonate production could be due to drowning as the result of severe basin subsidence during this period. The size of Baram Delta deposits in the area shrank, probably caused by the shift in progradation eastward.

3.6.4 Environment of deposition during Late Miocene (T4S)

The orientation of the coastal environment during the T4S time remains as the same in T3S time (Figure 3.24). The HIN-HMN environment formed an east-west orientated belt parallel to the coast. The whole area farther seaward of SK5, situated within HIN-HMN environment during the T3S times, now occurred within the deeper-water environment.

The COF and FIN environments of deposition started to develop in the area of SK15, north of SK9 and SK7 and to the south of SK10. The area to the north of SK3 remained as a high and another area to the northeast of SK8 formed as a new area without preservation of this sequence. Several isolated highs also developed during this time in the nearshore area.

One important event during the T4S time is the formation of the Baram delta. This is important to the history of petroleum exploration in the Sarawak Basin as the Baram delta formed a very prolific area for oil and gas accumulation. In the offshore area, mostly beyond the progradation limit of the Baram delta, this time represents the period of peak carbonate production in the Luconia Province especially in the centre and the northern part of SK8. However, in the southern area, carbonate deposition was terminated by drowning or smothering by siliciclastics of the encroaching Baram delta. At the same time the carbonates in the northern part of SK5 were also killed by the influx of terrigeneous material from the coastal area

3.6.5 Environment of deposition during Pliocene (T5S)

The orientation of the coastal and HIN-HMN environments remained the same as in T4S time and similarly for the area covered by the HON-BAT. However, the water depth during this time increased and most of the area was situated within the deeper-water environment as compared to T4S time. The progradation of the Baram delta shifted eastward leaving a small area of COF and FIN mainly confined to the area of SK15 and SK10. Another small delta developed to the north of SK4 during this time. The area to the south of SK4 and SK5 formed a new high. In contrast, the highs in the deep-water areas were submerged during the T4S leaving only a small area as a high in the northern part of SK8 (Figure 3.25). The interpretation of the environment of deposition during this time is supported from both the well data and seismic.

Another major event during the T5S time is the extinction of carbonate production in the whole area of the Sarawak Basin. Only two out of more than two hundred carbonate buildups in the whole Sarawak Basin are known to have continued growth in the deep-water area and in

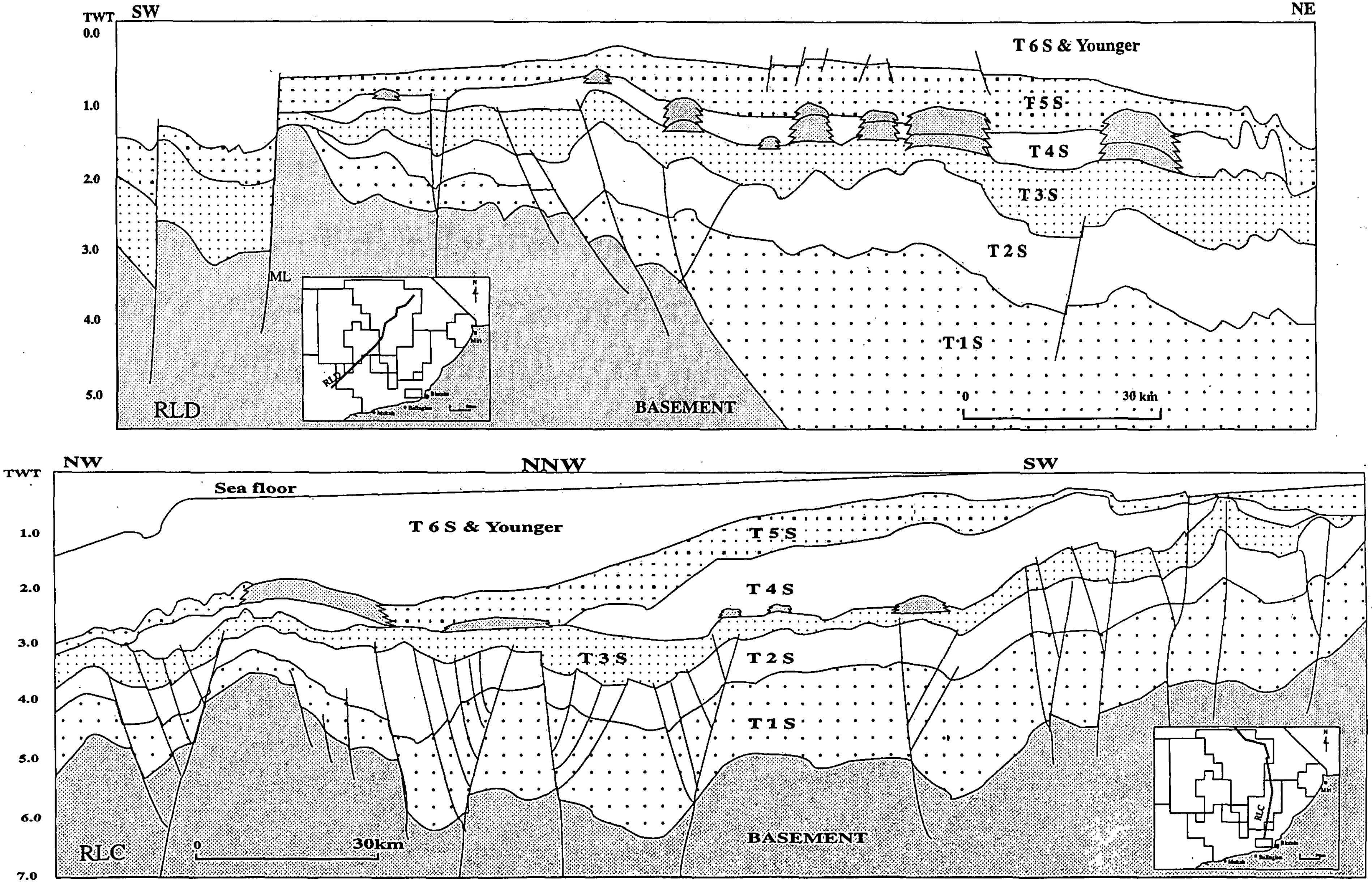


Figure 3.26. Geoseismic sections along RLC and RLD. The sections show the occurrence of carbonates in the Luconia Province. The location of the carbonates is always associated with basement highs or in the area of the inversion of T2S and T3S.

the northern part of SK8.

3.7 Depositional environments and the associated sedimentary facies

This section uses data from wireline logs from wells in the study area to discuss the associated depositional mechanisms and sedimentary facies for each depositional environment used in this chapter, which were made predominantly by Sarawak Shell, based primarily on the palaeontological assemblages. The aim here is to study the relationship between the depositional unit and the distribution of reservoir, seal and source rocks in the Sarawak Basin.

3.7.1. Upper and Lower Coastal Plain Facies.

A good example for the upper and lower coastal plain deposits is selected from the T1S of the D52.1 well (Figure 3.27). The sections A, B, C and D to the right are the examples of wireline log responses and the associated sedimentary facies from the published information.

The UCP facies is mainly characterised by blocky, box-shaped gamma ray and the area is dominated by sandy facies with high sand-shale ratio. No coal has been preserved. By comparing the log shapes from this interval with the log responses and the sedimentary facies from Serra (1985), it would appear that the upper coastal plain is dominated by braided stream deposits. These are typically composed of texturally and chemically immature gravel and sand with sand-shale ratios greater than 1. They are typically lithic arenites to lithic wackes (Pettijohn, 1972 ; Tucker, 1991). Only minor amounts of silt occur and they generally correspond to abandoned channel deposits. Carbonaceous organic matter is very rare due to the oxidising nature of the environment (Selley,1976).

Both sandy and gravely braided rivers migrate laterally leaving sheet-like and wedge-shaped bar complexes with only minor amounts of floodplain material (Cant,1982). Braided stream deposits are characterised by the typically smooth cylinder shape of spontaneous potential as well as gamma ray logs (Serra,1985). The major sand bodies could be low-sinuosity braided channel-fill sandstone with the associated sedimentary facies and structures shown in units (C) and (D) in Figure 3.27. Unit C is dominated by gravely longitudinal bar deposits and unit B records deposition of cross-bed channel-fill sandstones (Serra,1985).

The **LCP** facies is mainly characterised by fining-upward units as shown by the gamma ray response (Figure 3.27). It is characterised by lower sand-shale ratios as compared to the UCP

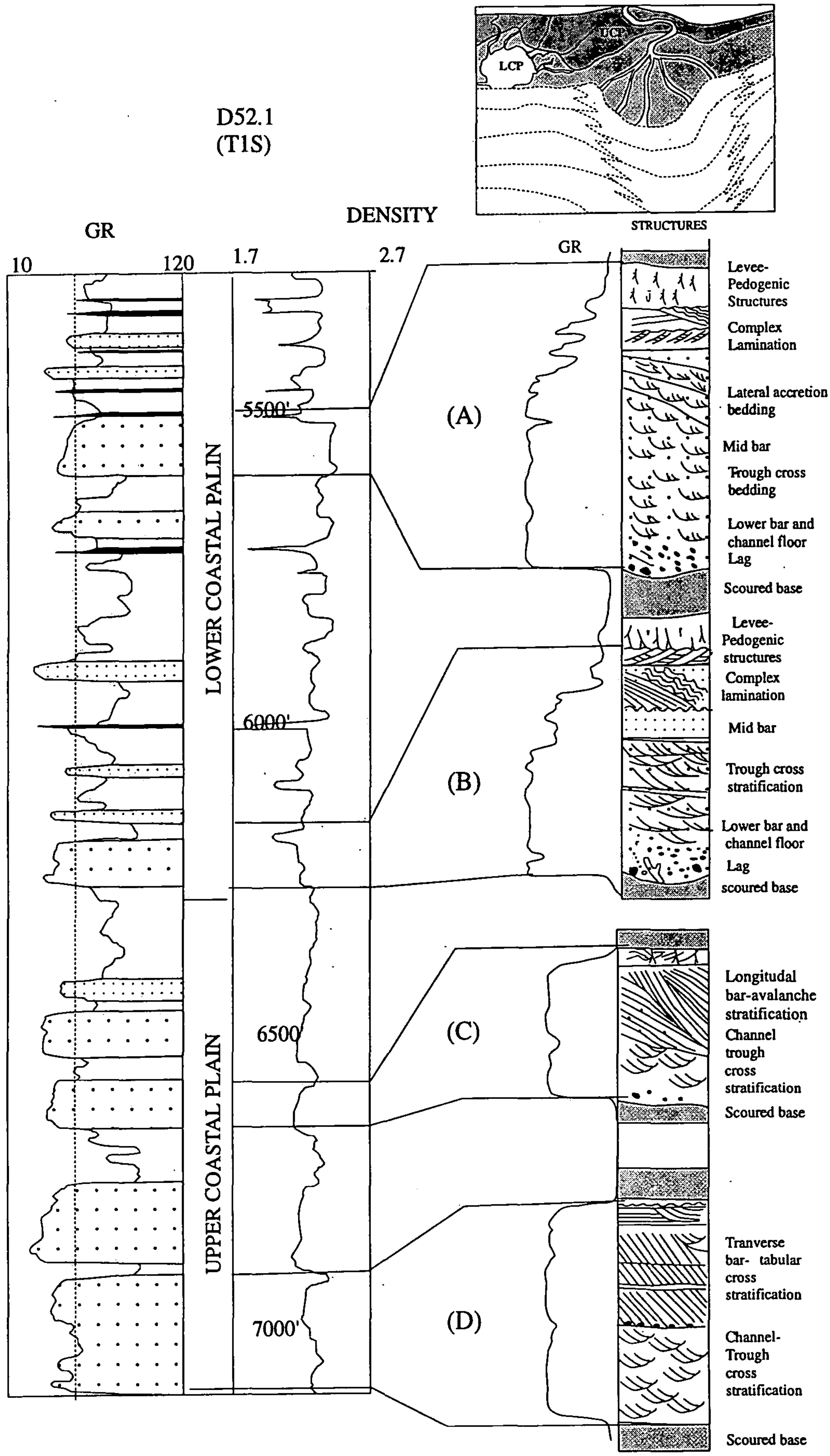


Figure 3.27. Wireline log example of LCP and UCP facies from D52.1 well. The figures to the right are the typical examples of meandering and braided stream facies, from Serra (1985).

facies and frequent coal beds. By comparing the log shapes and the lithological succession from this unit with the log responses and sedimentary facies from Serra (1985) it would appear that the lower coastal plain is dominated by high-sinuosity, meandering stream deposits.

The meandering river deposits show grading and are typically composed of sands, silts and shales with sand-shale ratios lower than 1. The basal zone is poorly sorted and ranges from conglomerates to coarse-grained sands. It grades upward to well-sorted medium to fine sands zone. The upper zone is generally composed of very fine sands, silts and some clays (Selley,1972). Meandering stream deposits are fundamentally fining upward, consisting of in-channel deposits (from lateral accretion) followed by overbank fines (from vertical accretion). The base of the channel is normally erosive with lag deposits covering a near-horizontal erosional surface and capped by trough-bedded sands, which in turn are overlain by small-scale cross laminated fine sandstones. Horizontal lamination can occur. After the lateral channel migration, the unit continues with vertical accretion deposits introduced during overbank flooding. In humid climates, vegetation may grow sufficiently to form coal seams (Allen,1970).

From the gamma ray responses, meandering stream deposits are characterised by a bell shape, often serrated, that reflects a general fining-upward sequence. The generalised vertical succession and idealised gamma-ray profile produced by a high sinuosity channel, based on Galloway and Hobday (1983), compared with the possible similar sand bodies from D52.1 well, are shown in Figure 3.27. Unit A illustrates a complete fining-upward unit typical of a point bar. Unit B illustrates the truncated vertical section commonly found in the more upstream part of a point bar.

3.7.2. Coastal and Holomarine Inner Neritic Facies.

The coastal facies is mainly characterised by a coarsening-upward succession with the grain size increasing from the shallow-marine to coastal deposits. The coastal and shallow-marine sands are normally coarsening-upward due to winnowing activity within the shallow-water environment and shoreline progradation. The coastal environment is characterised by high sand-shale ratio, and it includes the foreshore, upper shoreface and part of lower shoreface. The uppershore face is characterised by trough cross stratification and the lower shoreface by hummocky and wave-ripple bedding. The HIN environment of deposition approximates to the distal lower shoreface and shelf. The distal shoreface is mainly characterised by fine-grained material and burrows (Figure 3.28).

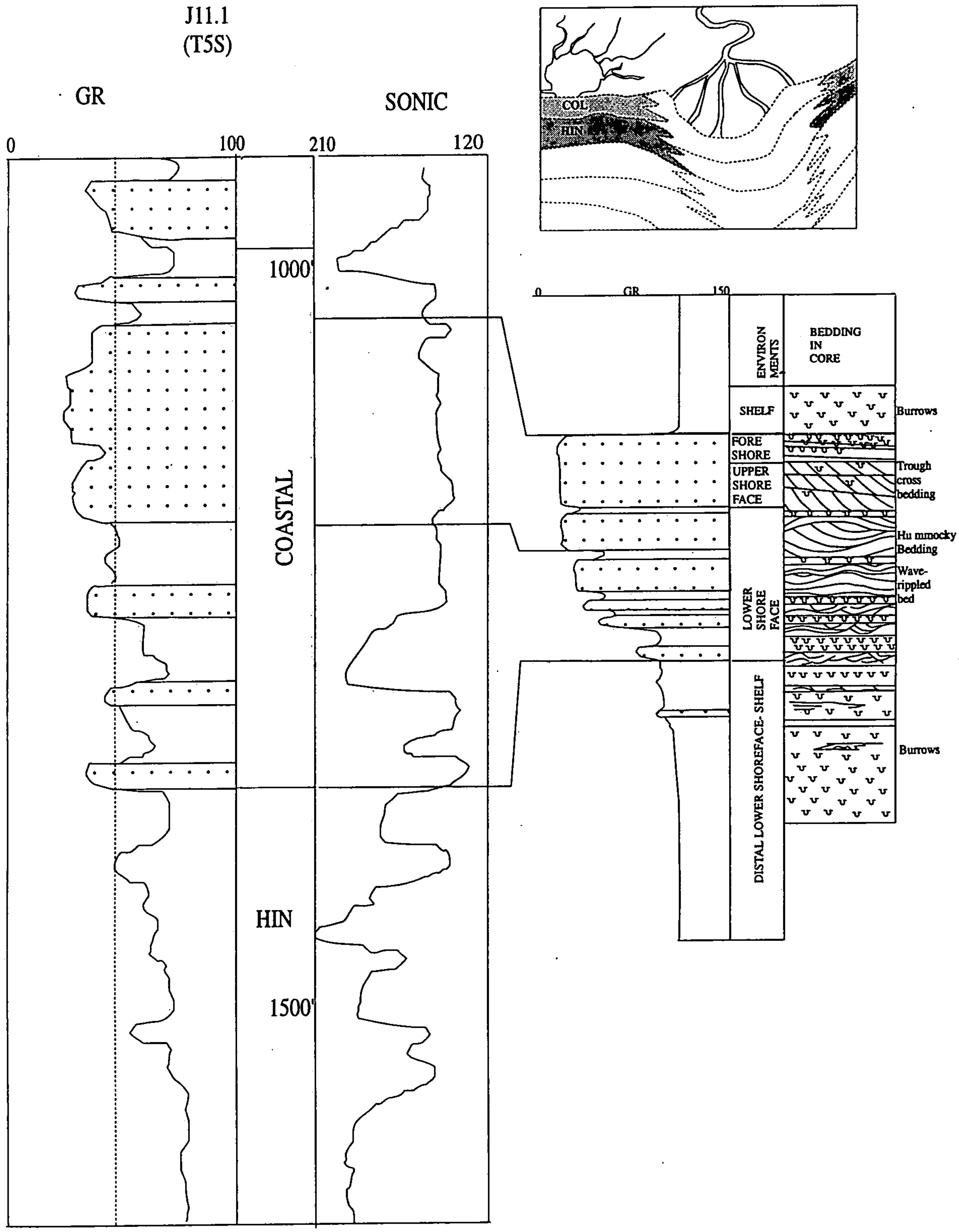


Figure 3.28. Wireline log example of COL environment of deposition from T5S of J11.1 well. The figure to the right is the typical example of coastal environment with the associated sedimentary facies from Wagoner (1990).

The COL and HIN environments compare with the shallow sea siliciclastic environment of the classification of Serra (1985). However, the shallow-water environment covers the area with deeper water than HIN (the area with the water depth less than 30 metres). According to Serra, the shallow-water environment is characterised by clastic deposits in moderate water depth (10-100 metres), under the influence of tides, waves, wind, longshore currents and storms. They include deposits of: estuaries, tidal ridges, tidal flats, sand waves, sand ribbons, inter-tidal bars, strandplains, barrier islands, beach ridges, cheniers, storms and offshore bars.

3.7.3. Coastal Fluvial and Fluvial Inner Neritic Facies.

The coastal fluvial environment as seen in the Beryl-5 well (Figure 3.29) is characterised by a thick sand succession with very high sand-shale ratio. The individual sandbodies are characterised by leftward shift in gamma ray suggesting coarsening-upward grain size. The sand bodies in the fluvial inner neritic environment are similarly characterised by a coarsening-upward unit with a lower sand-shale ratio (Figure 3.29).

By comparing the wireline log responses for the COF environment to the deltaic environment from Wagoner (1990), it seems that the COF could be ascribed to the outer stream mouth bar. This is mainly characterised by trough cross bedding and delta front distal bar by the current ripple lamination, parallel bedding and burrows. The FIN environment can be correlated to the prodelta environment.

The delta front is a high-energy environment where the sediments are constantly reworked by tidal and marine longshore currents and wave action. It includes delta front sheet sands, distributary mouth bar, river-mouth tidal deposits, nearshore, longshore and stream mouth bar deposits (Serra,1985). The prodelta environment is a transitional environment between the delta front and normal-marine shelf deposits. It is part of the delta that is below the effective depth of wave erosion lying beyond the delta front and sloping gently down to the floor of the basin into which the delta is advancing.

The distribution, orientation and internal geometry of deltaic deposits are controlled by a variety of factors including climate, morphology, vegetation, water discharge, sediment load, river-mouth processes, waves, tides, winds, currents, shelfslope and tectonics and geometry of receiving basin (Wright,1974). Delta has been classified into three types namely river-dominated, wave-dominated and tide-dominated (Galloway, 1975; Serra, 1985) . As for the Sarawak Basin, the major delta developed in the area during Late Miocene was the palaeo-Baram delta. The old delta is believed to have been similar to the present Baram delta which is a wave-dominated delta (Nagtegaal, 1989).

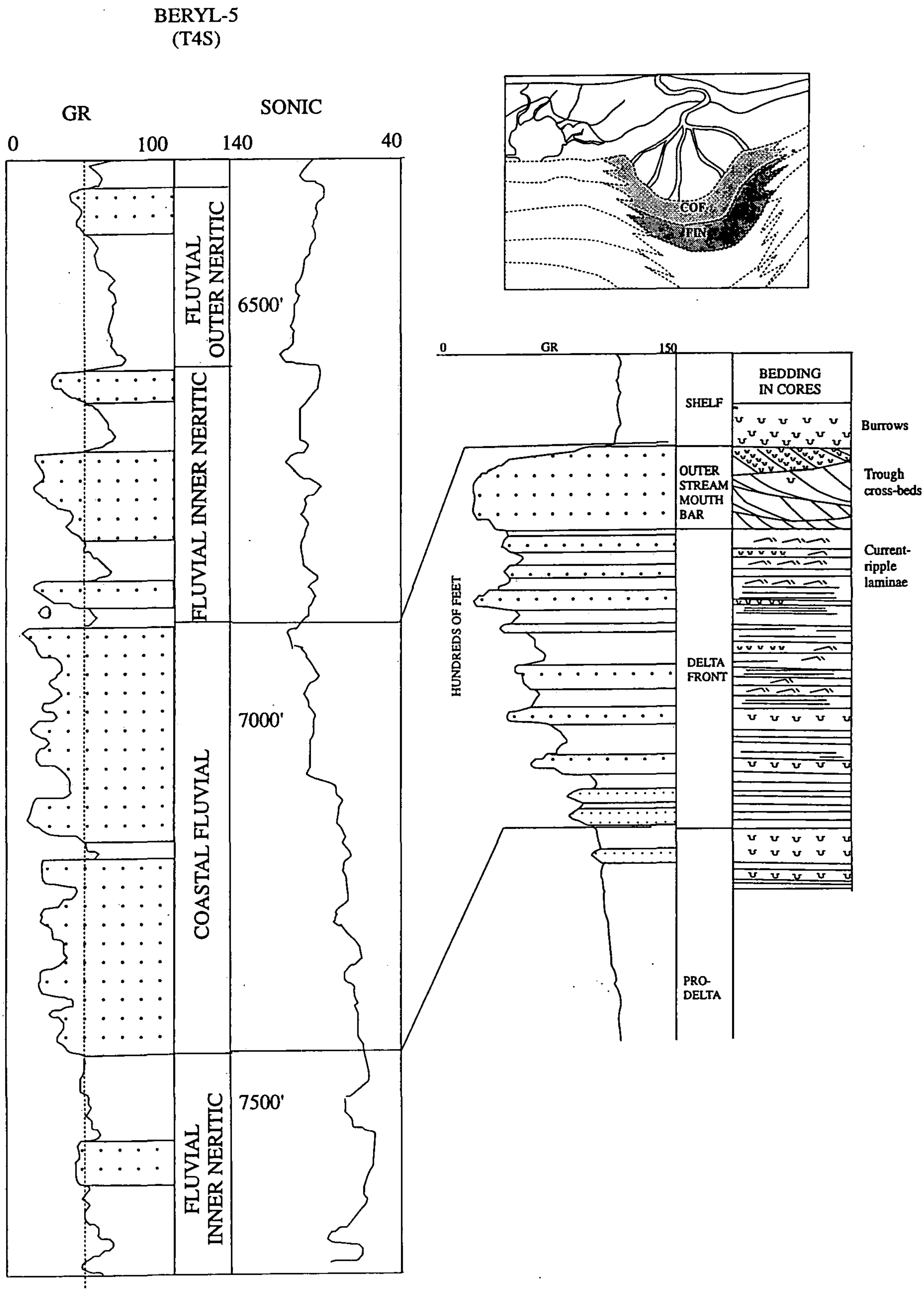
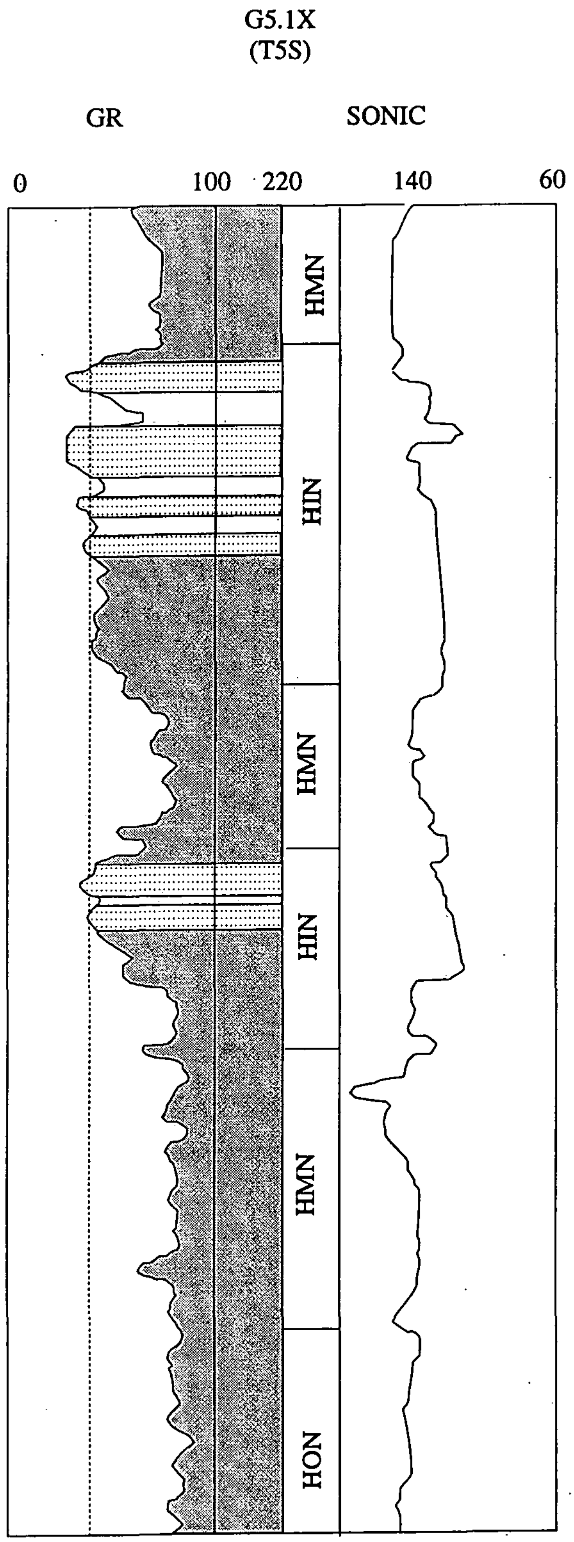


Figure 3.29 Wireline log example of COF facies from T4S of Beryl-5 well. The figure to the right is a typical example of delta deposits and the associated sedimentary facies from Wagoner (1990).



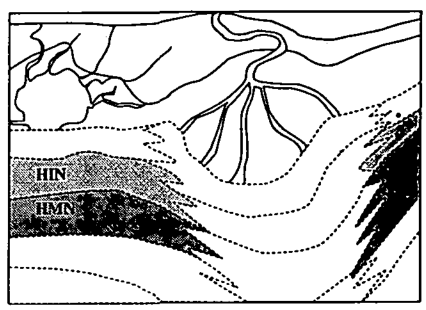


Figure 3.30. Wireline example of HIN and HMN facies from T5S of G5.1x well.

3.7.4. Holomarine Middle and Outer Neritic Facies.

Both the HMN and HON are characterised by hemipelagic shale (Figure 3.30). The transition from the HON to HMN to HIN is characterised by a coarsening-upward succession. However, the lithology in these environments does not have a good reservoir potential.

Turbidites deposited as the result of sediment-gravity flows below wave base can occur in the area with similar water depth to the HMN and HON environments. However, turbidite deposits have not been tested by the drill, in the Sarawak Basin to date. This is probably due

to several reasons. It is believed that turbidites are not likely to occur in the Sarawak Basin during T1S to T3S times because the basin is interpreted to have been a basin with a ramp margin during this time and therefore not likely to have had a clear shelf break. However, this does not exclude the possibility of the occurrence turbidite deposits because the deep-water sediments of this time are deeply buried at present, beyond a good seismic resolution. The younger turbiditic deposits, which are in the form of a lowstand wedge in T4S, however, have been identified in this study, in the area to the north of the present Baram delta.

3.8 Summary and conclusions

From this account of the depositional history of the Sarawak Basin in this chapter, the controlling factors are:

1. The sub-basins in the onshore area were mainly controlled by movements on tectonic lineaments and the timing of these movements is different. For example, the Lemai Fault was already in existence during T1S (Late Oligocene) while the Igan-Oya and Mukah Half-Graben formed during T3S (Middle Miocene). This resulted in a shift in the sediment depocentre through time.

2. Sedimentation in the nearshore area was mainly controlled by two tectonic lineaments, the Mukah Line and West Balingian Line. The Mukah Line separates the area without T1S and T2S sediments to the west from the area with preservation of these sequences to the east. The nearshore area preserves a thick succession of T1S and T2S to the east of West Balingian Line.

3. The Middle Miocene time marked a major change in the history of deposition in the nearshore region when almost the whole area to the west was covered by the T3S sediments.

This is related to cessation of the movement along the West Balingian Line and the whole nearshore area behaved as one structural unit and experienced further subsidence.

4. The offshore area farther north of the nearshore experienced a different sedimentation history as a new depression was formed during T3S (Middle Miocene) times and was filled up mainly by T3S and T4S sediments. Some places in the deep-water area remained as topographic highs until T5S (Pliocene) and were only covered by the T5S and younger sequences.

5. The palaeoenvironments for the Sarawak Basin record a broad coastal plain belt with a north-south oriented coastline covering both the nearshore and offshore area including the present-day deep-water area. The palaeo-coastline changed to an east-west orientation during T3S (Middle Miocene). This phenomenon is believed to be tectonically controlled.

6. Deposition of carbonates in the Luconia Province began during Middle Miocene times, possibly when nutrients were supplied from a broad shelf area and away from terrigeneous influx. The carbonates grew on the basement highs and inversion areas. The termination of carbonate deposition in the Sarawak Basin during Pliocene could be caused by several factors including smothering by siliciclastics of the encroaching Baram delta during the late Miocene and drowning as a combination effect of global sea-level rise and the latest subsidence during the Pliocene.

7. The study of the wireline responses from the Sarawak Basin helps in understanding lithofacies distribution and development of depositional environments.

Chapter 4

TECTONICS OF THE SARAWAK BASIN

4.1 Introduction

A good understanding of the tectonic setting of a basin, especially for such a prolific hydrocarbon area such the Sarawak Basin, is vital, and enables us to understand the mechanisms that are responsible for the generation of structural traps. Ultimately, this will help in planning effective exploration and exploitation strategies for these natural resources.

This chapter discusses the Tertiary tectonics of the Sarawak Basin in terms of general basin setting, the tectonic environments of the area with the tectonic evolution and basin formation, based primarily on the results of the seismic study carried out for the whole area of the Sarawak Basin.

Firstly, the tectonics of the Sarawak Basin will be described in terms of basement topography and the occurrence of sub-basins and major lineaments. Secondly, the formation of the major structural traps in the nearshore area will be discussed. Thirdly, we will discuss the tectonic evolution and sedimentation history of the basin. Finally the chapter will summarise the findings on the Tertiary tectonics of the Sarawak Basin.

4.2 Data and techniques

4.2.1. Data

The interpretation on the tectonics of the Sarawak Basin was based on thorough interpretation of the recently reprocessed regional lines and reinterpretations of the old prospect seismic lines from the study area. The list and the orientation of the seismic lines and the location of the wells with composite well logs used in the study can be seen in Section 2.2.1, together with forty-five composite well logs. T-Z curves for the time-depth conversion for a total of fifteen wells were also made available for the study.

Other than conventional seismic lines as listed in 2.2.1, the study also used the colour seismic sections generated by the SIDIS work station that enhances the seismic reflectors by using different colour contrast and different vertical and horizontal exaggeration. This helps in picking subtle structures and deep reflectors, e.g., in mapping low-angle unconformity boundaries and picking the basement reflectors. One of the seismic sections generated by SIDIS work station shown in black and white is in Figure 2.8.

This study also makes use of other data such as gravity and magnetic of Lavesque and Ooi (1989), the geological map of Sarawak (Heng, 1992), the results of the study using synthetic aperture radar (Kang and Kadir, 1990) and the findings and conclusions made by the previous workers.

4.2.2. Study Techniques

The techniques used in this study are mainly the conventional seismic structural interpretations. The interpretations involve the recognition of the geological structures and mapping exercises that include determining the structural styles, generating the basement topography map and delineating the main structural orientation and configuration.

4.2.2.1. Determining the structural styles

Classifications of structural style for the Sarawak Basin are based primarily on the involvement or non-involvement of basement in the observed structures. The table on the structural style and habitat (after Harding and Lowell, 1979, Table 4.1) with the diagrams of the structures (Figures 4.1 and 4.2) were used as the guide in interpreting the structural style of the study area.

Theoretically, the deformation styles that involve basement include wrench-fault structural assemblages, compressive fault blocks and basement thrusts, extensional normal fault blocks and warps. Detached structural styles include the décollement thrust-fold assemblages, detached normal faults (growth faults and others), salt and shale structures. By using the description in Table 4.1 as a guide, it is possible to infer the deformational force and mode of tectonic transport inferred from structural features.

4.2.2.2. Delineating the structural orientation and basement topography

Delineating the structural orientation was performed by transferring the information seen in vertical section, that is from the seismic section, to the base map. This is conducted by marking the tectonic features such as faults, seen on the seismic sections, on to the basemap and tracing the extension and the orientation of a particular structure.

The mapping of basement level was carried out by starting with the onshore area where obvious seismic reflectors for the basement could be seen. In the onshore area, the seismic

Table 4.1. ***Structural Style and Habitat (After Harding and Lowell, 1979)***

Structural Style Deformational	Dominant Force	Typical Transport Mode	Plate Tectonic Habitats Primary	Secondary
		BASEMENT INVOLVED		
Wrench fault assem blages	Couple	Strike slip of subregional to regional plates	Transform boundaries	Convergent boundaries: 1. Foreland basins 2. Orogenic belts 3. Arc massifs Divergent boundaries: 1. Offset spreading centres
Compressive fault blocks and basement thrusts	Compression	High to low angle convergent dip slip of blocks, slabs, and sheets	Convergent boundaries: 1. Foreland basins 2. Orogenic belt cores 3. Trench inner slopes and outer highs	Transform boundaries (with component of convergence)
Extensional fault blocks	Extension	High to low angle divergent dip slip of blocks and slabs	Divergent boundaries: 1. Completed rifts 2. Aborted rifts aulacogens Intraplate rifts	Convergent boundaries: 1. Trench outer slope 2. Arc massif 3. Stable flack of foreland and fore-arc basins 4. Back-arc marginal seas (with spreading) Transform boundaries: 1. With component of divergence 2. Stable flank of wrench basins
Basement warps: arches, domes, sags	Multiple deep-seated processes (thermal events, flowage, isostasy, etc.)	Subvertical uplift and subsidence of solitary undulations	Plate interiors	Divergent, convergent, and transform boundaries Passive boundaries
		DETACHED		
Decollement thrust-fold assemblages	Compression	Subhorizontal to high-angle convergent dip slip of sedimentary cover in sheets and slabs	Convergent boundaries: 1. Mobile flank (orogenic belt) of forelands 2. Trench inner slopes and outer highs	Transform boundaries (with component of convergence)
Detached normal-fault assemblages ("growth faults" and others)	Extension	Subhorizontal to angle divergent dip slip of sedimentary cover in sheets, wedges, and lobes	Passive boundaries (delta)	
Salt structures	Density contract Differential loading	Vertical and horizontal flow of mobile evaporites with arching and/ or piercement of sedimentary cover	Divergent boundaries: 1. Completed rifts and their passive margin sags 2. Aborted rifts; aulacogens	Regions of intense deformation containing mobile evaponte sequence
Shale structures	Density contrast Differential loading	Dominantly vertical flow of mobile shales with arching and/or piercement of sedimentary cover	Passive boundaries (deltas)	Regions of intense deformation containing mobile shale sequence

reflectors are tied to both the well logs and surface geology, where the basement outcrops in the area, to the south and in the Tatau Horst (Figure 3.1). A number of wells have penetrated the basement both in the onshore and the offshore area which also helps in verifying and checking the validity of the seismic correlation.

The seismic marker for the top basement's reflector is normally characterised by a doublet of high amplitude but low frequency (Figure 2.8). The nature of strong seismic contrast for the basement reflectors can be seen in the whole study area. However, in some places due to poor seismic acquisition and /or processing, the reflector for the basement could not be seen

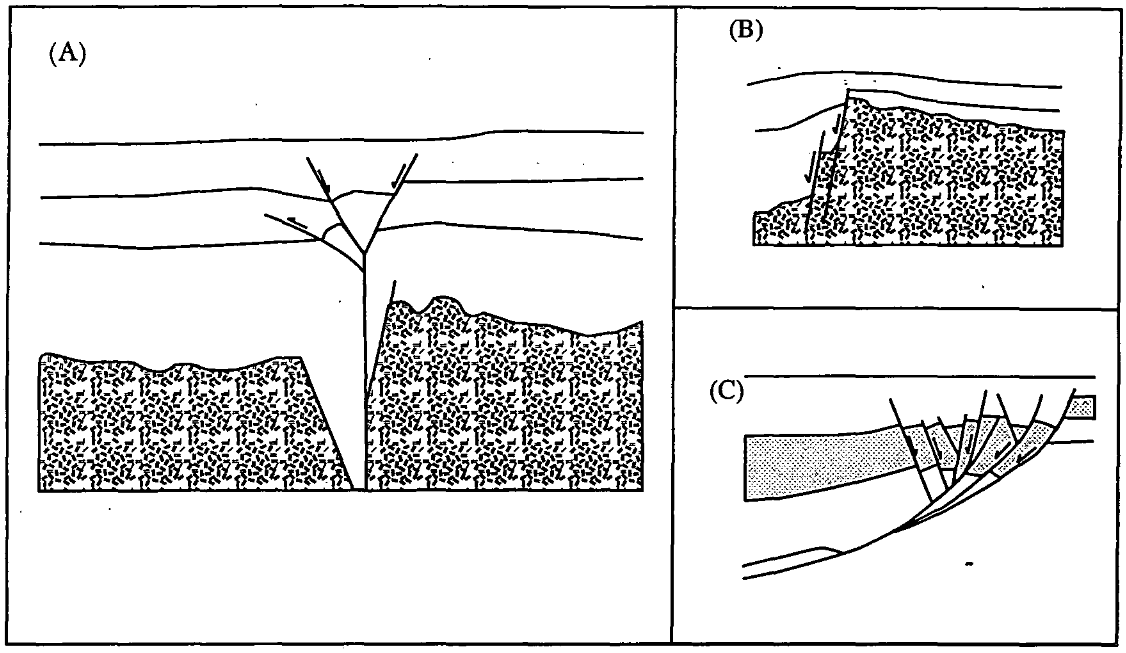


Figure 4.1. Diagram showing, (A) Negative flower structure, (B) Extensional fault block and (C) Detached normal/ growth faults. Extentional and superimposed structures may have several similar profile characteristics (after Harding,1985).

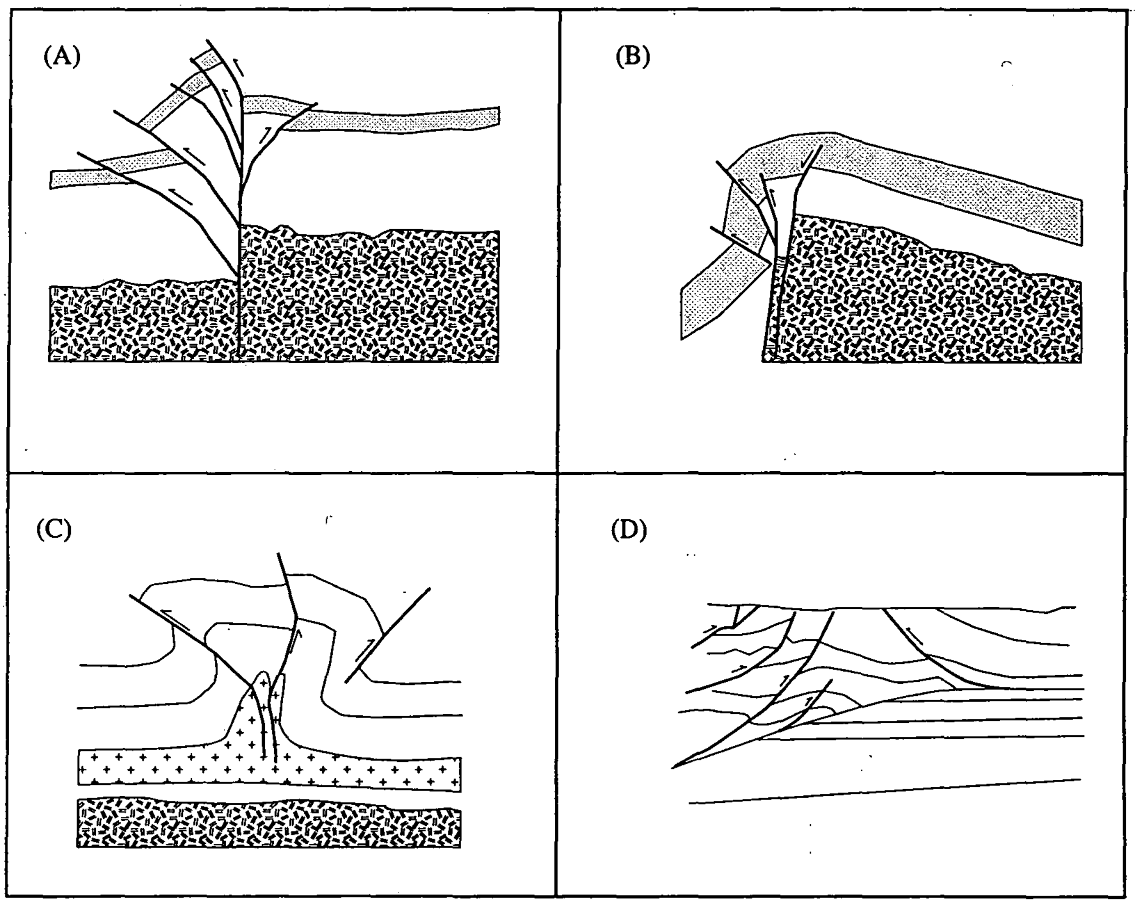


Figure 4.2. Diagram showing , (A) Positive flower structure, (B) Contractional fault block, (C) Detached box fold and (D) Delta Structure (After Harding, 1985).

especially on the normal prospect lines. As a consequence, mapping relied entirely on the newly reprocessed regional seismic lines for the basement mapping.

4.2.2.3. Determining the structural evolution and timing

The timing of structuration and the fault movements was determined based on the age of the affected sedimentary sequences. The tectonic movement will normally give rise to changes in the physical characteristics of the sequence, such as changes in thickness and the degree and the nature of deformation for the particular sequence.

The intervals intersected by the faults during a particular time could be determined by the contrasting sedimentary thicknesses in the up-thrown and the down-thrown side of the fault. Differences are not present everywhere as there may be no vertical fault displacement in some places.

4.3 Basement topography

The basement map for the offshore Sarawak Basin (Figure 4.3) shows that the offshore Sarawak area can be subdivided into **two basinal areas and one basement high** based on the present-day basement topography, with several **smaller sub-basins** within the basement high area. The two basinal areas, that will be referred herein as the ***Eastern Sub-Basin*** and ***North-western Sub-Basin,*** are separated by a narrow basement high which coincides with a pronounced NW-SE structural lineament termed the West Balingian Line (WBL), one of several NW-SE lineaments that will be discussed further in the next two sections. The basement high area is located to the SW and the two sub-basinal areas to the NW and E. The interpreted regional seismic lines across the whole Sarawak Basin including the two sub-basins and basement high areas are shown in Figures 4.5 and 4.7 whilst the location and orientation of the lines are shown in Figure 4.6.

4.3.1. Eastern Sub-Basin

The Eastern Sub-Basin formed as the main basin in Sarawak, and preserves mainly the Late Oligo-Miocene and younger sedimentary sequences including Pliocene to Recent sediments with the thickness exceeding 4 seconds Two-Way-Time (TWT) or about 8 kilometres. In the deepest part of the basin the sedimentary thicknesses reach 6 seconds TWT or about 13 kilometres (Figures 4.3 and 4.4).

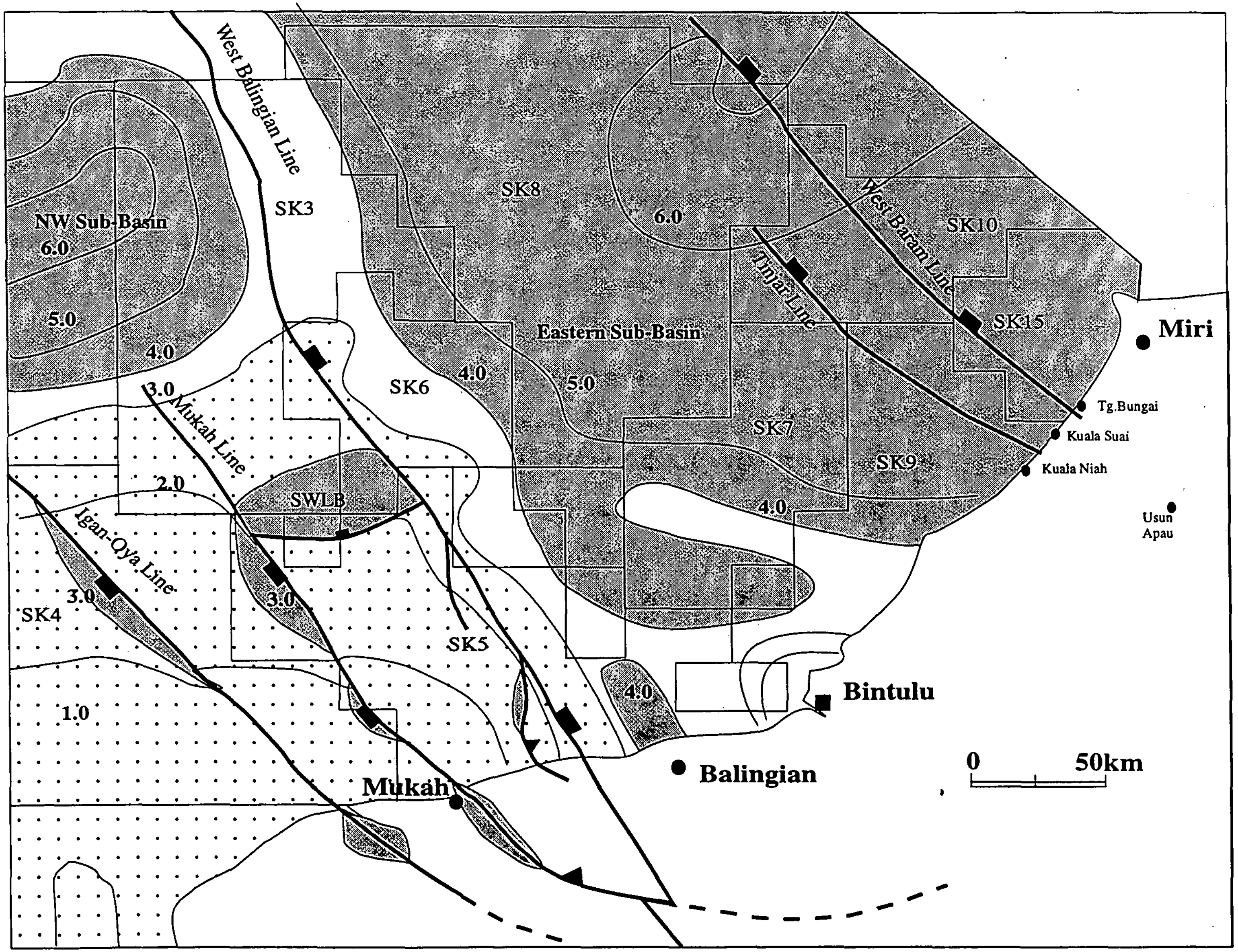


Figure 4.3. Basement map of the offshore Sarawak Basin with major tectonic lineaments identified from regional seismic mapping. The dotted area is the shallow basement and the areas in grey are the basins. The contour intervals are in seconds two-way time. SWLB- Southwest Luconia Sub- Basin.

In term of present hydrocarbon production from the Eastern Sub-Basin, the area to the north (SK6 and SK8, Figure 4.3) is the main gas production area in Sarawak. The hydrocarbons that are predominantly gas are produced from Miocene carbonates. The SK5 and other areas offshore Miri (SK15) are the main area for oil with substantial amounts of gas, producing from the Late Oligocene-Miocene and Late Miocene sedimentary sequences respectively.

In terms of its general structural setting, the basin in the offshore Miri area can be differentiated from the area further to the west mainly by the occurrence of two major lineaments called the Tinjar Line and West Baram Line. The two lineaments seem to play a important role in controlling the sedimentation between the area to the west and east of the lines during the Late Miocene to Pliocene times; this will be discussed further in Section 4.7.

The northern part of SK8 and other deep water blocks were interpreted to be influenced by both compression and extension with N-S trending faults forming structural trap features called buried hills (Smith and Micheal, 1994 and Ismail, 1994). The area farther to the east of the Eastern Sub-Basin, in the vicinity of the Tinjar and West Baram Lines, is the area with the Late Miocene to Pliocene Baram Delta deposits and characterised by the E-W trending growth faults (Scherer,1980). This thesis, however, has no intention to discuss further the structural history of that area.

The north-eastern part of SK5 and the southern part of SK7 are characterised by compression that is believed to be related to the formation of the main structural trap in the area. This type of structural trap is called in this thesis, a the faulted-fold structure, which will be discussed further in Section 4.6.

The shallower part of the Eastern Sub-basin extends farther to the onshore area where the southern boundary of the basin is marked by the Bukit Mersing Line (Figure 4.8) which is also the contact between the Tertiary sedimentary formations and the metamorphic rocks of Belaga Formation.

4.3.2. North-western Sub-Basin

The North-western Sub-Basin is about 100 x150 kilometres. The sub-basin preserves younger sediments of mainly Middle Miocene age (T3S) and younger sequences, as compared to the sedimentary sequences preserved in the Eastern Sub-basin with basal sediments of Late Oligocene age (RL7, Figure 4.7). In the deepest part of the sub-basin, the sedimentary thicknesses also reached 6 seconds TWT or about 13 kilometres (Figures 4.3 and 4.4). The sub-basin was also referred to by Tjia (1994) as the Rajang Delta area that is also characterised by an E-W trending growth fault, similar to the Baram Delta area. In comparison to the Eastern Sub-basin, this sub-basin has currently no hydrocarbon production and no major discovery has been made to date.

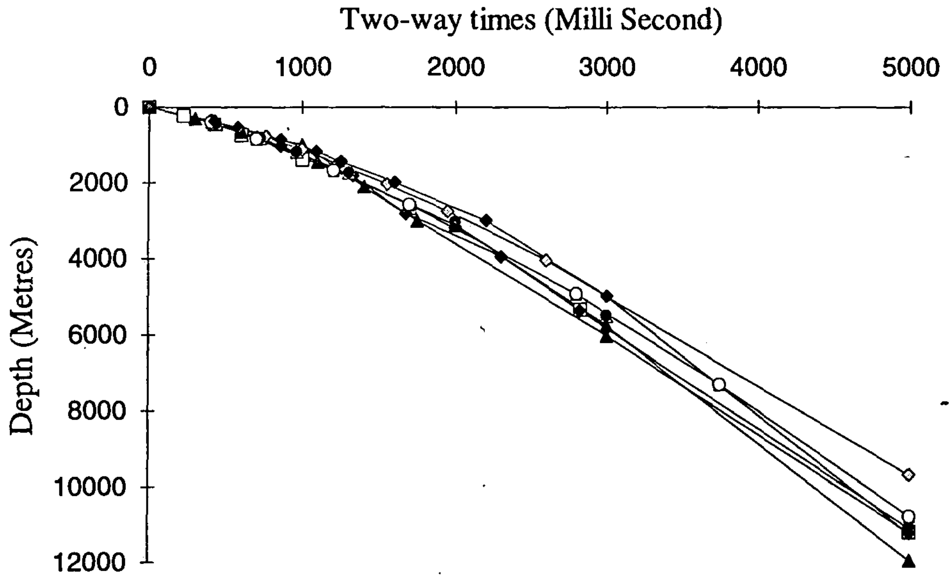


Figure 4.4. T-Z curves for the Sarawak Basin. These time-depth conversion curves were generated using the seismic interval velocity from the seismic sections acquired in the onshore Sarawak. The curves are used to convert the times' values (Two-way-time) from seismic sections to depths in metres.

4.3.2. Basement high area

The basement high area to the SW of the offshore Sarawak Basin (Figure 4.3) is characterised by a thin sedimentary cover which is mainly less than 3 seconds TWT; that is about 6 kilometres thick (Figure 4.4). The basement high area extends from the SW of the offshore area to the Mukah-Balingian area in the onshore (Figures 4.8 and 4.9). The whole western part of the onshore area is considered as a basement high area except for the area to the NE of the West Balingian Line (Figure 4.8), or in the vicinity of the Balingian Town which is also called the Balingian Sub-Basin (Figure 4.9).

Within the basement high area, both for the offshore and the onshore, several half-graben features have been identified to form along the prominent lineaments named as Igan-Oya Line, Mukah Line and the West Balingian Line. In the onshore area the half-graben features are called ***Igan-Oya Half-Graben*** and ***Mukah Half-Graben*** (Figure 4.9). Besides the two half-grabens, two other sub-basins have been identified, one is called ***Lemai Sub-Basin*** in the onshore area and another one in the offshore is called ***SW Luconia Sub-Basin*** (Figure 4.8).

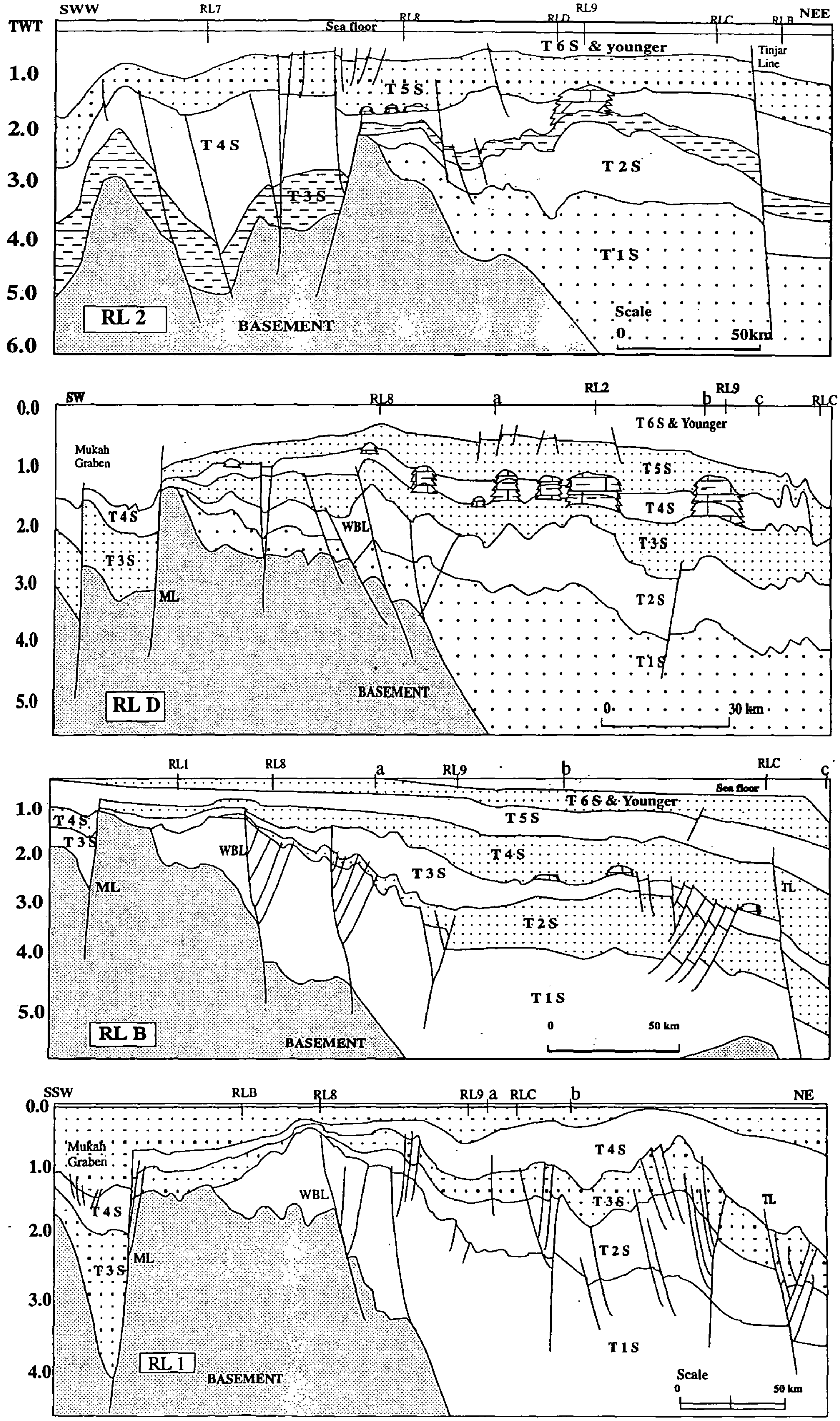


Figure 4.5. East-West regional seismic sections for the offshore Sarawak Basin. Refer to Figure 4.6 for the location and orientation of the seismic lines.

The basement topography map of the onshore area showing the geometry and orientation of the onshore sub-basins and the representative geoseismic sections for the onshore area are shown in Figures 4.9 and 4.10 respectively. More detailed discussion on the Igan-Oya and Mukah Half-Grabens is given in Section 4.5, as these are used as evidence to interpret the tectonic environments of the Igan-Oya and Mukah Lines.

4.3.2.1. *The morphology of Lemai and Southwest Luconia Sub-basins.*

The ***Lemai Sub-Basin*** is an E-W elongated fault-bounded basin with a dimension of about 30x10 km (Figure 4.9). The bounding fault to the south is a basement normal fault with a maximum throw in excess of 2.5 Seconds TWT; that is about 4,500 metres. The name "Lemai Fault" is proposed for this fault. The fault formed as the southern subsurface boundary of T1S in onshore Sarawak. The orientation of the Lemai Fault is about 250° for the mid-western portion of the fault and farther eastward, this normal fault has been replaced by a series of thrust faults with thrusting direction to the NE (Figure 4.9).

This sub-basin is separated from the onshore Balingian Sub-Basin by a major fault that is interpreted to be the onshore extension of the West Balingian Line (Figure 4.9). At present, the Lemai Sub-Basin is separated from the Mukah Half-Graben and Balingian Sub-Basin by the Mukah Line and West Balingian Line respectively. However, the three sub-basins, namely the Lemai Sub-Basin, Mukah Half-Graben and Balingian Sub-Basin were probably not separated until the T2S times as there is no clear break in the isopach map of T1S among the three sub-basins (Figure 3.3). Also as there is no clear indication that the basement becomes shallower to the east, it is believed that the Lemai Sub-Basin originally extended farther eastward of the present-day eastern basin limit marked by the West Balingian Line.

The deepest part of the Lemai Sub-Basin reaches a depth of 4.0 Seconds TWT; that is about 8,000 metres. The basin is filled up with the T1S, T2S, T4S and T5 and Younger Sequences but T3S is not preserved in this sub-basin. The absence of T3S in this basin suggesting that the basin was probably formed during or prior to the deposition of T1S and filled up during the T2S leaving no space for the deposition of T3S. The basin was later involved in further subsidence as the Lemai Fault was reactivated several times, including during the Late Miocene (T4S times).

The ***Southwest Luconia Sub-Basin*** is interpreted to be about the same size with a similar orientation to the Lemai Sub-Basin. The eastern part of the basin can be seen on RL8 at the intersection with RLB (Figure 4.7). The presence of the basin was also confirmed by a

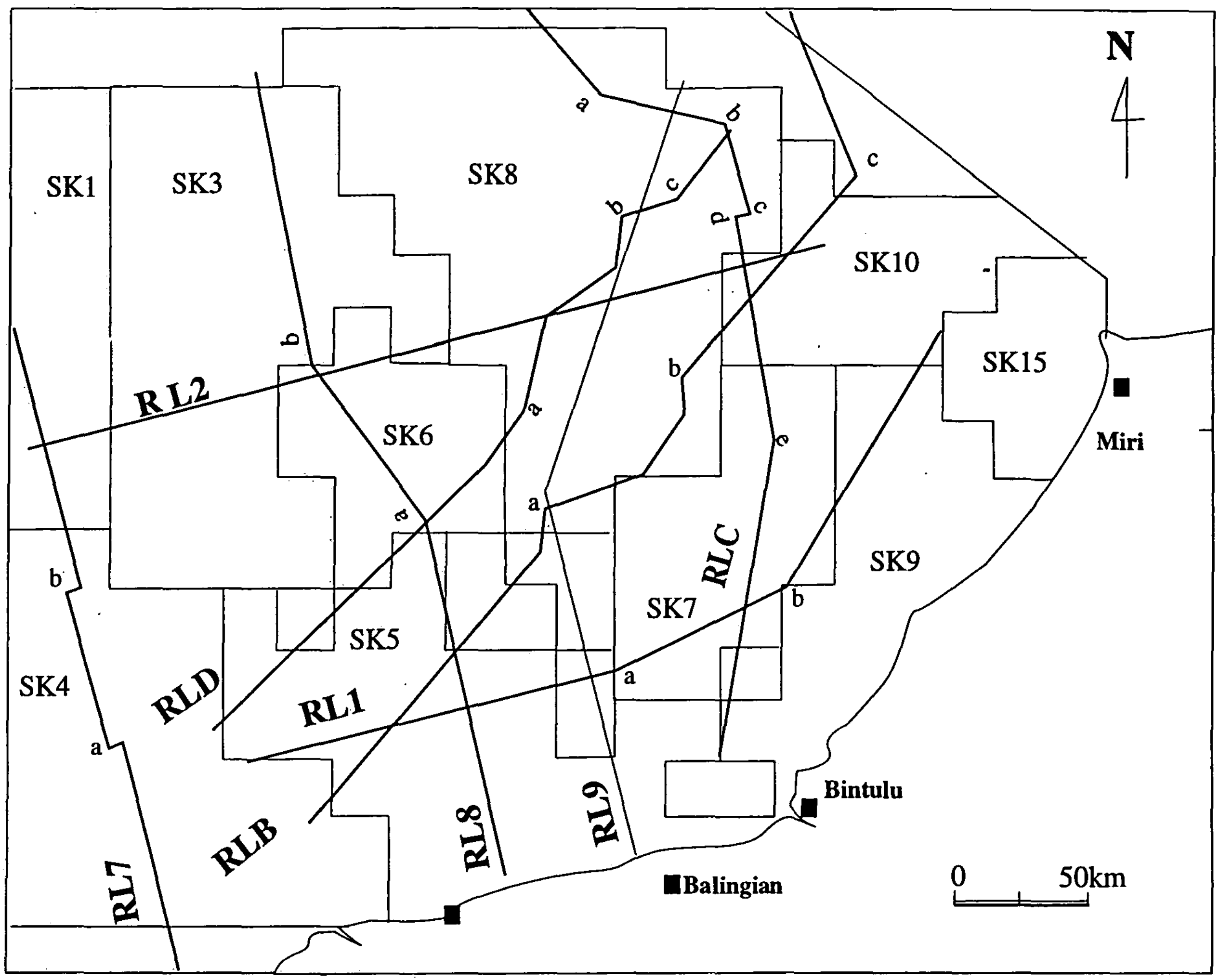


Figure 4.6. Map showing the location and orientation of the regional seismic lines in the offshore Sarawak.

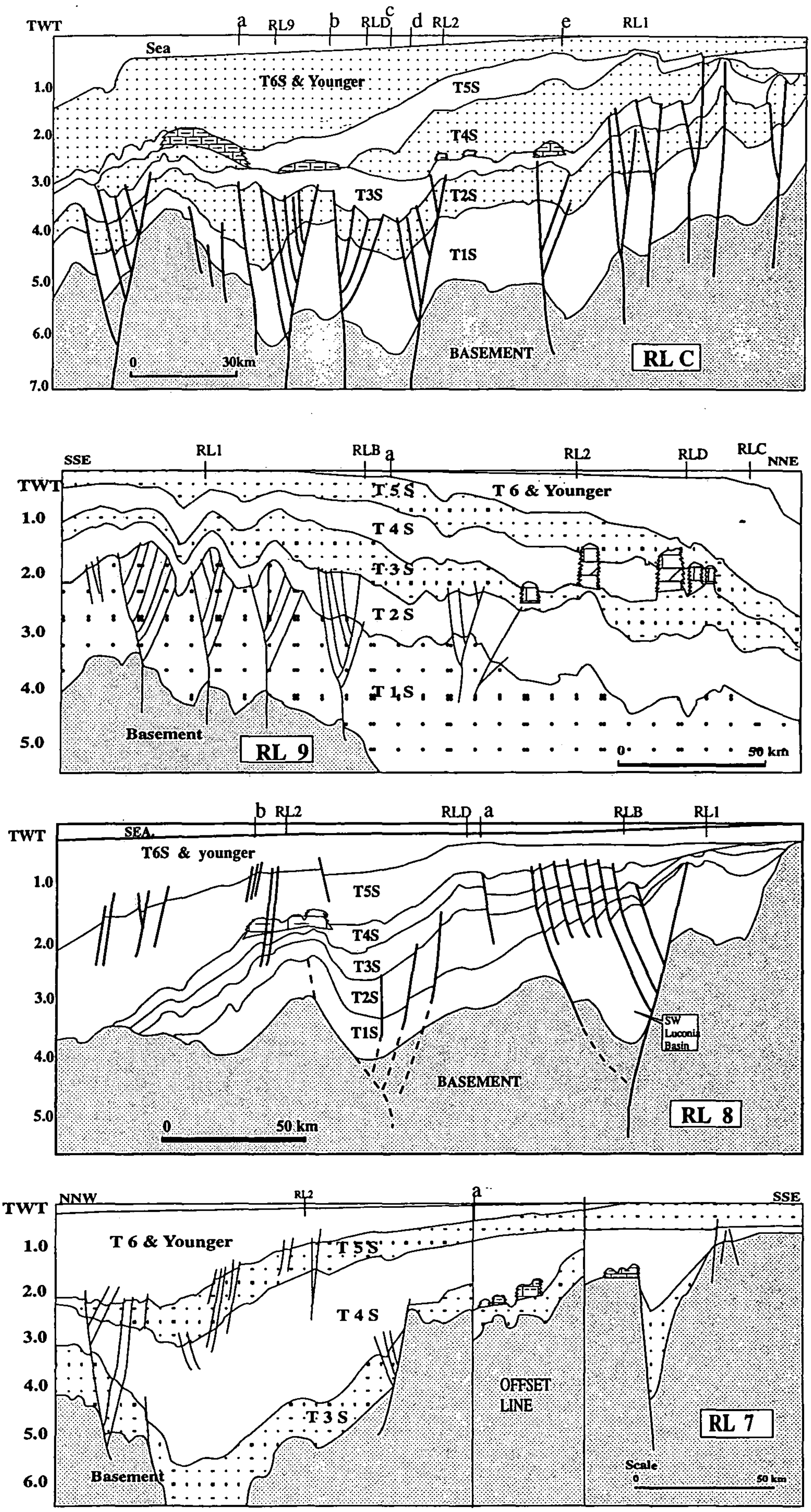


Figure 4.7. N-S regional seismic lines for the Sarawak Basin. Refer to the previous figure for the location and orientation of the lines.

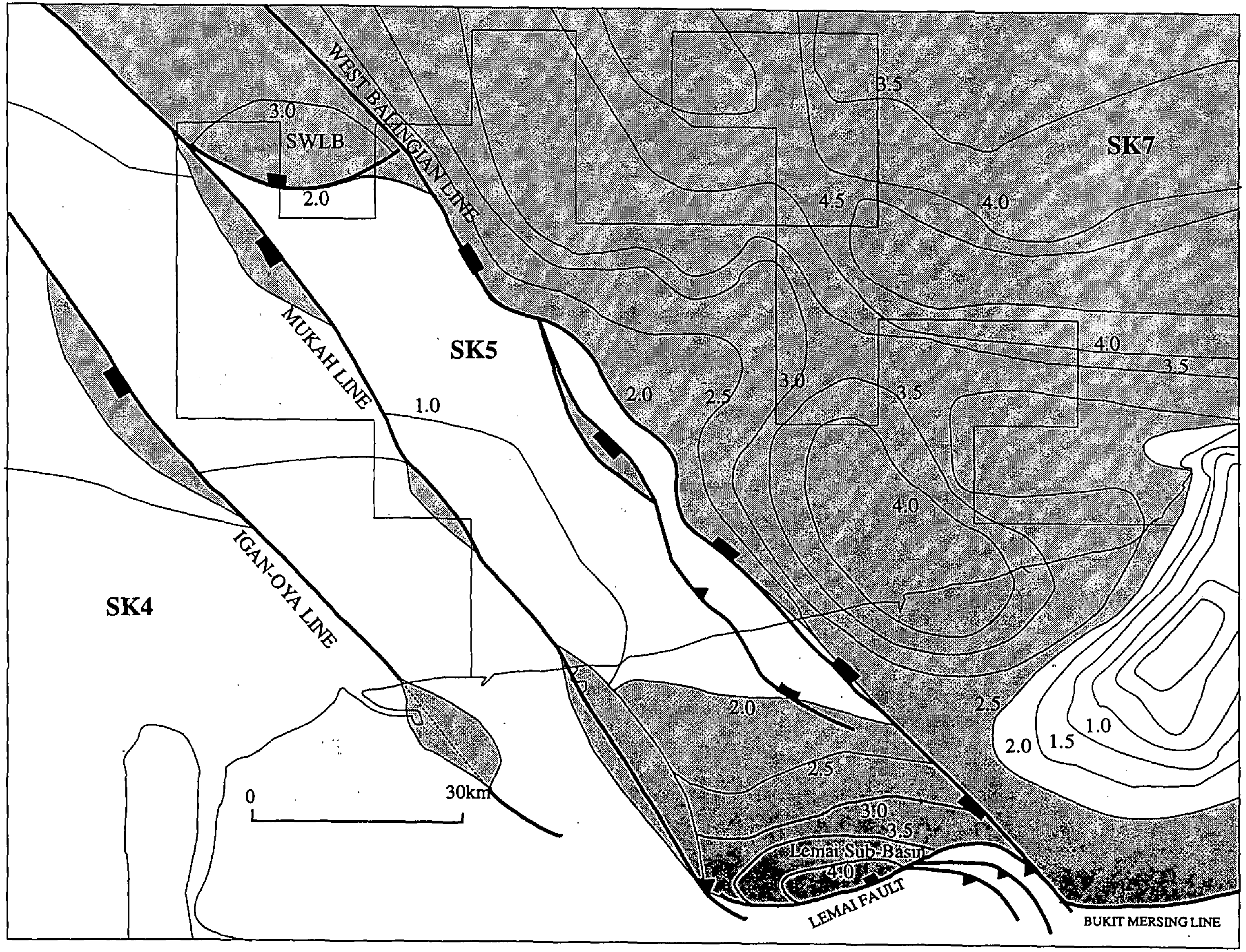


Figure 4.8. Basement topography map of the nearshore and onshore areas showing the orientation of the major tectonic lineaments in the area. Grey areas are the basinal area. SWLB-Southwest Luconia Sub- Basin.

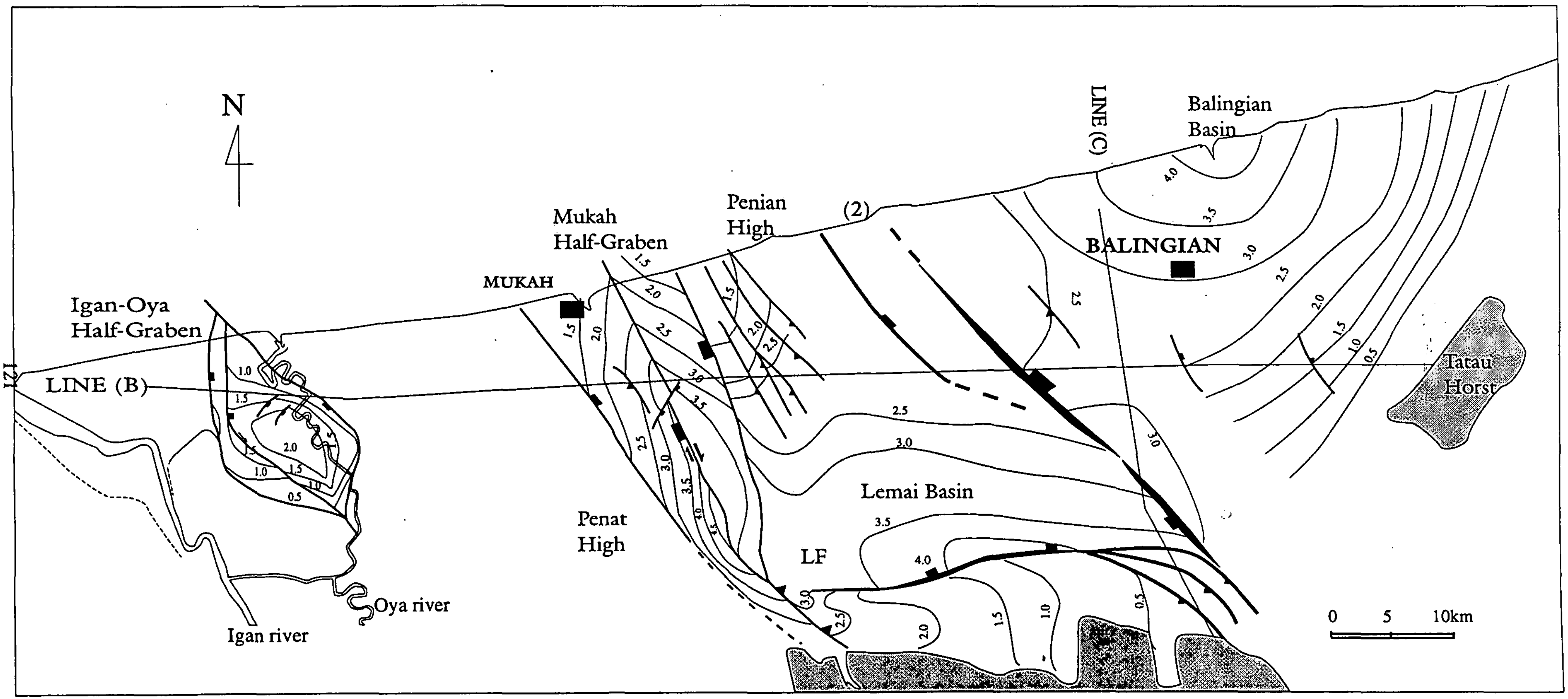


Figure 4.9. Basement topography map showing the major tectonic features in the onshore SK12 area. Contour intervals are in Second TWT.

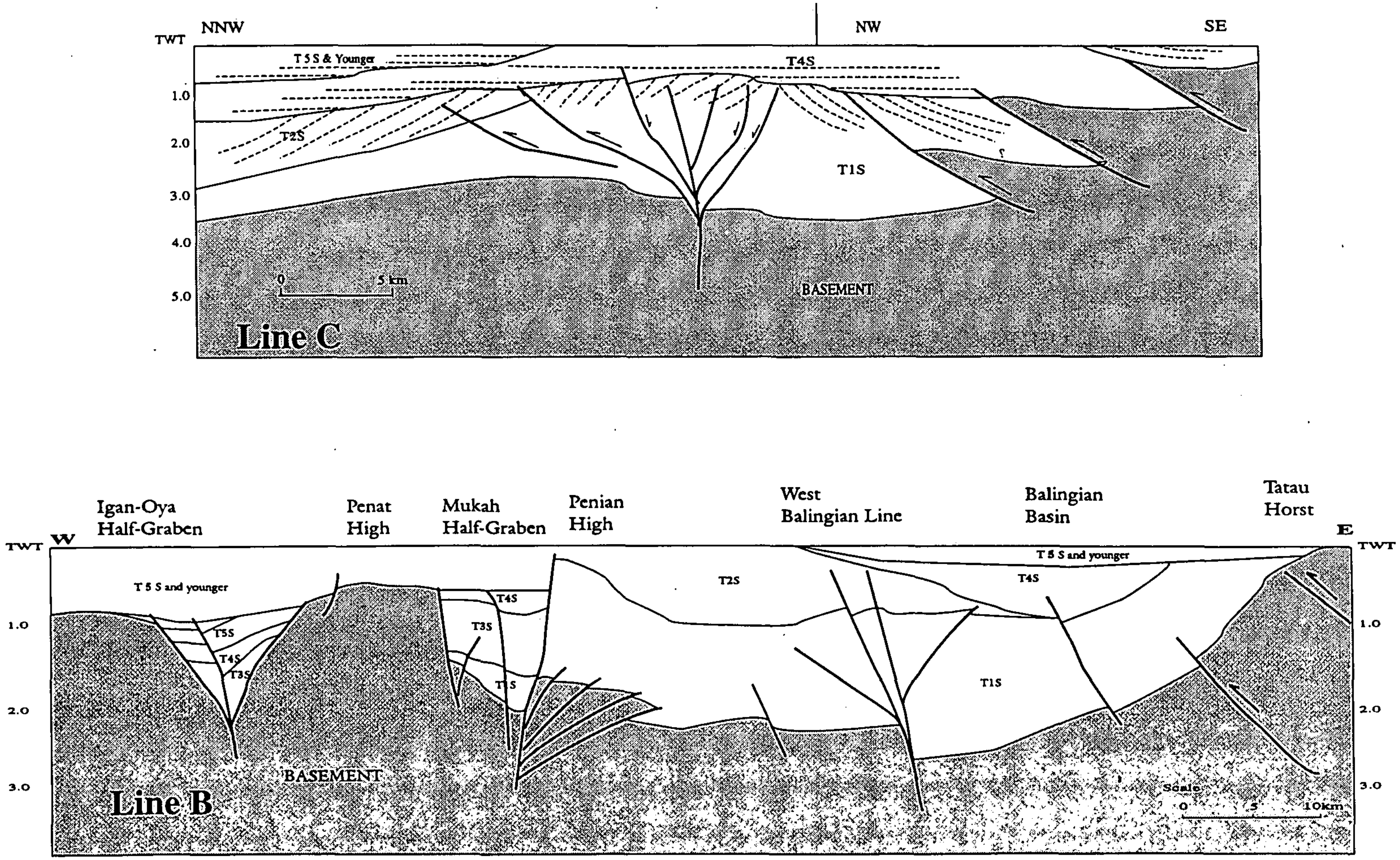


Figure 4.10. E-W and N-S geoseismic sections across the onshore area. Refer Figure 4.9 for the location of the two sections.

number of wells that penetrated the T1 sedimentary sequence in this basin. The occurrence of a small depression coincident with the location of the Southwest Luconia Sub-Basin has also been identified by several workers including Musbah (1991), and he named the area as the Southwest Luconia Graben. However, the detailed morphology of the depression could not be studied as the seismic data covering the area is very limited.

4.4 Tectonic Lineaments.

4.4.1. Introduction

As can be seen on the basement topography map for the offshore area of the Sarawak Basin (Figure 4.3), the Sarawak Basin comprises a series of NW-SE trending lineaments. A total of five major lineaments has been identified from this seismic mapping project and two of the lineaments are newly identified besides the three lineaments that have been described by several previous workers, as mentioned in Chapter One, Section 1.6.3.2. The five major lineaments are;

1. **Igan-Oya Line**
2. **Mukah Line**
3. **West Balingian Line**
4. **Tinjar Line**
5. **West Baram Line**

This section describes the orientation and the extent of these lineaments together with the occurrence of other geological structures that are believed to be related to them. The interpretation on the structural style and the tectonic environments of each of these lineaments will be discussed Section 4.5.

4.4.2 Igan-Oya Line

The Igan-Oya Line is a new proposed name for the western most lineament as this line passes through the area between the Igan and Oya Rivers (Figure 4.9). The basement topography and tectonic map of the Sarawak Basin (Figures 4.3, 4.9 and 4.9) show that the Igan-Oya Line extends from the offshore to the onshore areas. The line is in a NW-SE orientation and is sub-parallel to the Mukah and West Balingian Lines. The Igan-Oya Line is believed to continue farther to the south of the study area where the Synthetic Aperture Radar (SAR) interpretation by Kang and Khair (1990) identified a lineament that appears to be the southern extension of the Igan-Oya Line (Figures 4.11 and 4.12).

At least two narrow and deep half-grabens developed along the Igan-Oya Line, one in SK4 and another one in the onshore Igan area. The occurrence of this structure, the Igan-Oya Half-Graben, was identified by OPIC, the petroleum company currently operating in the SK12. Both the offshore half-graben and Igan-Oya Half-Graben have been tested by drilling. Although the seismic data in SK4 are sparse, the interpreted length of the half-graben structure is more than 50 kilometres, on the basis of well data that was drilled at about 30 km to the NE of the identified graben in RL7 (Figure 4.7) which penetrated the same sedimentary sequences. Further, this interpretation is also supported by the magnetic and gravity data (Figures 4.13 and 4.14). Therefore, the interpretation of the size of the graben in the area is believed to be conclusive. The Igan-Oya Half-Graben is smaller and measures about 25 x 10 kilometres.

4.4.3 Mukah Line

The Mukah Line is the new proposed name for the line passing through the depression called 'Mukah Half-Graben' by OPIC. The topography map of the Sarawak Basin (Figures 4.3), based on seismic interpretation, shows that it extends from the offshore to the onshore areas and continues southward. The line is in a NW-SE orientation and bends further in a E-W direction in the onshore area. On the basis of the data from SAR (Figures 4.11 and 4.12), Kang and Khair (1990) were able to trace a tectonic line that appears to be the continuation of the Mukah Line in the onshore farther to the south of the study area. However, the Mukah Line was not detected by the magnetic and gravity data, as can be seen in Figures 4.13 and 4.14.

Similar to the Igan-Oya Line, several elongated half-graben features developed along the Mukah Line (Figures 4.8 and 4.9). Each depression measures about the same size or slightly smaller than the Mukah Half-Graben which is about 10x30 km. Other than the Mukah Half-Graben, two other sub-basins have been identified located between the Mukah Line and the West Balingian Line, farther to the east of the Mukah Line. The morphology of the two sub-basins, namely the Lemai Sub-Basin and Southwest Luconia Sub-Basin, have been described earlier in Section 4.3.2.1.

4.4.4 West Balingian Line

The basement high and the Eastern Sub-Basin of the Sarawak Basin (Figure 4.3) are separated by the West Balingian Line (WBL). The WBL can be traced on seismic from the offshore area to the nearshore and the onshore areas. In the offshore area, the WBL has also been detected by both the magnetic and gravity data (Figures 4.13 and 4.14). The extension of the

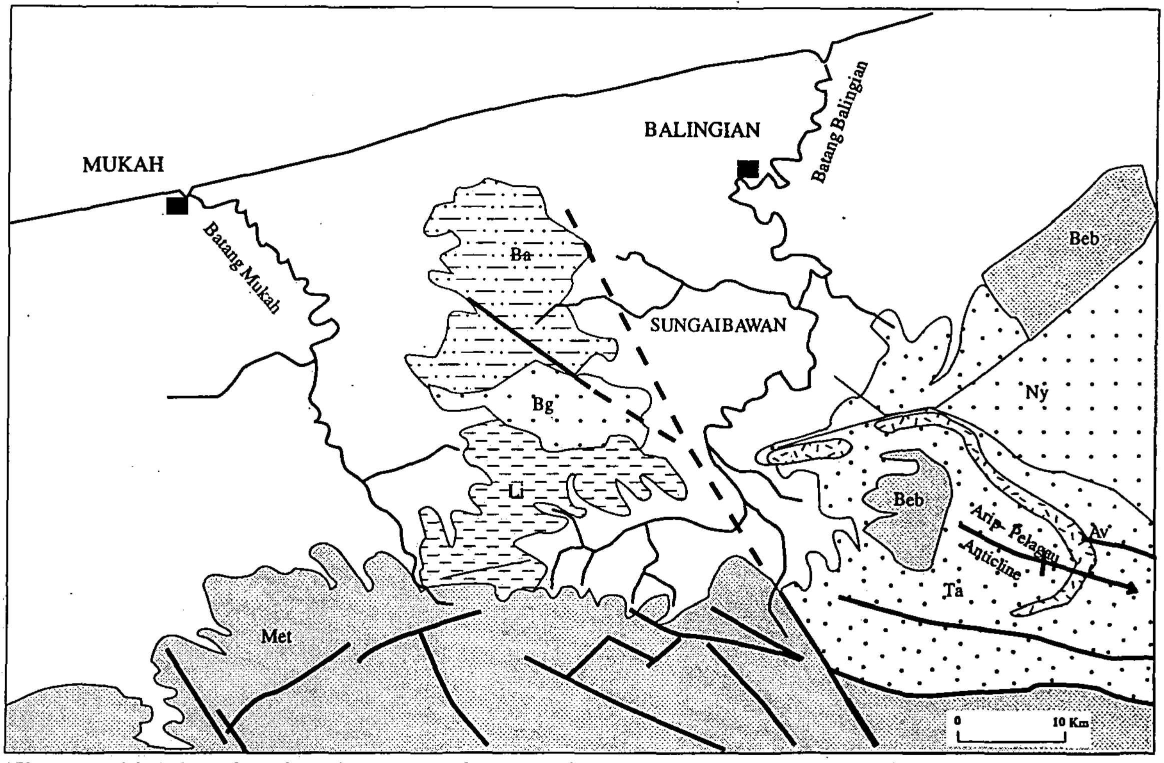


Figure 4.11. Map showing lineaments in the Balingian area, based on SAR interpretation: Beb-Bawan member and Met-Metah member of Belaga Formation, Beg- Begrih Formation, Li- Liang Formation, Ny-Nyalau Formation, Ta-Tatau Formation and Av- Arip Volcanic (after Kang and Kadir, 1990).

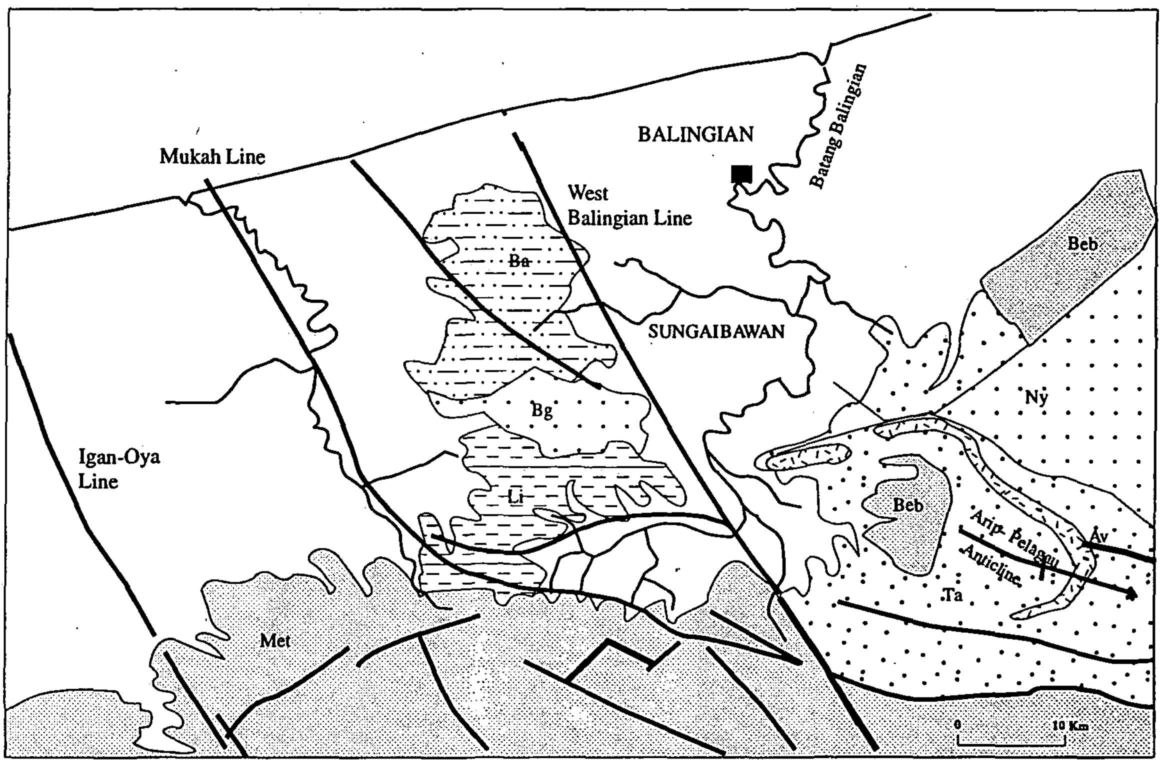


Figure 4.12. Map showing the tectonic lineaments in the onshore area, as a combination of seismic and SAR interpretations. Note the extension of the West Balingian Line, Igan-Oya Line and Mukah Line to the area farther south of the study area.

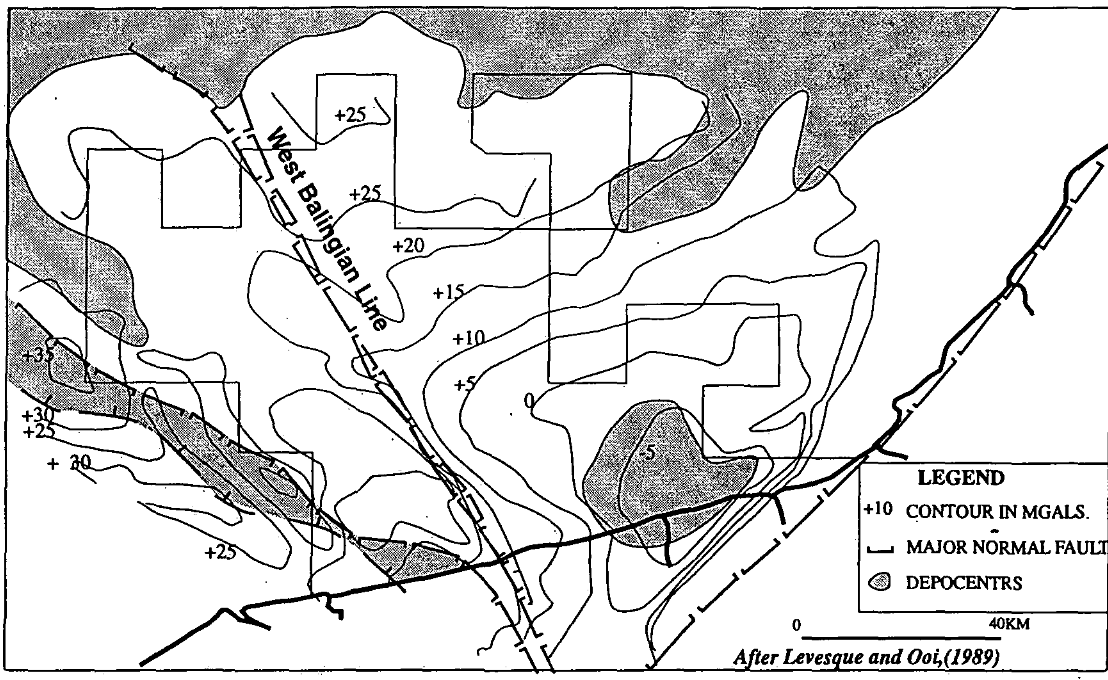


Figure 4.13. Bouger gravity basement map showing the depressions and the shallow basement in the nearshore area. Although the contour interval, sampling intensity and technique used between this figure and Figure 4.1 are different, the general features of the basement are in agreement with the seismic interpretation. This includes the shallow basement area to the west of West Balingian Line (WBL), mid-ridge to the east of WBL and the depression area of Balingian Basin .

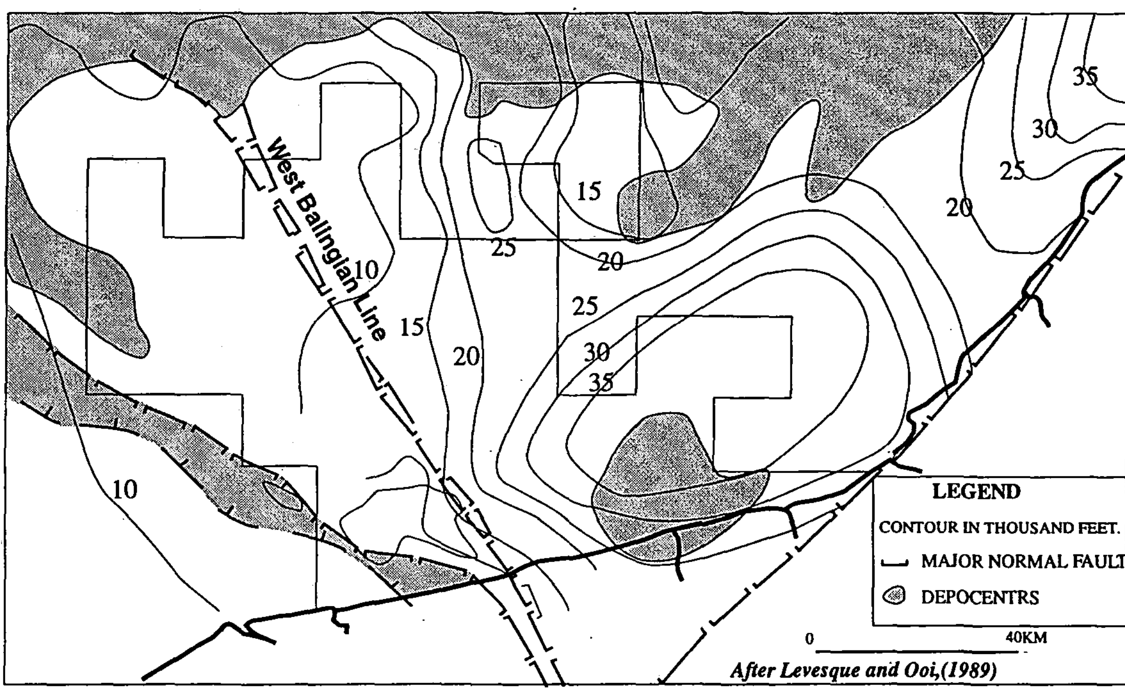


Figure 4.14. Magnetic basement map showing the depressions and the shallow basement in the nearshore area.. Although the contour interval and the sampling intensity and technique used are different from the seismic, the general features of the basement are in agreement with the seismic interpretations including the shallow basement area of the Penian and Penat Highs and the depression of Balingian Basin to the SE.

WBL in the onshore area has been detected by Synthetic Aperture Radar (Figures 4.11 and 4.12), as well as being evident from both magnetic and gravity data (Figures 4.13 and 4.14), besides the seismic. In the onshore area the WBL offsets the late Oligocene sediments of the TIS sediments in the Lemai Sub-Basin and the outcrops of Tatau Formation in the Bukit Mersing area for about 15 kilometres to the SE (Figure 4.8).

This major fault zone trends NW-SE, similar to known major strike-slip faults in the region including the Tinjar Line (Tan, 1990). Lavesque and Ooi (1989) suggested that the West Balingian Line coincides with a marked regional trend and the line was believed to have a history of right lateral movement. In contrast, Hazebroek (1993) deduced that the area was a sinistral wrench system. The interpretation of the tectonic nature of the West Balingian Line is discussed in Section 4.5.

4.4.5. Tinjar Line.

Farther to the east of the Sarawak Basin, in the offshore Miri area, two other lineaments have been identified, called the Tinjar Line and West Baram Line (Figure 4 3). The Tinjar line is interpreted to extend to the onshore area, where James (1984), Hutchinson (1988), Tan and Lamy (1990) and Tjia (1994) interpreted the line as a dextral strike-slip fault. To our knowledge, the occurrence of the Tinjar Line in the offshore area has not been reported to date. As has been discussed in Chapter One, Section 1.6.3.2, Tan and Lamy (1990) and Tjia (1994) interpreted the Tinjar Line in the onshore as the continuation of the West Baram Line in the offshore area.

The results of this mapping are different; two sub-parallel lines are recognised in the offshore Miri area. The line to the west which is here called the Tinjar Line can be projected into the onshore area and is coincident with the tectonic lineament along the Tinjar River (Figure 4.15). Therefore, it is concluded that the Tinjar and WBL are two different lines, instead of a single line which represents the onshore and offshore extension of a major strike-slip line in the Miri area called WBL.

4.4.6 West Baram Line

The West Baram Line in the offshore Miri area is sub-parallel to the Tinjar Line. However, the landward extension of the line offset the Tinjar Line in the area to the east of Usun Apau, near the Sarawak-Kalimantan border (Figure 4.15). As it has been mentioned earlier, the Tinjar Line in the onshore was interpreted to be the onshore extension of the West Baram Line. The interpreted location of the onshore extension of the West Baram Line is certainly

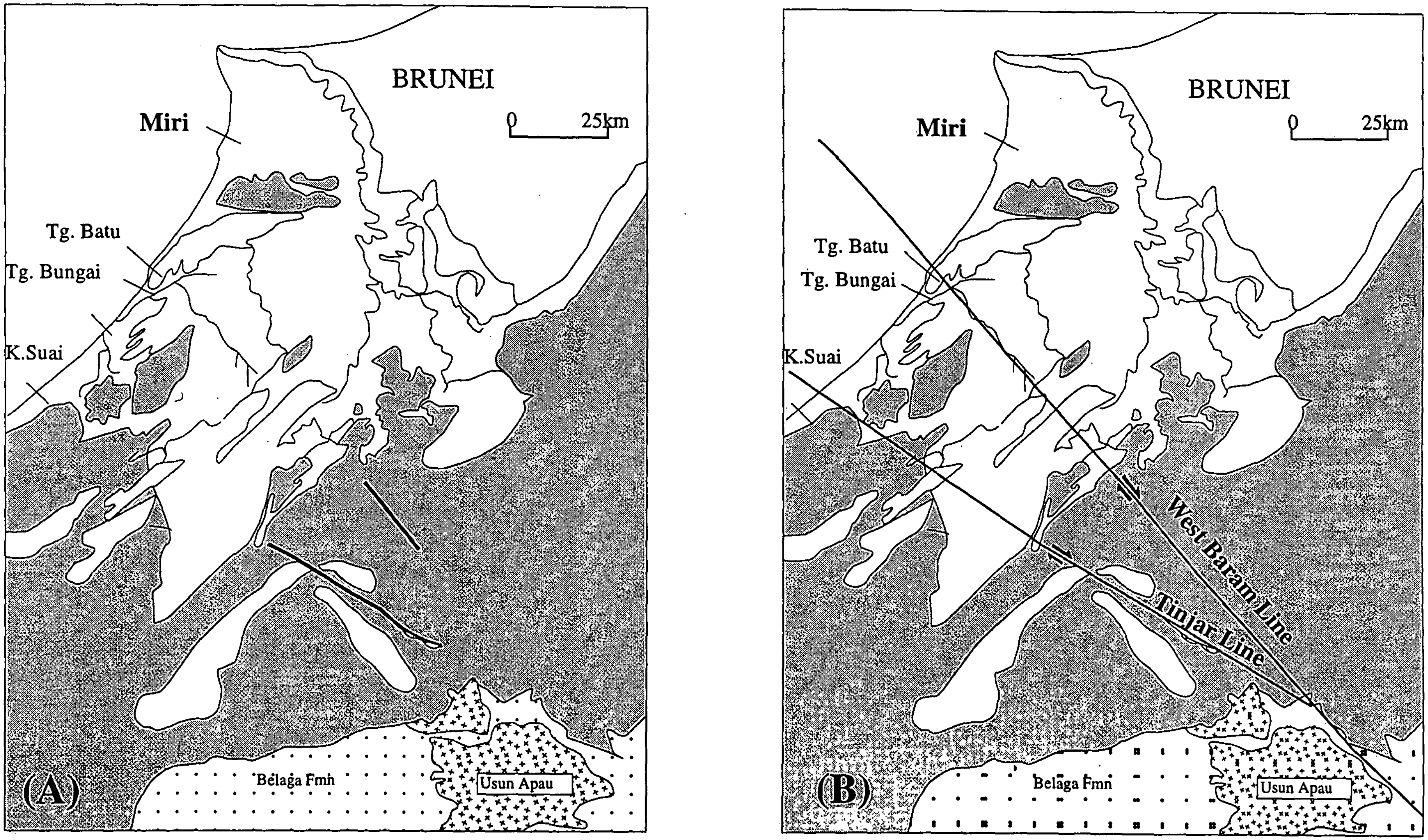


Figure 4.15. (A) Sketch geological map of the area to the south of Miri, Sarawak based on Heng (1992). Areas in grey are undifferentiated Oligo-Miocene Nyalau, Tubau, Lambir and Setap shale formations. Areas in white are the Miocene-Pliocene Belait, Sibuti and Tukau Formations. The map also shows the orientation of the onshore lineaments that aligned to the Tinjar and West Balingian Lines in the offshore area. The thick lines are the tectonic lineaments. (B) The onshore projection of the two tectonic lines.

different from the previous interpretations. The basis for interpreting the West Baram Line to be in the location and orientation as shown in Figure 4.15 is as below:

1. The projection of the West Baram Line from the offshore was made to the coastline, which falls at a point in the vicinity of Tanjung Batu.

2. There is a river to the landward of Tanjung Batu which has a similar orientation to the West Baram Line which is roughly in the NE-SW orientation.

3. Farther to the SE, in the highland area, a lineament which is in a similar orientation to the West Baram Line has been mapped by the Geological Survey of Malaysia (Heng,1992).

4. Further to SE, the Oligocene-Miocene Setap Shale was laterally offset to SE in a similar orientation to the West Baram Line

On the above basis, it is interpreted that the West Baram Line did continue to the onshore area with the orientation and location shown in Figure 4.15, instead of along the Tinjar Line as interpreted by the previous workers.

4.5 Structural styles and tectonic environments of the major tectonic lineaments.

4.5.1. Introduction

This section describes the structural style and the nature of each of the five lineaments and other geological structures, including the half-grabens; that are believed to have formed simultaneously with tectonic lineaments. This is done through description and analysis of the kinematics, and the possible source and direction of the generating force of these structures. Comparison of these features with published information is made, which should help in understanding the nature of the identified lineaments, particularly as to whether the lineaments have the characteristics of normal, reverse and/ or strike-slip fault systems.

As has been discussed in Section 4.4, several identified lineaments including the Mukah and Igan-Oya Lines are associated with the features called 'half-graben' that occurred along the lineaments. Therefore, prior to discussing the tectonic nature of the identified lineaments, the formation of the half-grabens is first reviewed to help in understanding the tectonic nature of the lineaments.

4.5.1.1. The formation of half-graben structures.

The formation of half-graben structures can be related to several tectonic environments including continental extension by ***large extensional faults*** (Robert and Yielding, 1993) and ***normal faults*** under the influence of lithospheric stretching (Allen and Allen, 1990). Similarly, the basins that resemble the 'half-graben' features could also be generated by ***strike-slip faults*** (Christie-Blick and Biddle,1985).

According to Robert and Yielding (1993), a ***large extensional fault*** is defined as one whose dimensions are sufficient to cut the entire seismogenic layer, that is the part of the crust which responds to stress by brittle failure. The faults are therefore those which can be reasonably assumed to penetrate the crust to a depth of about 15 km. There has been considerable debate about whether the major faults that accommodate crustal extension are essentially planar structures or whether they form linked networks of listric faults within the upper crust. The overwhelming evidence of earthquake data indicates that active, large normal faults are essentially *planar faults* (Straight in cross-section) throughout the seismic layer, with dips in the range 30-60 degrees. There is no evidence for the existence of seismically active, low-angle or markedly *listric faults* provided by earthquake data and there is no recorded example of active, normal fault surfaces with strike greater than 25 km. The role of isostasy and flexure in normal faulting causes subsidence of the hanging wall (forming the half-graben) and uplift of the footwall. The location of the half-graben and the uplifted footwall in respect to a major normal fault are shown in Figure 4.16.

The occurrence of half-graben induced by a ***normal fault*** in an extensional basin due to lithospheric stretching has been discussed by Allen and Allen (1990). They showed that the shape of the normal fault may be either planar or listric. The normal faults that exhibit rotation of beds are likely to be listric in shape but seismically active faults appear to be planar and inclined at roughly 45°. Two types of half-graben associated with normal fault have been identified. The half-graben with faults which show strong updip convergence of beds (Figure 4.17) indicates that the displacement was taking place at the same time as sedimentation. However, if sub-horizontal beds showing no major thickening or thinning, the displacement may be effectively instantaneous compared to the rate of sedimentation.

Several examples of basin formation along ***strike-slip faults*** zone have been discussed in Christie-Blick and Biddle (1985) including the basin along the North Anotolian Fault in Turkey, Walker Lake and the Vienna Basin. According to Allen and Allen (1990), in general, subsidence tends to occur where strike slip is accompanied by a component of divergence. This might result from a *bend* or an *overstep* in the fault trace, giving a *pull-apart basin*, or

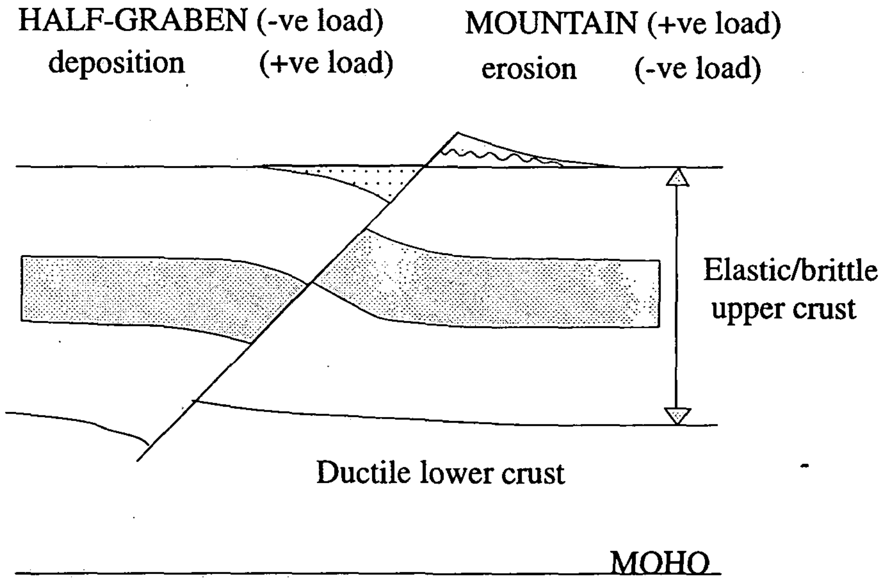


Figure 4.16. Schematic diagram of the isostatic loads generated by a large normal fault. Uplift of the footwall and subsidence of the hanging wall generate positive and negative load respectively. Erosion of the footwall and sediments deposition in the hanging wall act to reduce this initial loads. The isotatic loads are supported by the flexural rigidity of the elastic/brittle upper crust. Redrawn based on Robert and Yielding (1993).

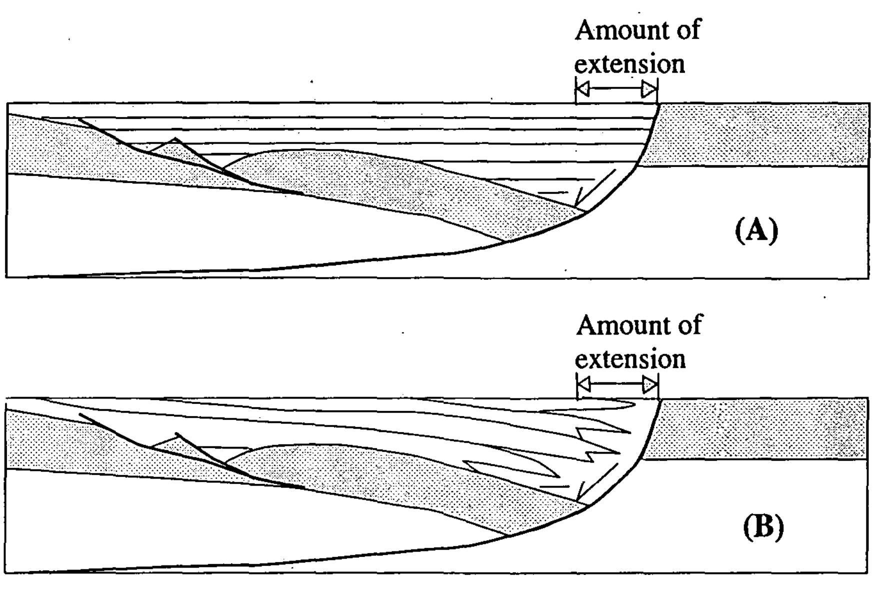


Figure 4.17. Extension in a half-graben with and without syntectonic sedimentation or 'growth' in the basin formed due to lithospheric strectching. In (A) the strata in the half-graben are parallel and do not show growth into the fault plain. In (B) the strata are divergent and thicken into the fault plain, indicating tectonic displacement at the same time of the deposition. Redrawn based on Allen and Allen (1990).

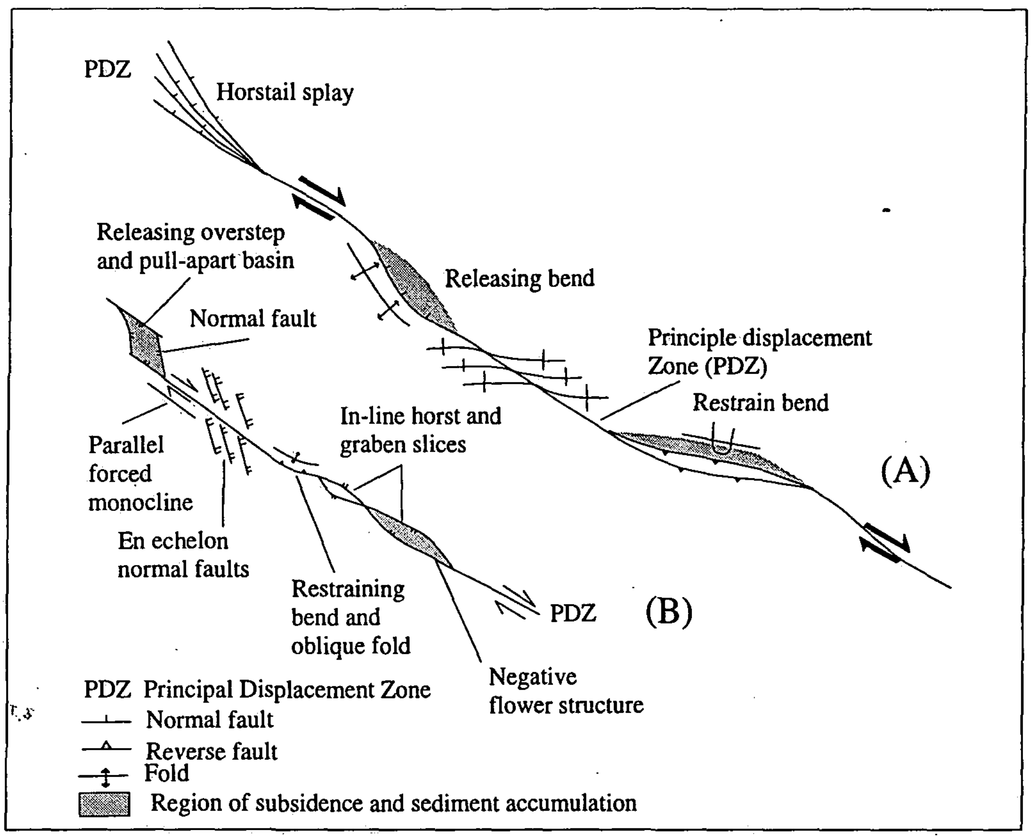


Figure 4.18. (A) The plan-view arrangement of structures associated with an idealised right-lateral (dextral) strike-slip fault. (B) Adaptation to a slightly divergent setting with the predominance of pull-apart, en echelon normal faults and graben slices within the PDZ. Redrawn based on Allen and Allen (1990).

through extension near a fault junction, giving a *fault-wedge basin* (synonym wedge graben). Bends, oversteps and fault junctions associated predominantly with extension and subsidence are termed *'releasing'*, whilst those associated with shortening and uplift are termed *'restraining'*. Figure 4.18 illustrates the terminology used and shows the location of the basins in a strike-slip fault system.

4.5.2. Igan -Oya Line

4.5.2.1. Morphology of Igan-Oya Half-Graben

The most striking aspect of the geometry of the Igan-Oya Half-Graben is its simple leaf-shape with elongation in NW-SE directions with a total length of about 25 km. The middle part of the basin measures about 15 km and the basin skews in the E-W direction. This sub-basin is preserving the T3S, T4S and younger sequences (Figure 4.19) as was confirmed by drilling. The deepest part of the graben reaches 2.8 seconds TWTs; that is about 5,000 metres (Figures 4.19D)

The Igan-Oya Half-Graben forms in between three main faults, with one major fault to the east and two faults to the west (Figure 4.19). Both faults are basement-involved faults and the three faults are eventually merged at depth, to form a single vertical axis, in the northern and southern part of the graben. The eastern fault has an angle of about 50° with the fault's heave of about 4 km over the throw of about 5 km at the shallower depth, which is very similar to the other two bounding faults (Figure 4.10D). Two normal faults with the strike of about N30°E and one anticline structure (within the T3S) with the fold axis in the similar orientation of the half-graben have been identified (Figure 4.19B). The fold structure that can be seen on Figures 4.19C and 4.19E, has been tested by drilling.

4.5.2.2. Timing and mechanism for the formation of Igan-Oya Half-Graben.

The basal unit of the sedimentary sequences preserved in the Igan-Oya Half-Graben and another half-graben structure along the Igan-Oya Line in the offshore area, as can be seen on RL7 (Figure 4.7), are made up of predominantly Middle Miocene (T3S) sediments. The age of the basal sediments suggests that the Igan-Oya Line was active and the formation the Igan-Oya Half-Graben had taken place during the Middle Miocene times.

In discussing the mechanism for the formation of the Igan-Oya Half-graben, the geometry, the size and the shape of Igan-Oya Half-graben, is first compared with half-graben structures

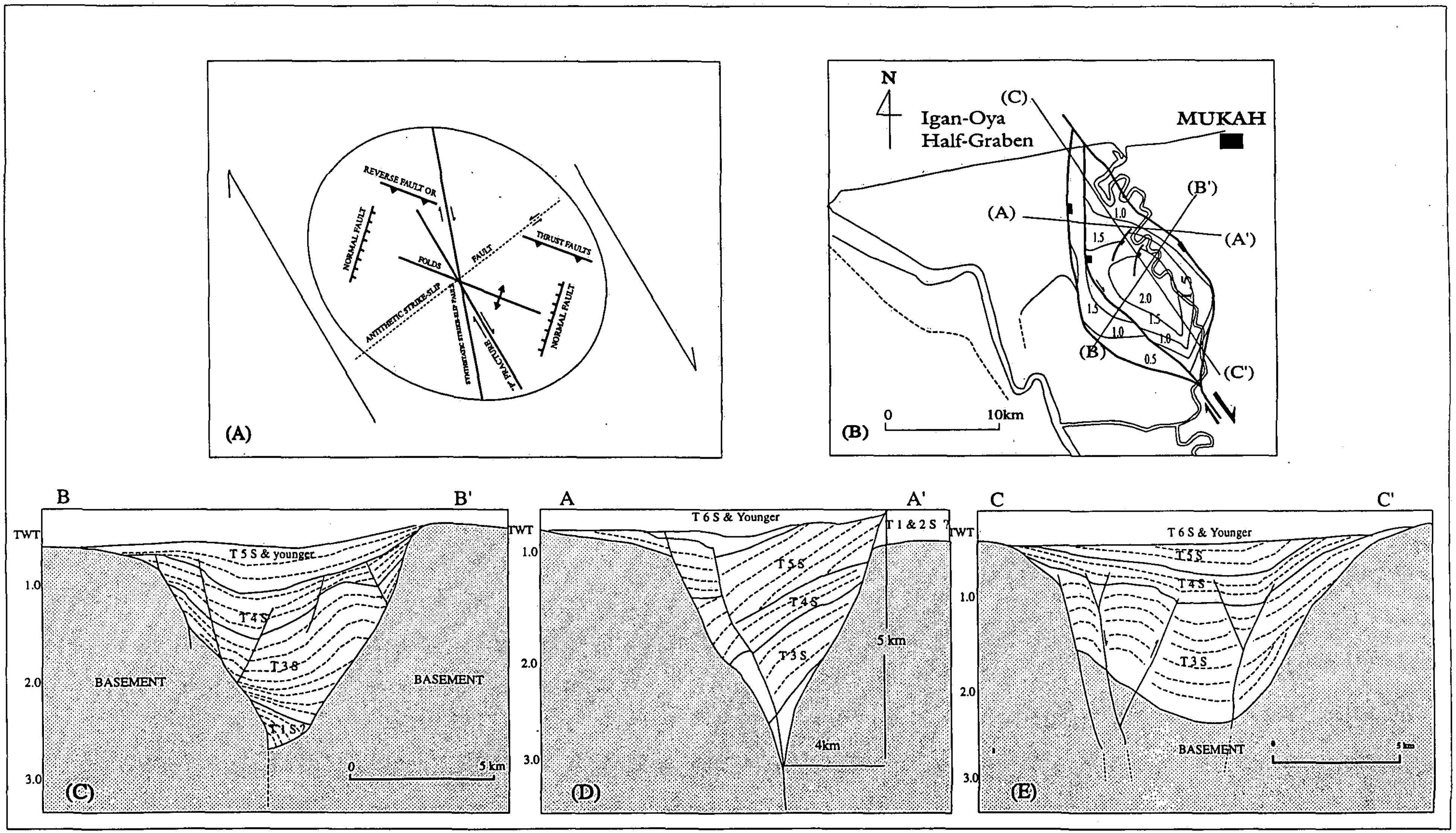


Figure 4.19. (A) Strain ellipse digram for strike-slip assemblage from a right-lateral couple based on (Lowell,1985). (B) Basement topography map showing the morphology of the Igan-Oya Half-Graben and the orientation of the geoseismic sections. (C) and (D) are the sections across the sub-basin and (E) is the line along the sub-basin.

induced by big normal or extensional faults. The half-graben structures created in the extensional setting are normally characterised by a steep wall on one side, produced by the major fault and the opposite wall is normally gentler (Figures 4.16 and 4.17). The geometry of Igan-Oya Half-Graben, however, is different from that bounded by steep faults on both sides (Figure 4.13).

In terms of size, the length of the Igan-Oya Half-Graben is about 25km; that is about the size of half-graben formed by large extensional faults. Other half-graben features along the Igan-Oya Line (in SK4) have the length along the fault strike greater than 25 km, with some structures exceeding 50 km.

The geometry, size and shape of the Igan-Oya Half-Graben is skewed in the E-W direction and the angle of the bounding faults are almost vertical in the deeper depth. This does not agree with the features of a half-graben structure that is associated or derived by either the large extensional normal fault or normal fault in extensional basin due to lithospheric stretching.

In view of: (1) The shape of the half-graben, which is skew in the E-W direction, suggests a direction of extension, and (2) the orientation of the normal faults and the anticline structure within the half-graben that having the spatial relationship to the dextral strike-slip movement with the principal displacement direction in the NW-SE orientation (Figure 4.19A), the Igan-Oya Half-Graben is interpreted as a dextral pull-apart basin. Comparing the structures associated with the dextral strike-slip fault (Figure 4.18) the Igan-Oya Half-Graben is identical to the structure called '*in-line graben slice*' rather than a typical pull-apart basin associated with releasing oversteps. The major opening of the half-graben, based on the preserved sediments, is interpreted to have taken place during the Middle Miocene (T3S times).

4.5.2.3. Analogous basins to Igan-Oya Half-Graben.

From the literature, there are many pull-apart basins that have a similar skewed shape in respect to the primary shear direction as the Igan-Oya Half-Graben. Examples include the pull-apart basin along North Anatolian Fault in Turkey that develops by dextral strike-slip movement (Figure 4.20A) based on the work of Sengor et al. (1985). The second analogous basin is the Walker Lake Basin, Nevada located between the Wassuk Range and the Gillsis Range (Figure 4.20B) within the dextral strike-slip system (Link et al., 1985).

Another basin with the shape analogous to the Igan-Oya Half Graben is the Vienna Basin (Royden, 1985). However, the Vienna Basin was formed by the thin-skinned pull-apart process within the sinistral strike-slip system. Nevertheless, by viewing the shape of the basin

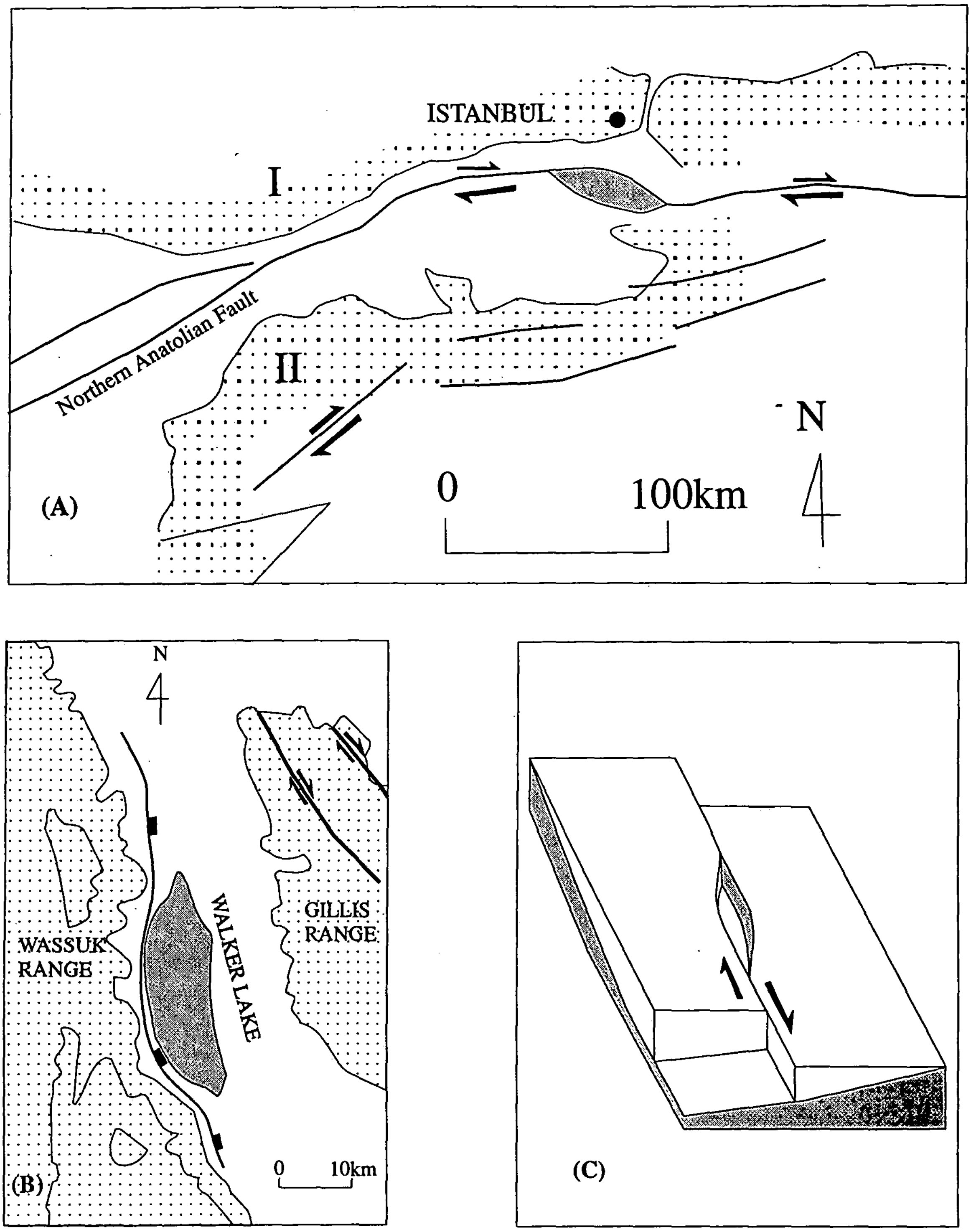


Figure 4.20. (A) Map showing a simplified version of the geometry and kinematics at the western termination of the North Anatolian Fault. I and II are the northern and southern strands of the North Anatolian Fault respectively. Note also the shape of the simple pull-apart basin along the fault (After Sengor, 1985). (B) Map showing the shape of Walker Lake that formed along the dextral strike-slip system along Gilis and Wassuk Ranges. Note the shape of the lake that is bounded by the normal fault on the west side, subparallel to the strike-slip fault to the east (After Martin et al., 1985).
(C) Schematic diagram showing how extension within the Vienna Basin is related to strike-slip faulting. Note the shape of the basin(in dextral slip motion) is similar to the shape of Igan-Oya Half-Graben.

from the back of the page, the shape of the Vienna Basin (Figure 4.10C) and the Igan-Oya Half-Graben are very similar.

4.5.2.4 Interpretation of the tectonic nature of Igan-Oya Line.

On a similar basis to the formation of Igan-Oya Half-Graben and the thorough-going nature of the line, it is interpreted that the Igan-Oya Line was unlikely to be formed by a normal extensional fault. Instead the thorough-going nature of the fault and the shape of the basin along the line that is analogous to several pull-apart basins world-wide, it is interpreted that the Igan-Oya is a dextral strike-slip lineament. Similarly, on the basis of the age of the preserved sedimentary sequences within the half-graben features along the Igan-Oya Line, it is interpreted that the main dextral strike-slip movement along the line took place during Late Miocene times.

4.5.3 Mukah Line

4.5.3.1 Morphology of the Mukah Half-Graben.

The Mukah Half-Graben in the onshore Mukah area is a wedge-shaped basin which opens up to the NW and narrows to the SE (Figure 4.21B). The sub-basin is bounded by steep faults to the east and the west. The wider part to the north measures about 15 km, and the basin terminates to the S near the outcrops of Belaga Formation. The total length of the basin in the onshore area exceeds 30 km and extends farther to the nearshore area. However, the exact measurement of the nearshore extension is not known due to sparse seismic coverage in the area to the north of the Mukah Half-Graben. The E-W cross section in the northern part of Mukah Half-Graben shows that there are three main faults that controlled the deposition of sediments in the structure. The faults are called the West-Bounding Fault, Mid-Fault and East-Bounding Fault (Figure 4.21D).

The West-Bounding fault marks the western boundary of the T1S. The Mid-Fault and East-Bounding faults eventually meet at a single vertical axis in the deeper subsurface (at the basement level) and small faults between the two main faults (Figure 4.21D) are mainly in a normal sense with the fault's penetrations limited to the shallow depth and younger sedimentary sequences. Farther to the south of the graben, the above-mentioned relationship among the two main faults is no longer seen. Instead, the East-Bounding Fault and Mid-Fault merge and form a reverse fault thrusted to the west (Figure 4.21C). Within the half-graben, a basement-normal fault with orientation about N30°E and one reverse fault with the orientation of about N30°W, thrusting to the NE, have been mapped (Figure 4.21B).

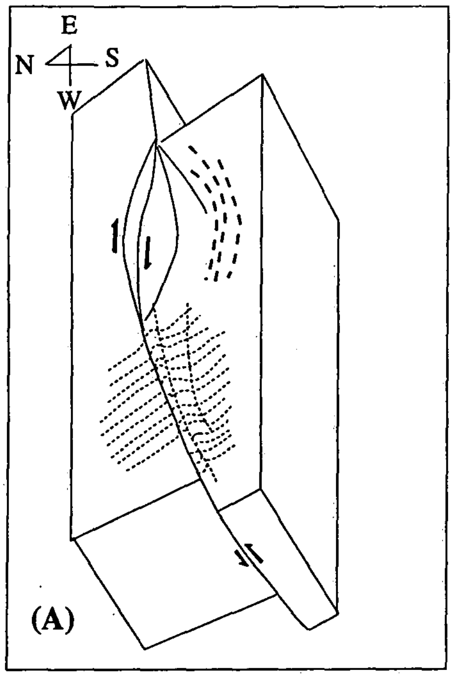
The deepest part of the Mukah Half-Graben reaches 4.5 Sec TWT (Figure 4.21B); that is about 9,000m (Figure 4.4). The basin is infilled by all the identified sequences except the T2S. The oldest sedimentary unit preserved within the Mukah Half-Graben is probably T1 Sequence (Figure 4.21D). However, the oldest sedimentary unit in the other offshore grabens along the Mukah Line is T3S as can be seen on RL1 and RLD (Figure 4.5).

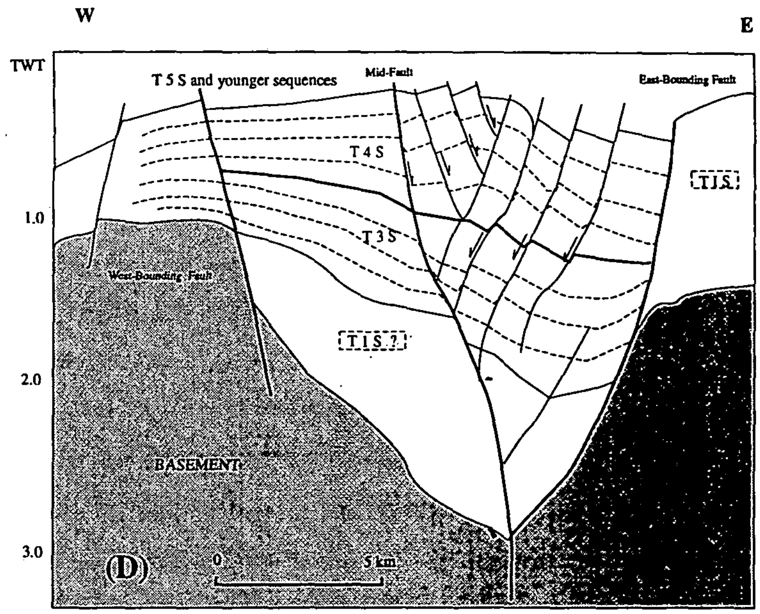
4.5.3.2 Timing and mechanism for the formation of Mukah Half-Graben.

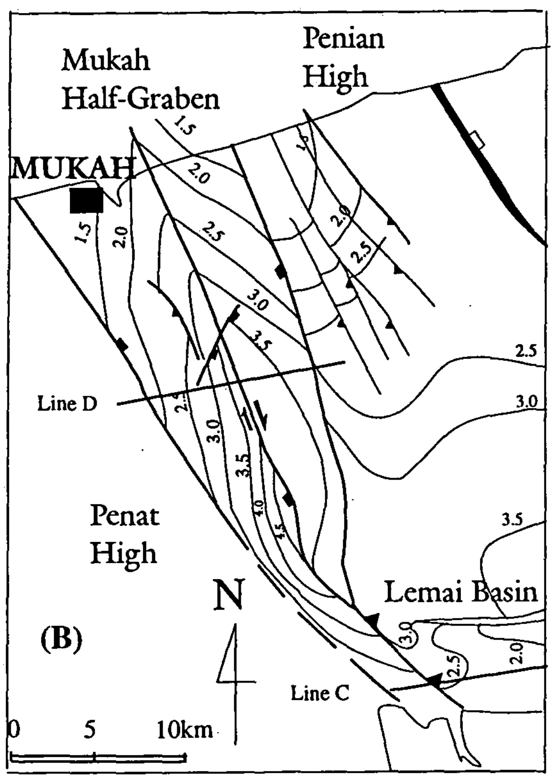
The preserved sediment of T1S and other sequences except the T2S in the Mukah Half-Graben, suggests that the graben was reactivated at least two times. The initial opening of the Mukah Half-graben might have taken place during or prior to the deposition of T1S (Eocene-Oligocene times) and reactivated during T3S times (Middle Miocene).

The presence of the composite faults in the area between the Mid-Bounding and the East-Bounding faults, which could possibly be either a negative flower structure or antithetic faults provides the information about the graben's movement during the T3S and T4S times. It suggests that the eastern and western blocks had moved obliquely apart during the opening of the half-graben, when the sediments adjusted to the newly created space. On the basis of the relationship between the Mid-Bounding and the East-Bounding faults that are characterised by extension to the north and compression to the south, it suggests that the opening of the Mukah Half-Graben not only involved vertical but also horizontal displacements. Therefore it is interpreted that the faults between the Middle and Eastern-Bounding faults are a negative flower structure instead of normal antithetic faults as one of the definitive structural criterion for differentiating the divergent wrench fault (negative flower structure) and normal fault is the presence of reverse faults that form locally at the restraining bends (Harding, 1985).

The interpretation and discussion therefore, imply that the Mukah Half-Graben was formed as a pull-apart basin as the result of strike-slip movement along the Mukah Line which is characterised by the transtension and transpression to the north and the south respectively. The interpretation is also supported by the presence of reverse and normal faults within the graben that have a consistent spatial relationship with dextral strike-slip assemblages (Refer to the strain ellipse diagram in Figure 4.19A), with the principal displacement direction in the NW-SE orientation. It is also suggested that the Mukah Half-Graben is unlikely to have formed by the large extensional fault or other normal fault that solely involved vertical displacement. Other than the above, the geometry and the shape of the Mukah Half-graben are analogous to known pull-apart basins along strike-slip lines elsewhere in the world.







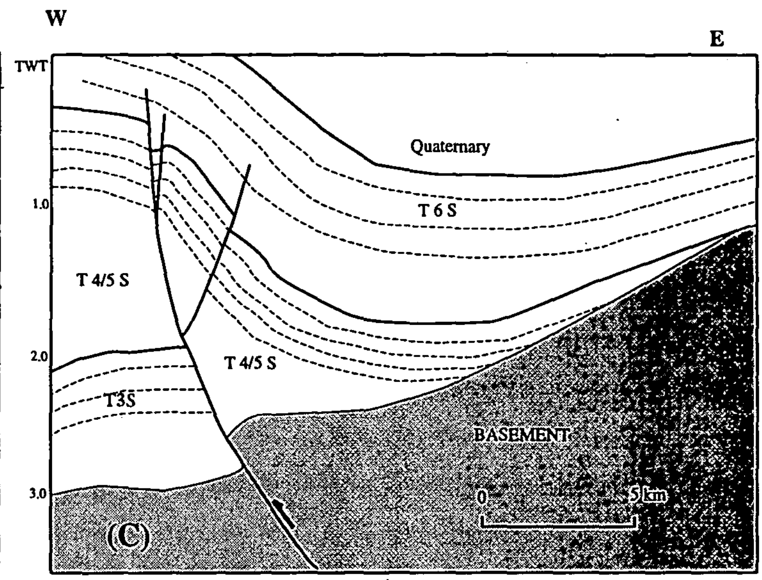


Figure 4.21. (A) Block diagram of Hanmer Basin, formed along Hope Fault in New Zealand. The basin is characterised by transtension and transpression to the west and east respectively (After Wood et al., 1994). The geometry and kinematics of the Mukah Half-Graben, as shown by the basement map in (B) and the geoseismic sections in (C) and (D), are believed to be analogous to the Hanmer Basin. Refer to (B) for the orientation on the geoseismic sections.

4.5.3.3. The analogous basins to Mukah Half-Graben

From the literature, there are many pull-apart basins that they have a similar wedge-shape as the Mukah Half-Graben which were mainly created transtension and transpression between the interacting blocks along the strike-slip line. Examples include the Hanmer Basin which is a pull-apart basin along the Hope fault, New Zealand (Figure 4.21A) as described by Wood et al. (1994). From the morphology of the graben, it is clear that the Hanmer Basin has undergone transtension in the area to the east while the area to the west has undergone transpression, in a similar shape but in different orientation to the Mukah Half-Graben. Therefore, the Mukah Half Graben is interpreted to be analogous to the Hanmer Basin.

4.5.3.4 Interpretation of the tectonic nature of the Mukah Line

On the basis of the interpretation here, the Mukah Line is interpreted as a dextral strike-slip fault with the Mukah Half-Graben formed as a pull-apart basin along the line where basement is involved. The main fault of the Mukah Line that is responsible for the formation of the Mukah Half-Graben and other half-graben features along the line, is thorough-going which is the main criteria for a strike-slip fault (Harding, 1985). The interpretation therefore, rejects the possibility that the Mukah Line formed as a normal fault as it is not the characteristic of a normal fault to have both vertical and horizontal displacements as it can be seen along the Mukah Line.

The Mukah Line is believed to have formed prior to the deposition of T1S suggesting Oligocene or as early as Eocene, based on the age of the oldest sedimentary rock, that is the Tatau Formation of Eocene-Oligocene age (refer Heng, 1992). The line was reactivated several times with the major movement during T1S and another movement during T3S. Similar to Igan-Oya Line, the vertical slip along the Mukah Line varies from almost no vertical slip to about 3,000 metres (from 2.0 seconds contour line down to about 3.0 seconds contour line) at the basement level in the northern part of the Mukah Half-Graben and other half-grabens in the nearshore area (Figure 4.3).

4.5.4. West Balingian Line

4.5.4.1. Characteristic of the West Balingian Line.

The West Balingian Line is made up of two major fault zones. The fault zone to the east is believed to be older and closely follows the eastern margin of the basement high (Figure 4.3). The fault zone is represented by the basement scarp between the basement high and the

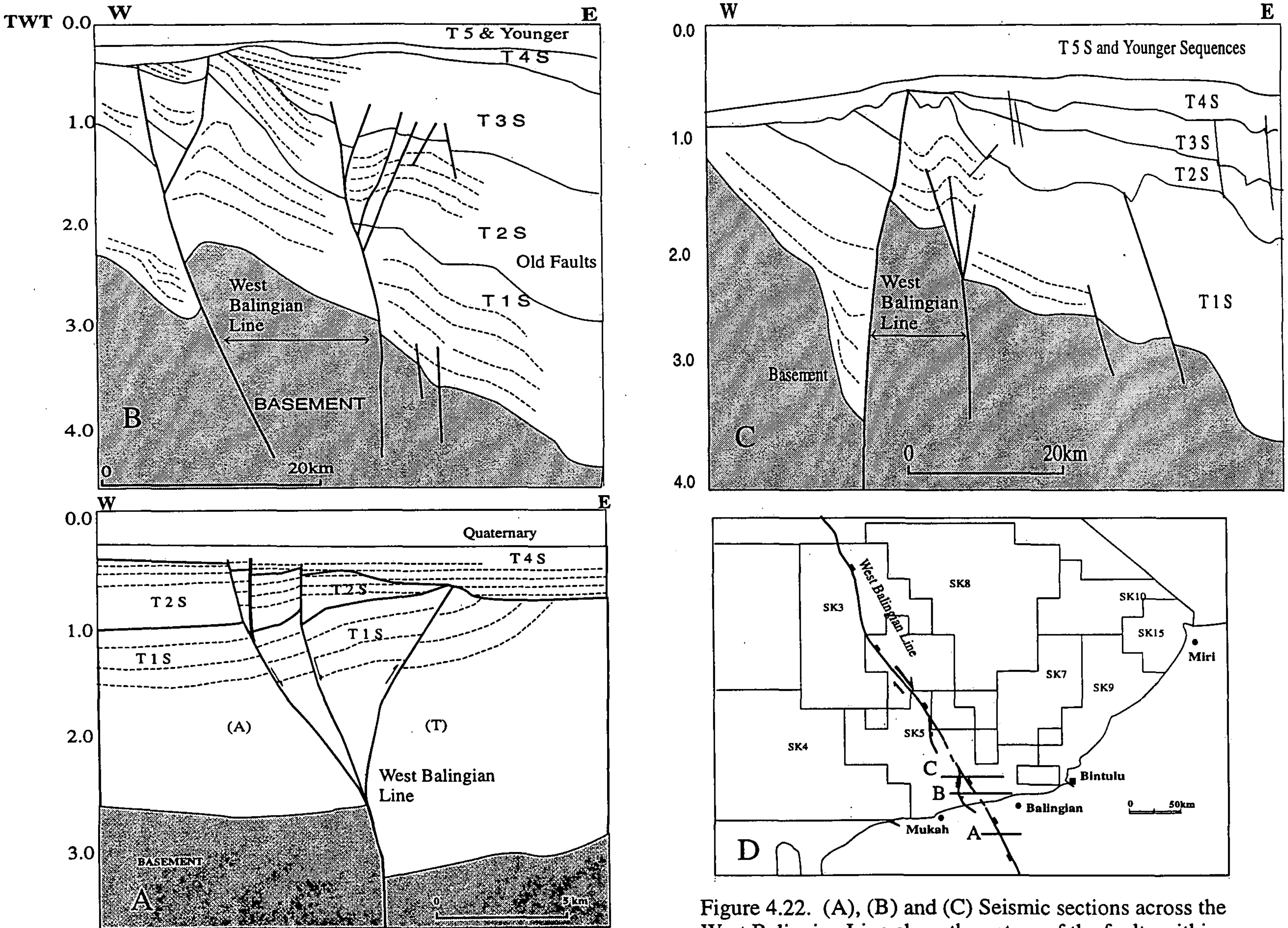


Figure 4.22. (A), (B) and (C) Seismic sections across the West Balingian Line show the nature of the faults within the line. (D) The orientation and location of the seismic lines.

Eastern Sub-Basin. To the east of this scarp, the basement plunged to a great depth (deeper than 5 Seconds TWT), beyond the resolution of the available seismic lines, in the northern part of the Eastern Sub-Basin (RL1, RLB and RLD in Figure 4.5) and decreases towards the shore. The western fault zone, which is believed to be younger than the eastern fault zone, passes through the eastern part of the basement high (Figure 4.3). This fault zone is referred to in the text and figures in this thesis, as the West Balingian Line (WBL).

The eastern fault zone is characterised, at shallower depths, by flower structures changing from positive (RLD) to negative (RLB and RL1) along strike (Figure 4.5). In the deeper part, however, the characteristics of the fault could not be interpreted conclusively, as the seismic quality deteriorated. On the map section (Figure 4.3), the eastern fault zone is highly winding in nature. The difference in the basement level across the fault zone exceeds 2.0 Seconds TWT, in the northern offshore area, it decreases to about 1.0 Seconds TWT (Figure 4.22C) and decreases further in the area close to the coastline (Figure 4.22B). However, the eastern fault zone, could not be traced further towards the onshore area.

The western fault zone of the West Balingian Line, which is also referred to as the West Balingian Line (WBL) herein, is also a thorough-going fault and can be traced through the western part of the Luconia Province (SK6). This lineament passes through the nearshore and onshore areas and extends farther landward (Figure 4.22). This lineament seems to control the distribution of the T1S sediment, since there is a significant difference in thickness, ranging from 1-1.5 Seconds TWT, from the east to the west across the lineament (RL1 and RLB, Figure 4.5). The sedimentary sequence that was affected by this fault is predominantly T1S. There was very little or no influence on the younger sequences.

The characteristics of the WBL remain unchanged from the offshore to the onshore Sarawak area. The lineament is a basement involved fault, vertical and characterised by a negative flower structure in the onshore and the area close to the coast. The nature of faults within the flower structure shows that it is bounded consistently by a dominant fault to the left and the upward divergent features are to the right of the master fault. Farther to the north, a positive flower structure was developed to the east of the master fault (Figure 4.22C). The apparent simultaneous development of extension and compression through time in the area of the WBL can be seen in Figure 4.22B. On the map section, the WBL can be seen to bifurcate forming the restraining fault junction (Figure 4.22B) and releasing fault junctions (Figure 4.22C).

In the onshore area, WBL is characterised by anomalous thickening of the T1S across the fault and most of the small faults in the flower structure have normal throws with one or two further to the right in a reverse sense (Figure 22A). On the map section, the WBL is characterised by scissoring when the fault throw direction changed from NE in the north, to SW in the south, in the area to the east of Lemai Sub-Basin (Figure 4.9)

4.5.4.2. Interpretation of the tectonic nature of the West Balingian Line.

Features of the West Balingian Line include negative flower structure, local fault inversion, evidence for both extension and compression through time and change in the direction of fault throw along strike. The faults involve the basement, are thorough-going and characterised by flower structures, with anomalous changes in the sediment thickness across the fault. The features seen on the WBL fit the descriptions of strike-slip fault as outlined by Harding (1985), Sylvester (1988) and D'Onfro and Glagola (1983).

The criteria of strike-slip faults that can be recognised on a single seismic section, outlined by D'Onfro and Glagola (1983), are:

1) Presence of "flower" and "palm" structures.
2) Abrupt changes across faults
3) Reversal of or change in fault throw with depth
4) Anomalous thickening or thinning of beds across faults and
5) Character change of seismic profile across predominantly dip-slip fault.

On the above basis, it is interpreted that the West Balingian Line was developed as a ***strike-slip system*** and not likely to be formed by normal extensional fault. This is mainly based on the through-going nature of the line that extends over 300km in the offshore as well as in the onshore area of Sarawak. According to Robert and Yielding (1993), there is no recorded example of active normal fault surfaces with a length greater than 25km. The evidence of strike-slip nature of the West Balingian Line seems conclusive. Besides all the characteristics of the fault, such as linear in nature, extensive, through-going, trace and change in the apparent upthrown block, that are present both along the course of the fault at increased depth, the NW-SE trending West Balingian Line is sub-parallel to the major strike-slip faults elsewhere in the region as interpreted by several workers including James (1984), Tan and Lamy (1990) and Tjia (1994).

The kinematic indicators of the WBL can be seen from the displacement on the southern boundary of the Tertiary sediment, in the onshore area. The southern boundary of the T1S is marked by the Lemai Fault and by the Bukit Mersing Line to the to the west and east of the WBL respectively (Figure 4.8). The distance from the two is, at present, about 15 kilometres in the SW direction. The distance between the Lemai Fault and the Bukit Mersing Line is presumed to be the horizontal displacement along the WBL as well as the kinematic indicators

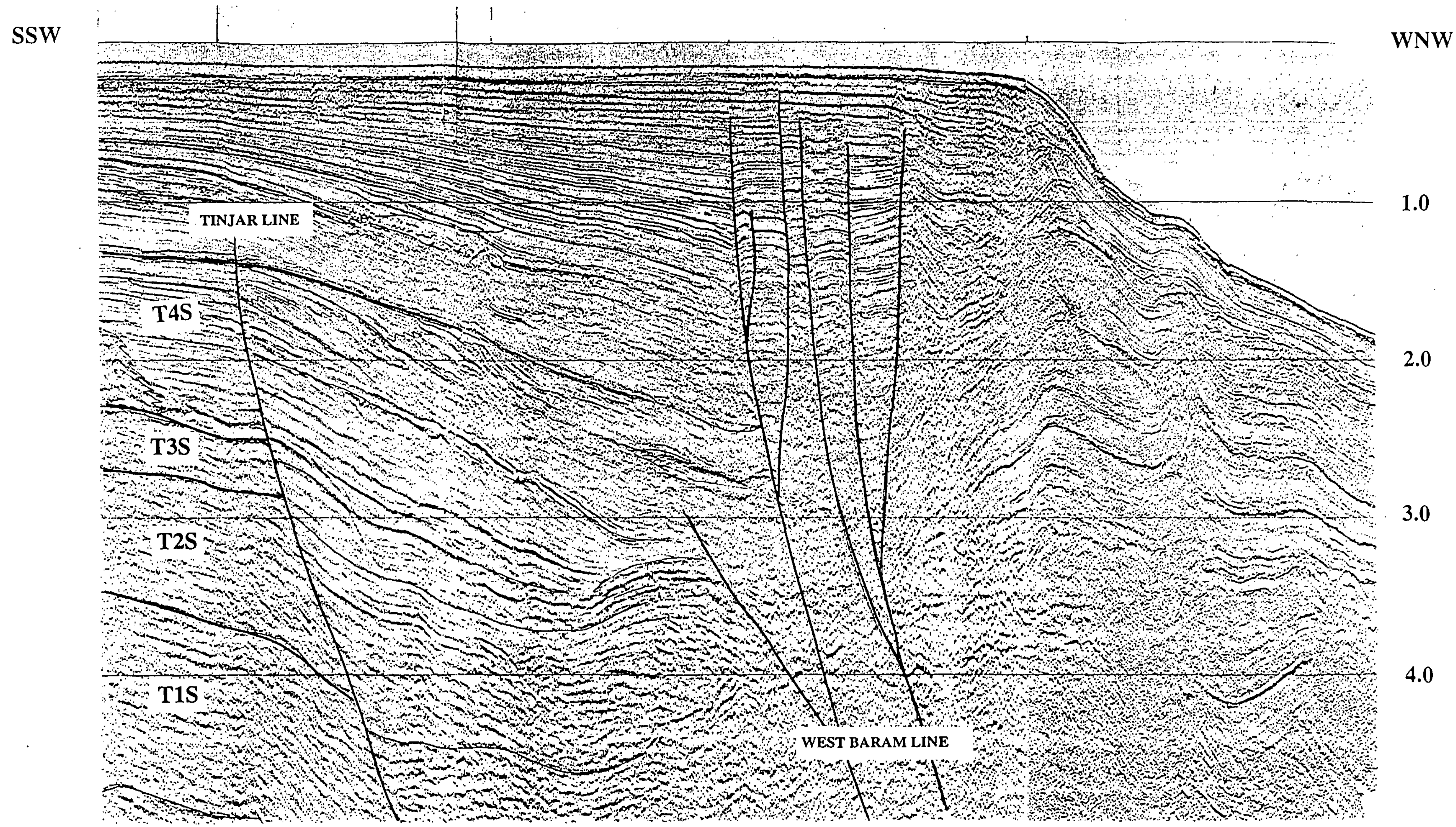


Figure 4.23. Seismic section showing the nature of the faults forming the West Baram Line and the northern part of Tinjar Line. The seismic section represents the eastern part of RLB. Refer Figure 4.5 for the location and orientation of the seismic line.

of the line, suggesting dextral movement. The indication for dextral movement is also evident from the outcrops of Arip Volcanics (Figure 1.5). Elsewhere along the fault zone, in the area further landward, facies changed within the Belaga Formation and dextral offset of the formation in northern Kalimantan, which will be discussed further in Chapter 5. All the above are evidence supporting the nature of the WBL as a ***dextral strike-slip*** fault.

The timing of the faults in the WBL differs from one to another. The eastern fault zone, which is marked by the basement scarp to the east of the basement high area, is interpreted to be generated prior to the deposition of the T1S. This interpretation is based on the age of sediments abutted on to the basement along the scarp. The movement along this fault zone is interpreted to have taken place during the Eocene or Oligocene. The estimated time was based on the age of the oldest sedimentary formation in the onshore area, namely the Tatau Formation, presumably equivalent to the basal unit of the T1S which is dated as Eocene-Oligocene in age (Heng,1992).

The WBL is interpreted to have formed during the deposition of the T1S; that is during late Oligocene and later reactivated in some places during the T2S, that is during early Miocene times. This is based on the seismic evidence that the whole interval of T1S has been affected by the faults with different thickness on both sides of the fault, whereas the T2S in some places was not affected by the fault.

4.5.5. Tinjar Line

4.5.5.1. Characteristics of the Tinjar Line.

The Tinjar line is characterised by a normal fault to the north in the offshore area and by a negative flower structure in the area towards the coastline (Figure 3.17). The normal fault to the north, with the throw to the NE, shows evidence of growth within the T4S, whereas the other sequences did not show any evidence of this. The characteristic of the line however changes in the area closer to the coastline where the lineament is characterised by a fault zone that is consistently bounded by a dominant fault to the left and smaller faults with upward divergence to the right of the master fault. Most of the small faults in the flower structure have a normal throw (RL1, Figure 4.5). At the younger sequence (T3S) level, the area to the east of the master fault is characterised by compressional features, similar to the other areas to the west of the Tinjar Line (RL1, Figure 4.5).

By looking at the sedimentary sequences affected by the fault, it is suggested that the Tinjar Fault was active mainly during T4S with possible earlier movement during T3S times. This interpretation is based on the thicknesses of the T1S, T2S and T3S which are similar in the area to the east and the west of the fault. However, there is a significant increase of the T4S to the east of the line (RL2, Figure 4.5).

4.5.5.2. Interpretations of the tectonic nature of the Tinjar Line.

The occurrence of both extensional and compressional features along the Tinjar Line cannot be described by a simple normal or growth extensional fault. An element of horizontal movement has to have taken place in order to create both the compression and extension. Alternatively, the phenomena could be described as the result of strike-slip movement which is termed as transtensional and transpressional respectively. Therefore, it is interpreted that the Tinjar Line was formed as a strike-slip fault, similar to the interpretations of the Tinjar Line in the onshore area by the previous workers including James (1984), Tan and Lamy (1990) and Tjia (1994).

The kinematic indicator of this strike-slip fault is clear as can be seen in the onshore area where the line offsets the Belait Formation for a distance of about 10 km towards the SE (Figure 4.15). The distance and the direction of the offset indicate that the Tinjar Line is a ***dextral strike-slip*** line. The major movement along the line is interpreted to have taken place primarily during Late Miocene times (T4S) with possible earlier movement during Middle Miocene times (T3S).

4.5.6. West Baram Line

4.5.6.1. Characteristics of the West Baram Line.

The West Baram Line is a fault zone consisting of several fault lines, influencing the stratigraphy at or close to the sea-floor to depths beyond seismic resolution (Figure 4.23). Most of the faults within the zone have a normal throw. The West Baram Line is close to the shelf-edge margin of the east Sarawak Basin, as the water depth changes abruptly eastward across the fault zone (Figure 4.23), from about 50 metres to 1000 metres in a distance about 50 km from the West Baram Line (Agostinelli et al., 1990). The West Baram Line also marks the western end of Sabah Trough (Tan and Lamy, 1990).

As can be seen in the seismic section, the West Baram Line represents a zone of 'tear-apart' and it is not feasible to correlate the seismic datum across the West Baram Line eastward to the Baram Delta area because of a severe character change of the seismic profile across the fault zone (Figure 4.23). The nature of the deformation caused by the faults can be seen in

Figure 4.23. However, based on other seismic lines crossing the West Baram Line, it seems that the major movement along the fault system took place during Pliocene times (T5S).

By projecting the line from the offshore to the coastal line, the West Baram Line passes through the area in the vicinity of Tanjung Batu and Tanjung Bungai in the district of Bekenu (Figures 4.3 and 4.15). The basis for correlating the line to the onshore area has been discussed in Section 4.4.6.

4.5.6.2. Interpretation of the tectonic nature of the West Baram Line

On the basis of the structural configuration along the West Baram Line, seen on the available seismic, no conclusively interpretation about the tectonic nature of the line can be made. However, based on the through-going nature of the fault that can be traced from the offshore area (Figure 4.3) to the onshore area (Figure 4.15), it rules out the possibility that the line represents a normal fault. As can be seen, there is a severe character on the seismic profile across the fault zone. This and the 'tear apart' nature of the zone, suggests that the West Baram Line formed by strike-slip movement rather than extension.

The kinematic indicator of the West Baram Line is clear in the onshore area where it is depicted by the south-eastward dextral offset of the Oligocene-Miocene Setap Shale for about 30km (Figure 4.15). Further, the dextral sense of movement along the West Baram Line can be seen by the severe changes of the fold-thrust direction when the areas to the west and east of the West Baram Line are thrusted to the NE and NW respectively (Figure 5.5 of Chapter 5). With that evidence, it is interpreted that the West Baram Line was formed as a ***dextral strike-slip*** system during Pliocene time (T5S).

The interpretation that the West Baram Line, for the offshore and onshore areas, is a dextral strike-slip fault agrees with the interpretation by previous workers including James (1984), Agostenelli et al. (1990), Hazebroek and Tan (1993) and Tjia (1994). However the interpreted onshore extension of the West Baram Line is mostly referred to as the Tinjar Line by previous workers including Tan and Lamy (1990). Nevertheless, the previous workers also interpreted the 'Tinjar Line' as a dextral strike-slip fault.

4.6 Formation of major structural traps.

The area to the east of the West Balingian Line (Figure 2.24A) is one of the main hydrocarbon producing areas in the Sarawak Basin, besides SK15, SK6 and SK8 (Figure 4.22). This section discusses the formation of structural traps in the nearshore area. It is believed that other areas have also been influenced by similar tectonic movements as in the nearshore area. However, the formation of structural traps in other areas is not discussed as the available seismic data for the area are mainly regional lines and these are insufficient to generate a conclusive interpretation.

Seismic mapping in the nearshore area shows that the location of the main hydrocarbon fields (Figure 4.24A) mostly coincides with the location of the structures here termed *'faulted-fold'* structure. A representative N-S seismic section showing the nature of the faulted-fold structures, in an area of hydrocarbon producing fields, is shown in Figure 4.25. The orientations of these folds are NW-SE in the northern area, parallel to the West Balingian Line and gradually fanning away and changing orientation to E-W in the eastern part of SK5 and farther to the east. The map view of the structure resembles a leading contractional imbricate fan (Woodcock and Fisher,1985; Figure 4.24C).

The understanding of the creation of the faulted-fold structures in the nearshore area is vital since the structure is believed to be the main trap style for hydrocarbons in the area. The seismic mapping found that most of the structures in the eastern part of SK5 and the adjacent areas, including the producing fields, have a similar structural setting whereby the main anticline is bounded by reverse faults. One of the fault lines passes through the D18 structure (Figure 4.24B) and the 3D structural map (Almond et al.,1990) shows that the D18 field is a fault-bounded anticline with a thrust fault to the south formed as a major structural bounding fault (Figure 4.24B). On the basis of the close association of major faults with hydrocarbon fields, the formation of structural traps in the nearshore area is interpreted to be related, to a certain extent, to the movement along the main strike-slip line.

4.6.1. Characteristics of faulted-fold structures.

A close examination of the faulted-fold structures (Figure 4.25) shows that the structures are characterised by an upward divergence of reverse faults that resembles a positive flower structure (Harding,1985), with the main reverse faults confined to the older sedimentary sequences. The folding involves younger strata, above the level affected by the faults (Figure 4.25).

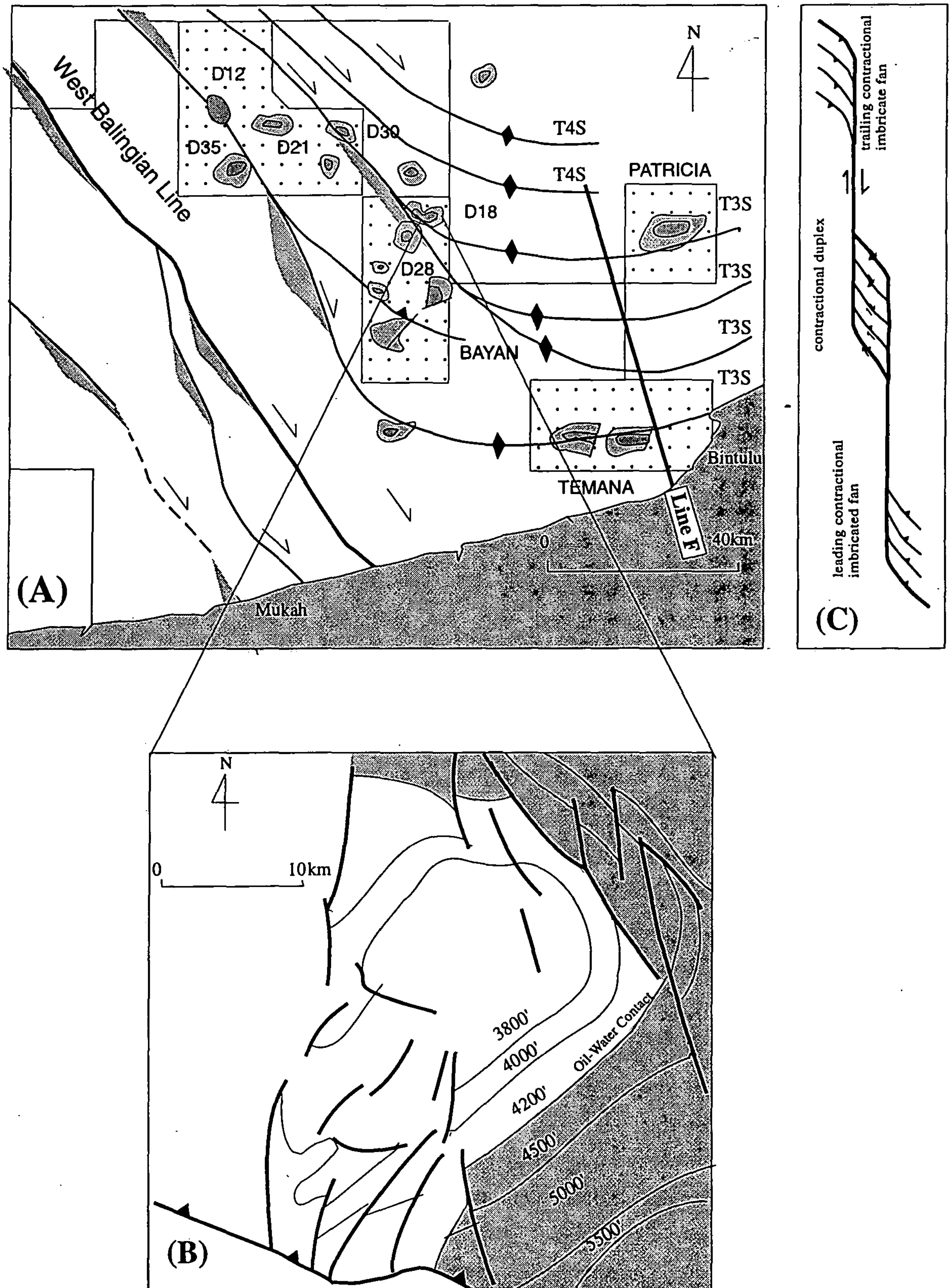


Figure 4.24. (A) Map showing the location of oil and gas producing fields in SK5 area. (B) Structural map of D18 field derived from 3D seismic (After Almond et al.,1990). Note the location of the fields and the lineaments of the faulted-fold structures and the nature of the D18 that is bounded by the reverse fault to the SW. (C) Map view of an idealised dextral strike-slip system illustrates the orientation and the nature of strike-slip duplexes and imbricate fans (after Woodcock and Fisher, 1985).

The digitised regional seismic line passing through faulted-fold structures (RLC Figure 4.7) and a representative digitised seismic section (Figure 4.25) are incorporated to portray the nature of the faulted-fold structures. By looking at these figures, it can be deduced that the formation of the faulted-folds structures is not synchronous across the entire area, but it became progressively younger toward the north. This is deduced from the evidence that the structures to the north were only affected by the later unconformities as opposed to the structures to the south that were truncated by the older unconformities. (Note that the line representing the boundaries of the sedimentary sequences are unconformities or their correlatable conformities). For example, the younger part of the T2S at Structure A and to the south of that structure was truncated by the base T3S unconformity and the T3S onlaps on to the structure which suggests that Structure A was most likely generated during the late stage or post-dated T2S times. In contrast, at Structure B the T2S was not truncated by the Base T3S unconformity and similarly for the structures further to the north.

The observed relationship is similarly applicable for the younger sedimentary sequences, i.e. the T3S. The sequence was totally eroded at Structure A and the upper part of the sequence was truncated at Structures B and C. It is also noticed that the degree of truncation on the T3S is more severe at Structure B compared to Structure C. Further, the T3S was not truncated by the unconformity and the whole T3S is present at Structure D. This suggests that Structure D was generated after the erosion period of the Base T4S unconformity.

From what was discussed in the two above paragraphs, it could be deduced that the structuration for the structure A, B, C, and D to have developed during different time, progressively younger to the north. The structuration of A is interpreted to take place during early T3S times, Structure B during the mid T3S times, Structure C during the late T3S times and Structure D during the T4S times. The timings for the formation of the major faulted-folds are also shown in Figure 4.24A.

4.6.2. Timing and mechanism for the formation of faulted-fold structures

A three-dimensional diagram (Figure 4.26) showing schematically, the nature and the position of the faulted-fold structures and the correlation with the major strike-slip faults (the West Balingian Line) has been generated to visualise the relationship between the faulted-fold structures and the dependency between the formation of the structures with the movement of the major strike-slip faults. The diagram was constructed primarily using the information from Line One (Figure 3.9) and Line F (Figure 4.25).

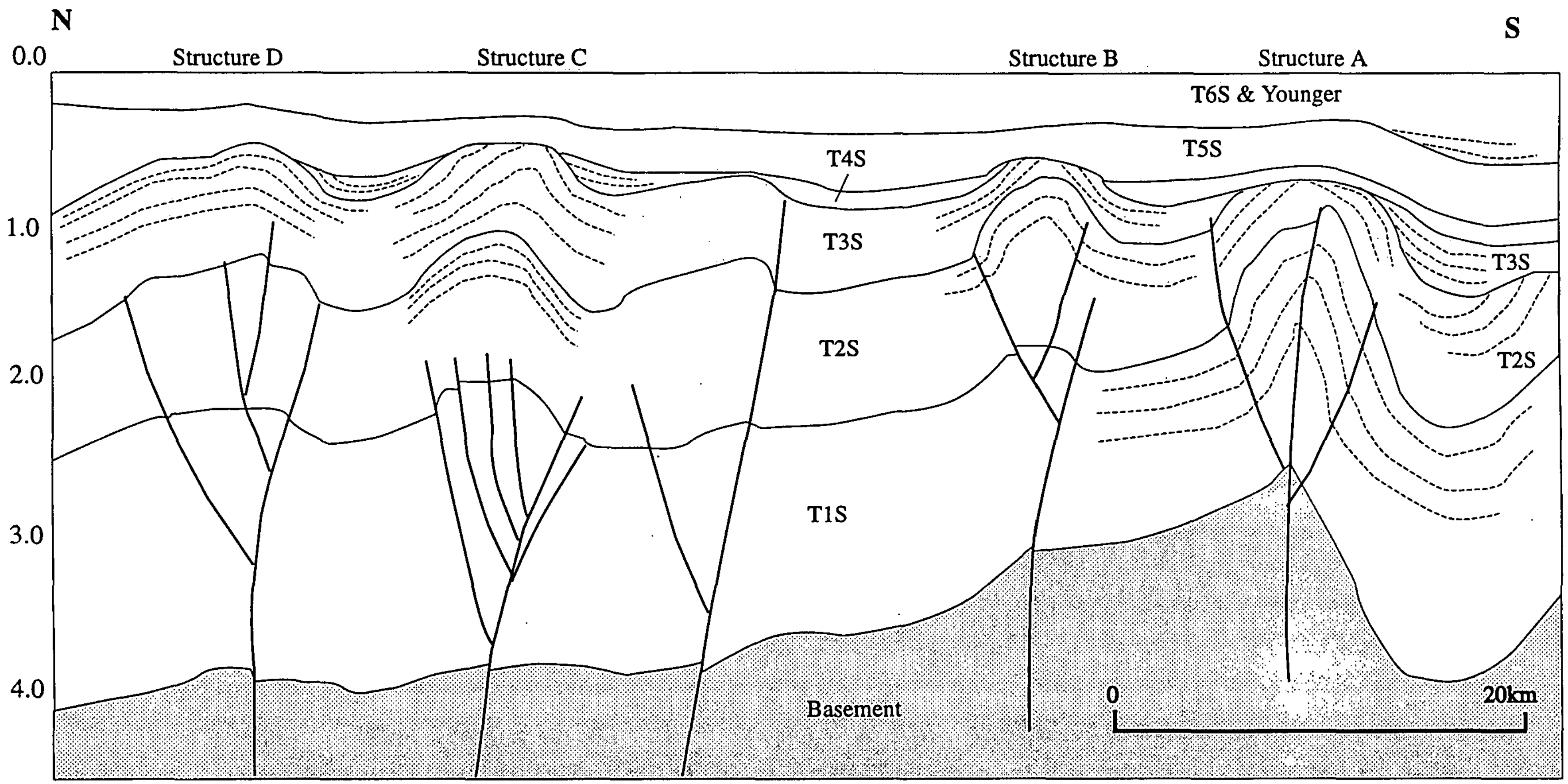


Figure 4.25. Geoseismic section along Line F. Note the time of erosion between the structure A, B,C and D. Structure A was truncated at the top of T2S but this level was not affected at other structure. T3S was truncated at the structures B and C while the same sequence was not affected at structure D, which suggest different timing of structural development between them. Refer Figure 4.15 for the orientation of the seismic line.

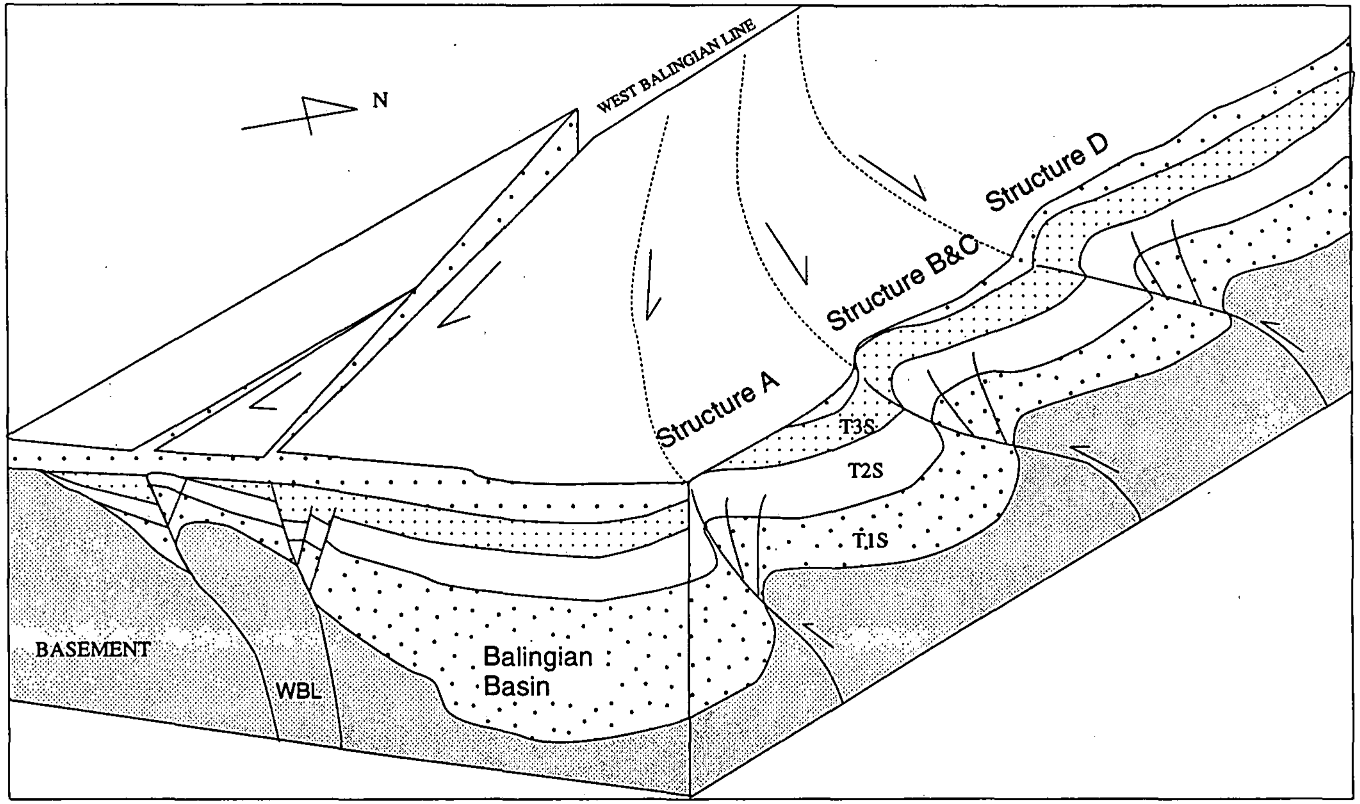


Figure 4.26. Block diagram showing schematically the relative movement of major strike-slip faults and the formation of the major structural traps in SK5. The traps are interpreted to be formed as sequential faulted-folds synchronous to the movement along the West Balingian Line.

From observations on the above-mentioned figures, one can deduce that the movement along the fault of the faulted-fold structures and the movement of the major strike-slip faults are mostly independent. This is based on the nature of truncation on every sedimentary sequence. For instance, the T1S and T2S were truncated in the vicinity of Structure A but almost the whole of these sequences are preserved in the vicinity of the West Balingian Line (Figure 3.9). This is also true for Structure D which took place during the T4S times. During that time, the West Balingian Line was no longer active. The deposition of the sequence in the vicinity of the West Balingian Line was not disturbed by the movement along the West Balingian Line (Figures 3.7, 3.8 and 3.9). In fact, most of the faults within the West Balingian Line terminated below the T4S level. This suggests that faulted-fold structures are independent of the movement along the major strike-slip fault.

On the other hand, judging from the structuration of structures B and C during T3S times, the structural development of the faulted-folds is believed to occur simultaneously with the movement along the major strike-slip line to a certain extent. Contemporaneous with the formation of structures B and C, the T3 sedimentary sequence in the area to the east of the West Balingian Line has similarly experienced compression as can be seen from the inversion features on the T3S (Line 1, B and D in Figure 4.5), suggests some relationship between the movement along the major strike-slip fault and the formation of the faulted-folds farther to the east.

4.6.3. Analogous features to the faulted-fold structures.

The occurrence of anticlinal structures that grew progressively away from the major strike-slip faults has been discussed by several workers. For example, Wilcox et al. (1973) studied this phenomenon from five known strike-slip areas and described these as en-echelon folds and said that the structures are important with potential value for trapping hydrocarbons.

The areas used by Wilcox et al. (1973) are:

1) Central and South Sumatra basin,
2) El-Pilar and associated faults in eastern Venezuela and Trinidad,
3) Dead Sea rift in Israel and Jordan,
4) Southern San Joaquin Valley,
5) Alpine fault and Awatere and Clarence wrench fault in New Zealand.

Three out of five examples used by Wilcox et al. (1973) are shown Figures 4.27A, 4.27B and 4.27C.

In determining whether or not the faulted-fold structures seen in the Sarawak Basin are en-echelon folds, the definitions of en-echelon by several workers are outlined here. Wilcox et al. (1973) stated: *The term 'en-echelon' refers to the arrangement of structures along a linear zone so those individual folds or faults of the same kind are parallel to each other and inclined equally to the strike of the zone. For most wrench-fault experiments with clay, the angle between en-echelon fold axes and the wrench fault approximates **30 degrees**. Folds that form later during the deformation have lower angles.*

Sylvester (1988) wrote: *Typically, en-echelon folds are distributed in a relatively narrow and persistent zone above and adjacent to a master strike-slip fault. They may form in a broad zone between two major strike-slip faults. Ideally, the crestal traces of en-echelon folds should make an angle of **45 degrees** in plan view to the shear zone.*

On the basis of these definitions, it seems that the faulted-fold structures seen in the nearshore area do not have identical characteristics to en-echelon folds. This is mainly because the orientation of the structures changed progressively to the east and reached the angle of almost perpendicular to the master strike-slip line which is the West Balingian Line (Figure 4.24A).

Alternatively, the faulted-fold structures, in plan view (Figures 2.24A and 2.24C) seem to have a similar array to the trailing contractional imbricate fan (Woodcock and Fisher, 1985) of a strike-slip system . However, the imbricate faults usually have a dip-slip component, dominantly with a reverse sense in a contractional fan or duplex (Woodcock and Fisher, 1985). This is found to be unsuitable for the faulted-fold structures in the study area as the structures have a very minimal vertical slip (Figure 4.24C).

The closer resemblance to the faulted-fold structure is the sequential folding feature in the west side San Joaquin Valley. The interpretation of the en-echelon faults on the west side San Joaquin Valley by Wilcox et al. (1973) was revised by Harding (1976). Harding (1976) showed conclusively that the anticlines in the west side of the San Joaquin Valley grew progressively basinward, synchronous with the history of strike-slip on the adjacent San Andreas fault. He called those anticlines as sequential folds synchronous with San Andreas faulting, instead of en-echelon folds.

Harding (1976) also concluded that the folds and the strike-slip faults are essentially independent. The timing of the folding was not of one age. On the basis of the diagram in his paper (Figure 4.28), it can be seen that the folding started in the area near to the main strike-slip fault with low-angle fold axes and gradually moved away from the main strike-slip fault with increasing angle between the fold axes and the main strike-slip line.

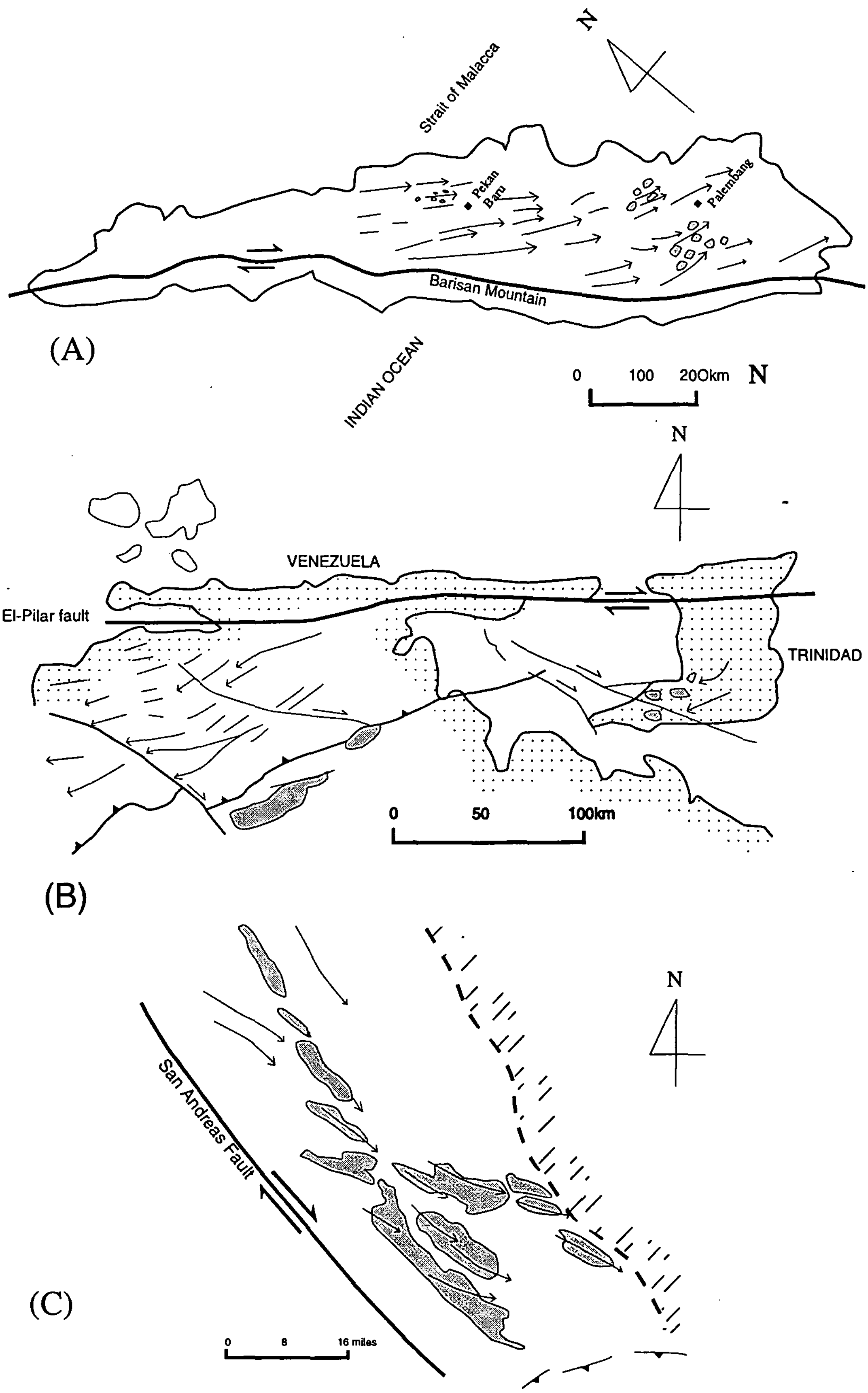


Figure 4.27. Maps showing examples of en-echelon folds in (A) Central and South Sumatra Basin, (B) El-Pilar fault and associated faults and en-echelon folds in eastern Venezuela and Trinidad and (C) the west side of San Joaquin valley in USA (Based on Wilcox et al.,1973). Areas shaded in grey are the oil-producing fields.

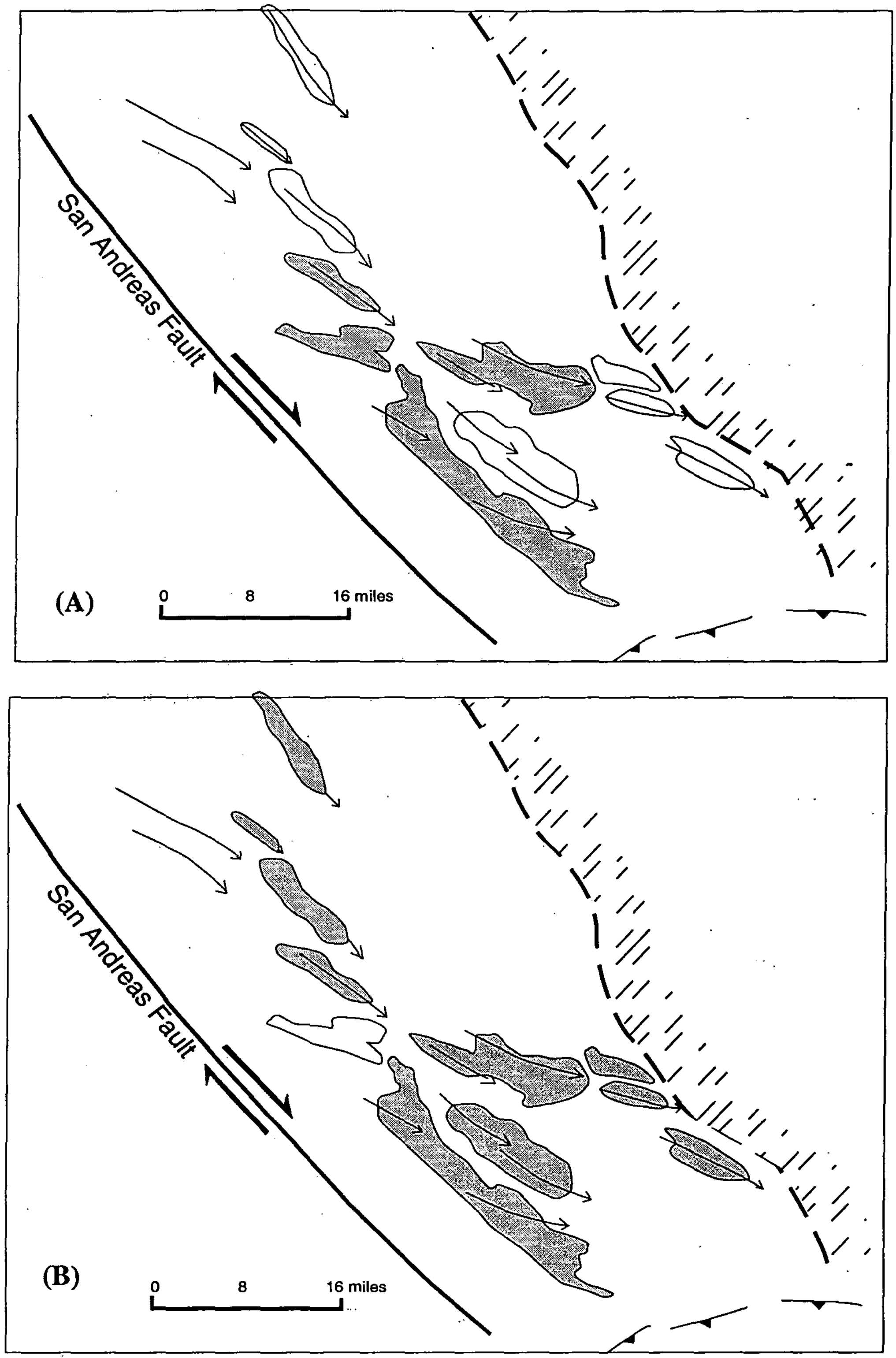


Figure 4.28. Maps showing structural growth periods of main producing anticlines in the southeast part of the San Joaquin valley. Structures generated during the time span are shaded in grey. (A) Pre and during Mohnian and Delmontian times, (B) during the later period of Pliocene and Pleistocene. The structuration are interpreted to be synchronous with the history of strike-slip on the adjacent San Andreas fault.(After Harding 1976).

By comparing the characteristics of the faulted-fold structures that grew eastward in the area to the nearshore area of Sarawak and the one on the west side of the San Joaquin Valley, it can be conclusively said that the phenomena seen in the two basins are analogous. Therefore, it is suggested that the **faulted-fold structure** in the Sarawak Basin is analogous to the **Sequential Folding** on the west side of the San Joaquin Valley as interpreted by Harding (1976).

4.7 Tectonic evolution and formation of the Sarawak Basin.

This section synthesises the structural evolution of the Sarawak Basin based on the evidence presented earlier. An attempt is made to reconstruct the tectonic movements along the major faults and to incorporate all the available tectonic evidence and to relate it to the formation of sub-basins within the greater Sarawak Basin. The discussion commences in Eocene times, prior to the initial formation of the basin and ends with the latest documented events during Pliocene times.

4.7.1 Eocene-Oligocene times (Prior to deposition of T1S)

The oldest tectonic movement to influence the Sarawak Basin is interpreted to be the movement along the eastern fault zone of the West Balingian Line (in the area between 3.0 and 4.0 Second TWT, in Figure 4.3) and the movement along the Mukah Line (Figure 4.29). This movement created the initial formation of the Sarawak Basin located to the east of the present-day basement high area (Figure 4.3). Besides the creation of the main depression, creating the Eastern Sub-Basin to the east, two sub-basins between the two major strike-slip lineaments have also been identified. The two sub-basins are the SW Luconia Sub-Basin and the Lemai Sub-Basin (Figure 4.8). The morphology of the two sub-basins has been described in Section 4.3.2.1.

4.7.1.1. Major tectonic activities and basin formation.

The movement along the eastern fault zones of the West Balingian Line is believed to have taken place during late Eocene or Oligocene times, based on the age of Tatau Formation that is interpreted to be of this age (Heng, 1992). This seems to be slightly older than the age of T1S (Figure 2.6), although it should be noted here that the base of the T1S was not penetrated by any well in the area to the east of the West Balingian line, mainly due to very deep basement in the area. Therefore it is possible that the basal part of the T1S was deposited earlier than the sequences penetrated by the wells, during Late Eocene times.

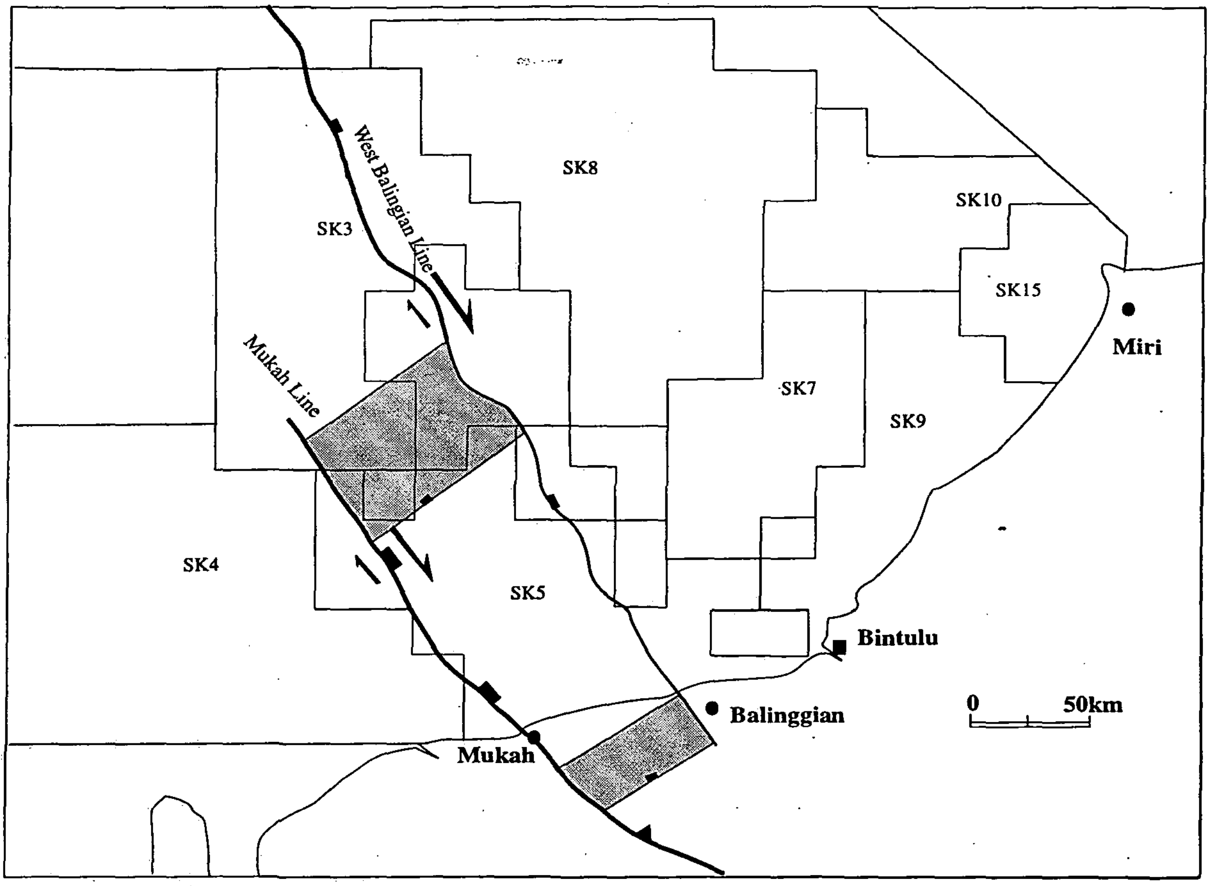


Figure 4.29. Map showing strike-slip movement during Eocene-Oligocene (Pre T1S). The major movements are along the Mukah and West Balingian Lines. The formation of Southwest Luconia and Lemai Basins are intepreted to be generated by the releasing oversteps between the two strike-slip lines.

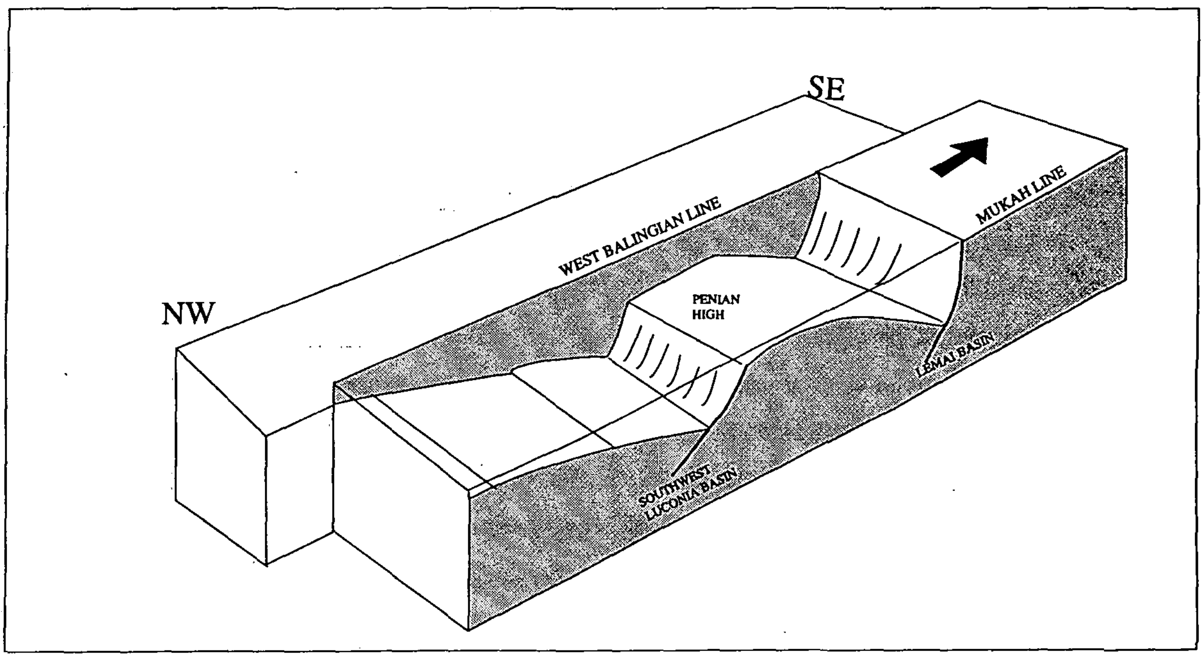


Figure 4.30. Schematic releasing overstep model for the two sub-basins modified from the pull-apart model for the Dead Sea Basin by Manspeizer, 1984.

The movement along the eastern fault zone of the WBL, however, ceased during the deposition of the T1S as seen on seismic (RL1, RLB and RLD, Figure 4.5) where the basal unit of the sequence abutts on to the scarp. The upper unit of the sequence on the other hand, onlaps on to the basement high and continued the deposition westward toward the Mukah Line, suggesting that the eastern fault zone of the WBL ceased during the Oligocene (T1S times).

As the movement along the eastern fault zone of the WBL ceased, the fault movement commenced along the Mukah Line (Figure 4.29). The evidence that the Mukah Line was active during this time is based on the role of the fault that formed the western boundary of the T1S (See Sections 3.4.1 (Figure 3.6) and 4.5.3.2).

The shifting in the movement along the lines has been described as "*overstep*" (Figure 4.18B). The Dead Sea basin is an example of an overstep basin (Manspeizer, 1984; Figure 4.30). There are numerous examples of overstep with a wide range of sizes along strike-slip faults world-wide (e.g. Aydin and Nur, 1985) and it is now believed that the oversteps on strike-slip faults are the rule rather than exception. The same phenomenon is also called "pull-apart" (including Manspeizer, 1985 and Sengor et al., 1985). The overstep event is interpreted to have taken place during the Oligocene between two major strike-slip faults, namely the West Balingian Line and the Mukah Line in the Sarawak Basin.

The SW Luconia and Lemai Sub-Basins are interpreted to be generated as the result of releasing oversteps between the two lines (Figure 4.29). A block diagram (Figure 4.30) was created to show the relative movement along the two strike-slip lines and the formation of the two sub-basins. The diagram has been modified from the schematic pull-apart model for the Dead Sea Basin (modified from K. Arbenz, in Manspeizer, 1985).

All the above-described geological features show that the major tectonic activity during terminal Late Eocene to Oligocene times in Sarawak Basin was strike slip-tectonic along the eastern fault zone of the WBL and subsequent movement along the Mukah Line that resulted in the opening of the Southwest Luconia and Lemai Sub-Basins. Although it is understood that there is also a possibility for a pull-apart basin to be formed within an extensional setting, the location of the two sub-basins between two lines interpreted to be strike-slip faults, suggests that the basins are not likely to be created by normal faults within an extensional basin.

4.7.2 Late Oligocene (During the deposition of T1S)

The deposition of the T1S continued in the fault-related depressions created in the area during Late Eocene to Late Oligocene times (Figure 4.31). The movement along the WBL took place during the deposition of T1S as can be seen on E-W regional seismic lines (Figure 4.5) creating a different thickness of the sequence in the area to the east and the west of the WBL. The throw of the fault is consistently to the east and diminishes in the onshore Balingian area and the fault throw changed to the west in the Lemai Sub-Basin area (Figures 4.8, 4.9 and 4.22).

The feature of a releasing fault junction, creating a deep and narrow extensional basin (also known as a fault-wedge basin, Christie-Blick and Biddle, 1985) is also present along the line (Figure 4.22C). Similarly, the feature of a restrained fault junction that is defined as a junction between two strike-slip faults associated with overall crustal shortening and uplift between the faults, can be seen on Figure 4.22B. All these phenomena are seen to affect the T1S and, resulted in different thickness of T1S between the area to the east and west of the faults, proving that the movement of the faults took place during the deposition period of T1S.

The outcrop of the Tatau Formation (T1S) located 15 kilometres to the SE of the Lemai Fault, is characterised by a fold structure known as the Arip-Pelagau Anticline (Figure 1.5). The orientation of the fold axis is almost 115°, consistent with the spatial relationship of PDZ's orientation about N30°W, which is the orientation of the WBL (refer strain-ellipse diagram, Figure 4.19A). This observation suggests that T1S was deposited to the east of the WBL and displaced to the SE direction for about 15 kilometres.

All the above-mentioned features suggested that tectonic activity in the Sarawak Basin during the Late Oligocene involved dextral strike-slip faulting along the WBL.

4.7.3 Early Miocene (During the deposition of T2S)

The movement along the western faults of the West Balingian Line was mainly terminated towards the end of T1S times (Figure 4.32). However, in some places the fault seems to have persisted during T2S times, mainly in the nearshore and onshore areas (Figure 4.33). The seismic lines that pass through the faults show slight to substantial differences in the sediment thickness across the faults (Figure 4.22B). The tectonic activity during this period of time is regarded as quiet, compared to the time prior to and during the deposition of T1S. The above interpretation is based on the intensity of truncation and the angular nature of the base T2S unconformity. The angular nature of this unconformity can be seen mainly in the Penian

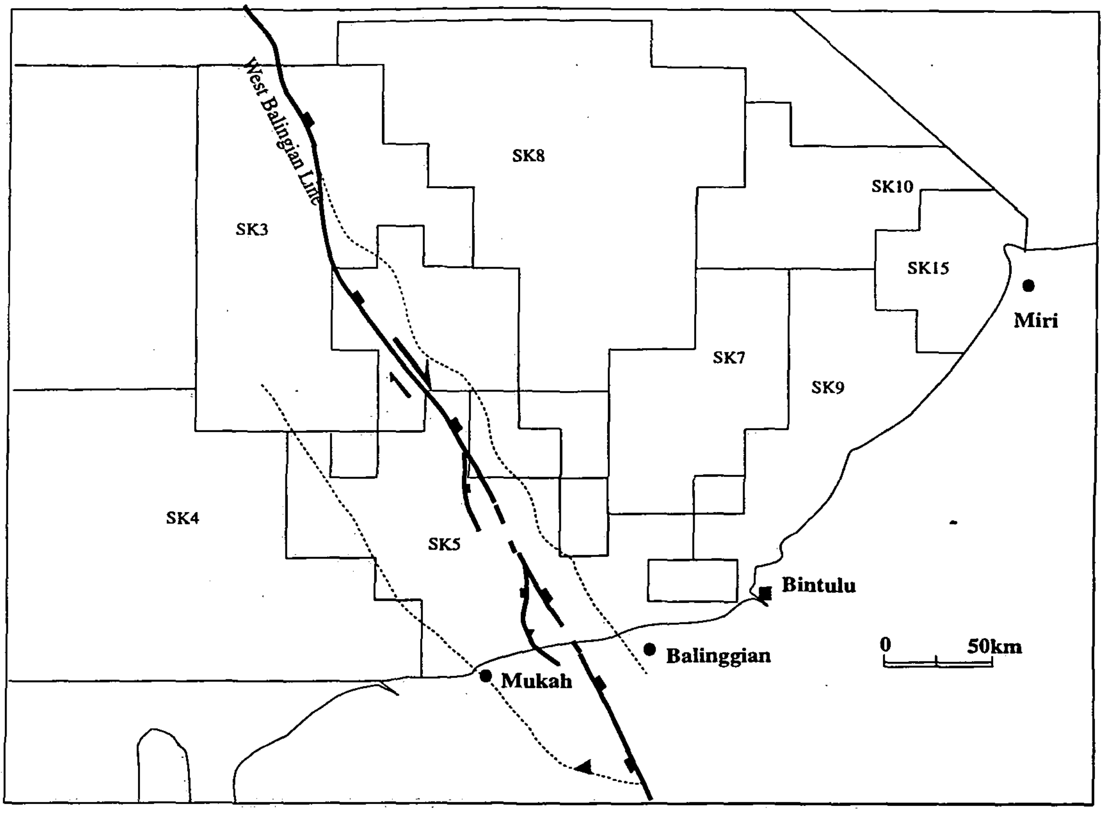


Figure 4.31. Tectonic map during Late Oligocene (during the deposition of T1S). The major activity during that period was the dextral strike-slip movement along the West Balingian Line.

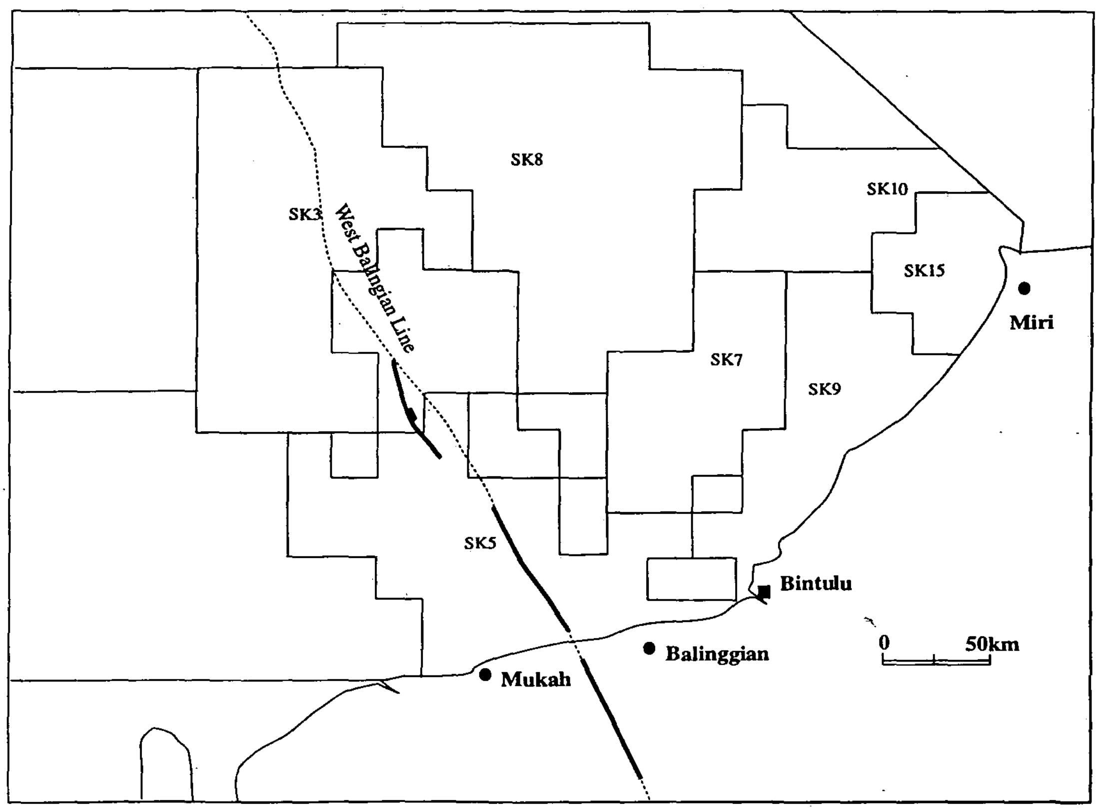


Figure 4.32. Tectonic map during Early Miocene (during the deposition of T2S). The movement along the West Balingian Line could only be seen in the nearshore and onshore areas. The WBL was no longer active in other areas.

High area (Figure 3.2), with grading to a low-angle unconformity and becoming conformable in other parts of the Sarawak Basin. The deposition of T2S can be considered as a continuation of deposition in the accommodation space left after the deposition of T1S and in the depressions mainly created by subsidence after the substantial loading of the T1S. This interpretation is also supported by seismic data, especially in the nearshore area, where the T2 sediments seem to infill the depressions and onlap on to the structural high of the T1S that formed after the structural development of T1S (Figure 4.22).

The depositional environment of the Nyalau Formation in the area between Arip and Bintulu (Figure 1.4) was reported (Ismail and Jaafar, 1993) to be primarily deposited within the lower coastal plain to coastal environments. The southern limit of the T2S (Nyalau Formation) in the onshore area to the east of the WBL is interpreted to be at a similar location to the present outcrop boundary between the Nyalau, Tatau and Belaga Formations, i.e. in the vicinity of the Bukit Mersing Line (Figure 1.4). It is also believed that there was no further significant southward movement of the Nyalau Formation after the Early Miocene (T2S times).

4.7.4 Middle Miocene (During the deposition of T3S)

The middle Miocene time was the most active tectonic period in the history of the Sarawak Basin. Among the major tectonic features developed during this period are the half-grabens along the Mukah and Igan-Oya Lines, the Rajang Delta depression, and the faulted-fold structures in the nearshore area (Figure 4.38).

After movement along the WBL terminated towards the end of T2S times, the strike-slip movement was relayed to the Mukah and the Igan-Oya Lines. The shift in movement from one fault to an other, similar to the relay action between the WBL, the Mukah and Igan-Oya Lines, is referred to as releasing oversteps. This resulted in the formation of depressions between two strike-slip faults, that is the Rajang Delta depression (Figure 4.33).

Giraut and Seguret (1985), in describing the nature of the releasing overstep of the Soria left-lateral strike-slip basin in northern Spain, produced a model showing the relative position of the area with induced tensile stress and the area with compressive stress. Their figure has been redrawn for a dextral strike-slip system (Figure 4.34A). According to the literature, the model has also adopted the mathematical model for the stress distribution in a pull-apart basin by Rodger (1980) and for a releasing overstep basin by Liu Xiahoan (1983). By referring to the releasing solitary overstep basin model (Figure 4.34A), the area with a concentration of compressive stress (area b), characterised by shortening and uplift, coincides with the compressional area to the east of the WBL and the area with faulted-fold structures.

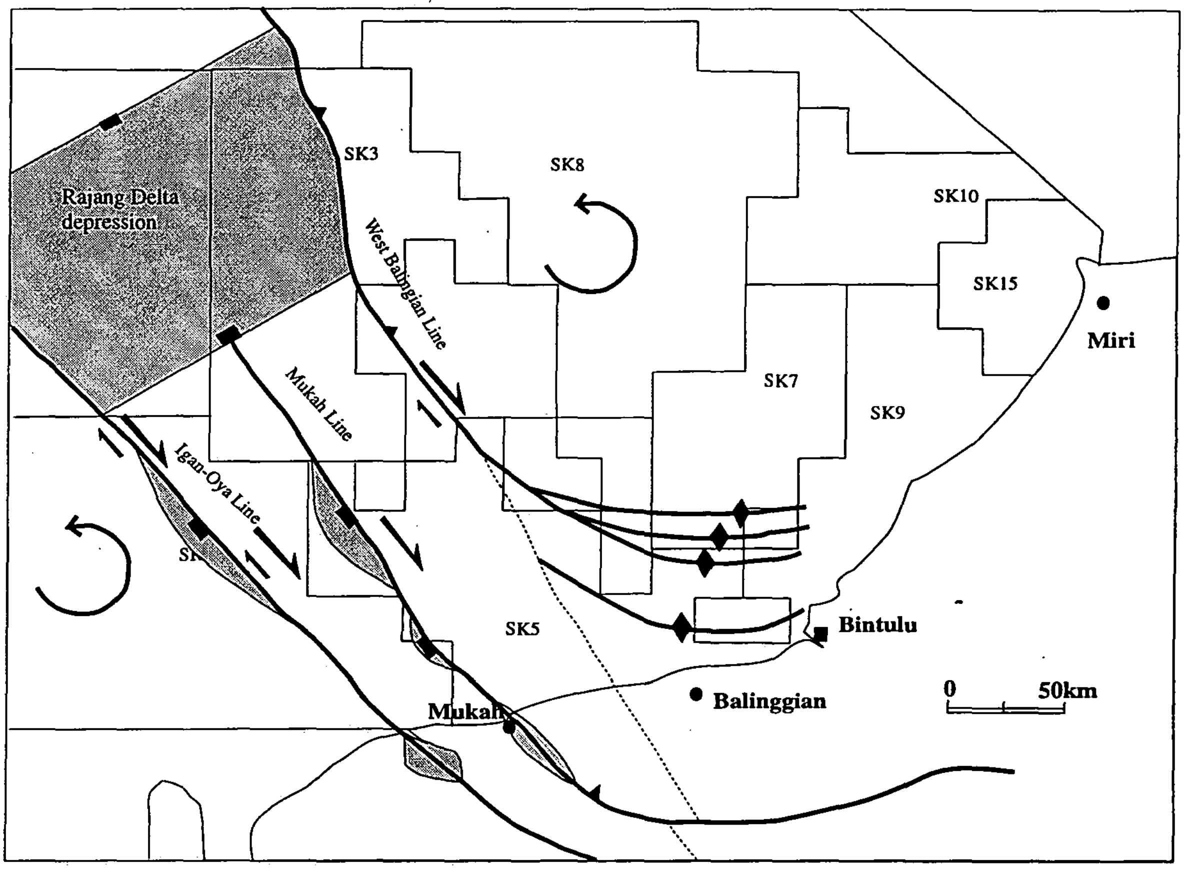


Figure 4.33. Tectonic map of Sarawak Basin during late Early to Middle Miocene (during the deposition of T3S).

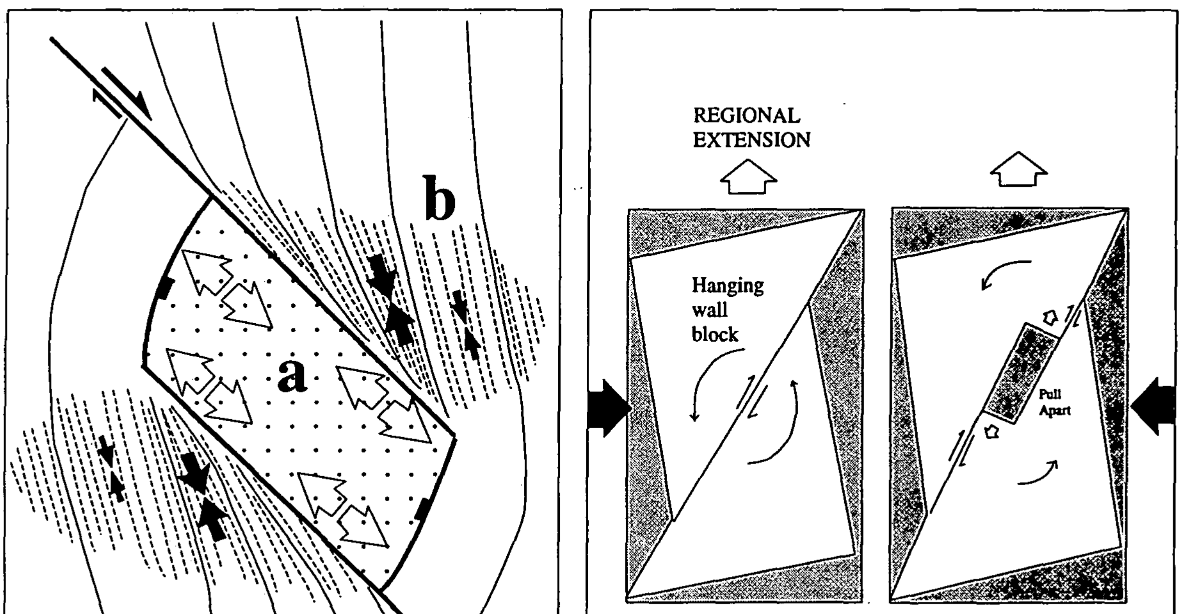


Figure 4.34. (A) Releasing solitary overstep basin model based on Giraud and Siguret (1985); a, is the area of induced tensile stress (basin) and b is the area of concentration of compressive stress (shortening,uplift,source of sediment). (B) Diagrams showing extension of hanging-wall block by strike-slip in cases where it is shortened sideways. Note if shortening keeps pace with extension, the strike -slip fault and any pull-apart basin that may form along it must rotate towards the direction of extension (Sengor et al.,1985).

Another model for releasing oversteps, illustrating the block rotation associated with the sinistral strike-slip releasing oversteps, is obtained from Sengor et al. (1985). The figure was redrawn from a dextral strike-slip system. By comparing the rotation direction of the interacted block (Figure 4.34B), resulting from the opening of a pull-apart basin and strike-slip movement (Figure 4.33A), one can infer that the blocks to the east and west of the WBL must be rotated in a counter-clockwise direction (Figure 4.33).

By using both models to interpret the evolution of the Sarawak Basin, it is possible to explain the formation of the faulted-fold structures in the nearshore area of the Sarawak Basin, as an area which underwent counter-clockwise rotation and compressive stress, as the result of releasing oversteps between the West Balingian Line and the Mukah and Igan-Oya Lines. The different timing of the folding that is progressively younger to the north can be explained by the compression initially taking place in the area adjacent to the major strike-slip fault and then progressively moving away in the counter-clockwise's centrifugal direction.

The effect of counter-clockwise rotation on the mobile blocks between the West Balingian Line, and the Mukah and Igan-Oya Lines is believed to be the cause for the major uplift for the onshore area and compression in the area to the east of the West Balingian Line. This also provides the answer as to why the strike-slip movement along the Mukah and Igan-Oya Line continued eastward in the onshore area, as opposed to the SW direction for the West Balingian Line.

In summary, the major tectonic activity in the Sarawak Basin took place in the Balingian area during the Middle Miocene, when the movement along the West Balingian Line ceased and oversteps to the Mukah and Igan-Oya-Lines resulting in the formation of the Rajang Delta depression, block rotation, faulted fold structures and the major uplift in the onshore area.

4.7.5 Late Miocene (During the deposition of T4S)

The tectonic activity during Late Miocene in the onshore and offshore Balingian-Mukah area was generated as the result of reactivation of the earlier major strike-slip faults. This resulted in further opening of the pull-apart basins along the Mukah and Igan-Oya Lines and also in the Rajang delta depression (Figure 4.33) and was followed by deposition of T4S. Similarly, the area that was subjected to compression during T3S times continued to be uplifted.

The intensity of the uplift is significant, especially in the onshore area where the base T4S unconformity seems to be capable of truncating not only the T3S but also the T1S in the area towards the Tatau Horst. The rate of sedimentation in the depression seems to have been

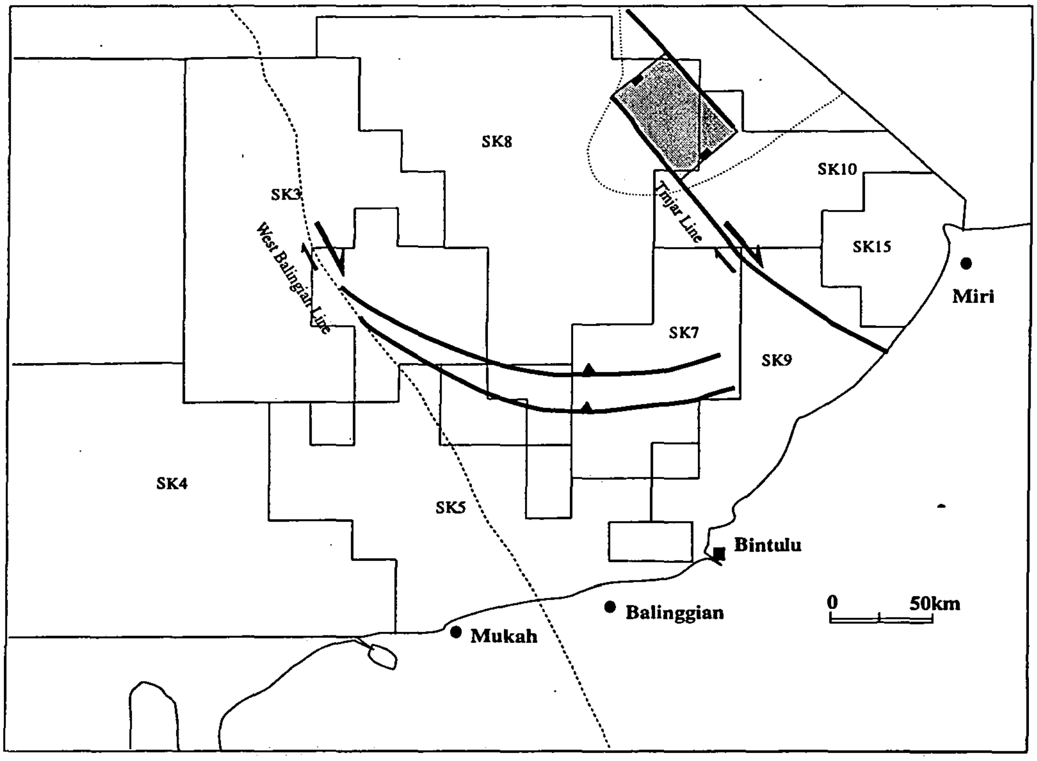


Figure 4.35. Map showing the main tectonic activities during the Late Miocene (T4S) are the formation of the younger faulted-fold structure and the formation of a depression by the releasing oversteps between the West Baram Line and the Tinjar Line.

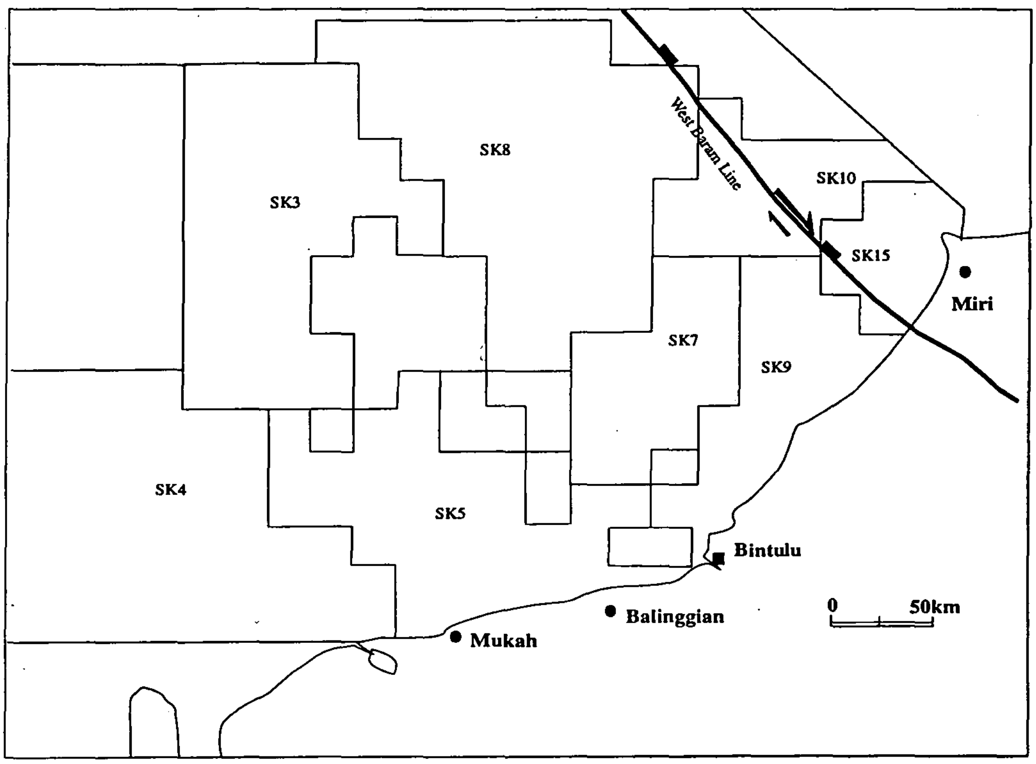


Figure 4.36. Map showing the main tectonic activity during the Pliocene (during the deposition of T5S) is the major strike-slip movement along the West Baram Line.

higher compared to the T3S times with thicker T4S deposited over about the same period of time (RL2, Figure 4.5 and RL1, Figure 4.7), suggesting the nearshore area to the west of the WBL was uplifted and formed the provenance area for the T4S deposited in the Rajang depression. At the same time, faulted-fold structures continued to develop farther to the north of SK5 (Figure 4.35).

In the offshore Miri area, the Tinjar Line started to be active during this time. Similar to the situation during the T1S between the West Balingian Line and the Mukah Line, it is interpreted as due to strike-slip movement in the Miri area which started with the movement along the West Baram Line, overstepping to the Tinjar Line (Figure 4.35). The interpretation is based on the occurrence of a deep depression evident at the top (Figure 4.3) where the basement depth exceeds 6.00 seconds TWT (about 14 kilometres). The Late Miocene times marked a shifting in the major tectonic activity from the Balingian-Mukah area to the Miri area when the strike-slip movement initiated the Tinjar Line, and later the West Baram Line.

4.7.6 Pliocene (During the deposition of T5S)

During Pliocene times all the highs in the deep-water area to the north of SK3 (Line 8, Figure 4.7) subsided and resulted in the whole area being covered by the T5 sediments. This suggests a large-scale basement collapse and major basin subsidence in the Sarawak Basin. The block rotations and uplift, which had been initiated during Middle Miocene times (T3S) in the nearshore and onshore Mukah-Balingian area, continued during this time, creating a high area in SK4 and SK5 (Figure 3.25) and in the onshore area (Figure 3.3). It is also believed that some faults, e.g. the Lemai, were reactivated during this time creating a local depression in which T5S was deposited.

In the Miri area, the West Baram Line started to develop during this time creating a very deep depression to the east of the line, and favoured the deposition of the sediments from the Baram river.

4.8. Tectonics and sedimentation history of the Sarawak Basin

This section discusses the relationship between the changes in depositional environment in the Sarawak Basin as discussed in Chapter 3, and the tectonic evolution as discussed in the last section. It should be noted here that the palaeoenvironment maps for each of the sedimentary sequences were generated from well data, ***independent*** of the seismic interpretation.

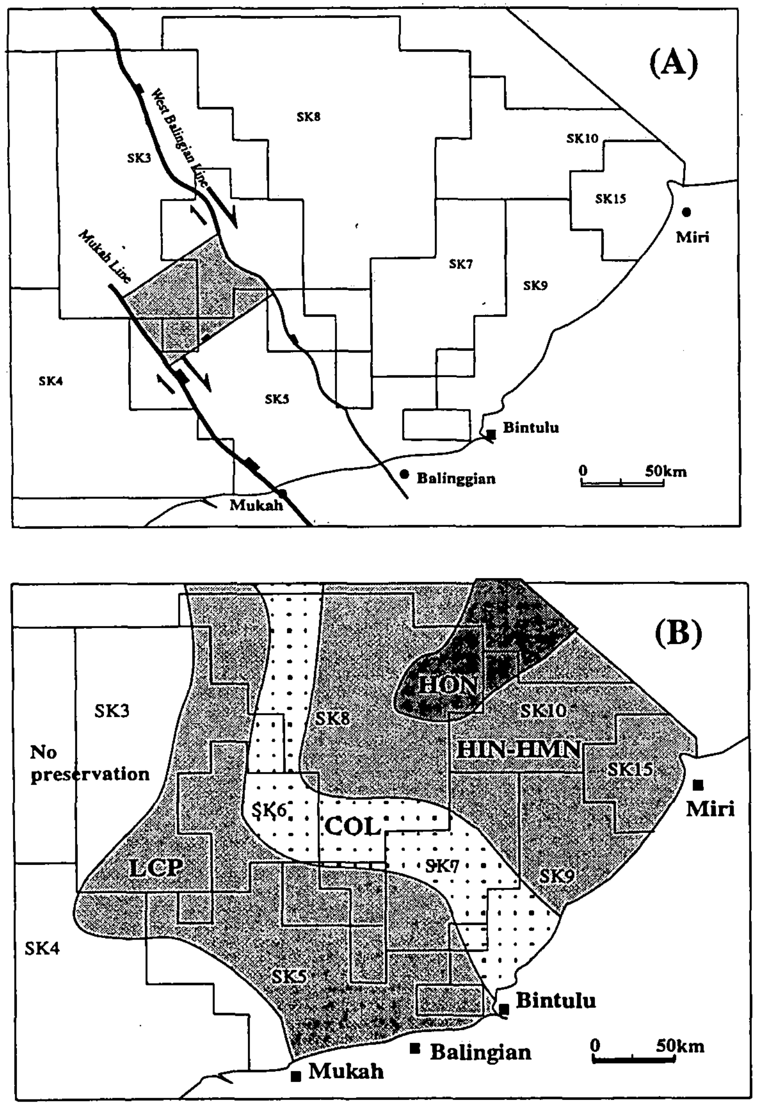


Figure 4.37. Figures showing the relationship between the tectonic and basin formation in Sarawak. (A) The major tectonic (strike-slip) movement during Eocene-Oligocene (Pre T1S) and (B) the lateral extent and environment of deposition of Late-Oligocene (T1S) sediments took place in the basin generated as the result of tectonic movements.

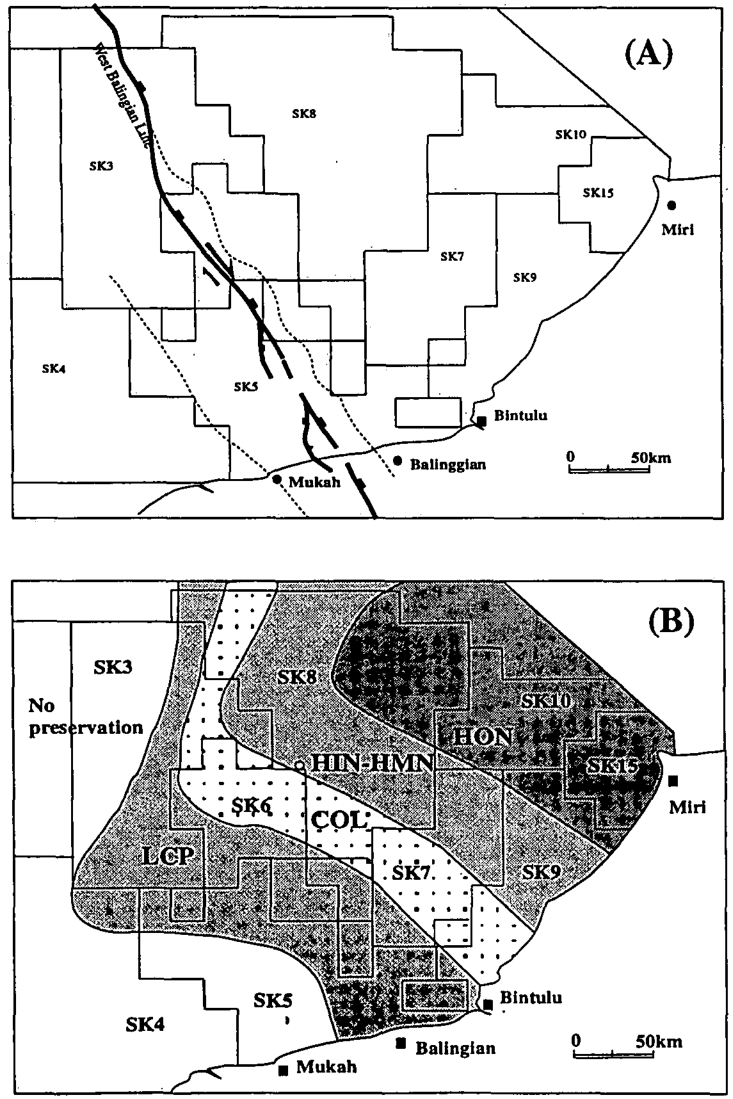


Figure 4.38 (A) Tectonic map of Sarawak Basin during Late Oligocene (T1S) and (B) The depositional environment map of the Early Miocene (T2S) sediments in the basin. Note that the orientation of the paleo-coastline during Early Miocene is almost similar to the Late Oligocene times but the area covered by the lower coastal plain sediments (in SK5) shifted slightly to the E, coincide to the position of the West Balingian Line.

However, the thickness and the lateral extent of each sequence were based on both the well and seismic data.

4.8.1 Eocene-Oligocene times (Prior to deposition of T1S)

The oldest tectonic movement prior to T1S times was along the eastern fault zone of the WBL which is believed to be responsible for the initial formation of the Sarawak Basin and the two sub-basins, the SW Luconia and the Lemai Sub-Basins, between the two major strike-slip lineaments (Figure 4.37A).

The depositional environment map of T1S (Figure 4.37B) shows that the western boundary to the T1S is coincident with the locations of the West Balingian Line and the Mukah Line in the offshore and nearshore areas respectively. Another amazing phenomenon is the occurrence of a westward embayment, in the area to the NW of SK5, which is confirmed by several wells, coincident with the location of the SW Luconia Sub-Basin. In the onshore area, it is known that the Lemai fault and Bukit Mersing Line formed the southern boundary for the T1S (Figure 4.8).

The above-mentioned relationship explains why the coastline of the Sarawak Basin during Eocene-Oligocene times was almost in a N-S orientation. This relationship suggests that the formation of the Sarawak basin was closely related to the generation of the fault line.

4.8.2 Late Oligocene-Early Miocene (During the deposition of T1S and T2S)

The main tectonic movement in the basin during the deposition of T1S was along the WBL (Figure 4.38A). The deposition of the T1S continued in the fault-related depressions created in the area during Late Eocene to Late Oligocene times (Figure 4.37a), creating a different thickness of the sequence in the area to the east and the west of the WBL. The T2S times could also be considered as relatively quiet tectonic periods, which also agrees with the depositional environment during the T2S times (Figure 4.38B) where the depositional environment of the sequence and T1S (Figure 3.37B) are basically similar except in the area to the NE of the Sarawak Basin where it is represented by the deeper-water environment suggesting more severe basin subsidence and/ or eustatic sea-level rise.

4.8.3 Middle Miocene (During the deposition of T3S)

The opening of Rajang depression and development of half-grabens along the Mukah and Igan-Oya Lines took place during the middle Miocene times (Figure 4.39A), which was the

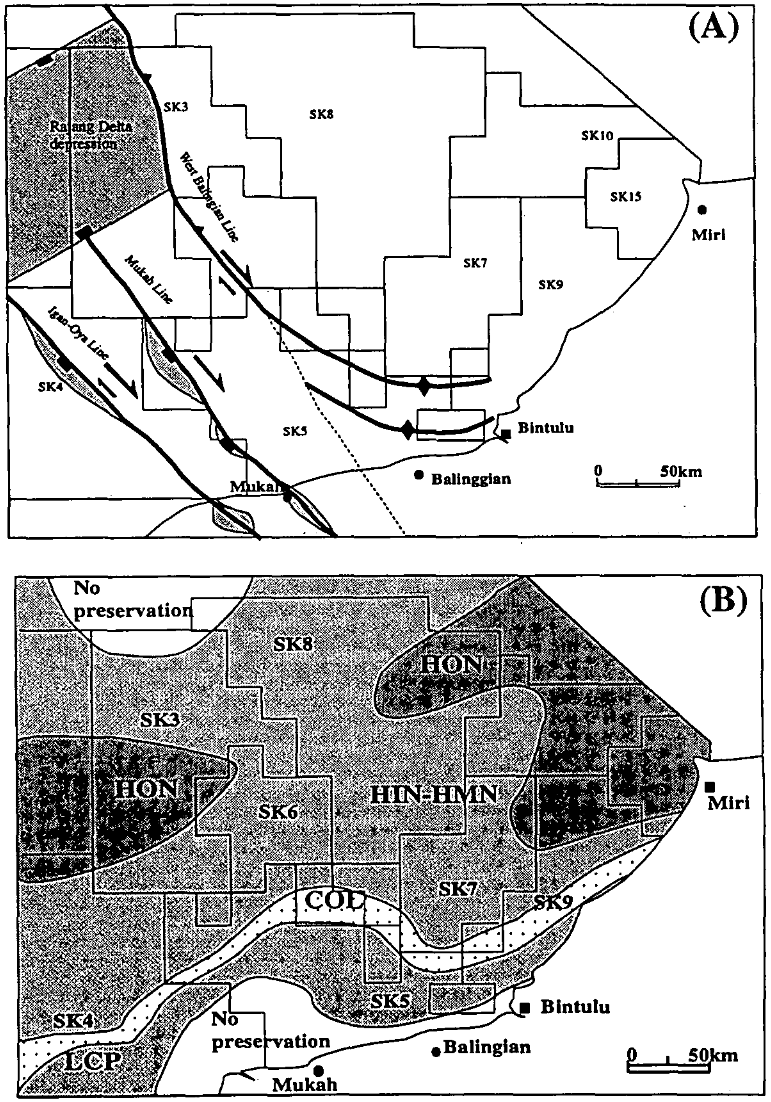


Figure 4.39. (A) Tectonic map of offshore Sarawak during late Early to Middle Miocene (T3S) showing the opening of the Rajang depression and (B) Depositional environments of Tertiary Three Sequence (T3S). Note the orientation of the coastline during this time is very different from the earlier times (T1S and T2S). The newly created Rajang depression is characterised by the holomarine outer neritic environment.

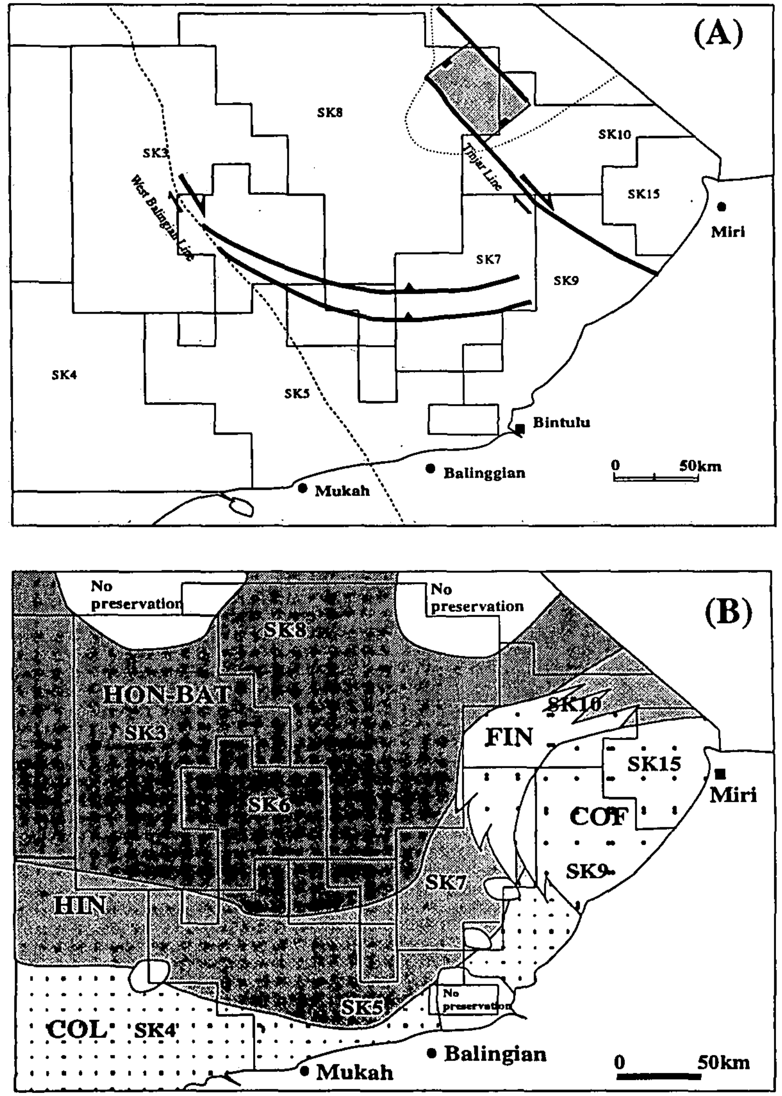


Figure 4.40. (A) Tectonic map of offshore Sarawak during Late Miocene (T4S) showing the formation of depressions by the releasing oversteps between the West Baram Line and the Tinjar Line. (B) Depositional environments of the T4S. Note the location of the Tinjar Line in the middle of the Baram Delta progradation unit which suggest that the Palaeo-Baram river could have been flowing along the Tinjar Line during the Late Miocene.

most active tectonic period in the Sarawak Basin. Similarly the depositional environment map during T3S times marked a severe change in the depositional environments of the Sarawak Basin. The coastline of Sarawak changed to an E-W orientation, as opposed to the N-S orientation during T1S and T2S, before the Middle Miocene times. Most of the areas including SK6 and the eastern part of SK3 which were within the coastal-plain environment during T1S and T2S times were located within the holomarine environment during T3S times.

The effect of active tectonic movement resulted in the formation of new depressions during T3S times and this is believed to be a possible explanation as to why the major changes in the orientation of the coastline happened during this time. This finding is believed to be very significant for petroleum exploration as the area for prospective T3S tremendously increased compared to the area for the older sequences. To the author's knowledge, the reason for change in the coastline orientation during the T3S times has never been understood before.

4.8.4 Late Miocene (During the deposition of T4S)

In the offshore Miri area, the Tinjar Line, which started to be active during this time created a depression by overstepping from the West Baram Line to the Tinjar Line (Figure 3.40A). The interpretation is based on the occurrence of a deep depression, evident on seismic where the basement depth exceeds 6.0 seconds (Figure 4.3). This interpretation seems coincident with the depositional environment map where the area to the NE of the West Baram Line is characterised by a high without preservation of T4S (Figure 4.40B). Similarly the location of the Tinjar Line is also coincident to the axis of Baram Delta, suggesting that the palaeo river supplying the sediment to the Sarawak Basin occurred along the Tinjar Line.

4.8.5 Pliocene (During the deposition of T5S)

The West Baram Line started to develop during this time creating a very deep depression to the east of the line, where sediments from the Baram river were deposited. This interpretation agrees with the depositional environment map of the Sarawak Basin where the West Baram Line also marked the south-western boundary of the sediment progradation limit for the Baram delta (Figure 4.41) and the delta shifted to the Brunei and Sabah areas to the east.

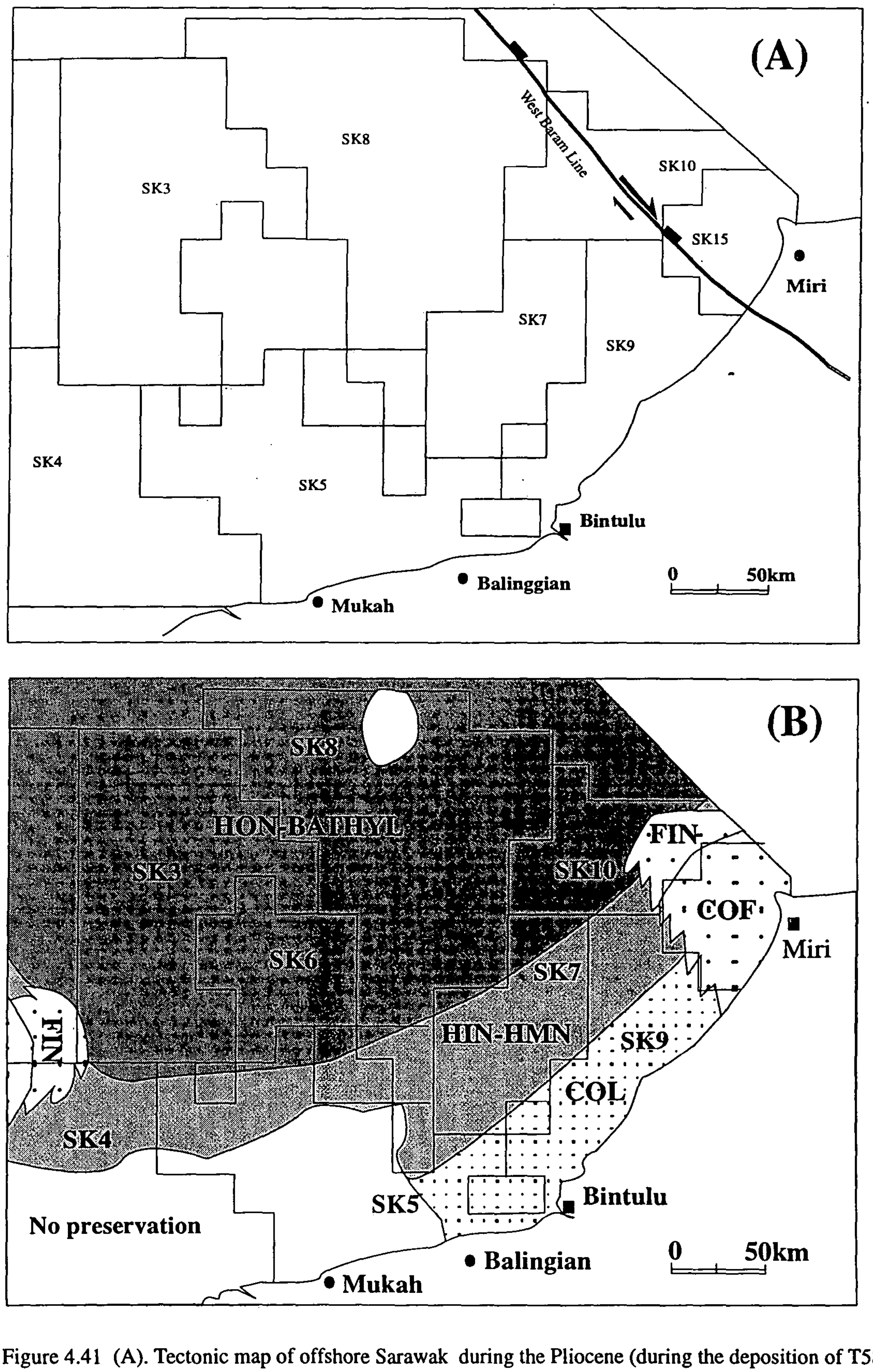


Figure 4.41 (A). Tectonic map of offshore Sarawak during the Pliocene (during the deposition of T5S). (B) Depositional environments map of T5S. Note that the progradational direction of the Baram Delta shifted further to the east and the West Baram Line forms as the western boundary of the Baram Delta.

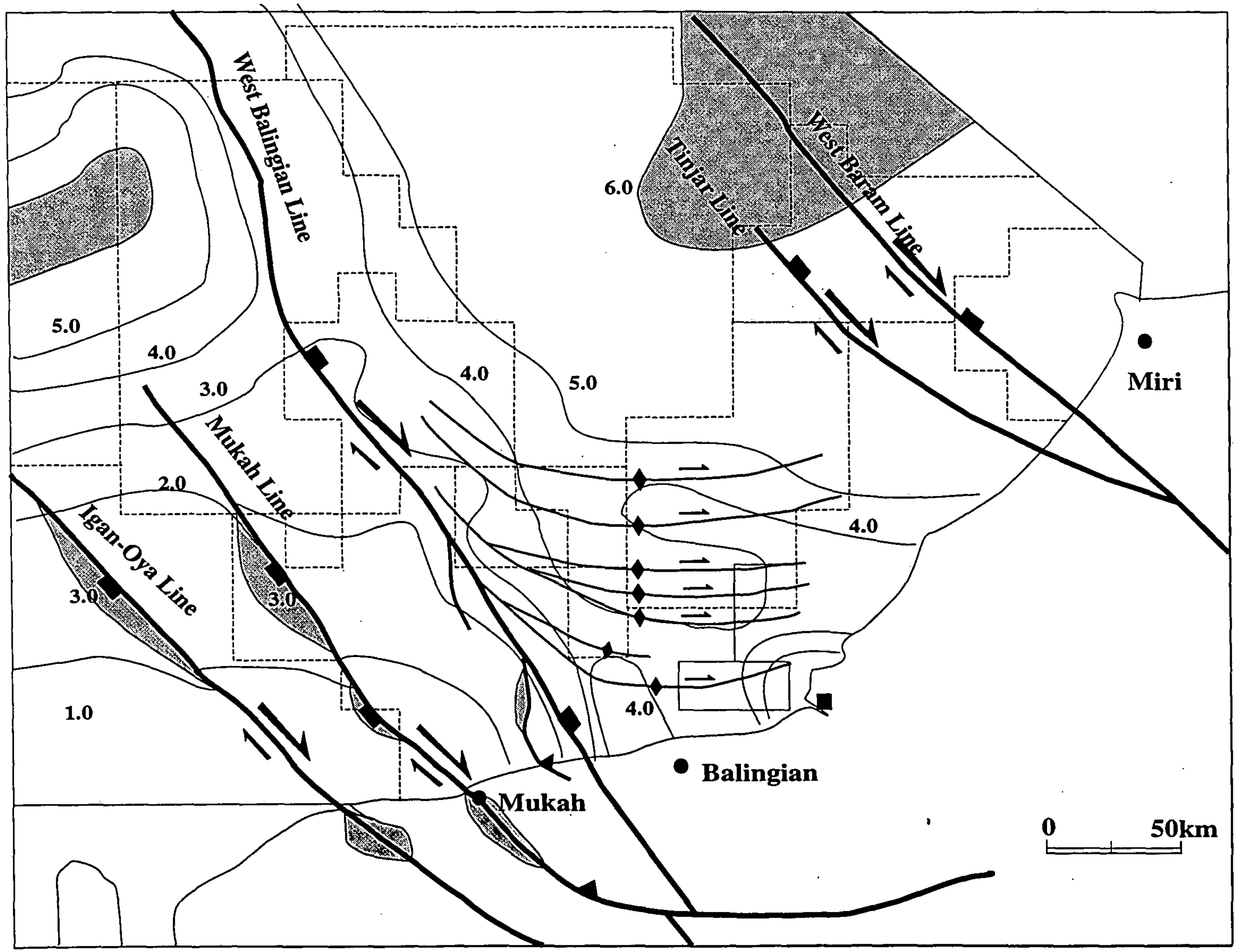


Figure 4.42. Basement topography map with major tectonic lineaments summarises the structural setting of the Sarawak Basin and the basin's formation related to the strike-slip tectonism.

4.9 Summary and Conclusions

The tectonic history of the Sarawak Basin is best explained by interpretation of the major structures related to a strike-slip fault pattern. The wide range of structural styles is consistent with an origin by strike-slip faulting.

The main findings on the Tertiary tectonics of the Sarawak Basin derived from this study are:

1) Strike-slip tectonism is the primary control during the Tertiary. Strike-slip tectonism is responsible for the basin formation and deformation and controlled the sedimentation in the Sarawak Basin. This study interpreted that the five major lineaments namely the Igan-Oya Line, Mukah Line, West Balingian Line, Tinjar Line and West Baram Line (Figure 4.42) are dextral strike-slip faults having characteristics analogous to known strike-slip faults elsewhere.

2. The generation of faulted-fold structures, which are the main structural traps for hydrocarbons in the nearshore area, were induced by the strike-slip tectonism. The formation of highs and lows in the Luconia Province that subsequently was followed by carbonate deposition and the formation of buried hills (formed by structural highs bounded by normal faults with N-S orientation) have the consistent spatial relationship to the strike-slip tectonics of NW-SE shear.

3. The timing of the movements along the major strike-slip lineaments in the Sarawak Basin are progressively younger in the eastward direction. However, some of the lines were reactivated in later periods. The orientations of the strike-slip lineaments are mostly in NW-SE in the offshore area and shifted to almost E-W orientation in the onshore, primarily due to the counter-clockwise rotation of the interacted blocks. The exception is the West Balingian Line and the West Baram Line that maintain the NW-SE orientation to the onshore area. The movement along the major strike-slip lines and releasing oversteps between the lines during a particular time has resulted in the formation of several sub-basins.

4. The tectonic evolution of the Sarawak Basin is closely linked to the palaeo-depositional environment data derived from the well data for each sedimentary sequence. Most of the time the information derived from an understanding of the tectonic evolution provides the explanations as to why there were changes in the depositional environments.

Chapter 5

BASIN EVOLUTION

5.1. Introduction

The current published interpretation of the tectonic setting of the Sarawak Basin is that the basin was developed as a result of subduction of South China Sea oceanic crust beneath the NW Sarawak continental crust (James, 1984; Figure 1.10). If that interpretation is correct, the Sarawak Basin therefore would conform most closely to a foreland basin in terms of its tectonic origin (Allen and Allen, 1990); i.e. it was created by lithospheric flexure. The finding of this study, however, propose an alternative interpretation for the Sarawak Basin. Instead, the Sarawak Basin is interpreted to be formed by strike-slip movement along five major lineaments identified by the most recent regional reflection seismic lines (Chapter 4). Therefore instead of foreland basin or trench-associated basin (Kingston, 1983), the Sarawak Basin can be classified as a strike-slip related basin.

The subsidence history of basins is strongly dependent on the tectonic origin. Most published studies have examined basins formed by lithospheric stretching (e.g. North Sea, Gulf of Lyons) and lithospheric flexure (e.g. Molasse Basin, etc.) where the profiles of subsidence are interpretable in terms of extension factors. There are few details published on the subsidence histories of strike-slip basins.

Theoretically, the subsidence history experienced by a basin formed by lithospheric stretching and a basin formed by flexure are different. The subsidence history for basins due to flexure (foreland basin) is normally characterised by increasing subsidence rate with time (Figure 5.1). In contrast, the post-rift subsidence history of an extensional basin shows exponential decrease in subsidence rate with time (Allen & Allen, 1990). Extensional basins can be generally divided into two types. Those which conform to McKenzie's (1978) model and those which do not. A basin generated within strike-slip zones may be expected to show rapid but short-lived subsidence, alternating with compression and uplift (Kneller, 1991).

McKenzie (1978) proposed a two-phase model for development and evolution of a rift-type sedimentary basin. The first phase consists of rapid stretching of continental lithosphere, which thins the lithosphere allowing passive upwelling of hot asthenosphere. This stage is associated with block faulting and subsidence. The second phase is characterised by thermally controlled subsidence due to lithospheric cooling and contraction, as the asthenosphere or

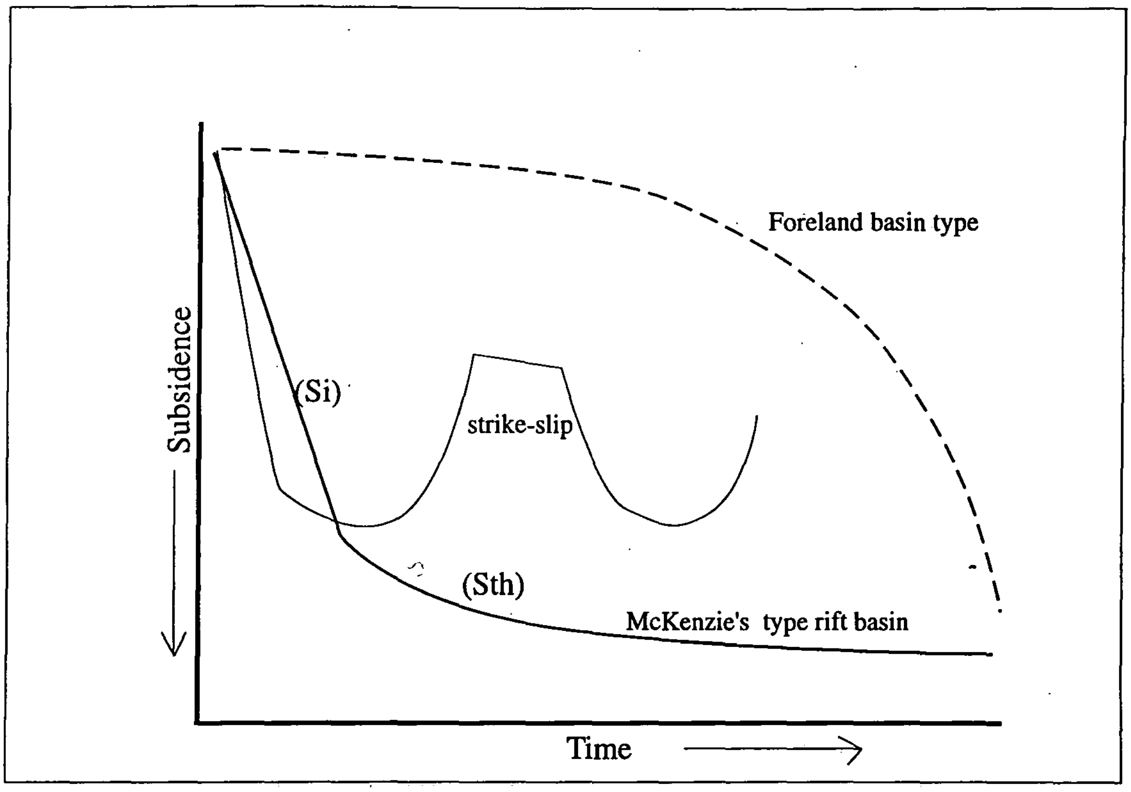


Figure 5.1. Different types of subsidence between foreland, rifts basin and McKenzie's type of rift basin, modified after Kneller, 1991 .

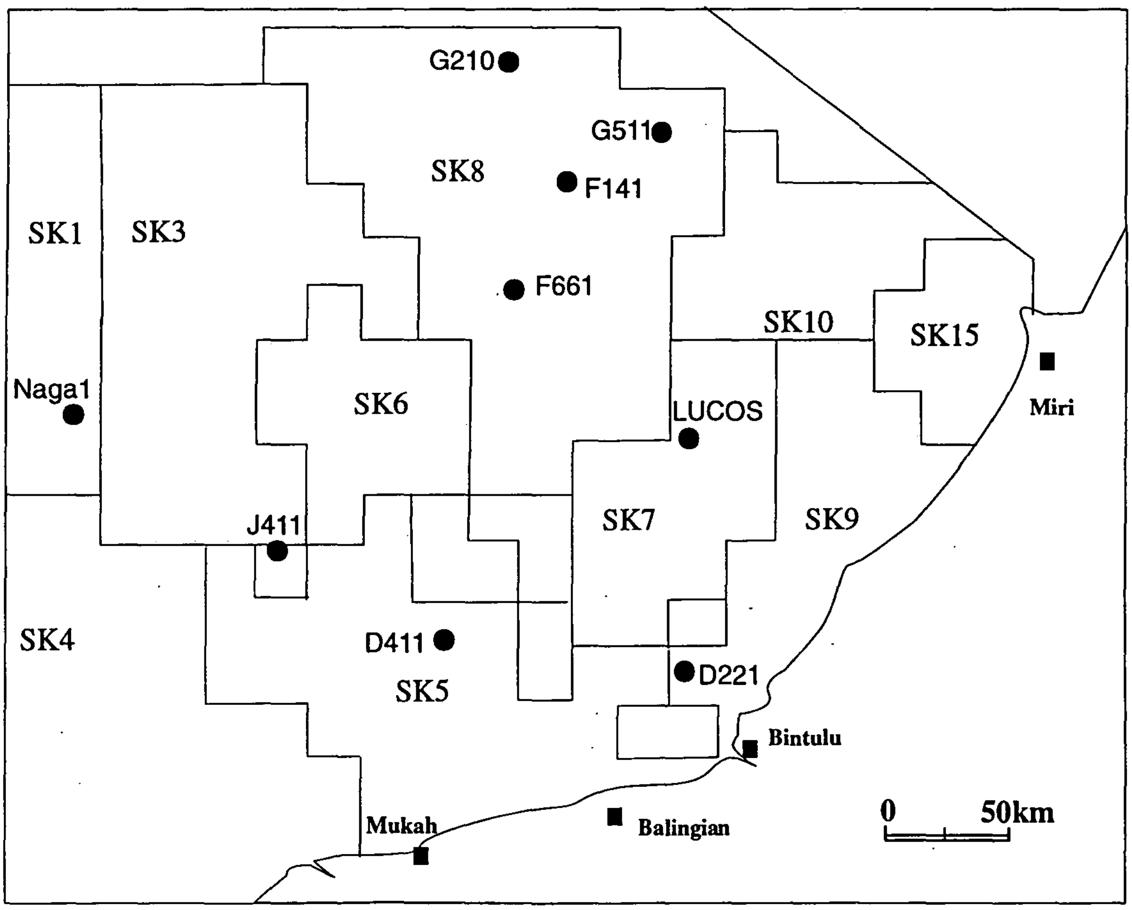


Figure 5.2. Map showing the location of the wells used for BasinMod studies.

lithosphere boundary returns to its original position. The amount of stretching (ß) can be estimated from changes in the thickness of continental crust, by analysis of extension of pre-rift markers, by analysis of fault heave and by examination and interpretation of the subsidence history (burial history curves). The subsidence history of nine wells from the Sarawak Basin has been used to investigate the tectonic origin of the basin using commercial software, Basin Modelling System Version 4 by Platte River Associates.

5.1.1. Objectives

The objectives of the study are:

1. To determine the tectonic subsidence history of the Sarawak Basin using the well data and BasinMod 1-D basin modelling software, and to compare the profiles with those for classical foreland and rift basins.

2. To determine whether the McKenzie model can be used as a model for the rifting and subsidence history of the Sarawak Basin.

3. To study whether the McKenzie model is applicable for a strike-slip related basin.

4. To compare the geothermic data, including geothermal gradients and present day heat flow estimated from the bore holes by the other workers, with values from modelling estimates.

5.2. Data

In order to compute the basement subsidence from the well data it is necessary to have the data on the stratigraphy and sedimentary thickness, water depth during deposition, sea-level and lithology.

The main source of information for this study was seismic and well data. A number of regional seismic lines (Figure 4.6) pass through the nine selected wells. In the case where no seismic passes exactly through the well locations, part of the structure could be seen on the regional seismic lines in Figure 4.5 and 4.7. In each case, the location of the well and the well penetration are not shown on the seismic lines for reasons of data confidentiality.

Nine wells from the Sarawak Basin were selected for the purpose of basin modelling studies. The locations of the wells are shown in Figure 5.2. The available well data are in the form of composite well logs plus original copies of several electric logs. All the well composite logs are furnished with gamma ray, resistivity and sonic curves in addition to the interpretation of the depositional environments, biostratigraphic data, dip meter and cycle boundaries. The geographic co-ordinates, spud date, water depth and drill floor elevation could also be obtained from the composite well logs.

The coded names of the selected wells are;

D411, J411, NAGA1, D221, LUCOS, F661, F141, G511, G210.

Data on the lithological percentage, water depth and the depositional environments were obtained from well logs. In the well data input for BasinMod (Table 5.1), the total depths (TD) of the well were also incorporated, which indicate that all the data below the well TD was not obtained from the well but from the seismic or based on the information from nearby wells. Detailed on the techniques used in obtaining the stratigraphic boundaries, lithological assemblages, paleo-water depth and sea level are described below.

5.2.1. Stratigraphic Scheme and Datum

The stratigraphic scheme used here follows the format developed in Chapter 2 (Figure 2.14). The same techniques have been applied to determine the sequence boundaries for the nine selected wells. Once the sequence boundaries were fixed, the age of each sequence was determined using the stratigraphic chart in Figure 2.14.

Mean sea level was used as the datum for depth measurement for all the wells, which means all the depth values for top of each formation from the composite well logs has been converted from measured to sub-sea depth.

5.2.2. Lithological percentage

The actual percentage of each lithology was calculated from the original wireline logs. For wells without the original wireline logs, an estimation was made using composite logs. For some of the wells in which the stratigraphic penetration was not deep enough to reach the basement, the lithological percentage beneath the maximum depth reached was estimated based on the depositional environments of the sequences present above basement, using the depositional environment maps in Section 3.6.

5.2.3. Water depth and sea level

The water depth during deposition was estimated, based on the palaeo-depositional environments of each sequence. The data on the palaeo-depositional environment interpretations are mainly based on the occurrence of benthonic foraminifera, obtained from the composite well logs. The relationship between water depth and depositional environment for the Sarawak Basin was established by Ho (1978; Figure 3.20). More often than not, the depositional environment for a sequence changed from shallower environment to deeper environment or vice versa. In this study, the maximum water depth is taken as the depositional depth of the particular sequence.

The changes in sea-level through time was determined using the third order eustatic sea-level curve of Haq et al (1987; Figure 2.14). The average between the maximum and minimum sea level in the sequence interval was taken as the sea level value for the sequence.

Table 5.1. Input for BasinMod 1-D modelling: Sarawak Basin wells.

Well: D411 Water depth: 101 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	101	1.5	99	10ss/20slt/70sh	HIN/120	-164
T6S	200	3	101	10ss/20slt/70sh	HIN/120	-164
T5S	301	5.2	400	10ss/20slt/70sh	HIN/120	196
T4S	701	11.5	600	20sst/25slt/45sh	HIN/120	-164
T3S	1301	16	400	20sst/25slt/45sh	HIN/120	396
Erosion		17	-600			
Haitus T2		18				
Missing T2S		22	600	35ss/20slt/45sh	LCP/0	295
T1S	1701	37	6560	35ss/20slt/35sh	LCP/0	164
Basement	8079					
Well TD	8261					

Well: J411 Water depth: 173 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	173	1.5	777	10ss/35slt/55sh	HIN/120	-164
T6S	950	3	773	10ss/35slt/55sh	HIN/120	-164
T5S	1723	5.2	583	10ss/20slt/70sh	HMN/300	196
T4S	2306	11.5	1342	30ss/30slt/40sh	HMN/300	-164
T3S	3648	17	821	65 lst/15slt/15sh	HIN/120	396
T2S	4469	22	1340	40ss/20slt/40sh	LCP/0	295
T1S	5809	32	7314	45ss/20slt/35sh	LCP/0	164
Well TD	7459					
Basement	13,123					

Table 5.1 cont.

Well: Nagal Water depth: 308 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	308	1.5	692	10ss/90sh	HMN/300	-164
T6S	1000	3	1691	20ss/23slt/57sh	HMN/300	-164
T5S	2691	5.2	2347	5ss/10slt/85sh	HON/600	196
T4S	5038	11.5	17271	23ss/57slt/20sh	HIN/120	-164
Well TD	7183					
T3S	22309	17	3937	30ss/35slt/35sh	HIN/120	396
Basement	26,246					

Well: D221 Water depth: 120 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	210	1.5	340	20sst/25slt/55sh	HIN/120	-164
T6S	550	3	358	40sst/20slt/ 40sh	COL/60	-164
T5S	908	5.2	539	40sst/20slt/ 40sh	COL/60	196
Erosion		6	-2500			
Haitus		8				
Missing T4S		10	2500	20sst/25slt/55sh	HIN/120	-164
T4S	1447	11.5	1			-164
Erosion		12	-3000			
Haitus		13				
Missing T3S		15	3000	40sst/20slt/ 40sh	COL/60	396
T3S	1448	17	578	40sst/20slt/ 40sh	COL/60	396
T2S	2026	22	5708	30sst/25slt/45sh	LCP/0	295
T1S	7734	37	8670	35sst/20slt/45sh	LCP/0	164
Well TD	8582					
Basement	16404					

Well: LUCOS Water depth: 214 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	214	1.5	336	15ss/15slt/70sh	HIN/120	-164
T6S	550	3	385	15ss/15slt/70sh	HIN/120	-164
T5S	935	5.2	1695	30sst/20slt/50sh	HIN/120	196
T4S	2630	11.5	6195	55sst/20slt/25sh	COF/60	-164
T3S	8825	17	1905	40lst/20slt/ 40sh	HIN/120	396
T2S	10730	22	7314	20sst/25slt/55sh	HIN/120	295
Well TD	10890					
T1S	18044	37	14764	40sst/20slt/40sh	COL/60	164
Basement	32808					

Table 5.1 Cont.

Well: F661 Water depth: 277 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	277	1.5	429	15ss/15slt/70sh	HIN/120	-164
T6S	706	3	940	15ss/15slt/70sh	HIN/120	-164
T5S	1646	5.2	2404	10slt/90sh	HMN/300	196
T4S	4050	11.5	2817	100 lst	HIN/120	-164
T3S	6867	17	1371	60lst/10slt/ 30sh	HIN/120	396
T2S	8238	22	11446	20sst/25slt/55sh	HIN/120	295
Well TD	10919					
T1S	19684	37	16403	20sst/25slt/55sh	HIN/120	164
Basement	36088					

Well: F141 Water depth: 347 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	347	1.5	1164	5ss/25slt/70sh	HIN/120	-164
T6S	1511	3	988	5ss/25slt/70sh	HIN/120	-164
T5S	2499	5.2	1767	10 slt/90sh	HMN/300	196
T4S	4266	11.5	3937	100 lst	HIN/120	-164
Well TD	4804					
T3S	8203	17	8201	35 lst/10ss/ 10slt/45sh	HIN/120	396
T2S	16404	22	9842	10ss/20slt/70sh	HMN/300	295
T1S	26246	37	16404	20sst/25slt/55sh	HIN/120	164
Basement	42650 ft					

Well: G511 Water depth: 369 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	369	1.5	1416	5ss/25slt/ 70sh	HON/600	-164
T6S	1785	3	8057	5ss/25slt/ 70sh	HON/600	-164
Well TD	3940					
T5S	9842	5.2	4921	35 lst/25slt/40sh	HON/600	196
Erosion		7	-3000			
Haitus		10				
Missing		12.5	3000			-164
T4S						
T3S	14763	17	3281	5ss/25slt/70sh	HON/600	396
T2S	19784	22	4921	5ss/25slt/70sh	HON/600	295
T1S	26246	37	19685	10ss/20slt/70sh	HMN/300	164
Basement	41010 ft					

Table 5.1 Cont.

Well: G210 Water depth: 468 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	468	1.5	1360	5ss/25slt/70sh	HON/600	-164
T6S	1828	3	2053	5ss/25slt/70sh	HON/600	-164
T5S	3881	5.2	2237	100 lst	HON/600	196
T4S	6118	11.5	930	5ss/25slt/70sh	HON/600	-164
T3S	7043	17	9956	20sst/25slt/55sh	HIN/120	396
T2S	7994	22	2239	10ss/20slt/70sh	HMN/300	295
T1S	10233	37	3500	20sst/25slt/55sh	HIN/120	164
Well TD	10921					
Basement	13,265 ft					

5.3 Techniques to generate subsidence curves

The methods used in analysing the well data are described in this section BasinMod 1-D for Windows Basin Modelling System Version 4 by Platte River Associates, hereafter referred to as BasinMod, was used to generate the subsidence curves for the nine wells from Sarawak Basin. The input data were obtained from either well logs or the seismic lines. In addition, BasinMod has its own default values for some parameters; for example thermal conductivity, compaction curves and poroperm.

Once both the input and default values were keyed into the programme, BasinMod is able to generate several options of display including *Burial History,* either with or without compaction correction, *Geohistory,* with or without ocean display, and *Tectonic Subsidence* curves which facilitates the analysis of subsidence history of the basin in the vicinity of the selected wells. For this study, only the total and tectonic subsidence for all the nine wells are displayed.

Before discussing the subsidence history of the basin (Section 5.5), it is appropriate to outline the process involved in generating the subsidence curves and to provide a brief description of both the default and the input data required by BasinMod.

5.3.1 Default Data

The rock data not required as a direct input into BasinMod include porosity and permeability values. BasinMod can supply default values using several calculation options offered by the programme, since BasinMod contains a lithology library. The library starts out with a default set of eight pure lithologies along with their rock property values which BasinMod requires for its calculations. The rock properties include initial porosity, compaction algorithms, density, grain size, conductivity and heat capacity. In practice, the formations to be modelled are often a mixture of these pure lithologies. The user can utilise the *Lithology Mixed* option for the default values. When the lithology of a formation cannot be effectively described in terms of a mixture of pure lithologies, BasinMod also allows definition of lithologies in terms of mineral composition.

a) *Porosity*

BasinMod calculates effective porosity by using the following equation:

$$\phi_* = \phi - 3.1\text{x } 10^{-10}\, So$$

Where; ϕ_* =Effective porosity

ϕ =Porosity (initial) from BasinMod lithology library

So =Specific surface area of rock, i.e., the surface area to volume ratio using the surface area of a sphere and the volume of a cube. Grain size is equal the diameter of the sphere and the side of the cube.

b) *Permeability*

Fluid flow (single phase) through porous media is modelled using Darcy's Law for the flow of water through sands. Later experiments using various fluids and porous materials showed that viscosity and density of the fluid plus size of grains all effect the flow. The equation (form the BasinMod software manual) has evolved to:

$$V = -\frac{k\rho g}{\mu} \times \frac{dh}{dl}$$

Where; V=	Specific discharge	g=	Gravitational acceleration
k=	Permeability	μ=	Viscosity
ρ=	Density	*dh/dl*=	Hydraulic gradient

BasinMod offers several methods for estimating permeability values including the Kozeny-Carman, Power Function and user-specified Porosity-Permeability relationships. The Kozeny-Carman method of calculation was used for all the wells, as measured porosity-permeability data for the nine wells are not available.

$$k = \frac{0.2\phi^2}{So^2(1-\phi)^2} When \phi > 10\%$$

$$k = \frac{0.2\phi^5}{So^2(1-\phi)^2} When \phi < 10\%$$

5.3.2 Input Data required by the BasinMod

The data needed as input to BasinMod for creating tectonic subsidence curves are as follows:

a) *Stratigraphy* includes Formation Name, Beginning Age, Well Top, Thickness, Hiatus and Missing Section, and Lithological Composition.

b) *Present Day Information* includes the present day water depth.

c) *Time Values* are the paleo-water depth and eustatic sea-level through time.

5.3.3 Correction for compaction (decompaction)

To calculate the thickness of a sediment layer at any time in the past, it is necessary to move the upper layer upwards along the appropriate porosity-depth curve: this is equivalent to sequentially removing overlying sediment layers and allowing the layer of interest to decompact. In doing so, we keep mass constant and consider the changes in volume and therefore thicknesses (Allen and Allen, 1990).

The curve corrected for compaction (decompacted) is always deeper than the uncompacted curve in the burial history plot. However, the beginning and end points of both curves are the same so the greatest variances will occur toward the middle of the burial history curves. The basic assumption of mechanical compaction is that the thicknesses of sediments and rocks are reduced by a predictable amount related to porosity reduction, varying according to lithology and depth of burial.

BasinMod offers four methods of correction for compaction including algoriths developed by Sclater and Christie, Falvey and Middleton, Baldwin and Butler and porosity table with coupled fluid flow compaction. For this study, the Sclater and Christie method was used because the modelled wells are dominated by siliciclastics, similar to the rocks for the North Sea which constitute the data for Sclater and Christie (1980). The porosity based on Sclater and Christie is:

$$P = P_0 \, Exp^{(-kz)}$$

Where: P_0= Initial Porosity

k= Compaction factor to adjust for varying compressibility of different lithologies

Z= Depth

5.3.4 Total Subsidence and Tectonic Subsidence

The total subsidence in a basin is a combination of basement (tectonic) subsidence and subsidence due to sediment loading. The process used to determine the amount of load-induced subsidence is isostatic backstripping. This method removes sediment layers, correcting for decompaction, fluctuation of sea level and sea-depth, and, assuming airy isostacy, adjusts for isostatic rebound. The equation used by BasinMod to calculate the effect of load-induced subsidence (Steckler and Watts, 1978):

$$Y = S\left(\frac{\rho m - \rho s}{\rho m - \rho w}\right) - \Delta SL\left(\frac{\rho w}{\rho m - \rho w}\right) - (Wd - \Delta SL)$$

Where:

$Y =$ depth of basement corrected for sediment load

$S =$ total thickness of sediment column corrected for compaction

$\rho m =$ average mantle density

$\rho s =$ average sediment density

$\rho w =$ average water density

$\Delta SL =$ change in elevation of mean sea level

$Wd =$ paleo sea depth

Once we know the load-induced component of total subsidence, we also know the amount of tectonic subsidence. The results of this computation are displayed on a backstripped subsidence curve (Graph/Burial history/Subsidence). The backstripped subsidence curves for the nine wells from the Sarawak Basin are shown in Figures 5.6-5.10.

In summary, the **Total Subsidence** of a basin is derived by the cumulative factors as listed below :

1. Sediment loading (from stratigraphic data)
2. Change in water depth (from palaeo-environment maps)
3. Change in eustatic sea-level (from Haq et al, 1987)
4. Tectonic (basement) subsidence (from burial history curves of BasinMod).

5.4 Method to analyse subsidence curves

The computer-generated results were analysed primarily according to descriptions by Allen and Allen (1990), by firstly assuming that the basin has experienced a subsidence history consistent with McKenzie's (1978) model. The results of McKenzie (1978) quantitative model of stretching can be summarised as follows:

1. The total subsidence in an extensional basin is made of two components; an initial fault controlled subsidence (Si) which is dependent on the initial thickness of the crust and the amount of stretching (β); and a subsequent thermal subsidence (Sth) caused by relaxation of lithospheric isotherms to their pre-stretching position, and which is dependent on the amount of stretching (β) alone.

2. Whereas the fault-controlled subsidence is modelled as instantaneous, the rate of thermal subsidence decreases exponentially with time. This is the result of decrease in heat with time. The heat flow reaches its original value after about 50 Ma for a lithosphere of 'standard' thickness, so at this point after the cessation of rifting, the dependency of the heat flow on β is insignificant.

5.4.1 Initial Subsidence

According to the McKenzie (1978) model, at time=0 a unit length of continental lithosphere is suddenly extended to length β, causing upwelling of hot lithosphere. The resultant thermal perturbation gradually decays, producing subsidence. The simplest model ignores the radioactivity of continental rocks and assumes that the temperature at a depth corresponding to the initial thickness of the lithosphere is fixed. Subsidence of the lithosphere is isostatically compensated both before and after extension. In brief, the model assumes:

1. Instantaneous stretching
2. No volcanism
3. Vertical heat conduction
4. Uniform extension
5. Thermal equilibration
6. Isostatic equilibrium.

The Initial Subsidence (Si) is given by:

$$Si = \frac{a\left(1-\frac{1}{\beta}\right)\left\{\frac{tc}{a}(\rho m-\rho s)\left(1-\frac{\alpha Tltc}{2a}\right)-\frac{\alpha\rho mTl}{2}\right\}}{\rho m(1-\alpha Tl)-\rho s}$$ ....**Equation (1)**

Where:Thickness of unextended lithosphere	*(a)*	=125km
Thickness of unextended crust	*(tc)*	=35km
Density of crust at 0º C	(ρc)	=2.8g cm^{-3}
Density of mantle at 0º C	(ρm)	=3.33g cm^{-3}
Density of basin infill (water)	(ρs)	=1.03g cm^{-3}
Coefficient of thermal expension	(α)	=3.28x10^{-5} ºC
Temperature at base of lithosphere	(T*l*)	=1333 ºC

The values of the parameters above are taken from McKenzie (1978). The unextended crustal thickness is estimated for the Sarawak Basin based on the average crustal thickness in Asia, for Tarim Basin and Korea (Holmes, 1965 in; Allen and Allen, 1990). A similar crustal thickness was used for the Gulf of Thailand by Helingger et al, (1984). The initial subsidence (Si) has an exponential relationship with β and is less significant when β is more than 3, as shown in Figure 5.3 and below:

β	1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0
Si (km)	0	1.49	2.24	2.99	3.36	3.59	3.74	3.84

5.4.2 Thermal Subsidence

The thermal subsidence (Sth) can be predicted from the extension factor (β), where:

$$Sth = \frac{4a\rho m\alpha Tl}{\pi^2(\rho m-\rho s)}\left\{\frac{\beta}{\pi}\sin\frac{\pi}{\beta}\right\}.\left(1-e^{-t/\tau}\right)$$ ....**Equation.(2)**

Lithospheric thermal time constant (τ) =62.8 Ma

By using the same parameters for the Initial Subsidence to equation (2) with β as variable, the relationship between β and thermal subsidence (Sth) can be understood as shown in Figure 5.4. In the same way as for the initial subsidence, the thermal subsidence (Sth) is less significant when β is greater than 3 (Figure 5.4).

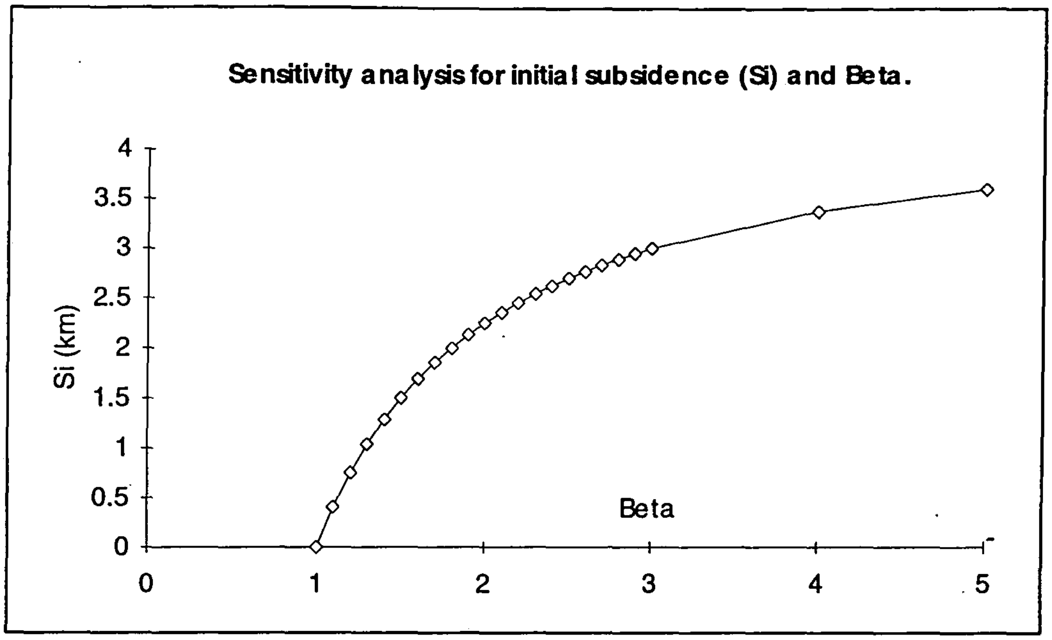


Figure 5.3. Sensitivity curve for initial subsidence (Si) with no sediment loading assumed, and stretching factor (β),

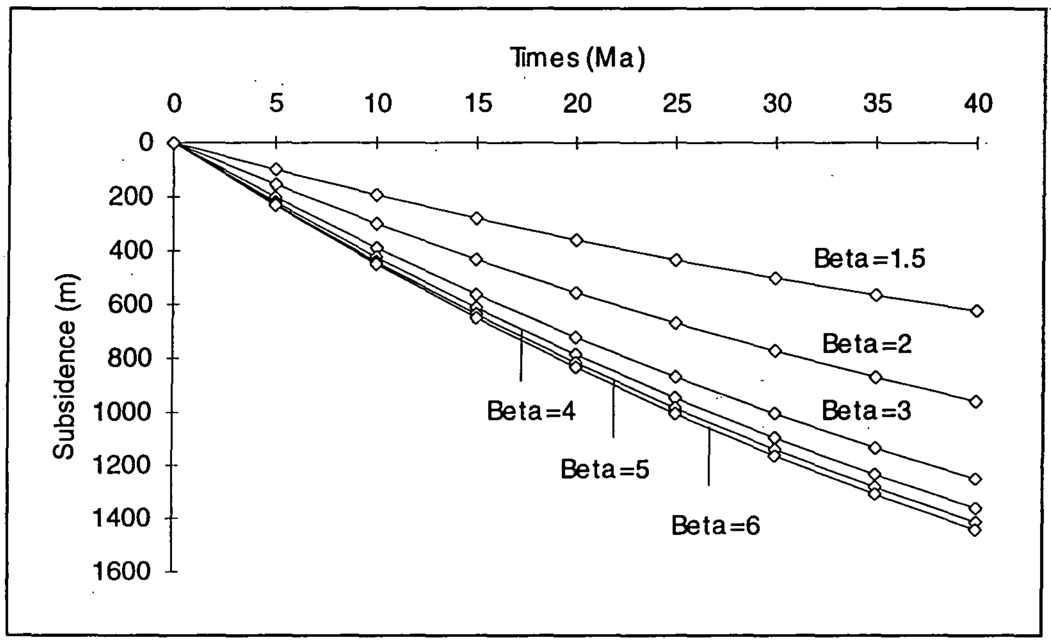


Figure 5.4. Sensitivity curves for thermal subsidence (Sth) with no sediment loading assumed, and stretching factor (β)

5.4.3 Total Subsidence (St)

The total subsidence (St) at time 't' after extension, based on Chadwick (1986), can be expressed by:

(St)= (Si) + (Sth)..............................Equation (3)

Solution of Equation (1) and (2), using the parameters in 5.4.1, allows the subsidence history of a sediment-starved basin (filled only with sea water), formed by varying amounts of lithospheric extension, to be computed (Figure 5.5).

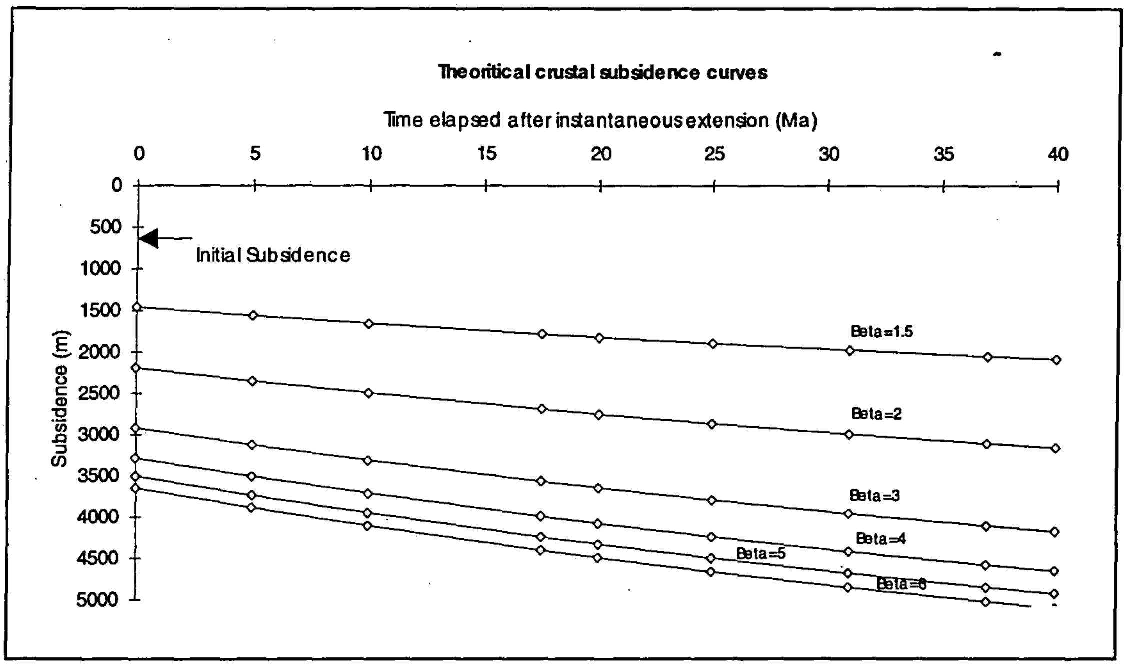


Figure 5.5. Sensitivity curves for total crustal subsidence (St) in sediments-starved basin by various amount of lithospheric stretching factor (β)

5.5. Interpretation of results

The subsidence pattern of the Sarawak Basin, and estimates of the stretching factors involved in the formation of the basin, are described in this section. Discussion on the validity of the selected model using guidelines by Jarvis and McKenzie (1980), and comparison between the model estimates and the geothermal estimations based on the well information from the basin (Wan Yussof, 1990), are also made.

For each well, two curves are displayed on the *geohistory* diagram, namely the Tectonic Subsidence Curve and Total Subsidence Curve (Figures 5.6 to 5.10). Tectonic Subsidence

Curve is derived after the removal of subsidence due to sediment load, correction for variations in water depth (palaeobathymetry) and eustatic sea-level fluctuation, and after the correction for compaction were made to the present day stratigraphic thickness.

5.5.1. Subsidence patterns

The tectonic subsidence curves give an immediate visual impression of the basement subsidence history, indicative of the nature of the driving force responsible for basin formation and development (Allen and Allen, 1990). This seems to be true when we are able to classify and group the type of subsidence patterns seen in the Sarawak Basin, which in turn may be used to determined the possible driving forces and the type of the basin for the each sub-area. By looking at Figures 5.6 to 5.10, three primary conclusions about the tectonic subsidence patterns of the area are found:

1. No single well has a subsidence pattern characteristic of a foreland basin (compare with Figure 5.1).

2. Visually several wells have a profile which matches a typical McKenzie rift basin, including wells J411 (Figure 5.6), Lucos and F661 (Figure 5.8) and F141 (Figure 5.9).

3. Other wells, namely D411 (Figure 5.6), D221 (Figure 5.7), G511 (Figure 5.9) and G210 (Figure 5.10), are characterised by subsidence patterns which conform to neither a foreland basin nor a McKenzie rift basin. Comparison of Figure 5.1 and the above mentioned figures illustrates a strong *prima facie* argument for these wells to have been drilled into a strike-slip related type of basin. Specifically the repetition of uplift and subsidence is not a characteristic of a McKenzie-type rift basin.

In the Eastern Sub-Basin (the area to the east of the West Balingian Basin; Figure 5.11), all the wells seem to experience an initial subsidence episode for the first few million years of the basin history, which suggest the whole area has undergone extensional tectonics during the initial formation of the basin. If this area has experienced lithospheric extension, the fault controlled subsidence (Si) and the post-tectonic thermally controlled subsidence (Sth), should yield the same values of β.

5.5.2. Beta (β1) values from Initial Subsidence.

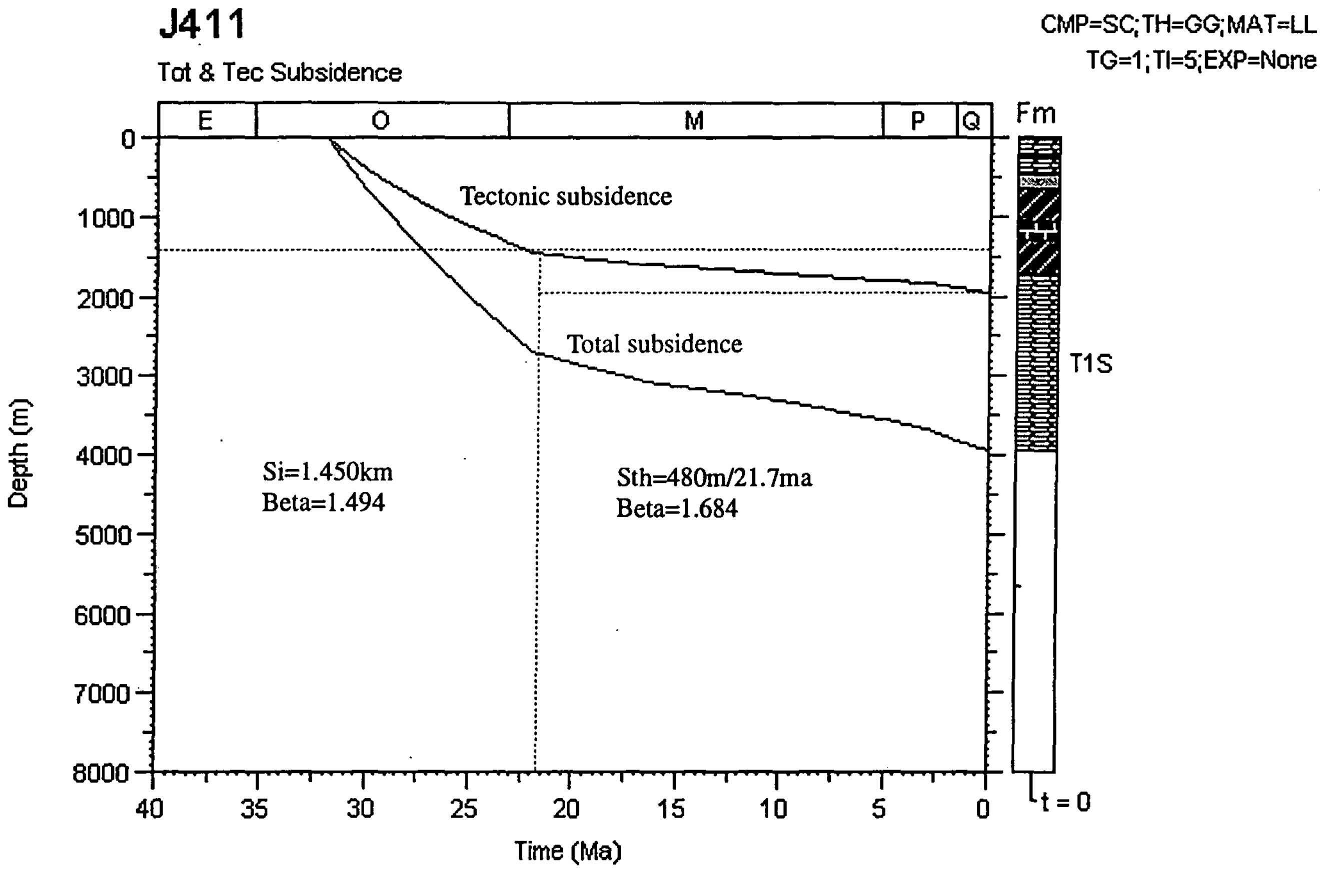
The initial subsidence for each of the wells was taken from the first subsidence episode of the tectonic subsidence curve, marked by the dotted lines on Figures 5.6 to 5.10. The calculation of stretching factor (β1) from the initial subsidence was then made using Equation (1). Other parameters are assumed to be similar to the Central Graben, North Sea (McKenzie, 1978) and Wessex Basin (Chadwick, 1986), in Section 5.4.1. The beta values for the wells in the study area are shown below, plus timing of stretching.

WELL	Initial Subsidence (km)	(β1)	Duration (Ma)
J411	1.45	1.494	15
D411	1.15	1.355	15
Naga1	1.12	1.343	6
D221	2.15	1.961	17.5
Lucos	2.35	2.154	15
F661	3.00	3.164	15
F141	3.00	3.164	15
G511	2.90	2.951	15
G210	1.10	1.334	15

5.5.3. Beta (β2) values from Thermal Subsidence

The calculation of stretching factor (β2) from the thermal subsidence was made based on the amount of subsidence after the initial subsidence. The estimation of the amount of subsidence is very complicated as curves are not smooth. However, the data for the calculation was taken from the best fit lines shown as dotted lines on Figures 5.6 to 5.10. The estimated stretching factors (β2) from thermal and (β1) from initial subsidence for the nine wells are as below, plus duration of subsidence.

WELL	Subsidence (m)	Duration (Ma)	β2	β1
J411	480	21.7	1.684	1.494
D411	100	5	1.495	1.355
Naga1	110	5.2	1.535	1.343
D221				1.961
Lucos	1200	22	>10	2.154
F661	1500	22	>10	3.164
F141	2000	22	>10	3.164
G511	900	15.5	>10	2.951
G210	520	12.25	4.9	1.334



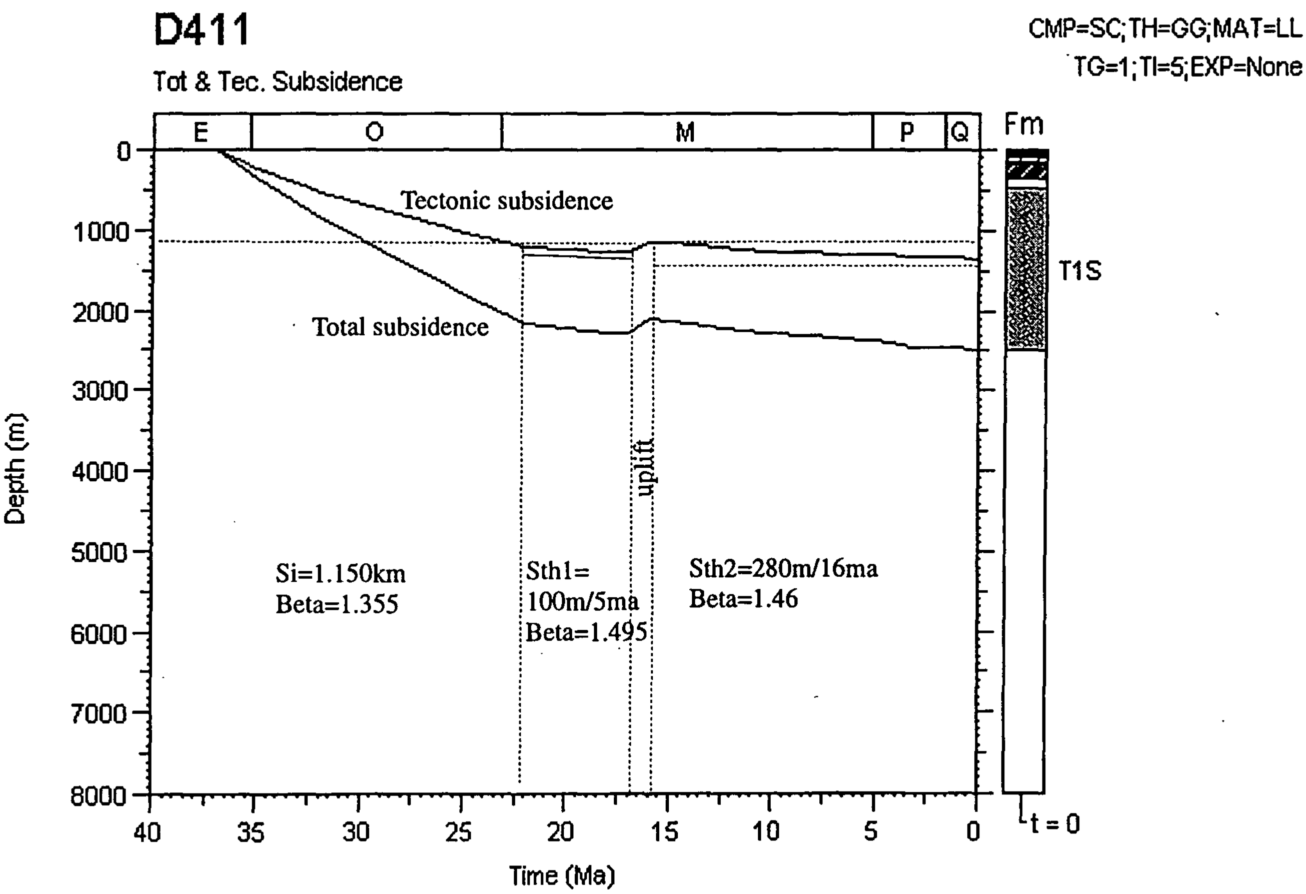
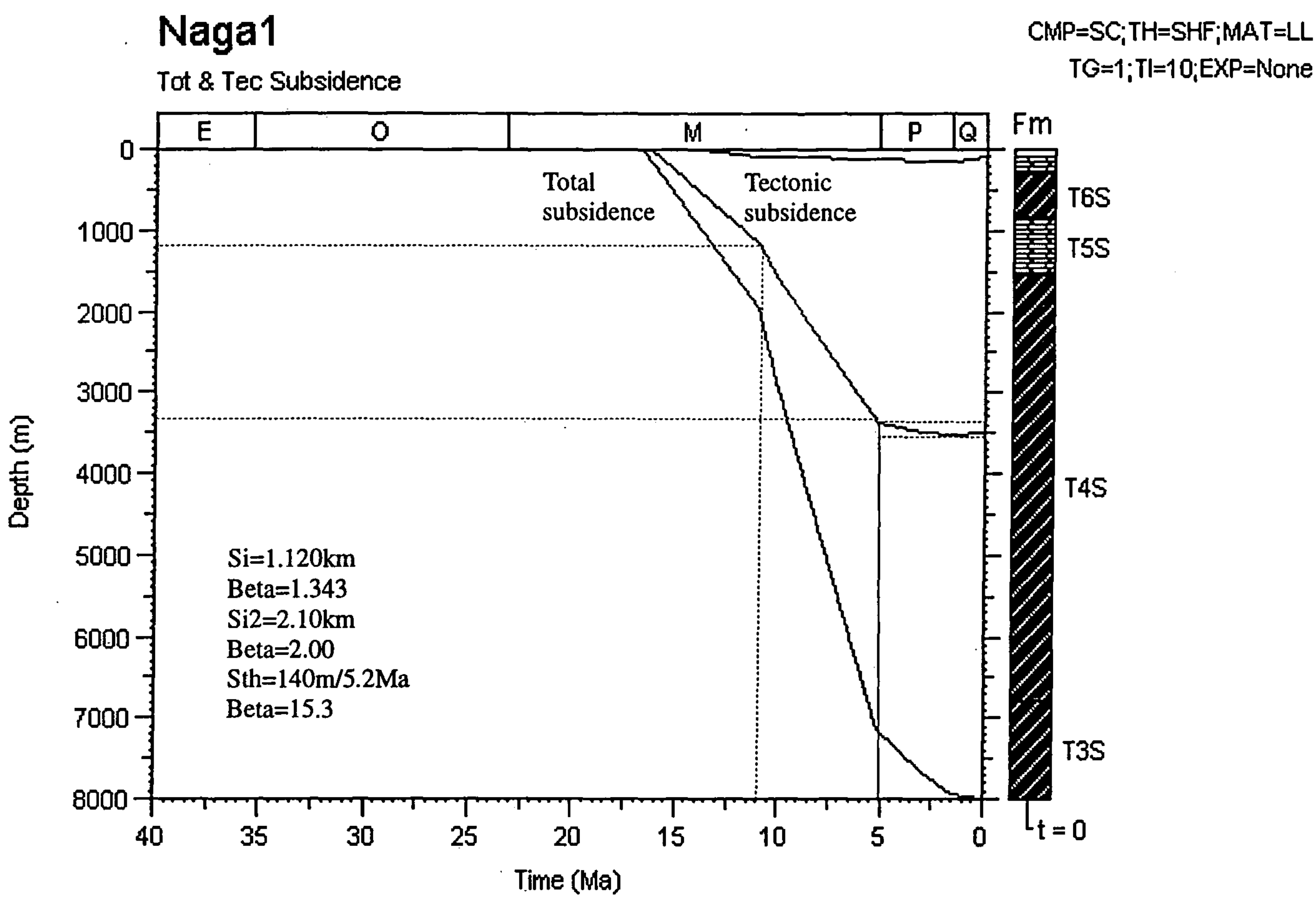


Figure 5.6. Total and tectonic subsidence curves for the J411 and D41l wells.



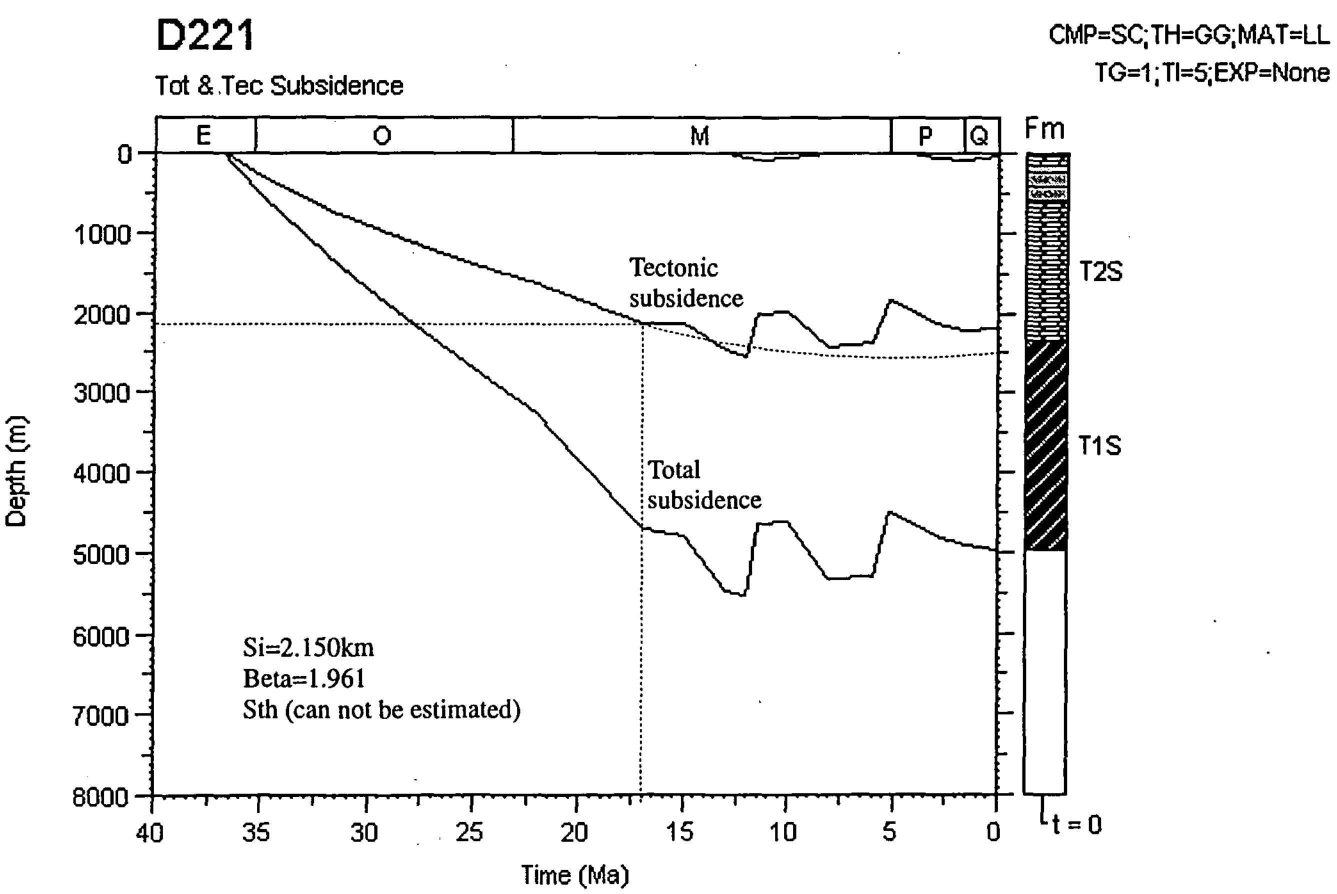


Figure 5.7 Total and tectonic subsidence curves for the Naga1 and D221 wells.

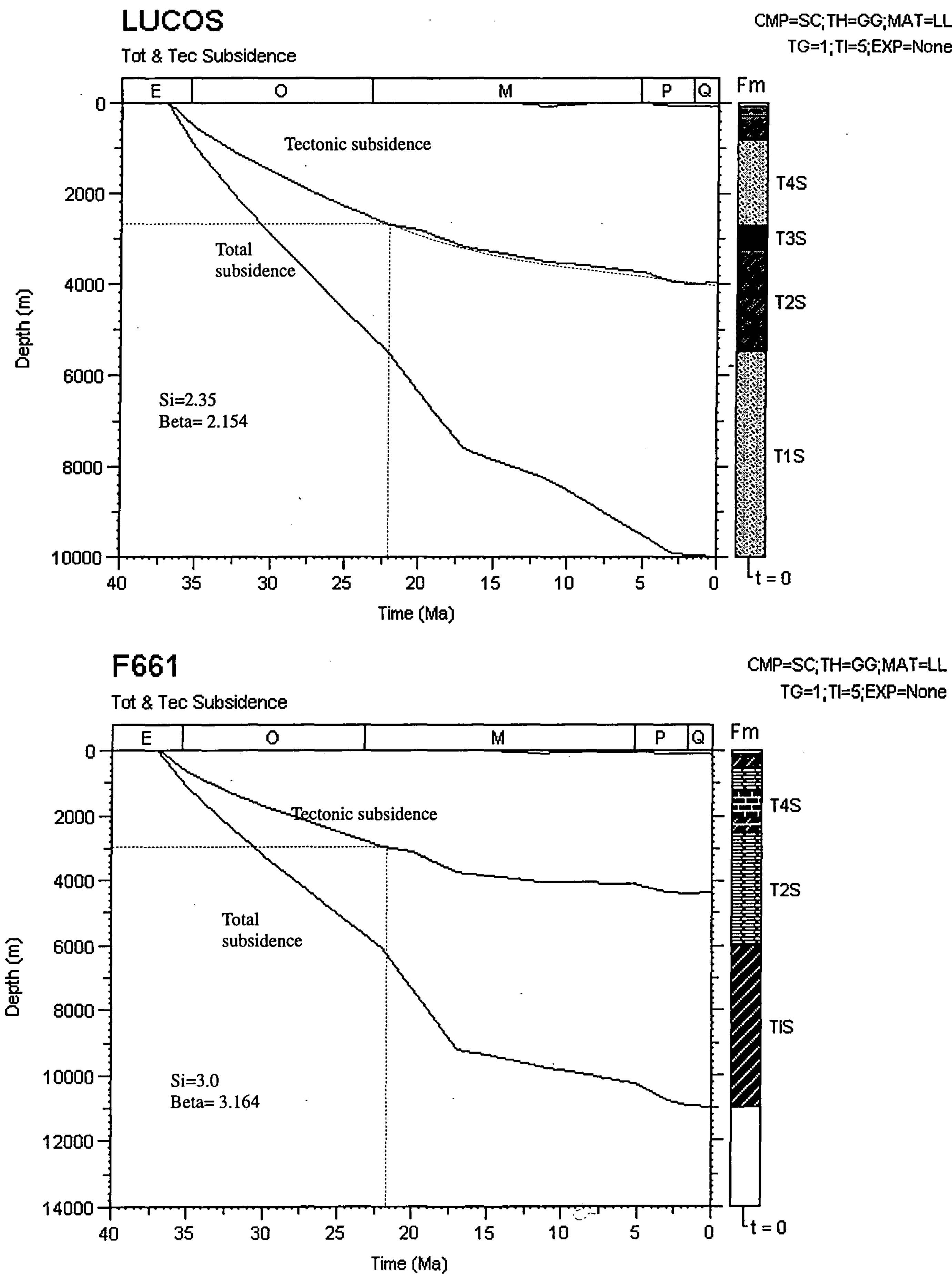


Figure 5.8 Tectonic and subsidence curves for the Lucos and F661 wells.

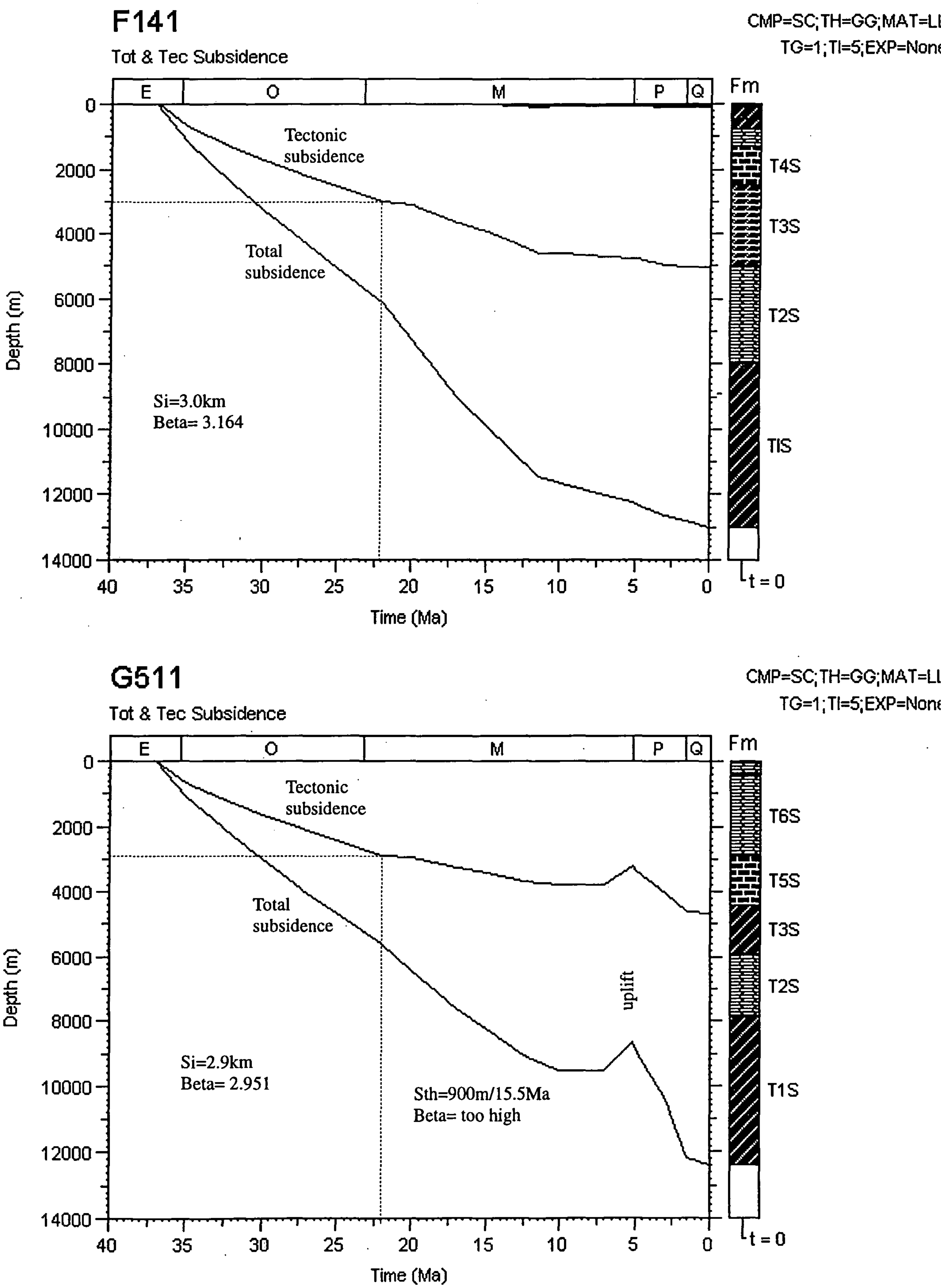


Figure 5.9 Total and tectonic subsidence curves for the F141 and G511 wells.

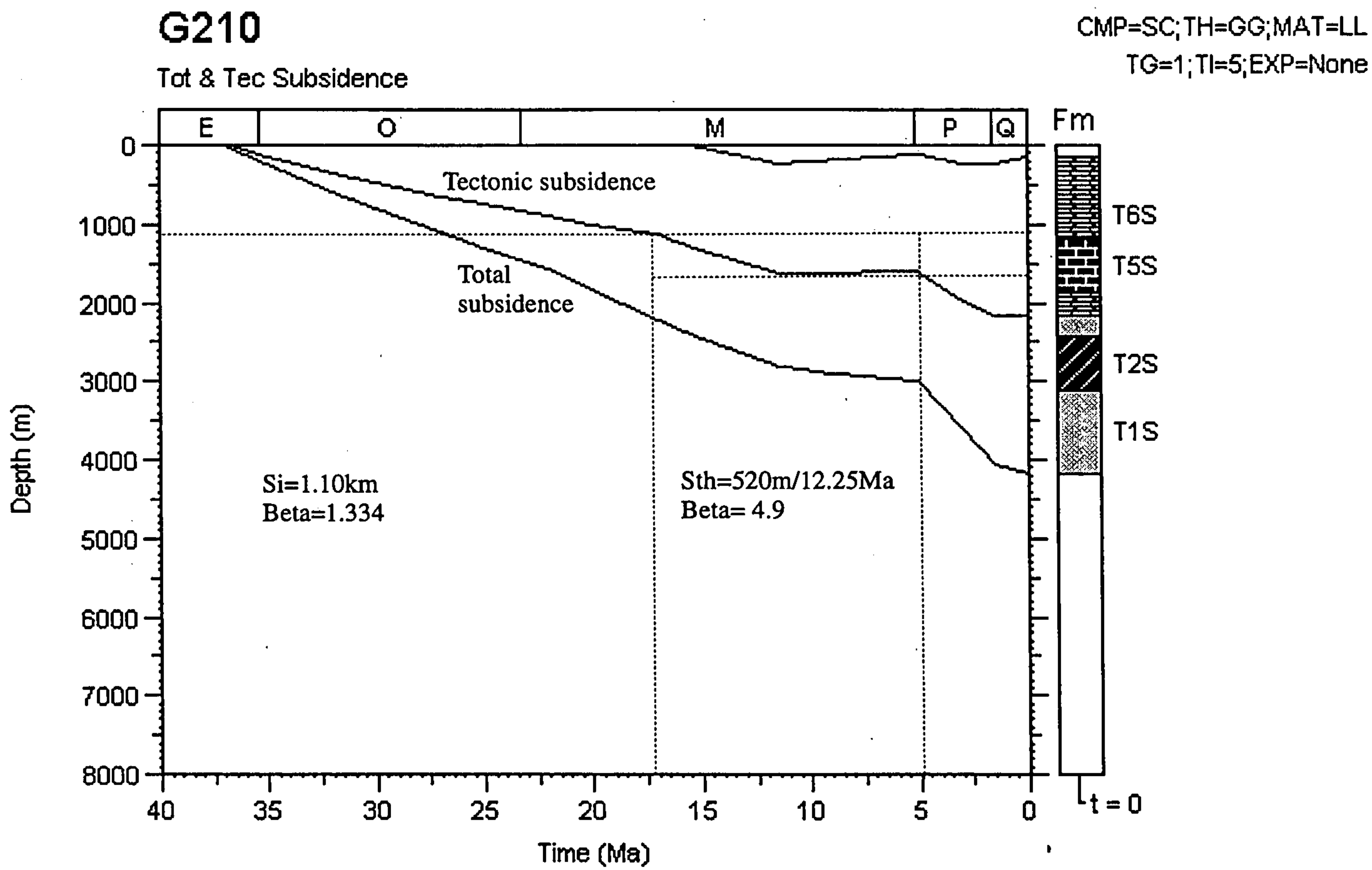


Figure 5.10 Total and tectonic subsidence curves for the G210 well.

5.5.4. Relationship between Subsidence Patterns and Tectonic History

Prior to discussing the relationship between the subsidence pattern and the tectonic history of the basin, it is appropriate to discuss the criteria for a McKenzie rift basin. It is then possible, using the subsidence pattern in each of the nine wells to determine whether or not they are of McKenzie-type. The criteria for a McKenzie-type rift basin can be summarised as:

1. Fault-controlled initial subsidence or uplift is followed by thermally-controlled regional sag.
2. The stretching factor from the initial subsidence (β1) should be similar to the stretching factor from the thermal subsidence (β2).
3. No major uplift during thermally controlled subsidence.
4. Evidence of volcanism when β is higher than 4.0.

By referring to Figure 5.11, it can be seen that the nine wells selected for the BasinMod studies are representative for several different tectonic regions of the Sarawak Basin. The wells and the tectonic areas in which they are, are shown below:

Well	Tectonic area
J411	SW Luconia Sub-Basin (SWLB) within the basement high area, formed as a releasing overstep basin.
D411	Basement high area, close to the West Balingian Line, interpreted as strike-slip faults.
D221	Southern part of Eastern Sub-Basin in the compressional area with faulted-fold structures
Nagal	Southern part of NW Sub-Basin, formed as a releasing overstep basin.
G210 and G511	In the deep-water area, within the Eastern Sub-Basin.
F141,F661 and Lucos	Middle part of Eastern Sub-Basin, interpreted to be formed as a strike-slip related basin.

<u>Well J411</u>

The tectonic history of the area (described in Section 4.7) shows the well is located within the SWLB (Figure 5.11) that was formed during the Eocene-Oligocene (T1S) times as a releasing overstep basin between the West Balingian and Mukah Lines (Figure 4.29). The SW Luconia Sub-Basin was not subjected to major tectonic movement after T1S times. The next major tectonic movement that took place in the Sarawak Basin was during T3S times but mainly

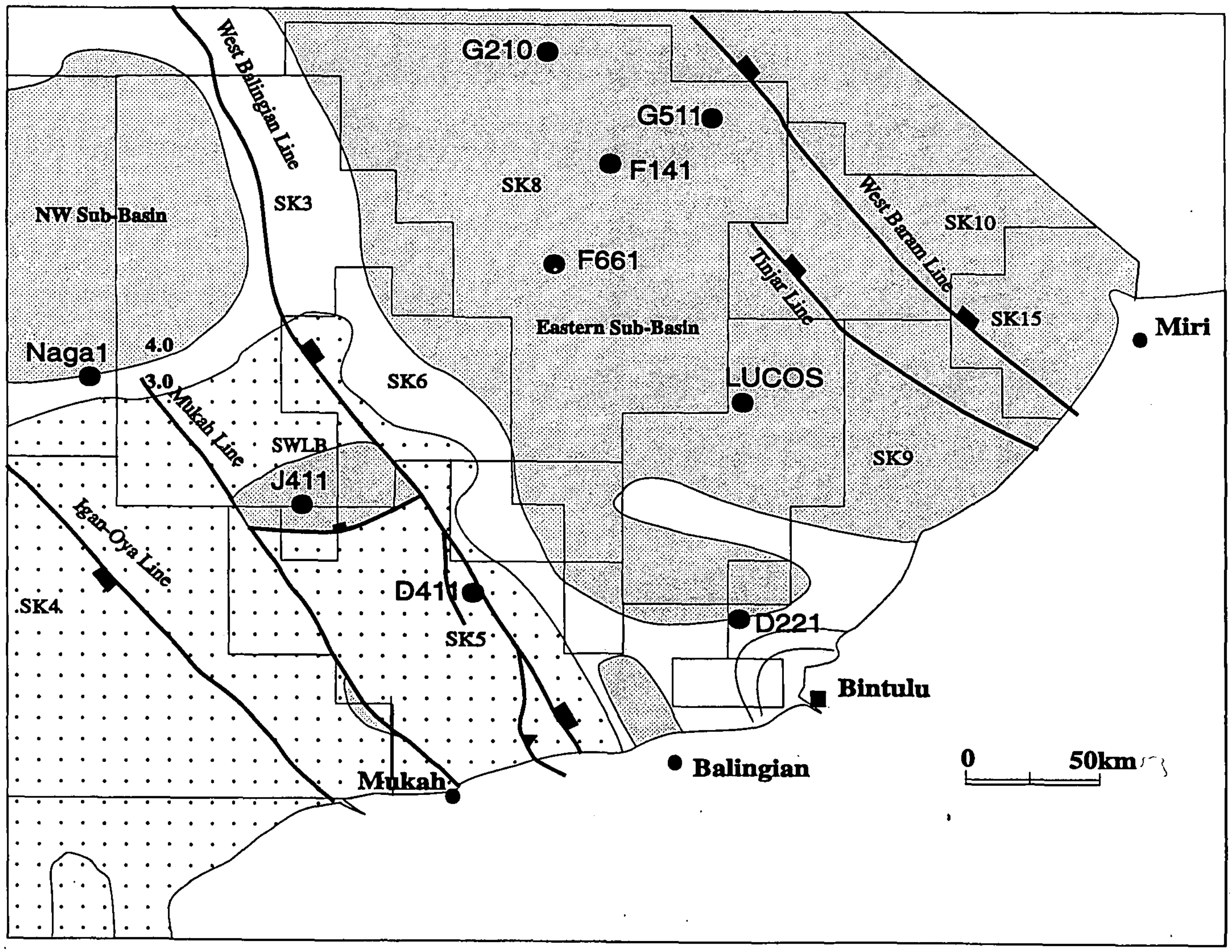


Figure 5.11 Map showing the location of the nine wells used for BasinMod analyses, in respect to the tectonic regions of the Sarawak Basin. SWLB= SW Luconia Sub-Basin.

From the subsidence profile, J411 is found to be the only well that has a McKenzie-type tectonic profile (Figure 5.6), where the β1 and β2 values (1.494 and 1.684 respectively) are very close, i.e. with only small variations of 0.19. The test for "instantaneous" subsidence during faulting event, when the value of $60/(\beta)^2 = 20.28$ (Jarvis and McKenzie, 1980), is met, since the timing for the initial subsidence is 15 Ma. The data available for the subsidence pattern of well J411 is consistent with stretching value of McKenzie model.

By relating the tectonic history to the subsidence of the area in the vicinity of the well, a relationship between subsidence and tectonic origin for the basin can be established. On the basis of this relationship, it can be interpreted that the rate of subsidence through time which took place after the initial rifting of the SW Luconia Sub-Basin, was mainly influenced by thermal relaxation. Although most likely strike-slip in origin, the subsidence data from J411 well fits the analysis for a McKenzie-type model as far as estimates for the amount and timing of extension. The well is located in the centre of a small pull-apart basin for which this relationship might be expected.

Well D411

The well is located to the west of the West Balingian Line (Figure 5.11) where the area underwent initial extension during T1S times, and continued to subside during T2S times. The area has also undergone compressional uplift during T3S times (17 Ma) after which it has been relatively stable up to the present-day.

D411 is another well that shows similarity between the values of β1 and β2 for the initial and thermal subsidence respectively (Section 5.5.3 and Figure 5.6). However, uplift can be seen to occur about 6 Ma after the termination of initial subsidence, followed by subsidence which is equivalent to a thermal subsidence yielding a β value of 1.46, which is very close the first episode of thermal subsidence where β is 1.495.

The observation of the D411 subsidence history leads to the interpretation that the small variation of β1 and β2 values suggest that the basin formed in the vicinity of a major strike-slip fault basin which can be also be explained by a McKenzie-type model. However, the later uplift history shows that this part of the Sarawak Basin is not characterised by a true rift basin profile.

Well Naga1

The well is located in the southern part of the young NW Sub-Basin (Figure 5.11) which was formed at a releasing overstep between the West Balingian Line and the Igan-Oya Line during T3S times (17.5 Ma). The basin continued to subside as the movement along the Igan-Oya

Line involved the Eastern Sub-Basin as well as movement along the Igan-Oya Line which resulted in the formation of the NW Sub-Basin (Figure 4.30).

The Igan-Oya Line continued to be active until T4S times (5 Ma), which is evident from the presence of T4S sediments in the Igan-Oya Half-Graben (Figure 4.19). The younger sequence (T5S) in the NW Sub-Basin was cut by E-W trending normal faults (Figures 3.14), which are interpreted to be the result of either:

(1). Differential Compaction (Gay, 1989)

(2). Thermal subsidence,

(3). Renewed extension.

The evidence for differential compaction, at least where thick carbonates are developed is illustrated in Figure 3.14 where normal faults with small throws dip away from the carbonate build-up. Elsewhere, where thick carbonates have not been recognised on seismic, differential compaction due to lithological contrasts might also provide an explanation for small shallow normal faults. Alternatively, the subsidence could be thermally driven but the rate of subsidence is low relative to a conventional McKenzie type rift-basin. Renewed extensive represents an unlikely third explanation.

The subsidence curve of the well suggests that the area has experienced an initial subsidence of 1.120 km, where $\beta1 = 1.343$. The second episode of fault-related subsidence occurred during T4S times which resulted in a tectonic subsidence of 2.2 km which is estimated to be equivalent to $\beta1 = 2.00$. (Figure 5.7). The later subsidence of the basin is interpreted to be due to thermal subsidence (Sth) with the $\beta2$ value of 1.53, with a small variation to $\beta1$. On the basis of episodic fault-controlled subsidence during the initial stage of the basin formation, despite the small variations between the beta values from Si and Sth, data for the Nagal well does not fit the McKenzie-type model.

By comparing the subsidence pattern between the Nagal and J411, it could be concluded that although the two areas were formed by the releasing overstep between strike-slip lineaments, the areas have experienced different subsidence patterns. This leads to the conclusions that the subsidence pattern for the strike-slip related basin vary, and may not always fit to the McKenzie type of rift basin.

Well D221

The well is located in the southern part of the Eastern Sub-Basin (Figure 5.11). The area of D221 well was subjected to a series of compressional uplifts where most of the sequence boundaries in the area are characterised by angular unconformities (Structure A, Figure 4.25). The well was drilled on one of the structures, called faulted-fold structure, which forms the main structural trap in the area (Figure 4.26). The area is characterised by a typical example of alternating compressional uplift and subsidence that occurred soon after the formation of the basin.

The subsidence pattern of the area suggests that the initial fault-related subsidence occurred for about 17.5 Ma with a stretching factor (β1) of 1.961. The area has experienced at least two periods of uplift in the past ten and five million years (Figure 5.7). The effects of thermal subsidence are obscured by the alternating series of uplift and subsidence. The beta value from thermal subsidence could not be determined, but is probably higher than 10.

Wells F661, F141, G511 and LUCOS

Wells F661, F141, G511 and LUCOS are located in the central part of the Eastern Sub-Basin (Figure 5.11), in an area where the basement depth is in the range 5.0 to 6.0 seconds TWT (Figure 4.3). The area is characterised by thick older siliciclastic sequences and later Miocene carbonate. The area where each of the wells is located has undergone a series of tectonic movements soon after the initial formation of the basin, resulting in uplift and subsidence in different areas at different times.

From the subsidence curves of the wells (Figures 5.8 and 5.9), it can be seen that the subsidence pattern of the three wells visually appear to fit the McKenzie-type rift basin. However detailed analysis of the beta values suggests otherwise. The β1 values from the fault-controlled subsidence are 3.164, 3.164, 2.951 and 2.154 for the F661, F141, G511 and LUCOS wells respectively. The thermally related β2 for the four wells are very high, in the region of 10 or greater (refer 5.5.2 for the details). Therefore, judging from the huge differences in beta values between the initial fault-controlled and later thermally controlled subsidence, it could be concluded that the area of each well has experienced the rate of subsidence much higher than the thermally controlled subsidence predicted by a McKenzie stretching model.

Another interesting observation as far as the subsidence history of the F661 is concerned, is that there was very little tectonic subsidence in the area during the Middle to Late Miocene times (11-5 Ma, Figure 5.8) This stable period coincides with massive carbonate production, normally referred to as the Luconia Carbonate, and now forms the major reservoir for gas in the Sarawak Basin. Several authors, including Epting (1980), have attributed the stable nature of the area to carbonate growth. Further, the stable nature of the area was used as the basis for the interpretation that the Luconia Province formed as a drifted fragment from the South China Sea (James, 1984). One of his main arguments for a subduction model is the long-living stability and lack of subsidence of the Luconia Province. The results in this study show only a limited period of basement stability (Middle to Late Miocene; i.e. 6-12 Ma), and challenge the interpretation of James (1984) who infers a much longer period of stability in his model. Further, the surrounding areas such as G511, F141 and LUCOS, which are also within the Luconia Province, were subjected to several episodes of uplift and subsidence.

Well G210

G210 is a well located in the northernmost part of Sarawak Basin (Figure 5.11), in the present deep-water area. As discussed previously (Section 3.5.4), the area remained as a high until T4S times, and the whole area was totally submerged after T5S times. The subsidence of the area is believed to have continued until the area, with subsidence outpacing sedimentation, formed the deep-water area seen today.

The subsidence profile of the well (Figure 5.10) shows that the β1 value from the initial fault-controlled subsidence is 1.33 and the thermally related β2 for the well is much higher, in the region of 4.9. The area later subsided by about 1,300 metres in the last 5 Ma (T5S and younger), which is too high for the thermally related subsidence and therefore it could be due to the later phase of fault-related subsidence. The current understanding of the tectonics of this part of the basin is that the area was influenced by strike-slip movement along the West Baram Line during Pliocene times (Figure 4.36). The subsidence profile of the well does not suggest that it fits to either McKenzie-type rift basin or foreland basin but it could fit a strike-slip related basin.

The difference in β1 values between G210 and the other four wells to the south, namely F661, F141, G511 and LUCOS, is probably due to the location of the area whereby the four wells are located in the centre of the Eastern Sub-Basin which was the most stretched area as compared to the fringe of the basin in the area of G210 in the north and D221 in the south (Figure 5.12).

In summary, from the subsidence profiles of the nine wells from the Sarawak Basin, it can be shown that:

a). The subsidence profile of one well (J411) matches a McKenzie-type stretching model, but the tectonic setting shows that the area formed in a releasing overstep (pull-apart) within a strike-slip setting, rather than a true rift basin.

b). Other wells in the basin have very different values of β1 and β2, which suggest they were not formed in a McKenzie-type basin, in particular they yield very high values of β2.

c). There is also evidence in several wells for local intermittent episodes of compression and subsidence.

All these factors are consistent with the evidence cited in Chapter 4 for a strike-slip origin to the Sarawak Basin.

5.5.5. Relationship between stretching factors, geothermal and heat flow

As discussed in Section 5.5.4, there is a close relationship between subsidence pattern and tectonic history for the Sarawak Basin. The findings also suggest that the formation of the Sarawak Basin is not consistent with a McKenzie-type rift model. One test of the validity of a McKenzie instantaneous stretching model, based on Jarvis and McKenzie (1980)'s formulation, can be performed, based on the length of time of the initial subsidence (Si) relative to the amount of stretching ($\beta 1$), by the formula:

(1) **Time (Ma)< $60/(\beta 1)^2$ for $\beta \leq 2$**

and (2) **Time (Ma)< $60(1-1/\beta 1)^2$ for $\beta \geq 2$**

A more rigorous analysis, which also allows a test on the validity of using heat flow estimation for calculation of amount of stretching is Jarvis and McKenzie's (1980) relationship:

(1) **Time<60 for $\beta \leq 2$**

and (2) **Timing <$60(2/\beta)^2$for $\beta \geq 2$**

The results are tabulated below:

Well	Timing for Si (Ma)	($\beta 1$)	$60/(\beta 1)^2$	$60(1-1/\beta 1)^2$	Instantaneous stretching assumption	$60(2/\beta)^2$	Heat flow estimation
J411	15	1.494	26.88	-	valid	-	valid
D411	15	1.355	24.11	-	valid	-	valid
NAGA	6	1.343	33.26	-	valid	-	valid
D221	14.5	1.961	15.60	-	valid	-	valid
LUCOS	15	2.154	-	17.22	valid	51.72	valid
F661	15	3.164	-	28.06	valid	23.97	valid
F141	15	3.164	-	28.06	valid	23.97	valid
G511	15	2.951	-	26.22	valid	27.56	valid
G210	15	1.334	33.71	-	valid	-	valid

5.5.5.1. Geothermal Gradient

The geothermal gradient of the Sarawak Basin was obtained from PETRONAS's in-house geothermal gradient map compiled and produced by Wan Yussof (1986), and redrawn in Figure 5.13. The methodology and assumptions for the calculations for the map are not known. However, based on a later publication (Wan Yussof, 1990) the geothermal gradient at each well was determined from the borehole formation temperature determined during logging, the known depth of measurement and the average temperature of the surface where drilling begins. Linear regression analysis was applied to the parameters to obtain the geothermal gradient, with corrections for time since circulation of the mud, etc. A large dataset of thermal conductivity measurement of core samples was available.

According to Wan Yussof (1990), the heat flow value was determined at well locations assuming only vertical conduction of heat. In the well, the heat flow is considered constant, with the geothermal gradients and the thermal conductivity varying. It is assumed here that the same techniques were used to generate the 1986 geothermal gradient map for the Sarawak Basin, which has been used.

The amount of well data available varies across the Sarawak Basin, leading to variability in the accuracy of the map (Figure 5.13). The geothermal gradient for the area to the west of the West Balingian Line is least well constrained. This is because the number of the wells drilled in the area is small, as compared to the number of the wells in the area to the east. For example, to date, only five wells have been drilled in the NW Sub-Basin. Out of that number, two of the wells, including Naga1, were drilled in the years after 1986, after the map was generated. The other three wells were drilled in the early 1970's. Further, the wells were only drilled in the basement high area, in the area in the vicinity of J411 and D411. No well was drilled on the basement high area to the west of D411 in block SK5.

The plots of beta (β1) against geothermal gradient are shown in Figure 5.14. If the data from the wells from the west of the West Balingian Line namely, J411, Naga1 and D411 are excluded, the relationship between beta and geothermal gradient shows a broad linear relationship, shown by a straight line (Figure 5.14), where the geothermal gradient values increase with beta.

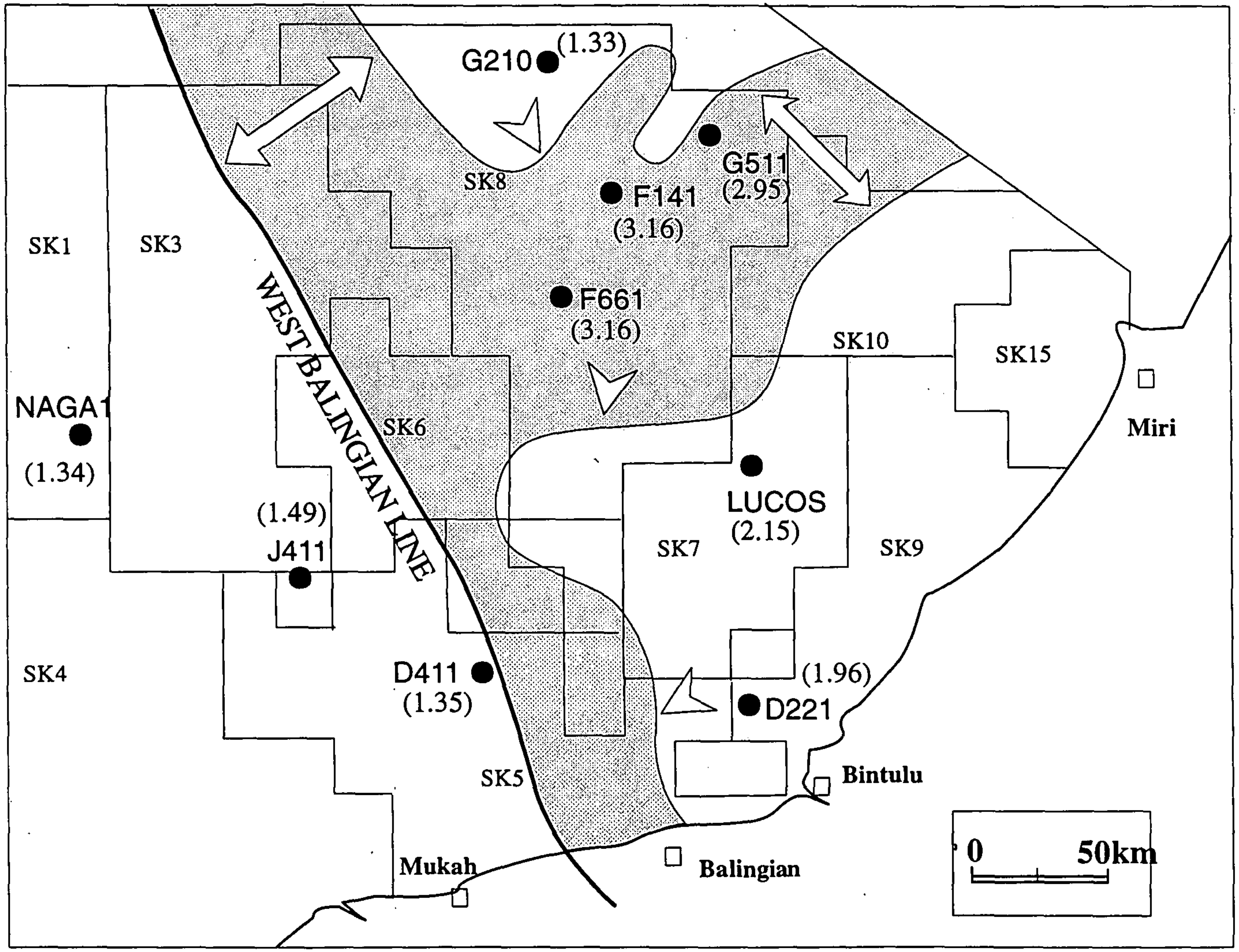


Figure 5.12. Map showing the shaded area as the area with high beta values (>2.5) which is coincident with the high geothermal gradient area. The beta values are shown in brackets. Double headed arrows show the directions of extension and arrow heads indicate the directions of compression seen on seismic.

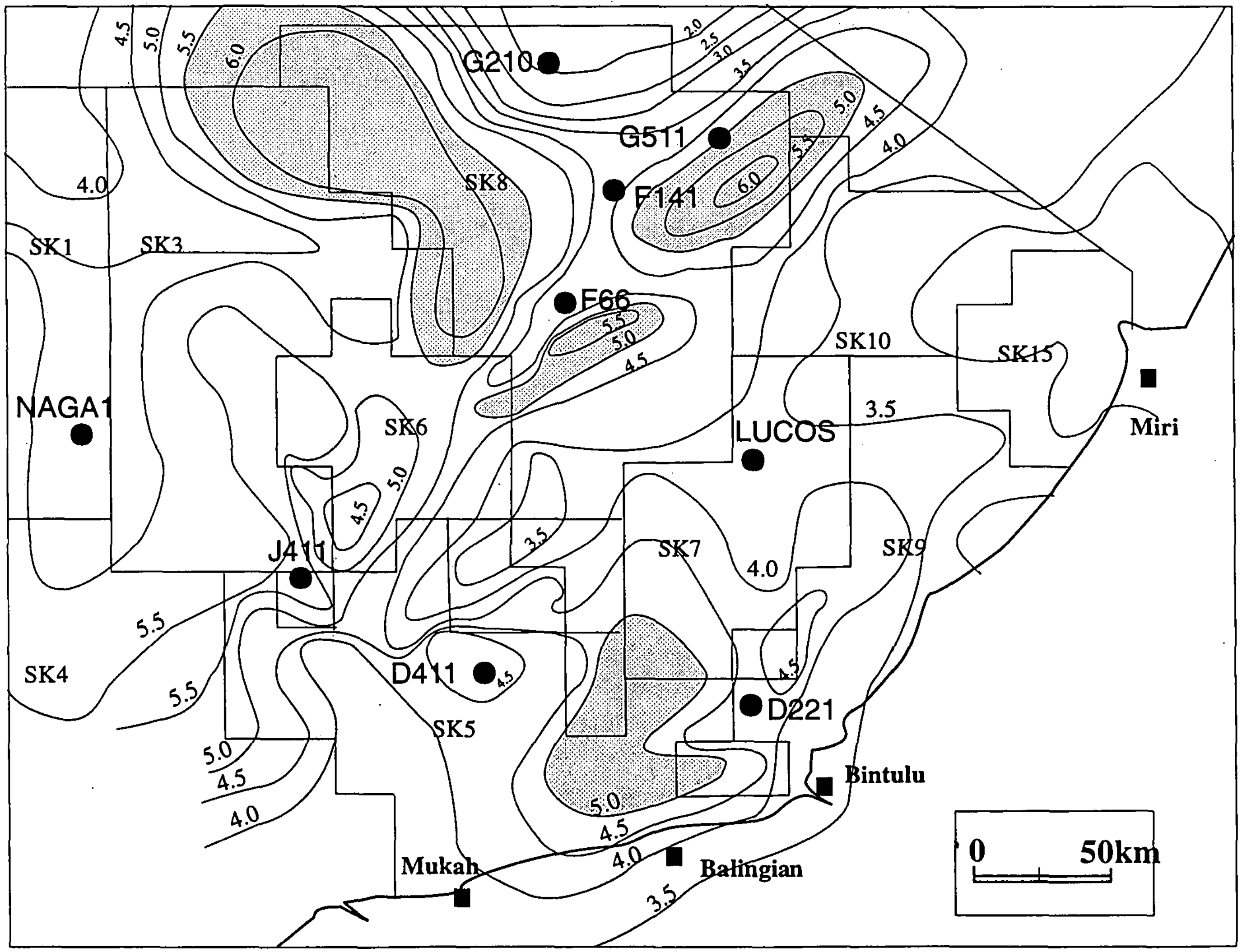


Figure 5.13. Geothermal gradient map of Sarawak Basin (After Wan Yussof, 1986), with contour interval of 0.50 °C/100m and the location of the wells used for BasinMod studies.

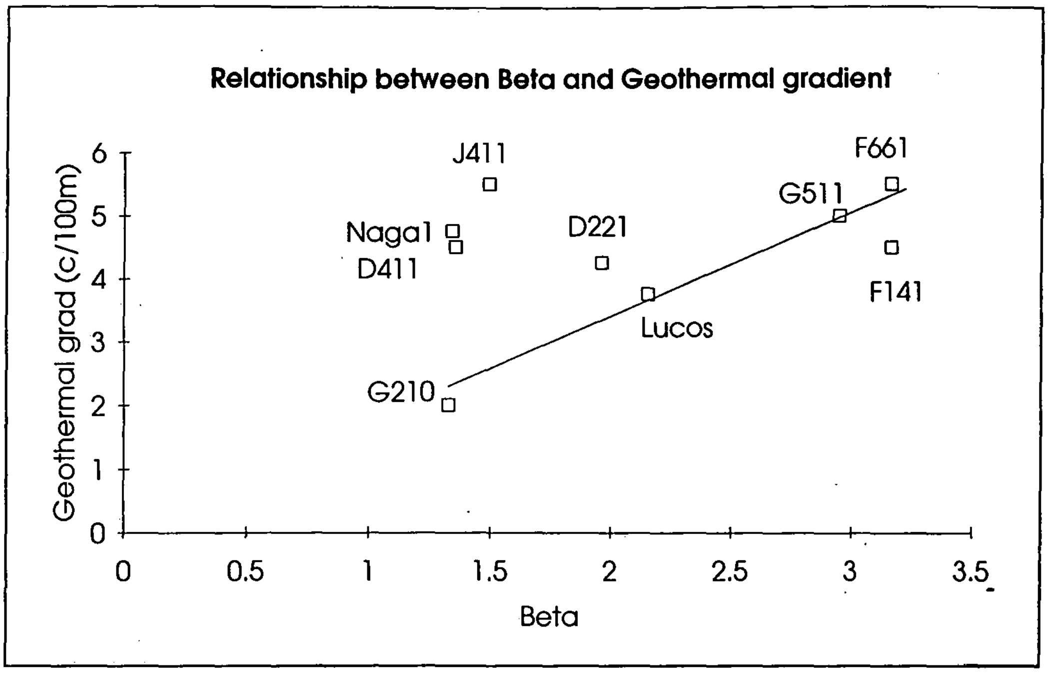


Figure 5.14 Relationship between the amount of initial subsidence and geothermal gradient.

Further, in the Eastern Sub-Basin, the beta values and the geothermal gradients show a relationship between the areas with high stretching factor (Figure 5.12) and with high geothermal gradient (Figure 5.13). Specifically, the data suggest that the areas with a high geothermal gradient (>5°C/100m) coincide with the areas which have experienced high stretching factor (>2.5) i.e. high rate of subsidence and high rate of sedimentation (Figure 5.8 and 5.9).

5.5.5.2. Heat Flow

The heat flux of a basin can be used to calculate a stretching factor in a McKenzie type basin, if the time since rifting is known. The heat flow values (calculated above) can be translated into heat flux unit (one HFU is equivalent to 10^{-6} Cal cm^{-2} s^{-1} or 41.84 mWm^{-2}, Allen & Allen, 1990). The data can then be used in Equation 4 (below) to determine the stretching factor, and to compare it to the stretching factors determined by other means (e.g. initial and thermally-controlled subsidence).

The surface heat flux (Q) is given by Fourier's Law which states that the heat flux is a function of temperature gradient (dt/dz) and the thermal conductivity (K) whereby $Q = K\frac{dt}{dz}$.

The stretching increases the heat-flow by β at t=0. As β reaches infinity, n=1, the solution for an oceanic ridge model when all the heat is conducted vertically, the surface heat flux (Q) is:

$$Q = \frac{KTm}{Yl}\left[1 + \frac{2\beta}{\pi} Sin\left(\frac{\pi}{\beta}\right) Exp^{-\frac{t}{\tau}}\right] \text{..................} \textbf{Equation (4)}$$

Where KTm/Yl= 0.8 μcal cm^{-2} s^{-1}

Lithospheric thermal time constant (τ)=62.8 Ma

The minimum, average and maximum values of heat-flow for the Balingian and Luconia Provinces (Eastern Sub-Basin) in the Sarawak are; 47.08, 78.80 and 123.17 mWm^{-2} respectively (Wan Yussof, 1990). By using this conversion factor, the minimum, average and maximum values of heat flux for the Balingian and Luconia provinces are; 1.12, 1.88 and 2.93 $x10^{-6}$ Cal cm^{-2} s^{-1} respectively.

The surface heat flux in the Eastern Sub-Basin at present, i.e. about 37 Ma after the basin formation, was calculated using Equation (4) with a range of β1 values from 1.334 to 3.164 (Section 5.5.2). The surface heat flux values (in 10^{-6} Cal cm^{-2} s^{-1}) as a function of time and beta are shown below and the graph showing their relationship is illustrated in Figure 5.15.

Well	G210	D221	Lucos	G511	F661/F141
Beta	1.33	1.96	2.15	2.95	3.16
Time (Ma)			Heat-flux		
0	1.403745	1.977478	2.077259	2.32569	2.364069
5	1.296315	1.82614	1.918285	2.147703	2.183145
10	1.197107	1.686384	1.771477	1.983338	2.016067
15	1.105491	1.557323	1.635904	1.831551	1.861776
17	1.070839	1.508509	1.584626	1.774141	1.803418
25	0.942758	1.328078	1.395092	1.561939	1.587714
32	0.843318	1.187996	1.247941	1.39719	1.420246
37	0.778779	1.097078	1.152435	1.290262	1.311554

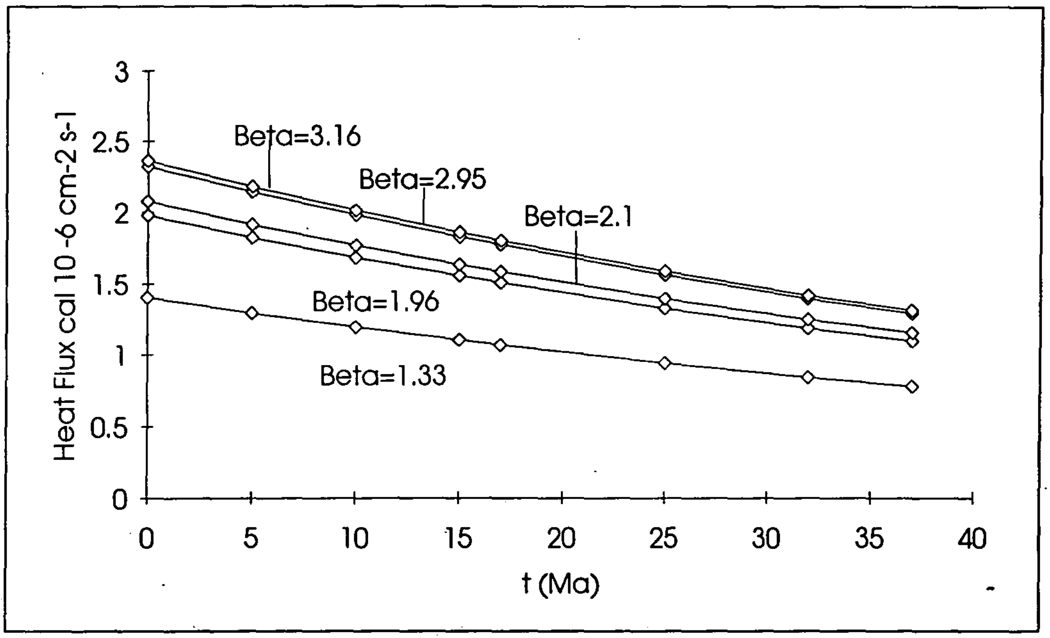


Figure 5.15 Heat flux as a function of time and a range of beta values appropriate for the Sarawak estimated using equation (4).

Estimation of the surface heat flux (unit = 10^{-6} Cal cm^{-2} s^{-1}), using Equation 4 are lower than the results from the borehole data (Wan Yussof, 1990) as shown below:

Surface Heat flux	From borehole measurement (Wan Yussof, 1990)	Calculated using Equation 4	Differences
Minimum	1.12	0.77	0.35
Average	2.02	1.04	0.98
Maximum	2.93	1.31	1.62

Sclater and Christie (1980) pointed out that in the North Sea, the present day heat flow (approximately 0.8 HFU) predicted by McKenzie is too low to agree with the present measurements of heat flow measured (approximately 1.5 HFU). They have proposed a modification of the McKenzie model in which the heat flow has an additional component of 0.8 HFU, coming from the decay of radioactive elements within the crust (Lerch, 1990). If the same value proposed by Sclater and Christie (1980) for the North Sea Basin, is added to the heat flux values estimated by the model for the Sarawak Basin, the average values for the two methods will be reasonably close (about 0.18 x 10^{-6} Cal cm^{-2} s^{-1}).

In summary, the estimation of surface heat flux for the Sarawak Basin using the McKenzie model estimation is too low to agree with the estimation measured from the well data. Nevertheless, if the heat flux values from model estimates are corrected by adding 0.8 HFU, as proposed by Sclater and Christie (1980), the values will be reasonably close to average heat flux values measured for Sarawak Basin, though too low for the maximum measured heat flux values for the basin.

5.6 Discussions

The subsidence curves for the nine wells from Sarawak Basin (Figures 5.6-5.10), are characterised by rapid rate of subsidence which is exceeding 10 km in 37 Ma for the area in the Eastern Sub-Basin, as compared to the North Sea Graben which is mainly less than 4 km in 100 Ma. Consequently, the stretching factor (β) calculated for the Sarawak Basin is high, reaching the value of 3.16, when compared to the North Sea Graben which is in the range of 1.5 to 2.0 (Sclater and Christie, 1980 ; Wood, 1981). The β values are similarly very high when compared to the Wessex Basin, Southern England, which are about 1.147 (Chadwick, 1986). The two basins mentioned above are classified as rift basins, although the Wessex Basin has some influence of strike-slip (Chadwick, 1986). The stretching factor for the Sarawak Basin is almost the same as the Pattani Trough (Gulf of Thailand, Hellinger et al. 1984) which is in the range of 1.21 to 3.23.

For the normal crustal thickness (30-40 km) and geothermal gradient (2.5-3.0 °C/km), a β value of approximately 4.0 can be used as a basis for determining whether volcanism is likely or not (K. Thomson, pers. comm.). Where the geothermal gradient is higher, a lower β value should lead to volcanism. In the case of the Sarawak Basin, where the geothermal gradient is close to 5.0 °C/km as an average (Figure 5.13), the β value of >3.0 might be expected to lead to volcanism when the McKenzie-type lithosphere extension by pure shear occurs. The absence of volcanism is indicative of non-pure shear stretching for the Sarawak Basin, possibly because, as argued above, the basin has a major strike-slip component.

Little is known about the stretching factor (β) for true strike-slip basins. Most data come from strike-slip related basins in California. However, it is known that strike-slip basins are characterised by extremely rapid rates of subsidence, even more rapid than many grabens and foreland basins. This is generally matched by an abundant sediment supply, leading to very thick stratigraphic sections, in comparison with the lateral basin dimension (Christie and Biddle, 1985). For example,

a) about 13 km of sediment accumulated in the Ridge Basin, California, in only 7 Ma,

b) about 5 km of sediments were deposited in the Vellecito-Fish Creek Basin in about 4 Ma. and,

c) The Ventura Basin, California, subsided nearly 4 km in the past 1 Ma.

Another potentially important mechanism for basin subsidence along strike-slip faults, in addition to crustal extension, is loading due to local convergence of crustal blocks.

Strictly for the purpose of comparison between the Sarawak Basin and known strike-slip basins, the tectonic subsidence has been assumed to be about 50% of the total subsidence (as could be seen in all cases in Sarawak Basin, and similarly estimated by Christie and Biddle, 1985) and the basins are assumed to be in the fault-related stage of subsidence. The estimated stretching factor, $\beta 1$, of these basins (by using Equation 1 and other parameters similar to the Sarawak Basin), are as below:

Basin	**$\beta 1$**
Ridge Basin	>10
Vellecito-Fish Creek Basin	2.32
Ventura Basin	1.83

Pitman III and Andrews (1985) found that strike-slip basins are characterised by very rapid subsidence and sediment accumulation in small "pull-apart" basins, and can be modelled using a McKenzie-type model. This study arrives at a similar conclusion for the J411 where the subsidence profile of the well fits to the McKenzie-type of rift basin. However, it is not applicable for other areas of the Sarawak Basin where many of the subsidence profiles are characterised by episodic uplift and subsidence taking place in different places and times around the Sarawak Basin as might be expected in areas close to strike-slip lineaments which variably experience extension and compression.

The rapid initial subsidence of small strike-slip basins is caused by crustal thinning combined with lateral heat lost to the basin wall, and the initial width has a major influence on the subsidence history, the narrowest basins loose heat most rapidly to the sides and therefore subside at a greater rate and with a greater magnitude than wider basin (Pitman III and Andrews, 1985). This fits the data for the J411 well where the $\beta 2$ value is slightly higher than $\beta 1$. However for other wells elsewhere in the Sarawak Basin which have experienced episodic tectonic movements, this observation is obscured.

Judging from the stretching factors, the rate of subsidence, the polycyclic episodes of deposition and uplift, the overall subsidence profile for the Sarawak Basin, is consistent with other known strike-slip basins elsewhere. This observation agrees with other evidences i.e. the basin is characterised by distinct shifts in the depositional setting with different source of provenance and migration of depocenter (as discussed in Chapter 3), the occurrence of several smaller sub-basins and the occurrence of strike-slip bounding faults (as discussed in Chapter 4).

Therefore the subsidence data support the model for the Sarawak Basin as a strike-slip related basin as opposed to rift or foreland basin. The finding is extremely consistent with the interpretation based primarily on seismic data, discussed in Chapter 4.

5.7 Conclusions

1) The subsidence data indicated on burial history curves for nine wells representative of the Sarawak Basin show the basin was not formed as a typical foreland basin. Many of the profiles show early rapid subsidence followed by a later phase where basement subsidence is slower, indicative of rifted style of tectonic origin. This conclusion challenges earlier models for a subduction-related origin for the basin.

2) Besides the subsidence pattern for the J411 well and the early phase of subsidence (37-17.5 Ma) for D411 well that agree with McKenzie's rift model, the Sarawak Basin is characterised by a high rate of subsidence, high β values plus local episodes of compression interspersed with extension.

3) Although the subsidence data from most of the wells do not agreed with the McKenzie-type rift model, the equations for the rift basin have been used to determine stretching factors. This is because the formula outlined by Jarvis and McKenzie (1980) to test the validity of assuming the instantaneous stretching are valid for the Sarawak Basin.

4) The geothermal gradient of the Eastern Sub-Basin shows a linear relationship with the value of the stretching factor. The central part of the basin which was subjected to a higher stretching factor is characterised by a higher geothermal gradient than the area at the fringe of the basin in the north and south. However, the same relationship does not hold for the shallow basement area to the west. The relationship cannot be established for western part of the basin possibly because the geothermal gradient data from the area is limited.

5) The model estimates of heat flux values for the Sarawak Basin, are too low when compared to the measured values with the difference in the range of 0.3 to 1.6 HFU. This is probably due to the same reasons as used in the North Sea basin (Sclater and Christie, 1980) where the higher geothermal gradient may have been caused by radioactive decay in the sediments, not accounted for by the formula in Equation 4.

6) The evaluation of stretching factors and heat-flow for the Sarawak Basin are consistent with the origin of a basin dominated by strike-slip tectonics.

Chapter 6

TERTIARY TECTONICS OF NORTHERN BORNEO

6.1 Introduction

This chapter describes the interpretation of the tectonic evolution of Sarawak and Sabah (Malaysia) and northern Kalimantan (Indonesia) which geographically is referred to as northern Borneo. The aim here is to determine whether or not northern Borneo has experienced the same strike-slip tectonism as the Sarawak Basin, discussed in Chapter 4. If the area has experienced a similar tectonic history, a model to describe this tectonism will be generated to facilitate a better understanding of the region as a whole.

This chapter comprises three major parts. The first part discusses the tectonics of the onshore and offshore part of Sarawak, excluding the area discussed in Chapter 4. This part will also provide analogues for an alternative model for the whole region of Sarawak and offers a comparison with previous tectonic models of Sarawak.

The second part of this chapter discusses the interpretation of the tectonics of the surrounding areas including Sabah and the northern part of Kalimantan. The aim here is to determine whether or not these areas formed a single tectonic entity to Sarawak.

The third part of the chapter describes the tectonic evolution of northern Borneo from Cretaceous to Recent, using plate tectonic reconstructions and other supporting evidence. The chapter ends with conclusions for a the new tectonic understanding of the region and their implications for future mineral and hydrocarbon exploration.

6.1.1. Background

In brief, as discussed in Chapter One, the well-accepted tectonic model for Sarawak is the subduction model (James, 1984). This model proposed subduction of the proto South China Oceanic plate beneath the West Borneo continental basement during Oligocene times. The Rajang accretionary prism that is mainly composed of the Belaga Formation was formed as the result of this subduction. The Luconia platform was interpreted to be part of a continental fragment from the South China Sea, prior to opening in late Oligocene times, which drifted southward and collided with the mainland of Sarawak. If the model were true, the Sarawak Basin was formed between the accreted Belaga Formation and the drifted block of Luconia

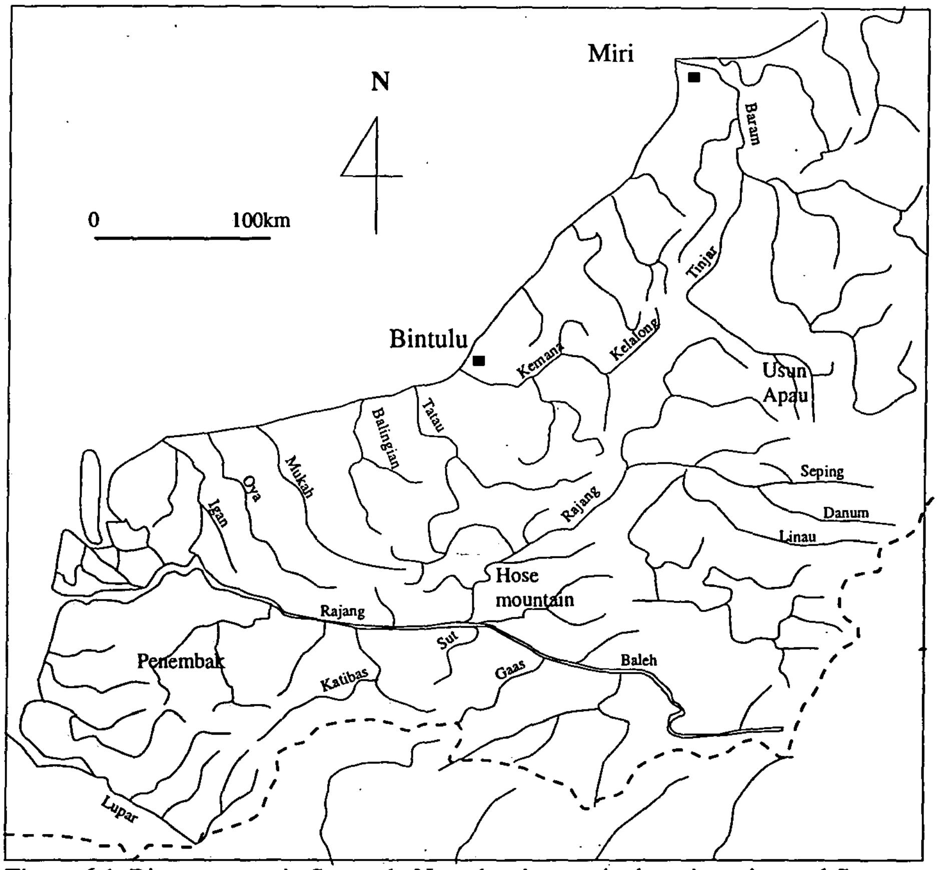


Figure 6.1. River system in Sarawak. Note the changes in the orientation and flow direction of the rivers in the north, south-east and south-west parts of Sarawak. Map redrawn from Fajar Bakti (1993).

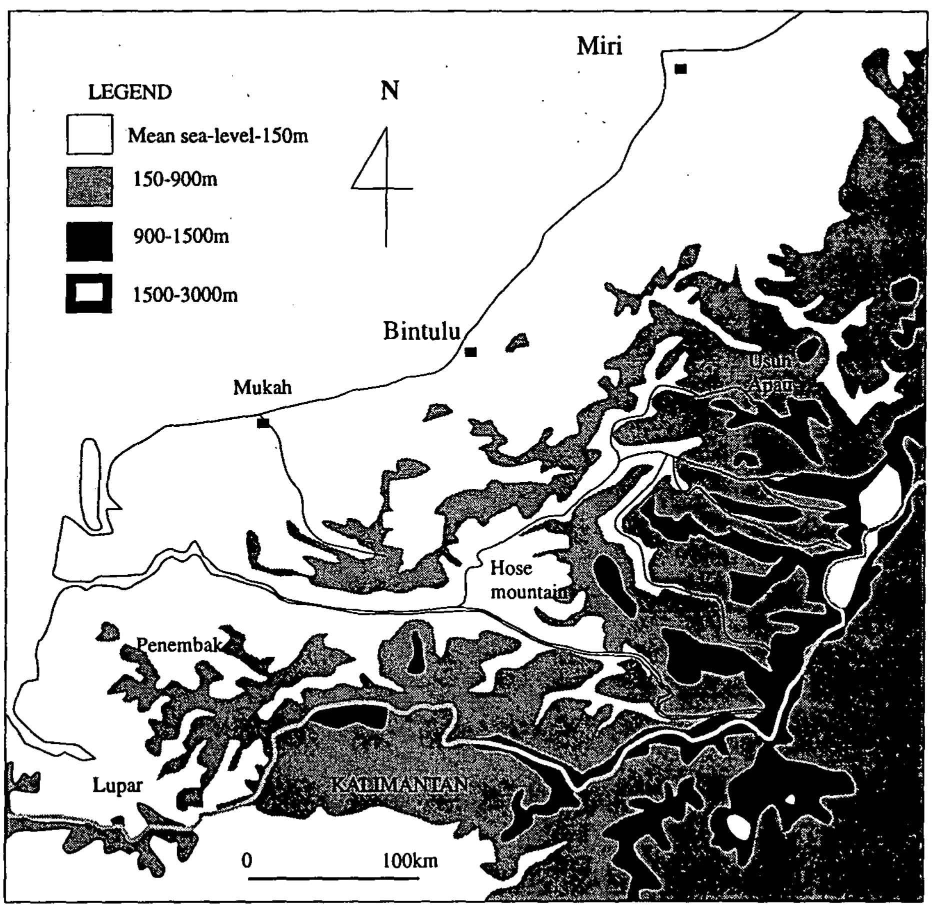


Figure 6.2. Topography map of Sarawak. Note the different orientation of the ridges in the north where the highlands are oriented in an east-west direction, the area near Penembak in the NE-SW orientation and the ranges to the east of Hose Mountain and to the south of Usun Apau are in the NW-SE orientation. Map redrawn from Fajar Bakti (1993).

province (Figure 1.10), and it could then be classified as a trench-associated basin (Kingston et al., 1983). This type of basin is not regarded as a prolific basin for hydrocarbons. However, this is not true for the Sarawak Basin which is one of the most hydrocarbon prolific basins in the region (Section 1.3).

The only available alternative model to the subduction model to date is the southward thrusting model (Untung, 1990, Figure 1.12). This model, however was not well accepted, judging from the recent publications on the tectonics of South East Asia including Hazebroek and Tan (1993) and Hutchinson (1994). Among the reasons for not accepting the thrusting model are that the geological structures in the offshore area do not concur to a simple thrusting model. Furthermore, the proposed model has been not been fully published and hence details of the model, beyond the abstract description, are not available.

Despite several publications on the identification of strike-slip lineaments in Sarawak, it cannot be regarded as one of the present tectonic models since the occurrences of strike-slip lineaments in Sarawak were only regarded as local phenomena. Levesque and Ooi (1989) and Swinburn (1993) have only discussed the occurrence of strike-slip features in the SK5 area, and other workers have reported the occurrence of strike-slip lineaments mainly for the Baram Delta and adjacent areas. There is no interpretation which relates these strike-slip lineaments and the deformation of onshore Sarawak to create a consistent structural model.

6.2 Tectonic model of Sarawak

The basic idea behind the new proposed tectonic model for the whole onshore and offshore Sarawak, which was not covered in Chapter 4, is that strike-slip tectonism is responsible for basin formation and deformation of the Sarawak Basin. This section discusses the geological evidence for interpreting the onshore lineaments, to determine whether or not strike-slip tectonism is applicable for the Tertiary tectonic model of Sarawak.

6.2.1 Major onshore lineaments

One of the ways to recognise strike-slip lineaments is to identify the distinctive physiographic features. Several strike-slip faults of heavily vegetated parts of Asia were recognised simply by the great length and linearity of the "rift" topography (Sylvester, 1988). As for onshore Sarawak which is densely forested, the drainage system, mountain range orientations and the linearity of the geological boundaries are the most important indicators of underlying geology.

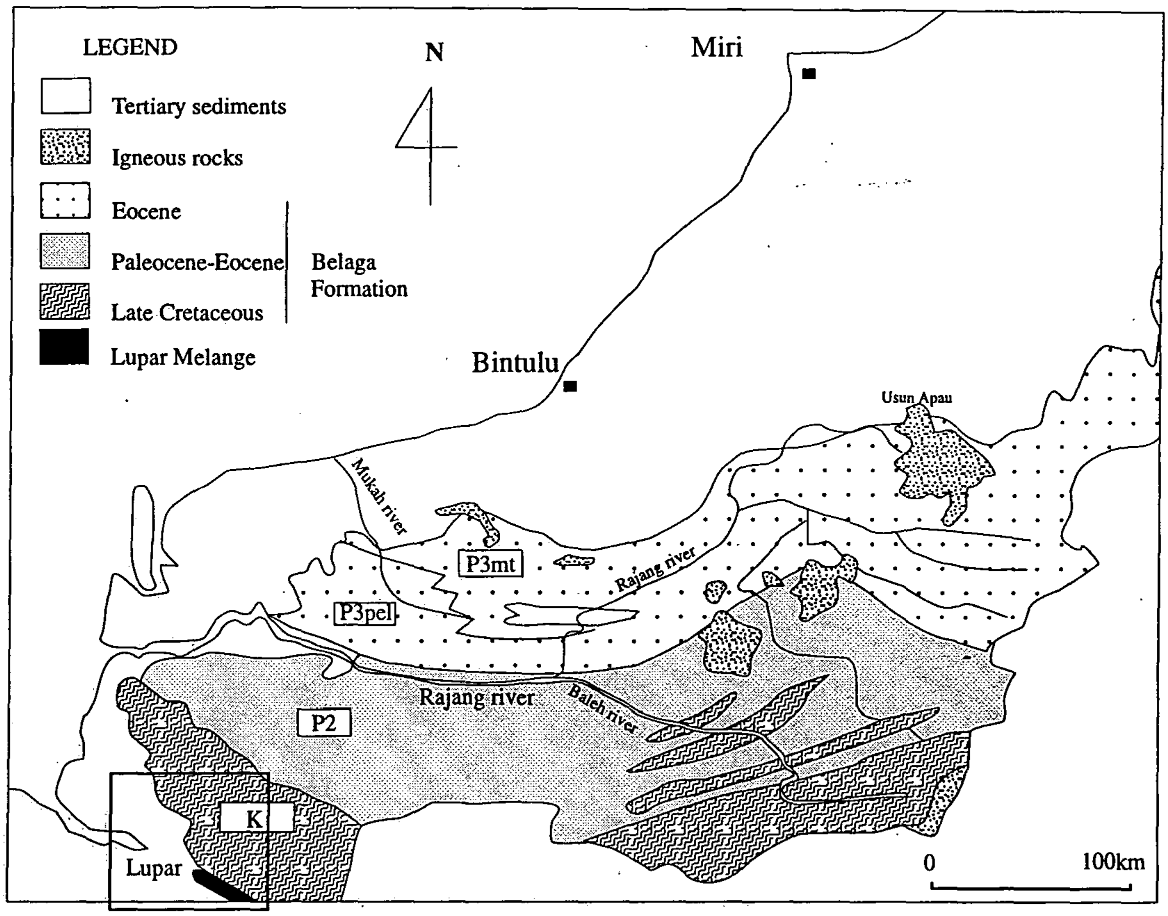


Figure 6.3 The geological map of Sarawak showing the subdivision of the Belaga Formation. The earliest subdivision made by Wolfenden (1960) remained unchanged until present. Map is sketched from Heng (1992). Note also some facies change in the Eocene Belaga Formation between the P3mt and P3pel to the south of Mukah River and the occurrence of Tertiary sediments outcropping within the Belaga formation.

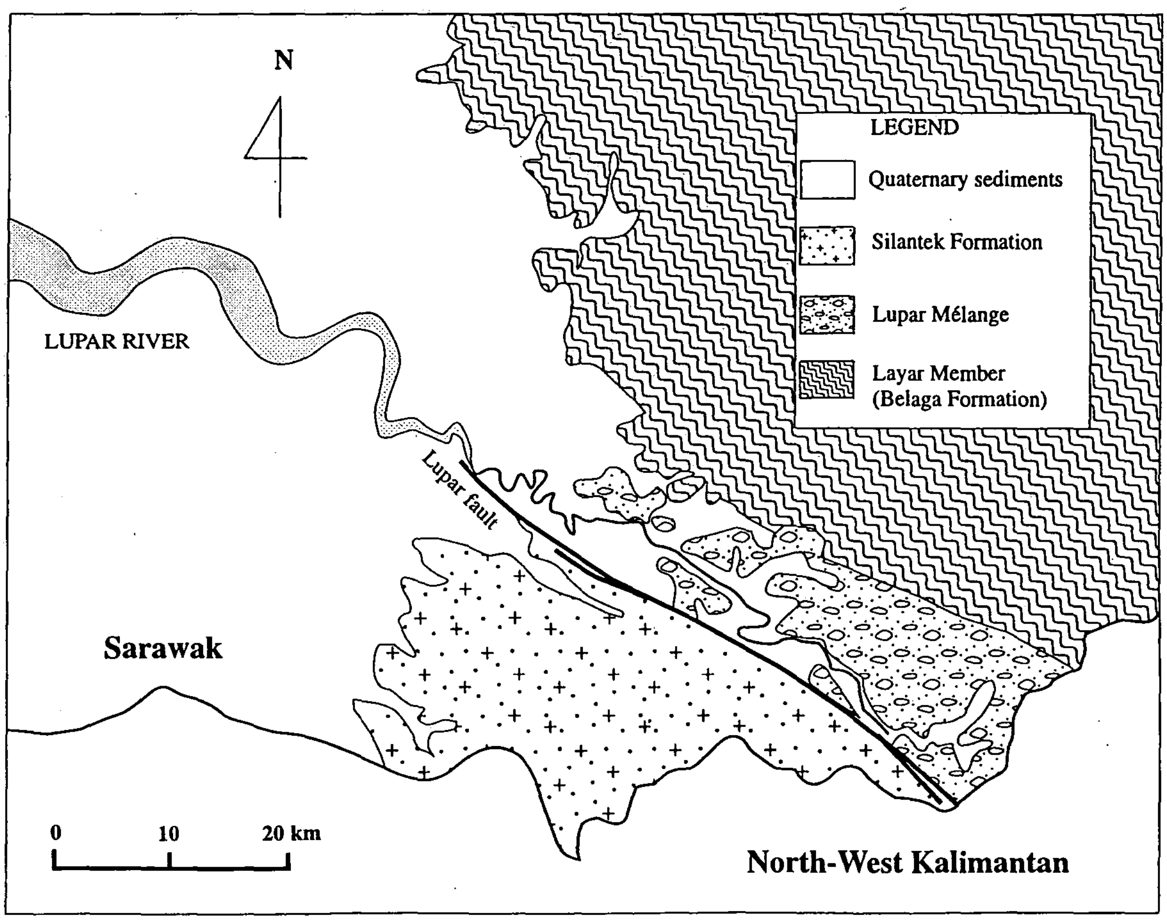


Figure 6.4 Geological map of Lupar area represents the area marked by the square box in Figure 6.3.

The drainage system, that is the flow direction and orientation of the rivers and the orientations of the ridges in onshore Sarawak, provides clues to the occurrence of tectonic lineaments in the area. It is also learnt that the occurrences of most of the identified lineaments in the onshore SK12 area coincide with the location of the rivers. The lineaments include the Igan-Oya Line with the Oya River (Figure 4.9), the Mukah Line with Mukah River (Batang Mukah, Figure 4.12) and the Lemai Fault with the Lemai River (Figure 4.12). Similarly the drainage system of onshore Sarawak (Figure 6.1), is peculiar in that it is characterised by a major river flowing in an E-W direction different from the other smaller rivers.

The mountain ranges in Sarawak (Figure 6.2) are in at least two major orientations. In the SE area, the mountain ranges are sub-parallel in a NW-SE orientation and these ranges are almost perpendicular to the lower hill ranges to north of the Rajang River which are in a NE-SW orientation and the area near Penembak.

The boundaries of the geological formations in Sarawak (Figure 6.3) also show a great linearity. For example the contact between the Kapit Member (P2) and Pelagus Member (P3pel) of Belaga has been mapped to continue for about 400 km in an E-W orientation. The contacts between other members of the Belaga Formation are almost sub-parallel to the contact between the Kapit and Pelagus Members including the contact between the Belaga Formation and the Oligo-Miocene sedimentary formation to the north, except for the Metah Member and Pelagus Member (P3pel) which is in a NW-SE orientation.

The changes in the physiographic features in onshore Sarawak are believed to be related to the tectonic movements as there is a close interaction between physiographic features and the boundaries of the geological formations. For example, the Rajang River is flowing parallel to the contact between the Kapit Member (P2) and Pelagus Member (P3pel) for about 150 km (Figure 6.3). Another example is the Lupar River (Figure 6.4), which is one of the biggest in Sarawak, which flows through the Lupar Mélange in the upstream part of the river. In fact, some of the features have already been utilised as evidence for the tectonic elements in proposing the model for the area. For example, the contact between the Belaga Formation and the Oligo-Miocene sedimentary formation was interpreted to represent the Neogene collision caused by the arrival of the Luconia microplate (Hutchinson, 1988). The Lupar mélange has been interpreted to represent the Oligo-Miocene subduction zone (Tan, 1982).

In this study, which is mainly based on physiographic features and geological data from the area, nine major tectonic lineaments (Figure 6.5) have been identified with some of them already identified by previous workers and a number of them are proposed by this study. The above-mentioned nine lineaments also include five lineaments that were discussed in Chapter 4. The data and evidence for interpreting the occurrence of tectonic lineaments are discussed in Sections 6.2.1.1 to 6.2.1.6. The lineaments are:

1. **Lupar Line**
2. **Sarikei Line**
3. **Rajang Line**
4. **Igan-Oya Line**
5. **Mukah Line**
6. **West Balingian Line**
7. **Tinjar Line**
8. **West Baram Line**
9. **Kemana Line**

6.2.1.1 Lupar Line

The Lupar Line coincides with the location of the Lupar River in Sarawak and is noteworthy for the occurrence of mélange rock known as Lupar mélange (Figure 6.4) which is also known as Lubuk Antu Mélange. This mélange zone marks the boundary between the Belaga Formation (Late Cretaceous to Eocene) and the Basement complex (Carboniferous-Cretaceous) in the Kuching Area which in places is overlain by the Tertiary sediments known as Kayan and Silantek Formations (Figure 1.3).

The Lupar Mélange, with a width of about 20 km, is composed of blocks of mudstone, shale, sandstone, chert, hornfels, basalt, gabbro, limestone and serpentinite in a strongly-cleaved pervasively-sheared chloritised black pelitic matrix (Tan, 1979). The matrix contains foraminifera and nannofossils of Lower Eocene age and the chert contains Lower Cretaceous radiolaria. The chert has not been found in the adjacent Belaga Formation (Tan, 1982).

Jasin and Haile (1993) identified sixteen radiolarian species indicating the age of the Lupar mélange's chert as Albian-Cenomanian (Lower to Upper Cretaceous) which is slightly younger than previously thought. Mahadhir (1994) reported the occurrence of blocks of interbedded shale with thin sandstone laminae which has a lithological resemblance to the Silantek Formation. The age of the Silantek Formation, based on the geological map of Sarawak by Heng (1992), ranges from Eocene to Early Miocene.

According to Tate (1991), the Lupar Mélange extends to NW Kalimantan and is known as the Kapuas complexes. The mélange zone formed as two belts known as the Boyan Mélange and Kapuas Mélange. In the south, the Boyan Mélange extends in an E-W direction for over 200 km in a 5-20 km belt bordered by a prominent fault.

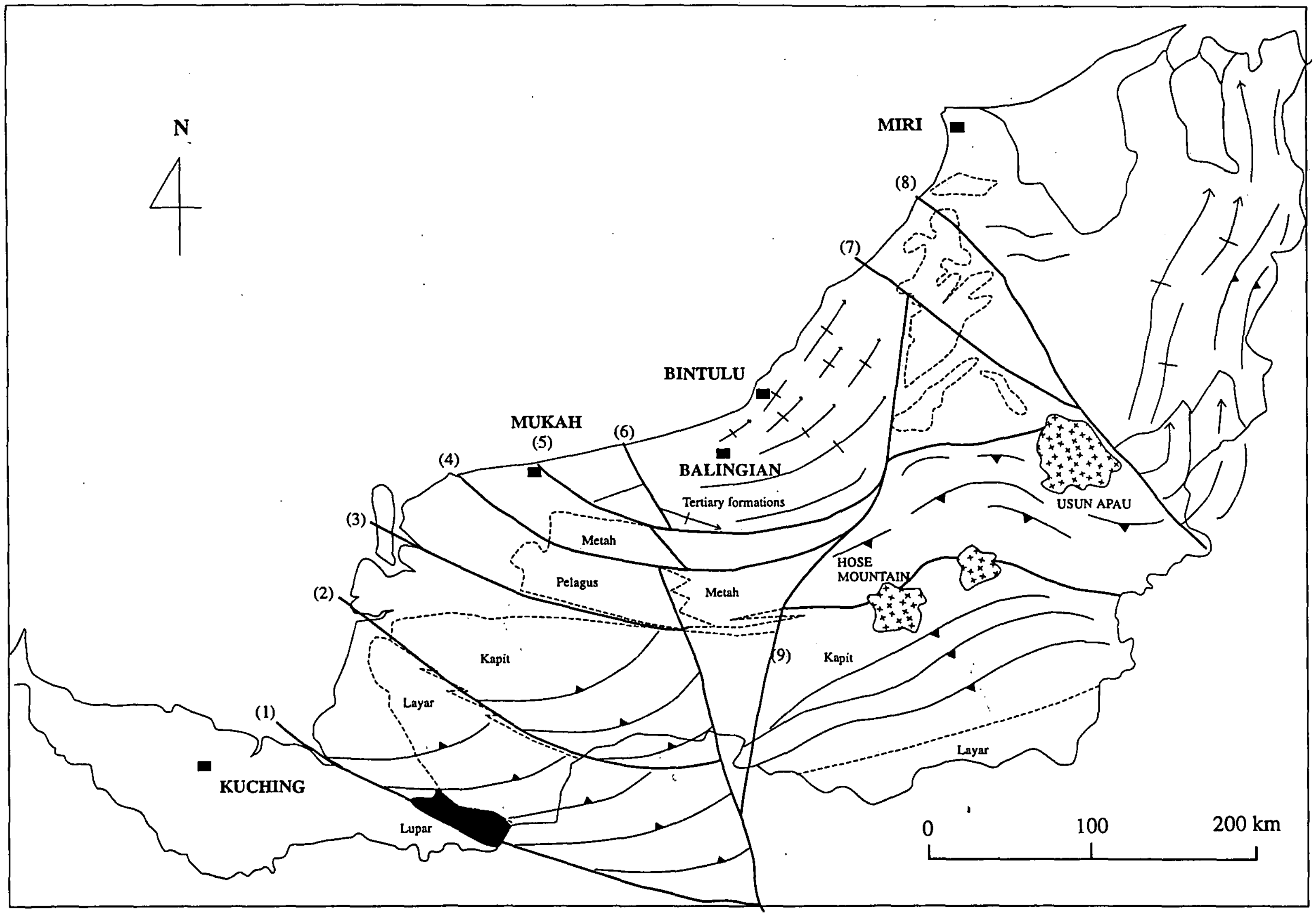


Figure 6.5. Tectonic map of Sarawak showing the major tectonic lineaments and the thrusting directions. Some of the lineaments have been proposed by previous workers including (1) Lupar Line, (6) West Balingan Line, (7) Tinjar Line and (8) West Baram Line. The new tectonic lineaments proposed by this study are (2) Sarikei Line, (3) Rajang Line, (4) Igan-Oya, (5) Mukah \ Bukit Mersing Line and (9) Kemana Line.

In the offshore area of Kuching (SK19, Figure 1.2), based on the works of Rapaee (1979) and Ismail (1993b), there is a fault-line that appears to be the extension of the Lupar Line characterised by a half-graben filled by Late Miocene sediments (T4S).

Several tectonic models have been proposed by previous workers for the Lupar Line and the occurrence of the mélange rocks, including Holloway (1982), Tan (1982) and James (1984). However, as briefly discussed here, the timing and significance of the Lupar Line to the tectonic models does vary. Among the models that have been proposed are:

1. Holloway (1982, Figure 6.16) interpreted the Lupar Line as the SW limit of subducting proto China Sea into Borneo during late Cretaceous and terminating during Palaeocene times. This interpretation concurs with those of many workers including Hutchinson (1975), Himilton (1979), Holloway (1982) and Taylor and Hayes (1983).

2. Tan (1982) speculated that the subduction of the northeast oceanic plate and its skin of Lupar Formation (Layar Member of Belaga Formation) and pelagic sediments beneath the southwest continental basement probably took place from very late Cretaceous or Palaeocene to terminal Miocene times. He also interpreted the development of a wedge of deformed "mélange" at the subduction front with incorporated blocks of chert and blocks of Lupar Formation (Figure 6.6a).

3. James (1984)' s model proposed that the subduction of the proto South China Oceanic plate was beneath the West Borneo continental basement during Oligocene times. The Rajang accretionary prism that is mainly composed of the Belaga Formation was formed as the result of this subduction (Figure 6.6b).

There are some differences in location of the Lupar Line in the three.models. For example, the location of the line is behind the accretionary prism for James (1984)' s model and the line represents the subduction front according the Tan (1982)' s model (Figure 6.6); this is similar to Holloway's (1982) model but different in timing. Besides the inconsistency in interpreting the significance of the Lupar Line in the earlier models, all the models cannot explain the absence of volcanic arc, trench, and any remnant of oceanic plate in northern Borneo. This, together with other data such as the ages of the Luconia sediments contradicts James's (1984) model in particular, and suggest that the Lupar Line should be reinterpreted.

The observations of the nature of the Lupar Line suggest that the line has characteristics consistent with a strike-slip lineament, on the basis of:

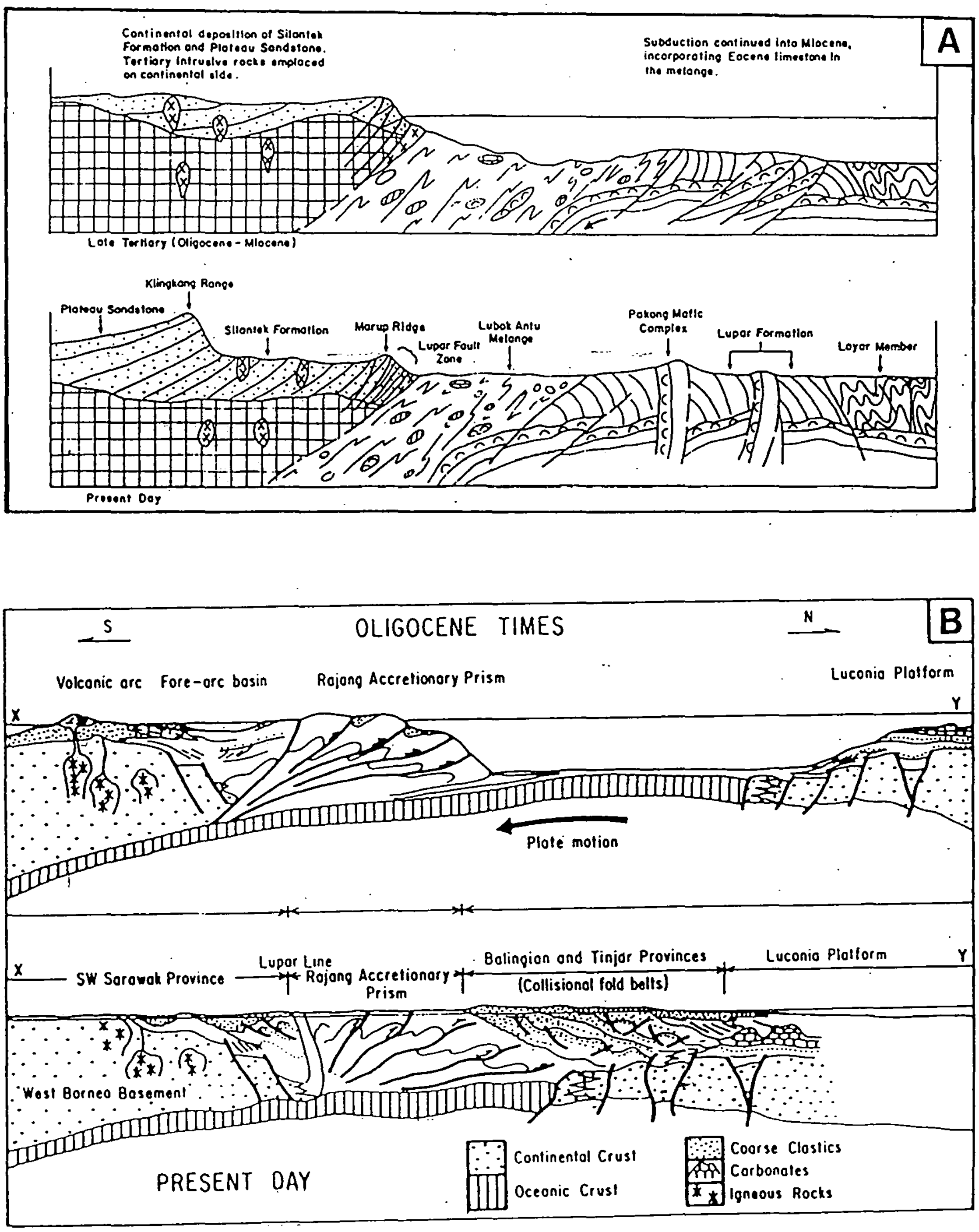


Figure 6.6. (A) The hypothetical evolution of the Lupar Valley during late Tertiary as proposed by Tan (1982). (B) The subduction model of Sarawak based on James (1984). Note the location of the Lupar Line in the two models.

1. The Lupar Mélange is consistently bounded by through-going dominant faults to the SW that extend over 50 kilometres in the Lupar area (Figure 6.4). The equivalent rock in the Kapuas complexes in NW Kalimantan is similarly bordered by a prominent fault (Tate, 1991), formed as the extension of the Lupar fault.

2. The composition of the mélange comprises chert, hornfels, basalt, gabbro, limestone and serpentinite cannot be found elsewhere in the Belaga Formation (Tan, 1982). It is similar to the composition and age of Late Jurassic to Late Cretaceous Kedadom and Pendawan Formations (Table 1.1) that outcrop in the vicinity of Kuching area to the west or NW of the location of Lupar Mélange (Figure 1.3).

3. The mélange rock could be formed by strike-slip movement, unlike previously interpreted tectonic mélanges which are commonly associated with a subduction zone. The tectonic model cannot satisfactorily explain the absence of volcanic and other features related to subduction. The formation of mélange by strike-slip tectonics is further discussed below.

4. Although there is no publication to the author's knowledge on the formation of mélange rocks by strike-slip tectonics, several workers have reported the occurrence of mélange associated with strike-slip faulting including Sylvester (1988) and Swarbrick (1993). This will be further elaborated below, and are probably analogous to the formation of Lupar Mélange.

In most cases, the formation of tectonic mélanges has been interpreted to be through deformation along fault zones and the association with subduction zones has often been made (Figure 6.7a). This does not agree with the conclusions made by Needham (1987). Based on his study of the nature of the mélanges in Japan and Scotland it was concluded that they are characterised by asymmetric extensional structures operating to develop the block-in-matrix structure of this rock type. The secondary zone of displacement has a similar overall geometry regardless of mechanism, fractures being referred to as R1 Riedel shears (Figure 6.7b) and structures formed by more plastic processes being variously known as shear bands or extensional crenulated cleavage (Needham, 1987). These structures have been recognised from many different fault zones and shear zones over a wide range of scales and deformation conditions (Tchalenko, 1970 in Plate and Visser, 1980 in Needham, 1987).

On the basis of the above descriptions it is strongly believed that mélange could also be generated by strike-slip faults since the strike-slip movement has similar extensional elements (transtensional of Harland, 1971, which appear to be accumulated dominantly by stepped oblique movement), able to develop the block-in-matrix structure.

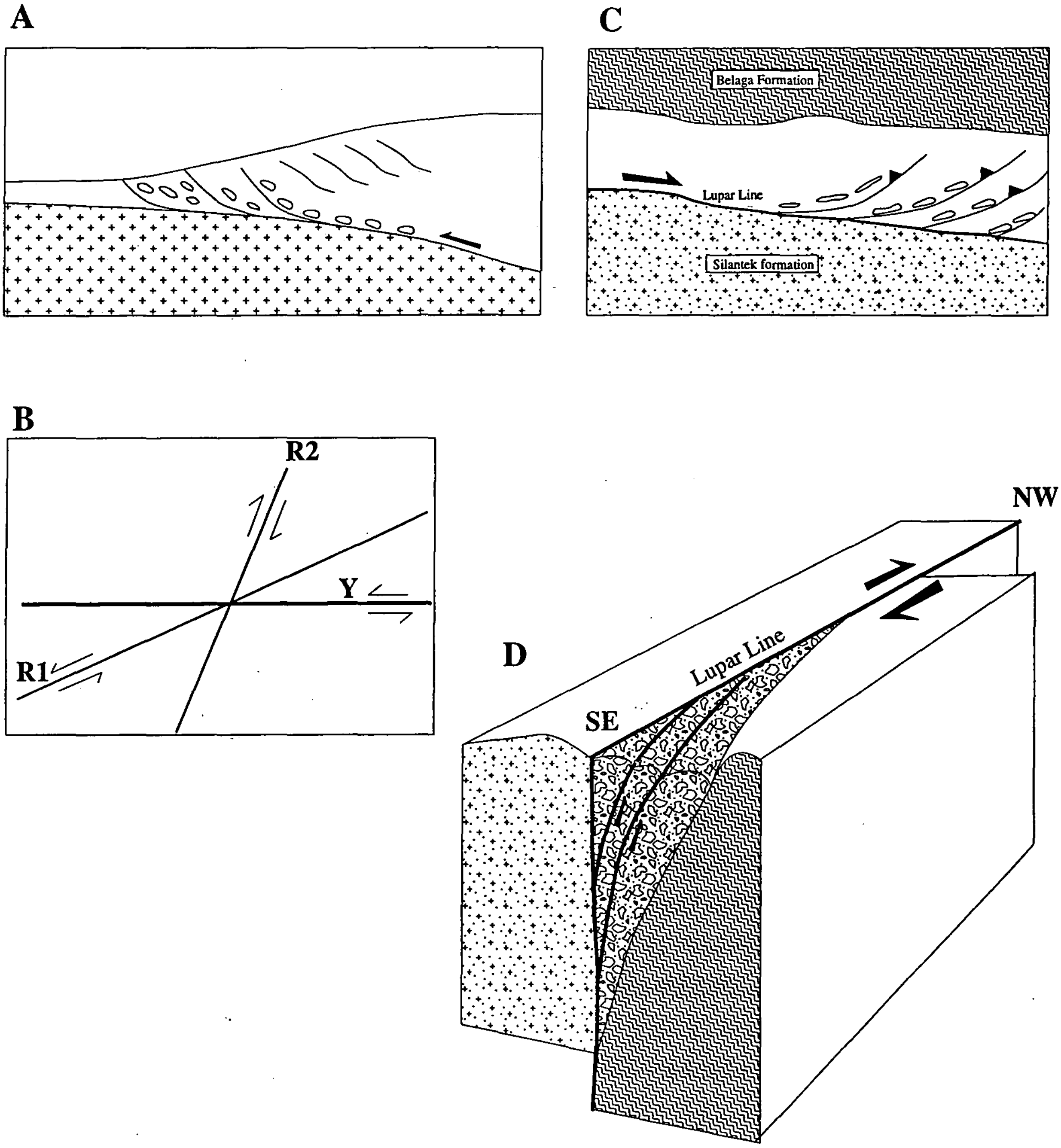


Figure 6.7. (A) The formation of mélange along thrust-fault zones and (B) geometry of secondary structures formed by fracture with Riedel shear fractures around major fault Y. The R1 orientation is of particular interest in this section, based on Needham, 1987. (C) and (D) are the proposed model of strike-slip tectonics along the Lupar Line in two and three dimensions respectively.

The analogous mélange formations to the Lupar Melange know to be derived by strike-slip movement are;

1. The Violin Breccia (among other terms used for the mixed-rock assemblage, similar to mélange) that now lies faulted against the San Gabriel Fault in southern California (figure 3 of Sylvester, 1988) that originated from the Medelo Formation from the north-east. The units were displaced by right slip on the fault zone.

2. The Mamomia complex in south Cyprus which was earlier regarded as a subduction-related mélange, has been interpreted to have formed as the result of sinistral strike-slip movement with high-angle fault between the Mamomia complex against the Troodos Complex (Swarbrick, 1993).

This study therefore suggests that the Lupar mélange was derived by **dextral strike-slip** along the **Lupar Line** (Figures 6.7c and 6.7d). The model suggests that these rock components have been transported for about 150 kilometres from the original outcrop location to Lupar Valley. The movement along the line most likely occurred during the Late Cretaceous, on the basis of the age of the rocks that were displaced and formed as matrix and blocks in the Lupar Mélange. The line was possibly reactivated several times until Eocene times.

6.2.1.2 Sarikei Line

The Sarikei Line passes through a small tributary of the Sarikei River and is coincident with the boundary between Late Cretaceous Layar Member (K) and Palaeocene-Eocene Kapit Member (P2) of the Belaga Formation (Figure 6.3). The contact between the two members has been mapped as an inter-bedding in the SE direction in the west and more linear to the east (Figure 6.5). Besides the contact, there is an abrupt change between the ages for the two members. There is also a marked difference in topography and flow direction. The area to the south is characterised by high land with the ridges in a NE-SW orientation (in the Penembak area of Figure 6.2) and most of the rivers are flowing either to the SW or to the west. The area to the west of the contact however, is generally characterised by low land with rivers flowing to the NE (Figures 6.1 and 6.2).

The contact between the Late Cretaceous Layar Member (K) and Palaeocene-Eocene Kapit Member (P2) of the Belaga Formation (Figure 6.3) has not been interpreted to be of any geological significance before.

Judging from several peculiar features outlined below, the contact between the Layar Member (K) and the Kapit Member (P2) of the Belaga Formation is interpreted to represent a strike-slip lineament similar to the Lupar Line. Among the characteristics of the contact and the reasoning for the interpretation of a strike-slip origin for the Sarikei Line are:

1. The high linear nature of the contact which has been mapped to continue for about 400 kilometres. The contact marks the abrupt change in age between the two members of the Belaga Formation and the flow directions of the main rivers.

2. The south-eastward direction of inter-bedded facies can be related to the en-echelon array along the strike-slip fault, suggesting dextral movement. The occurrences of Layar Member (K) within the Kapit Member (P2), which are elongated and sub-parallel to the main contact (Figure 6.3), could be strike-slip duplexes which brought the older rocks to the surface in the younger member to the north.

3. Judging from the nature of the contact between the two members, including the orientation of the ridges to the north, it is interpreted that the strike-slip movement post-dated the formation of the Layar Member (Late Cretaceous) and pre-dated the end of the Kapit Member (Palaeocene-Eocene). It was probably reactivated several times including Late Miocene time when the half graben structures in the offshore Kuching area (Ismail, 1993b) were filled by Late Miocene sediments

6.2.1.3 Rajang Line

The proposed Rajang Line (Figure 6.5) passes along the western half of the Rajang River before the river branches to form the upstream section of the Rajang River and Baleh River in central Sarawak (Figure 6.3). The line also marks a significant shift in the orientation of the ridges, in the area to the north and south of the Rajang Line. The ridges to the north are trending E-W as compared to the ridges to the south which have a NE-SW orientation and the area to the east of Hose Mountain, where the ridges' orientation is predominantly NW-SE (Figure 6.2).

The Rajang Line, however does not exactly coincide with the mapped boundary between the Palaeocene-Eocene Kapit Member (P2) and Eocene Pelagus Member (P3pel) of the Belaga Formation (Figure 6.3). The difference in location can be explained since the Pelagus Member (P3pel), located immediately to the north of the Rajang River, forms an antiform, as evident from the topographic map and river's flow direction with most of the small rivers in the area flowing southward toward the Rajang River and the rivers farther north flowing northward (Figure 6.1). The area between the Rajang River and the southern boundary of the Pelagus Member was eroded, leaving the Kapit Member outcropping in the area (to the north of Rajang River) and the present contact between the two geological members located farther to the north.

The contact between the Kapit Member (P2) and Pelagus Member (P3pel) of the Belaga Formation extends eastward through the Hose Mountain area. The mapped contact passes through two igneous bodies of Pliocene-Pleistocene basalt lava at Hose Mountain to the east (Figure 6.5).

As for the previous interpretation on the tectonic significance of the Rajang River and the contact between the Kapit Member (P2) and Pelagus Member (P3pel) of the Belaga Formation (Figure 6.3), no interpretation has so far been made.

It is strongly believed, however, that the Rajang River in the western half of Sarawak which is parallel to the contact between the Kapit Member (P2) and Pelagus Member (P3pel) of Belaga Formation is geologically significant and has features consistent with a strike-slip lineament. This is due to the fact that;

1. The highly linear nature of the contact between the two geological members which has been mapped continues for about 400 kilometres. The contact marks abrupt changes in age between the two members.

2. The Rajang River is very large compared to any other river in Sarawak and the river is also sub-parallel to another big river, the Lupar River. The Rajang River and the contact between the two geological members are sub-parallel to the interpreted Sarikei and Lupar Lines.

3. Magmatic rock occurs along the contact between the Kapit Member (P2) and Pelagus Member (P3pel) in the Hose Mountain area. Occurrences of magmatism associated with strike-slip have been reported in several places in the world including Vietnam, where the larger (tholeiite) melt fractions were generated within pull-apart basin, while lower (alkali basalt and basanite) melt fractions were associated with a conjugate strike-slip fault (Flower et al., 1993) and the Great Tonolite Sill in southeast Alaska (Hutton and Ingram, 1992).

On the basis of these facts, it is strongly believed that the contact between the Kapit Member (P2) and Pelagus Member (P3pel) of the Belaga Formation that is sub-parallel to the Rajang River in the western half of onshore Sarawak, herein called the Rajang Line, represents a strike-slip lineament. The movement along the Rajang Line post-dated the formation of the Kapit Member (Palaeocene-Eocene) and pre-dated the end of the Pelagus Member (Eocene); it was probably reactivated several times during the later times.

6.2.1.4 Igan-Oya Line, Mukah Line and West Balingian Line

The Igan-Oya Line and Mukah Line are two new lineaments recognised from the seismic study for the onshore and nearshore Sarawak, discussed in Section 4.4 of Chapter 4. The West Balingian Line, however, is an old name used by several workers but restricted in use for the nearshore area of Sarawak, i.e. in SK5 area. This study uses the same name for the same lineament in SK5 and it extends farther offshore from SK5 (Figure 4.42) and into the onshore Sarawak area (Figure 6.5).

The Igan-Oya line formed as the boundary between the Pelagus Member and Metah Member of the Belaga Formation (Figure 6.5). The boundary between the two members changed in the area further eastward with the boundary of the Metah Member shifted southward closer to the Kapit Member. An outcrop of Nyalau Formation (Tertiary sediment) has an elongate shape parallel to the contact (Figure 6.3). Further to the east, the contact between the two members appear to be rather disturbed and they are inter-bedded with each other.

The Mukah Line continues eastward from the south of the Lemai Sub-Basin, along the contact between the Metah Member of the Belaga Formation and the Tatau Formation and Nyalau Formation further eastward (Figure 1.5). In the vicinity of the contact, several igneous bodies have been mapped including granodiorite at Bukit Piring and andesite and rhyolite lavas at Arip (known as the Arip Volcanic). Farther to the east, an elongated outcrop of andesite at Bukit Mersing has also been mapped (Figure 1.5).

The location of the West Balingian Line in the onshore area is coincident with the contact between the Pelagus Member (P3pel) and Metah Member (P3mt), when the southern boundary of the Metah Member shifted southward, in irregular contact with the Pelagus Member (Figures 6.3 and 6.5).

Although the name of the Igan-Oya and Mukah Line have been proposed by this study, the Mukah Line is believed to coincide with the tectonic lineament called the Bukit Mersing Line which was interpreted to represent the site of the Neogene collision caused by the arrival of the Luconia micro-plate with mainland Sarawak (Hutchinson, 1988).

As an alternative interpretation, the three lineaments could represent the major strike-slip lineaments that were possibly active during Eocene to middle Miocene times as discussed in Section 4.7 of Chapter 4. Other than evidence from seismic data, the information from the onshore area similarly supports the interpretation in Chapter 4, which includes:

1. The locations and orientations of the Igan Oya Line and Mukah Line coincide with the changes in the geological formations, i.e. the contact between the Metah and Pelagus Member and the contact between the Belaga Formation and the Tertiary sedimentary formations respectively. The projection of the West Balingian Line also coincides with an irregular facies change between the Metah and Pelagus Members of the Belaga Formation (Figure 6.5).

2. A detailed map of the Arip Volcanic (by Wolfenden, 1960) shows it has been dextrally offset (Figure 1.5); this suggests that not only the intrusion and extrusions of the igneous rocks in the area are associated with the strike-slip tectonism but that they were also subjected to later strike-slip movements. The elongation of the Eocene-Oligocene andesite along the Mukah Line suggests the same.

3. The orientation of the ridges within the Tertiary formations to the north of Igan-Oya and Mukah Lines, swing from east-westerly in the area to the south of Balingian to a NE-SW orientation in the area in the vicinity of Bintulu (Figure 6.5). The orientation of the ridges agrees to the interpreted movement along the two lineaments. These lineaments also marked the changes in structural elements between the area to the north of the lineaments and the area to the SE, near the Sarawak-Kalimantan border (Figure 6.5).

On the basis of these facts, the physiography and geological evidence from the onshore area of Sarawak have further strengthened the interpretation that the Igan-Oya Line, Mukah Line and West Balingian Line are strike-slip. The lines were active during Eocene to middle Miocene and were reactivated several times. The interacted area between the lines and other related movement resulted in a severe deformation in this area.

6.2.1.5 Kemana Line

The Kemana Line (Figure 6.5) is a new proposed name for the line in a NE-SW orientation passing through the upstream part of the Kemana River and farther to SW, along the Rajang River (Figure 6.1). The line marked a very distinctive topographic and drainage pattern between the east and the west of the line (Figures 6.1 and 6.2).

The area to the NW of this line (in the onshore area of Balingian and Bintulu, Figure 6.5) is characterised by the ridges in the E-W orientation and gradually changing to NE-SW, with most of the rivers in the area flowing northward. In contrast, the area to the SE of the line is characterised by rivers such as Seping, Danum and Linau flowing to the NW near the Kalimantan border, merging with the upstream part of the Rajang River and shifting the flow direction to the SW near Hose Mountain (Figure 6.1). The flow directions of the rivers in the area are mainly because of the ridge's orientation changes, whereby the hill ridges in the area to the south of Usun Apau are in the NW-SE orientation and the area near the Hose Mountain in the NE- SW orientation.

A sinistral strike-slip line, which is in a N-S orientation extended from Miri, almost the same orientation to the northern part of the proposed Kemana Line (Figure 6.5), which has been proposed by Tjia (1994). The line was called the Tubau Line. However, due to a very schematic nature of the drawing, coupled with the unknown location of Tubau, it is decided to propose a new name, Kemana Line which represents the line that is passing through the area mentioned in the above paragraphs.

On the basis of river and ridge offsets, the line is interpreted to be a sinistral strike-slip lineament, and probably formed as the conjugate fault to the West Balingian Line. The age of this line is not certain but it is believed to be younger than Middle Miocene on the basis that the line offsets the Mukah Line (Bukit Mersing Line) that was active until Middle Miocene. Further, the Kemana Line was offset by the Tinjar Line that was active until Late Miocene times.

6.2.1.6 Tinjar Line and West Baram Line

The Tinjar Line and West Baram Line marked a significant change in the structural orientation in onshore Sarawak. As it has been discussed in Sections 4.4.5 and 4.4.6 of Chapter 4 and Figure 6.5, the area to the east of these two lineaments is characterised by structures with an almost N-S orientation, in the area to the west with structures have predominantly E-W and NE-SW orientations. Similar to the interpretations that were previously discussed (Section 4.4.5 and 4.4.6 of Chapter 4), both the Tinjar Line and West Baram lines are interpreted to be dextral strike-slip lineaments.

6.2.2 Proposed tectonic model for Sarawak.

The discussions in Section 6.2.1 show that onshore Sarawak comprises nine major **strike-slip lineaments** and these findings are not consistent with the available tectonic models for Sarawak which were briefly outlined in the Introduction of this chapter (Section 6.1.1).

Besides the structural and geological phenomena related to the strike-slip tectonism, the **block rotation** should also be considered as the main control to the tectonic evolution of Sarawak, as its influence can be seen in the formation of the Rajang Delta depression and structural traps in the nearshore area (Figure 4.33) which mainly have a counter-clockwise direction.

This section discusses the alternative tectonic model for Sarawak after considering the combination effect of block rotation together with episodic movements of strike-slips and the analogous model for the proposed alternative tectonic model of Sarawak.

6.2.2.1 Strike-slip lineaments and block rotations

A total of nine lineaments, eight with dextral strike-slip trends and one with a sinistral strike-slip trend have been identified in the onshore Sarawak area (discussed in Section 6.2.1). Although the identification of the four lineaments namely the Tinjar, Rajang, Sarikei and Kemana Lines was mainly based on the significant physiographical changes and the geological features, there coincidence with lineaments can be substantiated by seismics for their extensions in the offshore area. Further, the interpretations of the nature of the four lines are consistent with the other five lines namely Igan-Oya, Mukah, West Balingian, Tinjar and West Baram Lines whereby the occurrence and the nature of the lines have been confirmed by the most recent regional and exploration seismic lines in the Sarawak Basin, making the interpretations more conclusive.

The tectonic lineaments are generally progressively younger in an eastward direction whereby the Lupar Line is most likely to have been active in Late Cretaceous times and the West Baram Line, which is the youngest line active during Pliocene times. The orientations of those lines are sub-parallel and curve southward with a general orientation in the E-W direction, except for the West Baram, Tinjar and West Balingian Lines that are in the NW-SE orientations (Figure 6.5).

The effect of block rotation has been seen to influence the formation of the Rajang Delta depression and structural traps in the nearshore area (Figure 4.33), suggesting counter clockwise rotation. Several magnetic surveys have been conducted in Sarawak and Sabah including Haile et al. (1977) who suggested that Borneo has undergone approximately 45° of counter-clockwise rotation since the Cretaceous and this ended during the Miocene. Paleomagnetic data from Upper Jurassic to Miocene rocks in Sarawak (Schmidtke et al., 1990) show 8°-52° of counter-clockwise deflection with declination deflection with age.

6.2.2.2 The effect of block rotations

The normal strike-slip duplex geometry (Woodcock and Fisher, 1986) and the counter-clockwise rotated geometry (Stone, 1995) are shown in Figures 6.8a and 6.8b. The orientations of the ridges (Figure 6.2) have been compared to the geometry of the rotated duplex, by first assuming the movement along the Lupar Line and the other lines sub-parallel to it, then by the movement along the West Balingian Line. A three-dimension block diagram (Figure 6.9) shows the orientation of the ridges and the possible origin of the ridges in relation to the strike-slip duplexes.

Whether or not there is sufficient evidence to support the possibility of the above, it is useful to test the observations with the known information about the area. Based on the constructed 3-D diagram (Figure 6.9), the formation of the ridges in the onshore Sarawak can be explained as below:

1. The Kapuas Range in-between the Lupar and the Sarikei Lines, with the orientation of the ridges (Figure 6.2) and the orientations of the rivers (Figure 6.1) dominantly in the NE-SW orientations can be explained as a trailing contractional fan or rotated contractional duplex (Figures 6.8 and 6.9).

2. The ridges to the south of Usun Apau and to the east of Hose Mountain, with the NW-SE orientation can be explained as a rotated trailing contractional imbricated fan or a thrust fold, probably generated after the formation of the trailing contractional fan in the Kapuas Ridge as a result of the later block rotation.

3. The area to the east of West Baram Line (Figure 6.9) characterised by the NE-SW trending hill ridges with structures thrusting to the NW could also have formed as thrust folds as the result of the strike-slip movement along the line and the later block rotation.

4. The hills and anticline to the north of the Rajang Line including the area close to the shore with the ridges mainly in the E-W orientation and changed directions to NE-SW orientation further eastward (Figure 6.2) and sub-parallel to the orientation of the Igan-Oya

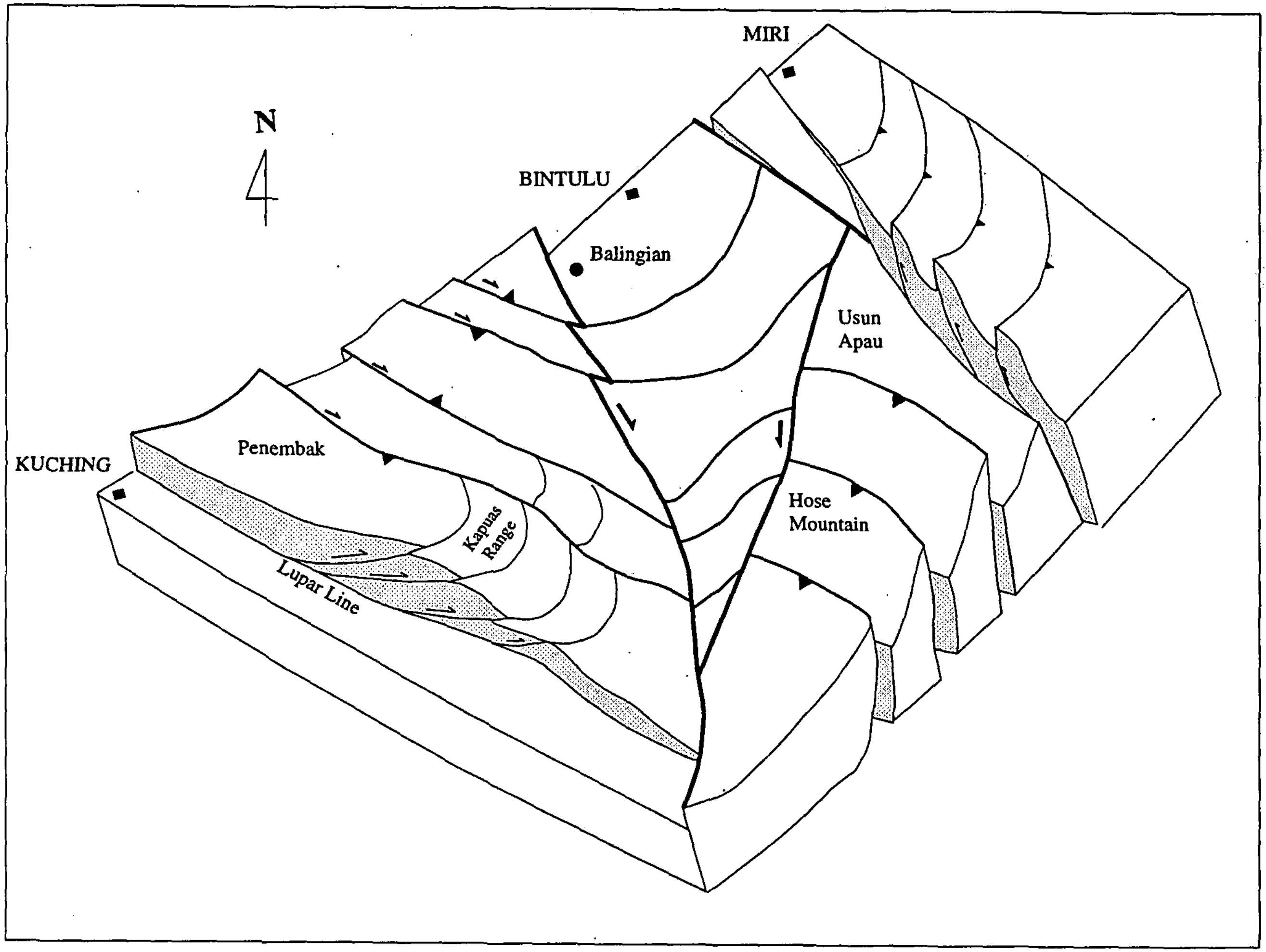


Figure 6.9. Three dimension diagram showing the relative movement and changes in the thrust direction and the orientation of the ridges forming the morphology of the Belaga Formation as the combined result of the strike-slip movement and block rotation.

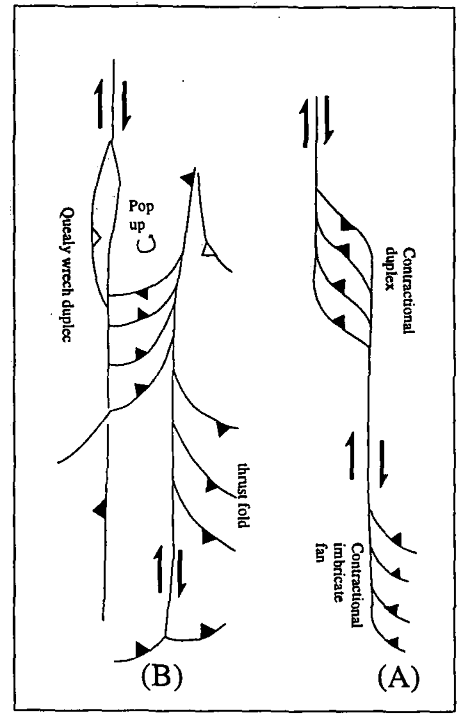


Figure 6.8. (A) Map views of dextral strike-slip system illustrating terminology for a fully developed contractional wrench duplex with a trailing contractional imbricate fan. (B) Example from Quealy wrench duplex. The idealised duplex geometry in (A) has been modified by counter clockwise rotation (After Stone,1995)

and Mukah Lines may represent the en-echelon folds and anticlines along the main strike-slip lines.

6.2.2.3 Analogies for the new model

Spitsbergen is possibly tectonically analogous to Sarawak as there is no subduction in both areas, a lack of igneous activity of large-scale batholithic intrusives and extrusives, and strike-slip tectonism is responsible for the deformation and the basin formation in the areas.

Spitsbergen is located to the NW of Greenland and forms part of the Eurasia Shelf. The edge of the shelf is situated to the south of Spitsbergen. The Spitsbergen fracture belt, according to the interpretation of Lowell (1985), was created by compressional dextral strike-slip movement on the Spitsbergen fracture zone system as Spitsbergen moved past the Norwegian and Greenland seas. The interpretation follows the previous interpretation (Harland, 1965, 1969 in Lowell 1985) but gives primary emphasis to strike slip as the driving mechanism for deformation.

The Spitsbergen orogenic belt as a strike-slip orogenic belt differs from a subduction orogenic belt in having a discrete pattern of en-echelon folds, a narrow zone of deformed sedimentary cover with a much greater degree of basement involvement, different cross-sectional profile of thrusts, upthrust versus downward flattening, in being shorter in length, and probably in lacking alpine ophiolites and metamorphism (Figure 6.10).

A strike-slip orogenic belt can be considered a new term for describing a deformed belt associated with laterally moving and rising, lithospheric welt, rather than a downgoing lithospheric slab. The terminology, however, has been used by Lowell (1985) in describing the tectonics of the Tertiary fold and thrust belt of Spitsbergen. Also according to Lowell (1985), there is sufficient contrast between Tertiary orogenic belts of Spitsbergen and, for example the Alps, that the former can be considered as a strike-slip orogenic belt caused by some compression but mainly lateral plate movement, and then later a subduction orogenic belt caused by some lateral but mainly compressional plate movement.

In Spitsbergen, deformation is associated with a laterally moving and rising lithospheric welt; in the Alps, much of the deformation can be related to a downgoing lithospheric slab. In the absence of subduction, a strike-slip orogenic belt should lack igneous activity of large-scale batholithic intrusive and extrusive tectonic volcanic type, and deep-water turbidite flysch sediments of trench origin should also be lacking; none of these features is known in Spitsbergen.

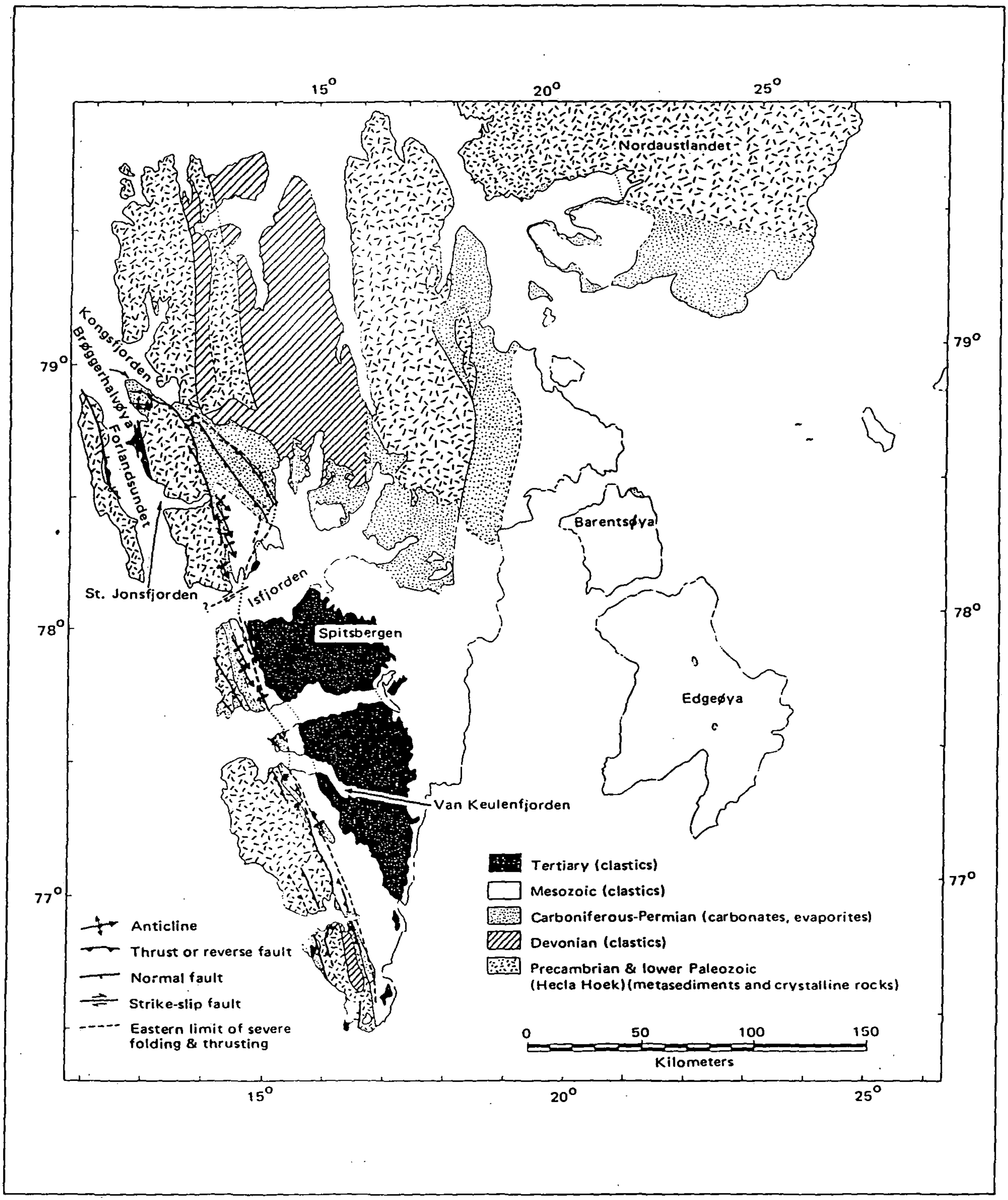


Figure 6.10. Generalised geological map of Spitsbergen showing the Tertiary structures of the Spitsbergen orogenic belt. The location of the limit of severe folding to the east between Isfjorden and Kongsfjorden coincides with the presence of gypsum t the top of the Lower Permian that is not present in the south; several hundreds metres of gypsum may have served as a mobile layer (Lowell, 1988).

Descriptions of the Spitsbergen orogenic belt are very similar to the geology of Sarawak. The Belaga Formation that was formerly interpreted as the accreted prism has been metamorphosed to green-schist facies slate (Wolfenden, 1960 and Hutchinson, 1988). Other similar features between Sarawak and Spitsbergen, beside the occurrence of a series of strike lines and discrete en-echelon folds respectively, are lack of igneous activity of the large-scale batholithic intrusive and extrusive volcanic belt, and deep water turbidite flysh sediments of trench origin. These therefore strongly suggest that the strike-slip orogenic belt of Spitsbergen is analogous to the new proposed tectonic model of Sarawak.

6.2.2.4 Proposed model

As has been discussed in Sections 6.2.1 and 6.2.2, the main tectonic control for Sarawak is strike-slip movement with the combination of block rotations (probably in partitions). The situation in Sarawak with no (large-scale) igneous or trench sediments suggest similarities with Spitsbergen.

The new understanding is that strike-slip deformation in Sarawak commenced with the Lupar Line during the Late Cretaceous and progressed to the east through time, ending with the youngest West Baram Line during Pliocene times. The strike-slip lines, however, have been subjected to several episodes of reactivation and counter-clockwise rotation during their history. The strike-slip tectonism is not only responsible for the uplift and deformation of the basement rocks but also the formation of the Sarawak Basin and structural traps. The Belaga Formation that formed the hilly backbone area of the Sarawak hinterland and also formed the basement for the Tertiary basin partly in the onshore but mainly in the offshore area, previously called the Rajang Accretionary Prism, is a strike-slip belt, which is the new interpretation, is called the **Rajang Strike-Slip Orogenic belt**.

By gathering the data from the Sarawak Basin (Chapter 4) together with other unpublished information on offshore Kuching and the south Natuna area (Simon-Robertson, 1992), a map showing the proposed tectonic model of Sarawak shown in Figure 6.11. The model differs significantly from several earlier models; it is superior to other models in that it explain the absence of volcanic belts and lack of igneous activity and trench sediments which are required to support the previous models. The significance of the proposed model is the ability to explain the formation of the basin and the structural traps in the Sarawak Basin.

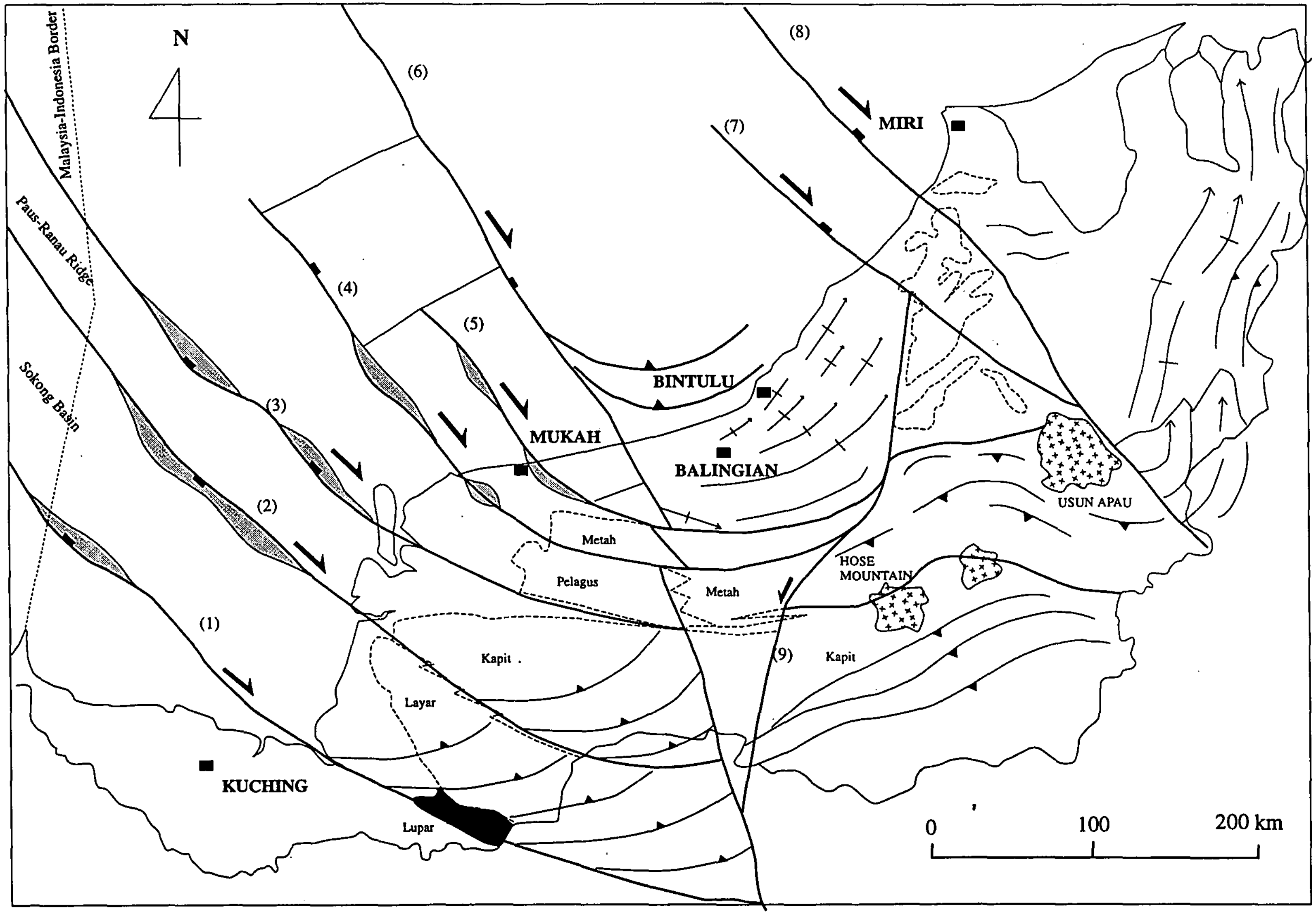


Figure 6.11. Proposed tectonic model of Sarawak. (1) Lupar Line, (2) Sarikei Line, (3) Rajang Line, (4) Igan-Oya line, (5) Mukah \ Bukit Mersing Line, (6) West Balingan Line, (7) Tinjar Line (8) West Baram Line and (9) Kemana Line.

6.3 Tectonic framework of northern Borneo

This section continues the discussion as to whether Sabah and northern Kalimantan have undergone strike-slip tectonism during the late Cretaceous to Pliocene in a manner similar to Sarawak. However, it should be stressed here that no new data have been collected in this study for northern Kalimantan. The interpretation is mainly based on the geological map of Indonesia and few publications. More information on Sabah area is available from published geological maps and some seismic lines for the offshore areas. Despite the limited data, attempts have been made to recognise the structural trends in northern Kalimantan and Sabah which could be the extension of the lineaments identified in Sarawak.

6.3.1 Structural trends in northern Kalimantan

Figure 6.12 shows the extent of the Cretaceous-Tertiary sediments, the equivalent formation to the Belaga Formation in Sarawak and the major fault lines in northern Kalimantan, based on the geological map of Indonesia by Sukamto et al. (1992). The map shows that the Belaga Formation's equivalent rock unit is cropping out to the N and NE of Kalimantan with the south-eastern outcrop limit bordered by prominent NE-SW trending faults. Another fault with similar orientation to above-mentioned faults is situated within the Cretaceous-Tertiary formation.

Two major trends in the fault system in the area can be recognised. The trends are in: (1) a NE-SW orientation and (2) a NW-SE orientations. The faults in the NE-SW orientation are marked as faults (A), (B), (C) and (D) in Figure 6.12. The Fault A is located within the rock formation equivalent to the Belaga Formation and the second dominant fault (Fault B) formed as the southern boundaries of the Belaga Formation's equivalent rock, in the middle part of northern Kalimantan. Fault C is in a more N-S orientation to Fault B, and extends to the northern boundary of Kalimantan. Fault D marks the SE boundary of a rock formation equivalent to the Belaga Formation, to the south of Tanjung Redeb.

The prominent faults in the NW-SE orientations are the faults (1), (2), (3) and (4) in Figure 6.12. Fault 1 is located in the upstream part of Barito River and formed the western boundary of the Belaga Formation's equivalent in the central part of northern Kalimantan. Fault 2 is located at about 50 km to the west of Tanjung Redeb and offsets Fault B in a dextral sense. Fault 3 is located about 100 km to the NW of Tanjung Reded and offsets Fault A in a sinistral sense and Fault 4 that has a similar orientation could be the extension of Fault 3.

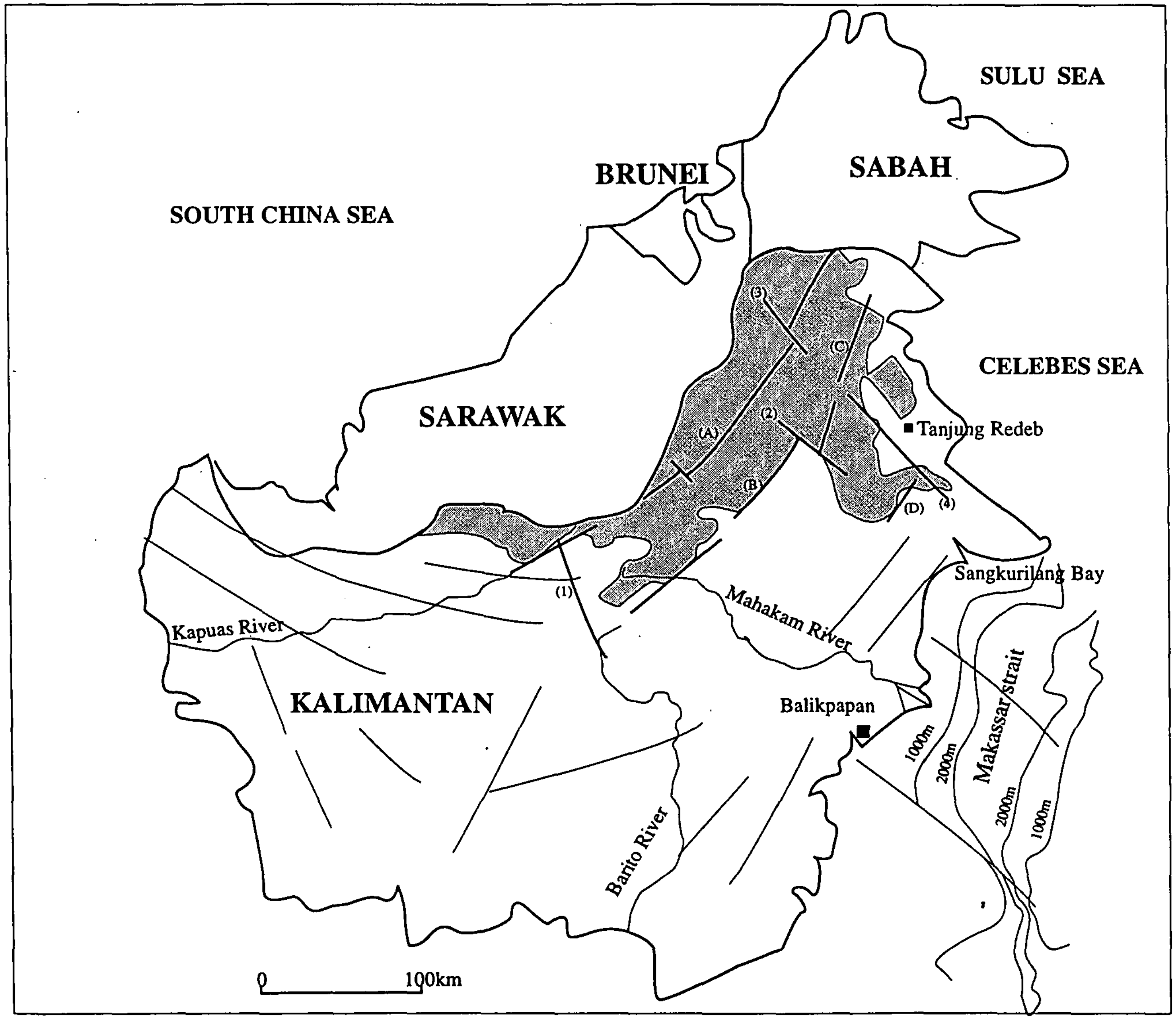


Figure 6.12. The map of Borneo showing the extent of the rocks equivalent to the Belaga Formation in Kalimantan. Note also the major tectonic lineaments in the area and the flow directions of major rivers in Kalimantan. Map is redrawn based on Sukamto et al. (1992).

Figure 6.12 also shows the location of the Makassar Strait located to the SE of Kalimantan. The strait is bounded to the NW-SE by a fault which has a similar orientation to one mapped in the middle part of the strait. The SW bounding fault marks a drastic change in the bathymetry, and is possibly a transform fault with a sinistral sense of movement.

6.3.2 Structural setting of Sabah region

6.3.2.1 Onshore and shelf areas.

The western part of onshore Sabah is characterised by the almost N-S trending structures and thrusting to the west (Figure 6.13). The structural trend ('fold-thrust' of Tongkol, 1994) changes in NE Sabah to NW-SE, with thrusting to the NE. Tongkol (1994) interpreted that the interaction between the NW-SE trending fold-thrust belt, the NE-SW trending wrench faults and ongoing extension in the Sulu Sea during Middle Miocene resulted in the formation of Neogene circular basins in onshore Sabah. Several sinistral strike-slip faults cut through Palaeogene rock (Tongkol, 1994).

The shelf area of offshore west Sabah (locally less than 100 km wide) is much narrower as compared to the shelf in central Sarawak that generally exceeds 300 km from the shelf edge to the coast (Scherer, 1980). The orientation of palaeo-coastlines from middle Miocene has remained unchanged and is sub-parallel to the present-day coastline. The Tertiary sediments have been sub-divided by a series of regional unconformities (Rice-Oxley, 1991). However, the unconformities in Sabah do not coincide with the Tertiary unconformities in the Sarawak Basin, suggesting independent structural events between the two basins.

The shelf area is characterised by compressional structures trending NE-SW, thrusting in the NW direction. The structural trend ends with the main thrust forming the NW Sabah Trough, also known the Sabah Trough and occasionally referred as the NW Palawan Trough (Figure 6.13). The area farther landward is mainly characterised by strike-slip tectonics which created the structures for most of the hydrocarbon producing fields in the area (Bol and Van Hoon, 1980) including St Joseph, Barton and South Furious.

The strike-slip generated structures in offshore Sabah are very prominent, so that Lowell (1985) used the seismic examples from the hydrocarbon fields in Sabah as classical examples of such structures, in his book on Structural Styles in Petroleum Exploration.

6.3.2.2 NW Sabah Trough.

The origin of the NW Sabah Trough is controversial. Many workers interpreted the Sabah Trough as formed in a subduction zone between the drifted block from the South China Sea when the opening took place during late Oligocene to Early Miocene (32-17 Ma). Among the workers who agreed with the interpretations are: Himillton (1979), Taylor and Hayes (1980), Holloway (1982) and Hazebroek and Tan (1993).

However, there are problems with the NW Borneo subduction zone. Palaeogene or Neogene subduction-related volcanic or plutonic rocks have not been recognised so far in Borneo and the end of subduction along the Sabah Trough was not marked by major Palaeo-Neogene tectonic deformations (Taylor and Hayes, 1983). Among the workers who questioned the existence of a subduction zone associated with NW Sabah Trough are: Taylor and Hayes (1983), Tapponnier et al. (1986) and Braise et al. (1993).

Tapponnier et al. (1986) proposed an alternative model, incorporating a prominent sinistral strike-slip fault trending NE-SW passing from the northern tip of Sabah to northern Kalimantan (figure 10d of Tapponnier et al. 1986) which coincides with the proposed Kinabalu Fault (K in Figure 6.15). The model involves a large left-lateral strike-slip fault trending NW within Sundaland, with right-lateral movement along minor N-S trending faults. The tectonic model speculated that the deformation of the Belaga-Crocker Formations is mainly due to tectonic movement along this left-lateral strike-slip line in NW Borneo. Braise et al. (1993) speculated that the North Palawan Trough (the Sabah Trough) merely results from elastic downwarping in response to loading by a thrust along the NW edge of Palawan.

Hazebroek and Tan (1993) included several reduced seismic lines passing through the Sabah Trough in their paper. Despite good quality seismic lines, they were only able to trace the subducted plate from the north, for only a limited distance (about 10 km). It is not known whether the down thrusting continues further landward or terminates at the point where the seismic image of the downthrust ends (Figure 6.14a). Therefore, although the features seen in the Sabah Trough resemble those of subduction, the occurrence of a subduction zone in the Sabah Trough is believed to be inconclusive. What is clear about the Sabah Trough is that the area marks the boundary between a highly deformed sequence near the coast line and an undeformed area to the north.

From the observations made in this study on similar seismic lines to those published by Hazebroek and Tan (1993), it is believed that an alternative interpretation to subduction in the Sabah Trough is a low-angle thrust (Figure 6.14b). It is suggested that the thrust sheet from the south was upthrusted with a steep angle at depth which becomes gentler near the surface. The phenomenon where the thrust angle changes with depth has been documented in the Broggerhalvoya area in Spitsbergen (in Lowell, 1985), where the thrusts are interpreted to steepen with depth and be upthrusts related to strike-slip faulting. This created a similar feature to a subduction zone whereby the northern block appears to have been subducted beneath the thrust sheet from the south.

If the above alternative interpretation is true, the NW Sabah Trough should represent the northern limit of the strike-slip zone in the Sabah shelf area. This interpretation is similar to that of Bol and Van Hoon (1980) as the Tertiary sedimentary block was called a thrust sheet (Hazebroek and Tan, 1993), and was interpreted to be mainly the result of strike-slip tectonism. Thus, this alternative interpretation explains why there is no tectonic event associated with cessation of subduction in NW Sabah (Taylor and Hayes, 1983), in contrast to the subduction along Palawan that was associated with regional uplift and the unconformity firmly dated as late middle Miocene (Holloway,1981).

6.3.3 Proposed tectonic model for northern Borneo.

6.3.3.1 Tectonic lineaments

The Lupar Line (Figure 6.15) which is almost in a E-W orientation in onshore Sarawak, is probably the extention of Fault B that formed as the SE bounding fault for the rocks equivalent to the Belaga Formation in the middle part of northern Kalimantan (Figure 6.12). The line probably continued to the east, along Fault D into the area of present location of Celebes Sea.

The Sarikei Line and Rajang Line (Figure 6.15) might extend further to the south into northern Kalimantan. One of the lines could be the extension of Fault A, and continuing to the east, through northern Kalimantan and experiencing counter-clockwise rotation to form the banded 'fold-thrust' in the border area in SW Sabah (Figure 6.13). The Igan-Oya Line and Mukah Line , however, are believed to be limited to the Sarawak area only.

The West Balingian Line (Figure 6.15) extends through the NW-SE trending major fault in the upstream part of the Barito River (Fault 1, Figure 6.12) and borders the same river to the east. By extending the line further to the SE, the line ended in the Makassar Strait and probably merged with the sinistral strike-slip system produced by the opening of the Makassar Strait. However, the interaction between the southern extension of the West Balingian Line and the sinistral strike-slip line that marked the southern limit of the Makassar Strait is not

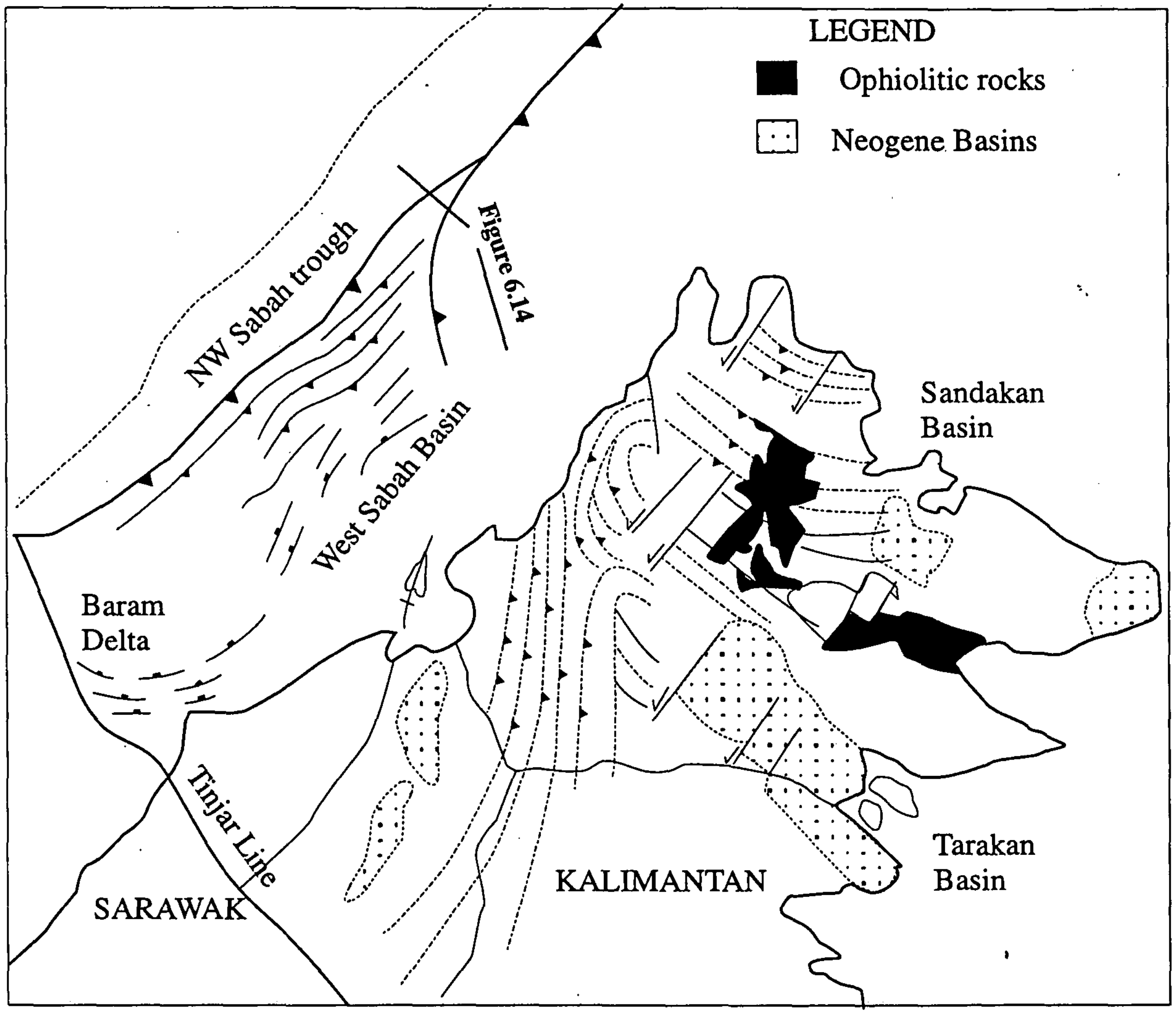


Figure 6.13. Structural trend of onshore and offshore Sabah based on Tongkol (1994). The map shows the structural trend in west Sabah in a N-S orientation and thrusted to the west. The orientation is similar to the structural trend for the Belaga Formation to the east of the Tinjar Line, in east Sarawak. The left-lateral strike-slip faults which cut through the Palaeogene thrust-belt also affect the Neogene basins.

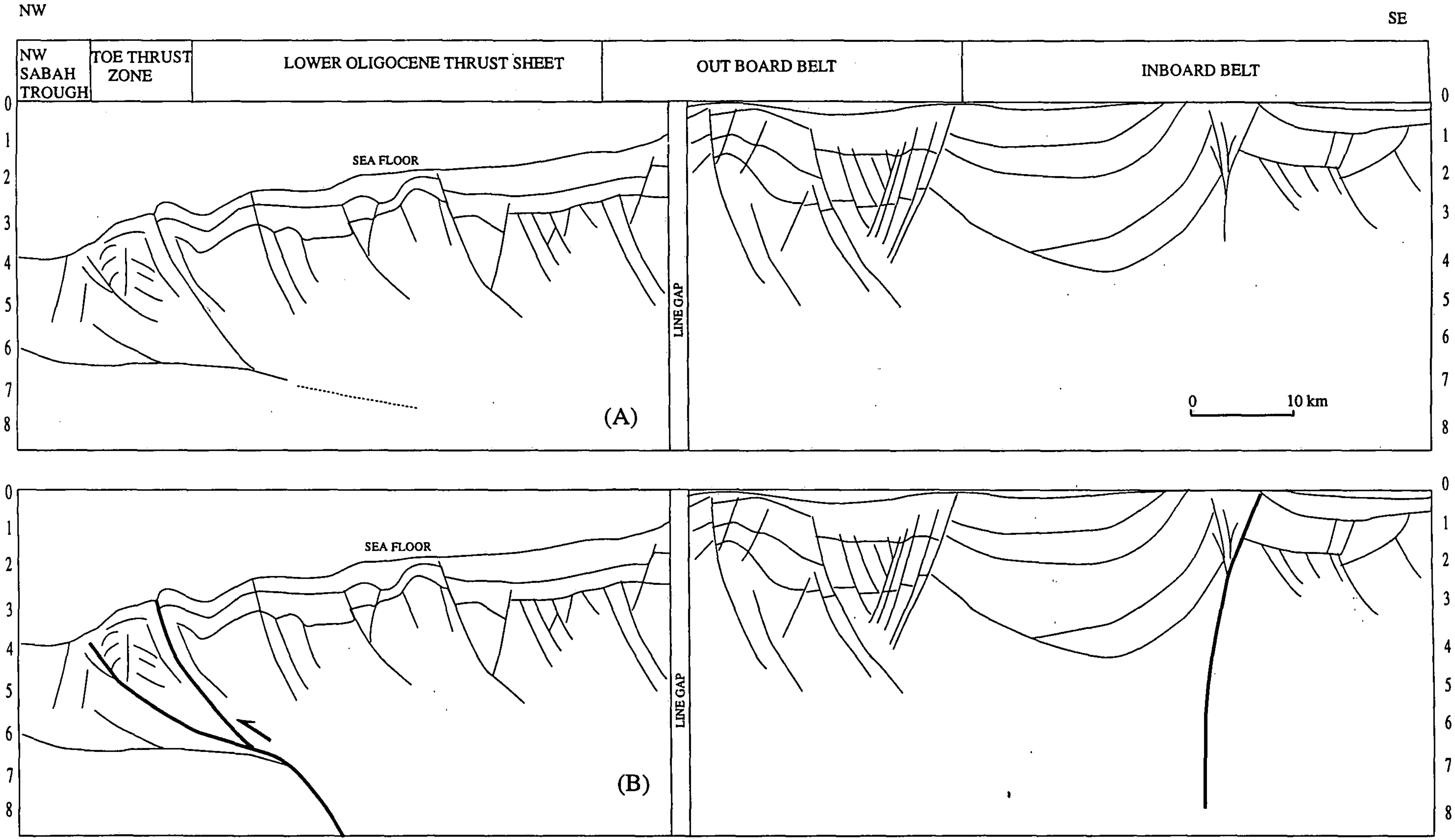


Figure 6.14. Geoseismic cross sections in a NW-SE orientation across the shelf area to the Sabah Trough. (A) is the interpretation by Hazebroek and Tan (1993) proposing a subduction zone at the toe thrus. (B) an alternative interpretation by this author suggesting the toe thrust area is a low angle thrust at near surface becoming steeper with depth. The thick lines are the new interpretations. Refer Figure 6.13 for the location of the lines.

well understood. This is because an accurate age for the opening of the strait is not available. Hall (1994) speculated that the Makassar Strait and Celebes Sea opened between Late Eocene and Middle Oligocene. Nicolas and Hall (1994) suggested that the Celebes Sea was being subducted to the south during early Miocene (c.22Ma) and the influx of terrigenous sediments to the area continued until Late Miocene (c.8 Ma).

It is believed that the cessation of movement on the West Balingian Line during late Miocene (T2S times, 23 Ma) has some relationship with the opening of the Makassar Strait, whereby the movement was terminated by the opening of the Makassar Strait that possibly lasted until Late Miocene (c 8 Ma). However, the broad estimation of the timing of the opening of Makassar Strait was based on very sparse data compared to a very precise age determination in the study area; this hinders an accurate interpretation of the relationship between the movement along the West Balingian Line and the opening of the Makassar Strait.

The West Baram Line (Figure 6.15) is interpreted to continue further to the SE across the Sarawak-Kalimantan border along the fault that is located about 50 km to the west of Tanjung Redeb (Fault 2) that offsets Faults B and C. With further extension to the SE, the West Baram Line merged into the subduction system of the Celebes Sea. The movement along the West Baram Line during Pliocene (T5S times, c. 5.0 Ma) agrees with the interpretation of southward subduction of the underlying crust beneath the northern arm of Sulawesi that commenced about 8 Ma (Nicholas and Hall, 1994).

The Balabac Strait Line was interpreted by James (1984) as a dextral strike-slip lineament and the **Pengi fault** was interpreted as a sinistral strike slip lineament (Tate, 1992) that marks the eastern limit of the Brunei-Limbang province where there are northerly-striking folds. To the east this fault, fold-strikes are NE, sub-parallel to the shore-line of Sabah (Tjia, 1994).

The Kinabalu Line (Figure 6.15) marked the boundary between the N-S trending 'thrust-folds' in west Sabah and the mainly NW-SE trending 'thrust-folds' in east Sabah. The lines extend from the northern tip of Sabah to the Mount Kinabalu area, continue to the south and coincide with the sinistral fault (Fault 3, Figure 6.12) located about 100 km to the northwest of Tanjung Redeb. Tapponnier (1986, Figure 6.18b) has already proposed a sinistral strike-slip lineament with the same orientation and location as the Kinabalu Line, without the name given.

6.3.3.2 Proposed model

With the new findings of Sarawak tectonics together with the data on structural trends in northern Kalimantan and Sabah (discussed in Sections 6.3.1 and 6.3.2) whereby several

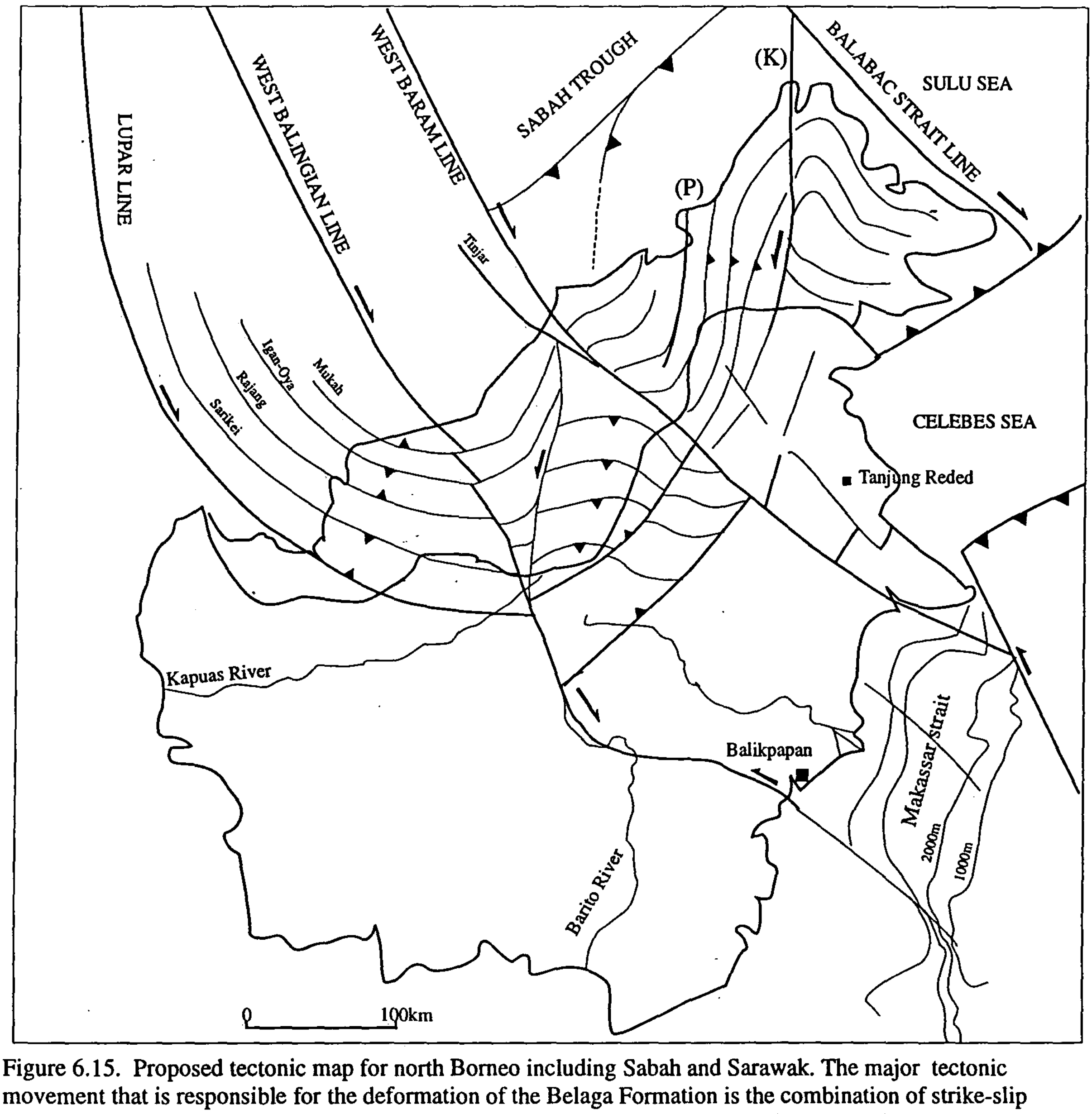


Figure 6.15. Proposed tectonic map for north Borneo including Sabah and Sarawak. The major tectonic movement that is responsible for the deformation of the Belaga Formation is the combination of strike-slip and counter-clockwise rotation of the interacted blocks. (P)- Pangi fault, (K)-Kinabalu fault.

lineaments identified in Sarawak extend farther to the south (in northern Kalimantan), it is believed that the data are sufficient for the purpose of generating a new tectonic model for northern Borneo. It should be stressed here that the proposed tectonic model for northern Borneo only includes the principal tectonic features without detailed consideration of local events. As yet sufficient information for Kalimantan is not available to do this in detail. Nevertheless good data from the Sarawak Basin and a certain amount of data from onshore Sarawak, Sabah and Kalimantan can be fitted into a single tectonic model of northern Borneo.

The proposed tectonic model of northern Borneo is shown in Figure 6.15. The model suggests that the whole area of northern Borneo was subjected to a series of strike-slip movements with two dominant directions, in NW-SE and east-westerly directions. The Sabah toe thrust zone (Figure 6.14) represents one of the sinistral strike-slip lines. The Sabah area was located in between two major dextral strike-slip lines (Balabac Strait Line and West Baram Line) and subjected to counter-clockwise rotation during late Oligocene and later during Pliocene times (Schmidtke et al., 1990). The model therefore suggests that the Sabah Trough did not form as part of Palawan subduction, as the two have distinct differences, including the absence of Paleogene or Neogene subduction-related volcanics or plutonics in Borneo, and a major tectonic deformation that marked the end of subduction along the Sabah Trough, as compared to the Palawan area (Holloway, 1981).

6.4 Tectonic evolution of northern Borneo.

6.4.1 Background

The tectonic evolution of northern Borneo is not well understood until today. However, to simplify this complicated subject, present ideas on the tectonic evolution of the area can be grouped into two different schools of thought.

1. The first group believes that the evolution of NW Borneo commenced by the subduction of Mesozoic (Proto China Sea) oceanic crust beneath the Sundaland at the Lupar Line during Late Cretaceous times (Figures 6.16 and 6.17). The subduction line was interpreted to have migrated northward to the Bukit Mersing Line during the Palaeocene as the result of sinistral strike-slip movements in the offshore NW Borneo region and later by the opening of the South China Sea (Figures 6.16b,c, d and Figure 6.17b). The subduction zone along the Bukit Mersing Line ceased during the Late Oligocene but persisted along the Sabah or Palawan Trough until Early Miocene (Figures 6.16d and 6.17d). Another important aspect

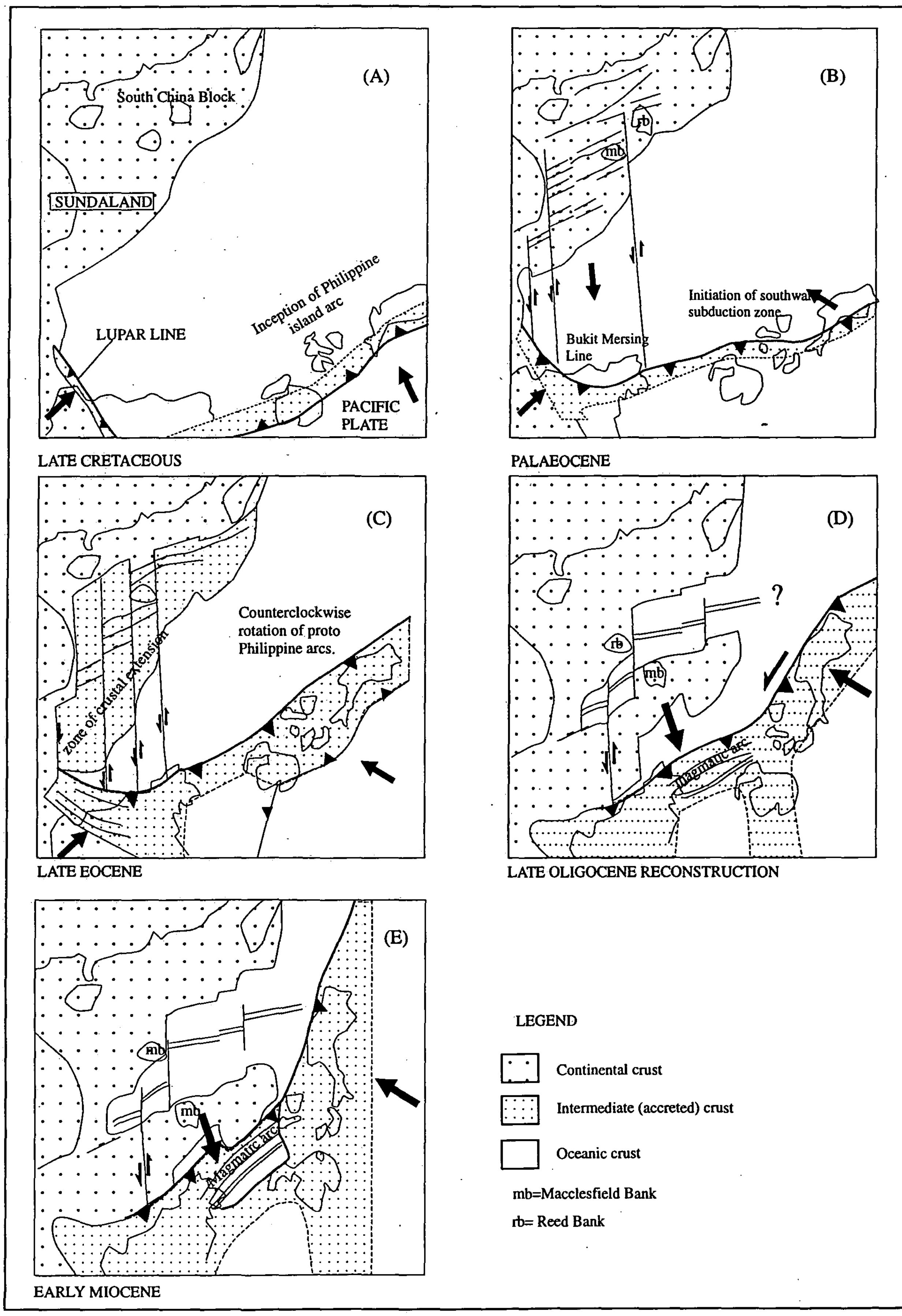


Figure 6.16. Plate reconstruction of South China Sea and its relation to Borneo and Philippines from Late Cretaceous to Early Miocene based on Holloway (1982).

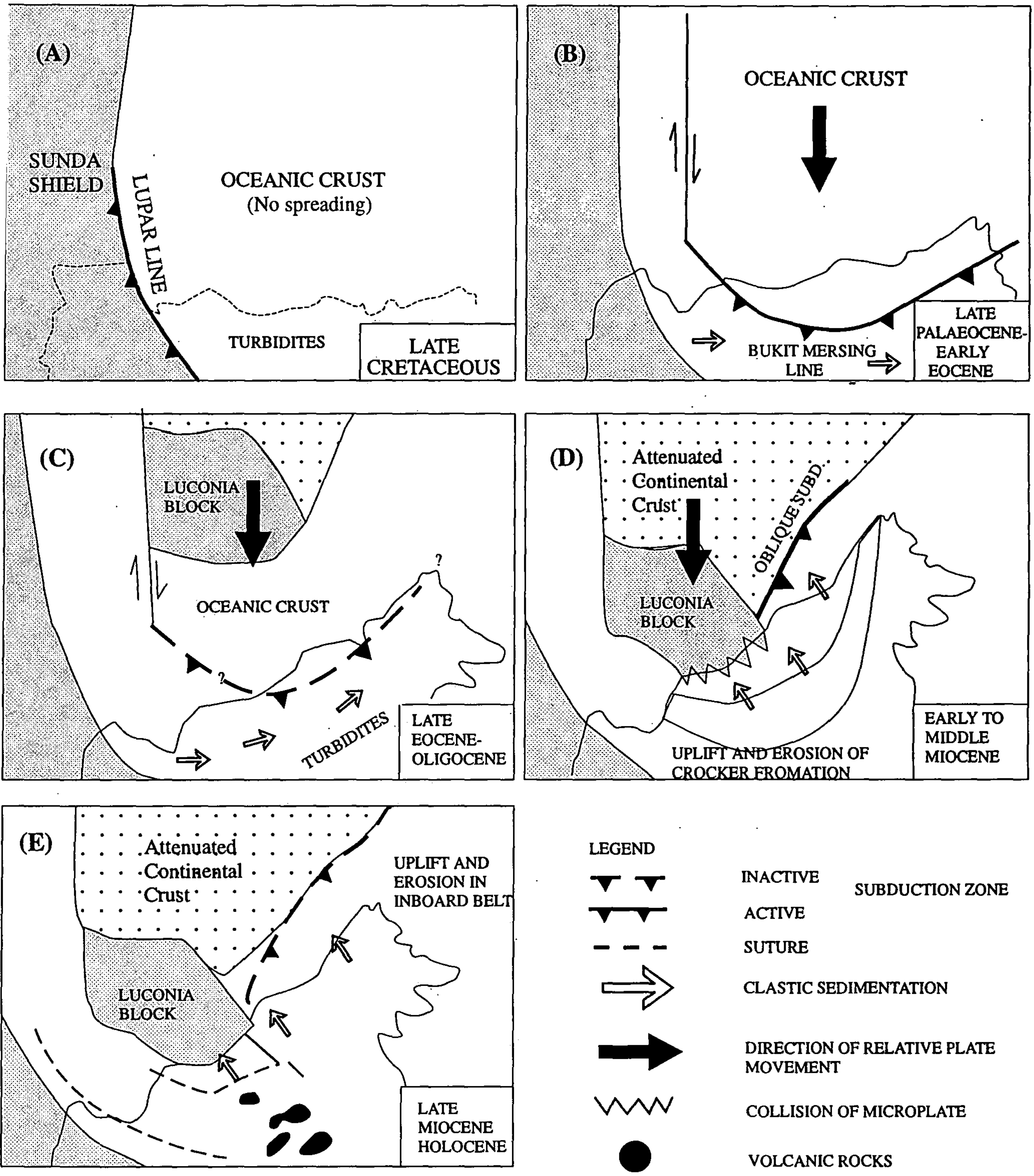


Figure 6.17. Tentative Tertiary Evolution of NW Sabah continental margin(Hazebroek and Tan,1993)

of the model is the counter-clockwise rotation of Borneo, as much as 45°, from Late Cretaceous to Miocene.

This author does not know exactly who was responsible for the fist tectonic model for NW Borneo, but among the workers who accepted this model are:

1a. Taylor and Hayes (1980) 1b. Holloway (1982)
1c. James (1984) 1d. Hutchinson (1988)
1e. Tan (1990) 1f. Hazebroek and Tan (1993)

2. Another school of thought questioned the occurrence of subductions in NW Borneo and its relationship with the opening of the South China Sea. Among them are:

2a. Taylor and Hayes (1983) 2b. Tapponnier (1986)
2c. Briais et al.,(1993).

This concern was initiated by Tapponnier (1986) and later strengthened by Briais et al. (1993). Tapponnier (1986) speculated that the deformation in NW Borneo together with the opening of the South China Sea that produced stretched continental crust could be kinematically linked with the large right-lateral movements along the Red River Fault and Borneo may have formed as part of Vietnam that later drifted and deformed through the opening of the South China Sea (Figure 6.18a). Briais et al. (1993) believed that the continental rift first developed at the tip of propagating left-lateral strike-slip faults, and the extension driven by the relative motion of Indochina, or slices of it, that pushed towards the SE or SSE relative to South China, by the penetration of India into Asia.

The plasticine extrusion model of SE Asia (Tapponnier, 1986) proposed that India may have pushed sideways, part of Sundaland (including SW Borneo, Sumatra and Peninsula Malaysia) and then all the Sundaland areas, in the first 20-30 Ma of the collision process (between India and Central Asia plates). The Red River Fault (Figure 6.18a), then left lateral, would have taken most of the intrusion to SE Asia as much as 800-1000 km and simultaneously in the Oligocene and early Miocene, Sundaland would have rotated by 20°-25°, and the South China Sea would have opened. The extrusion model also proposed that the northern part of NW Borneo may have been originally part of Vietnam which was later moved for several hundred kilometres south along the eastern edge of the Sunda Shelf and Natuna Arch (Ben Avraham and Ayuda 1973; in Tapponnier,1986). The alternative model discussed here (Tapponnier, 1986) involved large left lateral strike-slip faulting such as the Red River Fault and N-W trending faults within Sundaland (Figure 6.18b)

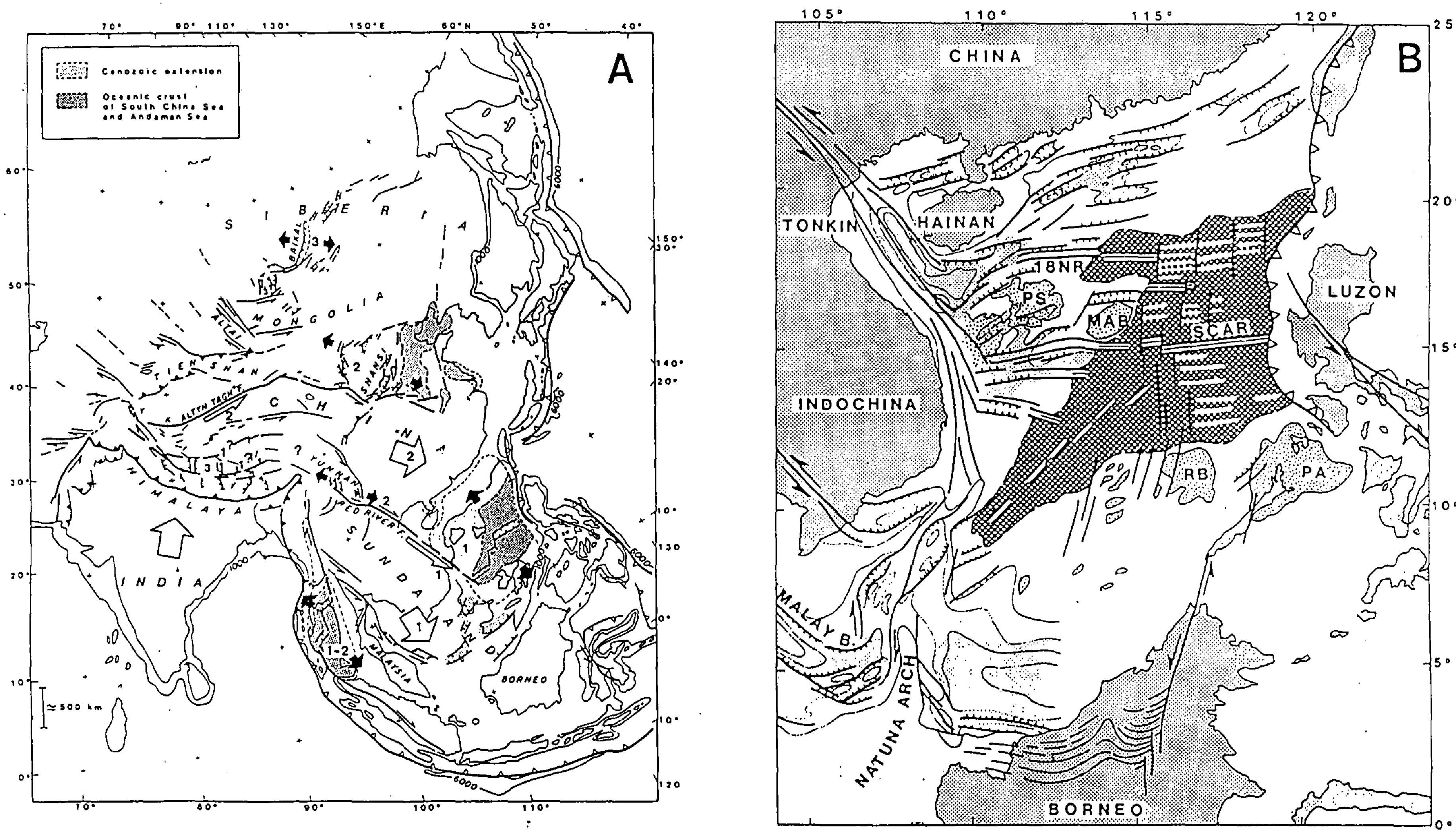


Figure 6.18. (A) Schematic map of Cenozoic extrusion and large faults in east Asia. (B) Possible pattern of faulting and rifting in the South China Sea. Limit of Oligocene-Miocene sea floor (dark shaded area), positions of major spreading centres and transform fault in the east part of the sea. Dotted areas are presumed continental fragments detached from South China Sea. Faults along the eastern edge of Sundaland. From Tapponnier et al.

6.4.2. Proposed tectonic evolution model for northern Borneo.

The main differences between the models of the tectonic evolution of northern Borneo that is proposed in this study and the interpretations by both present schools of thought are the roles of dextral strike-slip tectonism as opposed to the intrusion model (sinistral strike-slip) and the questions about the occurrence of the subduction trench both for the Lupar Valley and NW Sabah Trough. The proposed tectonic evolution model from Cretaceous to Recent is described below.

6.4.2.1 Cretaceous

The southern part of Borneo and the Kontum Massif in Vietnam formed a single entity called Sundaland. The South China Continental Plate (SCCP) located to the NE of Sundaland formed another in the area.(Figure 6.19a). The two plates were separated in the SW by a deep sea that formed the main depocentre during this time, where the older member of the Belaga Formation and the equivalent rocks in Sabah and northern Kalimantan where deposited. In contrast on the continental Sundaland and SCCP, little or no deposition took place, as is evidenced by the absence of most of the Late Cretaceous strata in the Pearl River Mouth Basin (China), the occurrence of a major hiatus between early Cretaceous and the overlying Palaeocene-Eocene sediments at Reed Bank and the hiatus between early Cretaceous and the overlying Lower Oligocene sediments in offshore Taiwan (Holloway, 1982).

During late Cretaceous times, the two continental plates started to separate along the Red River suture (Holloway, 1982) and along the narrow suture of the present Vietnam continental slope (Taylor and Hayes, 1980) and continued farther south along the Lupar Line with a dextral sense of strike-slip movement (Figure 6.20a).

6.4.2.2 Paleocene to Eocene

Palaeocene-Eocene times marked the severe breaking event in the SE Asia region between the SCCP and Sundaland. The SCCP moved in a SE direction and rotated in a counter-clockwise direction simultaneously but with a different magnitude of rotation between the two plates, creating a dextral movement along the Red River fault and Lupar Line (Figure 6.19b). As a result of south-eastward movement of the South China Sea Continental Plate, the northern coast of Sundaland (present area of Sarawak and Sabah) experienced compression that resulted in the initial deformation of the Belaga Formation. At this time, Sundaland may have rotated for about 10°-15° in a counter-clockwise direction from its orientation during the

Cretaceous. As the interaction between the two plates continued, a series of dextral strike-slip lines was generated to the east of the Lupar Line, which are progressively younger to the east (Figure 6.20b).

The interpretations of the plate movements during Palaeocene-Eocene times are based on:

1. The features seen in Sarawak, whereby the deformation of the Belaga Formation took place during this time along with the strike-slip movements on Lupar, Sarikei and Rajang Lines (Figure 6.20b).
2. The speculation by Holloway (1982) that the attenuation of the continental crust had begun during Palaeocene time with the southward movement of the crust.
3. The occurrence of a possible suture zone to the east of the Vietnam shelf causing a narrow shelf has been suggested by Taylor and Hayes (1980).

However, this interpretation disagrees with Tapponnier (1986) who speculated that a major left lateral movement along the Red River fault took place since the Eocene and Sundaland would have rotated clockwise by 20°-25° based on two main reasons.

1. The interpretation of sinistral movement along the Red River fault is essentially hypothetical, based on the simple plasticine intrusion model. It probably agrees to the features seen from Landsat but it was not supported by the field observations.
2. The field observations were, however, interpreted as a dextral movement on the Quaternary sequences (Allen et al 1984; Tapponnier 1986) at the Red River fault, with a similar sense of movement along lineaments in Sarawak.
3. The counter-clockwise rotation of Sundaland during Early Miocene contradicts the palaeomagnetic data (Schmidtke et al., 1986 and Schmidtke et al., 1990) from Sabah and Sarawak which show that both areas experienced strong counter-clockwise rotations from Late Oligocene to Pliocene.
4. The counter-clockwise rotation could explain more convincingly the plate reconstruction model of northern Borneo, from Oligocene to Recent (Figures 6.20c and 6.20d) when the model can only accommodate the later opening of the Sarawak Basin, Malay Basin and Mekong Basin, instead of clockwise rotation.

6.4.2.3 Oligocene-Miocene

Further counter-clockwise rotation of the Sundaland plate during this time has resulted in the initial opening of the Mekong and Malay Basins separated by the Khorat Ridge and Con Son Swell (Figure 6.19c). The opening of the South China Sea has also taken place during this time. The southern end of the SCCP could have encroached the area to the north of the

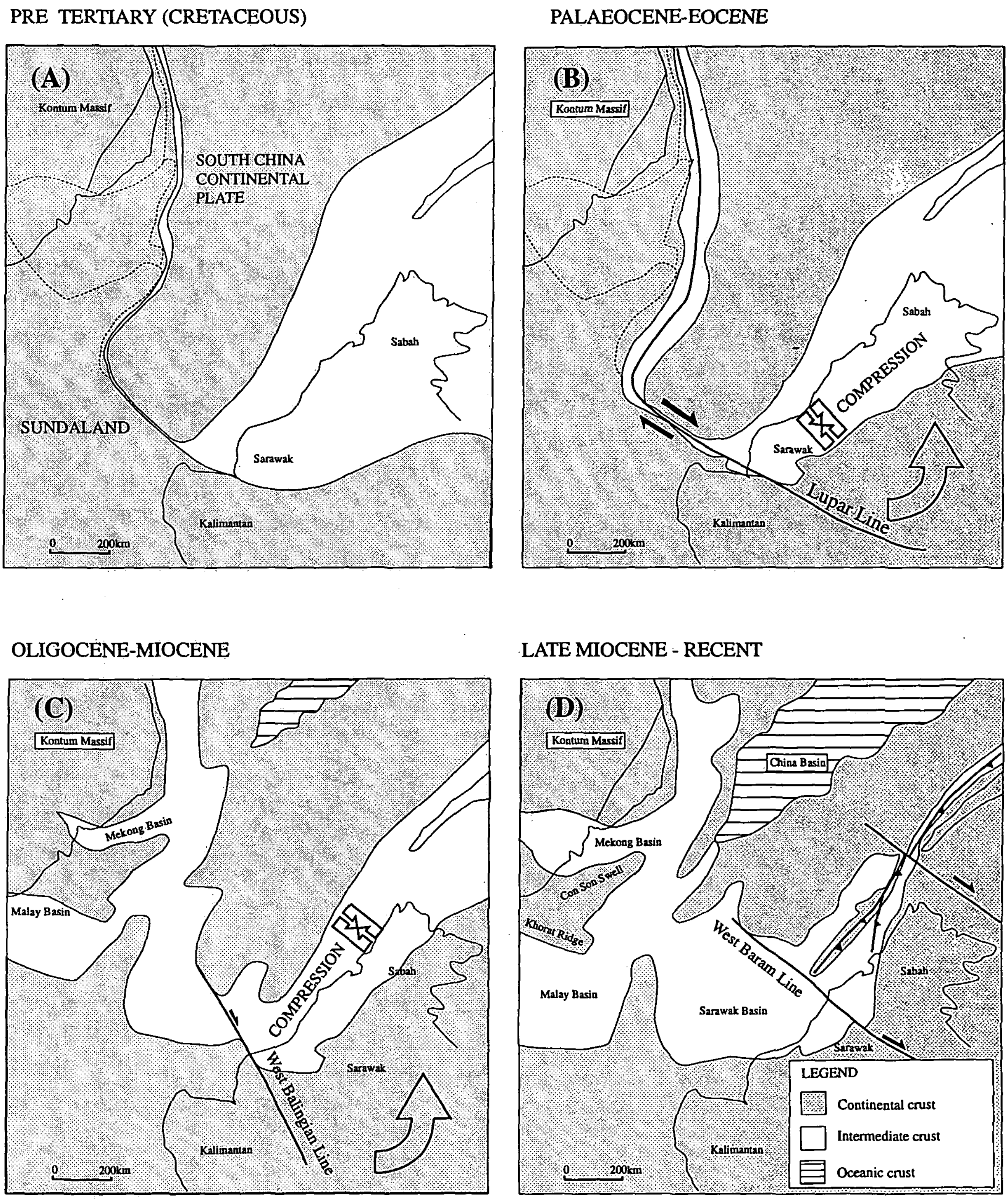


Figure 6.19. Plate tectonic reconstruction from Cretaceous to Recent illustrating the proposed tectonic evolution of northern Borneo.

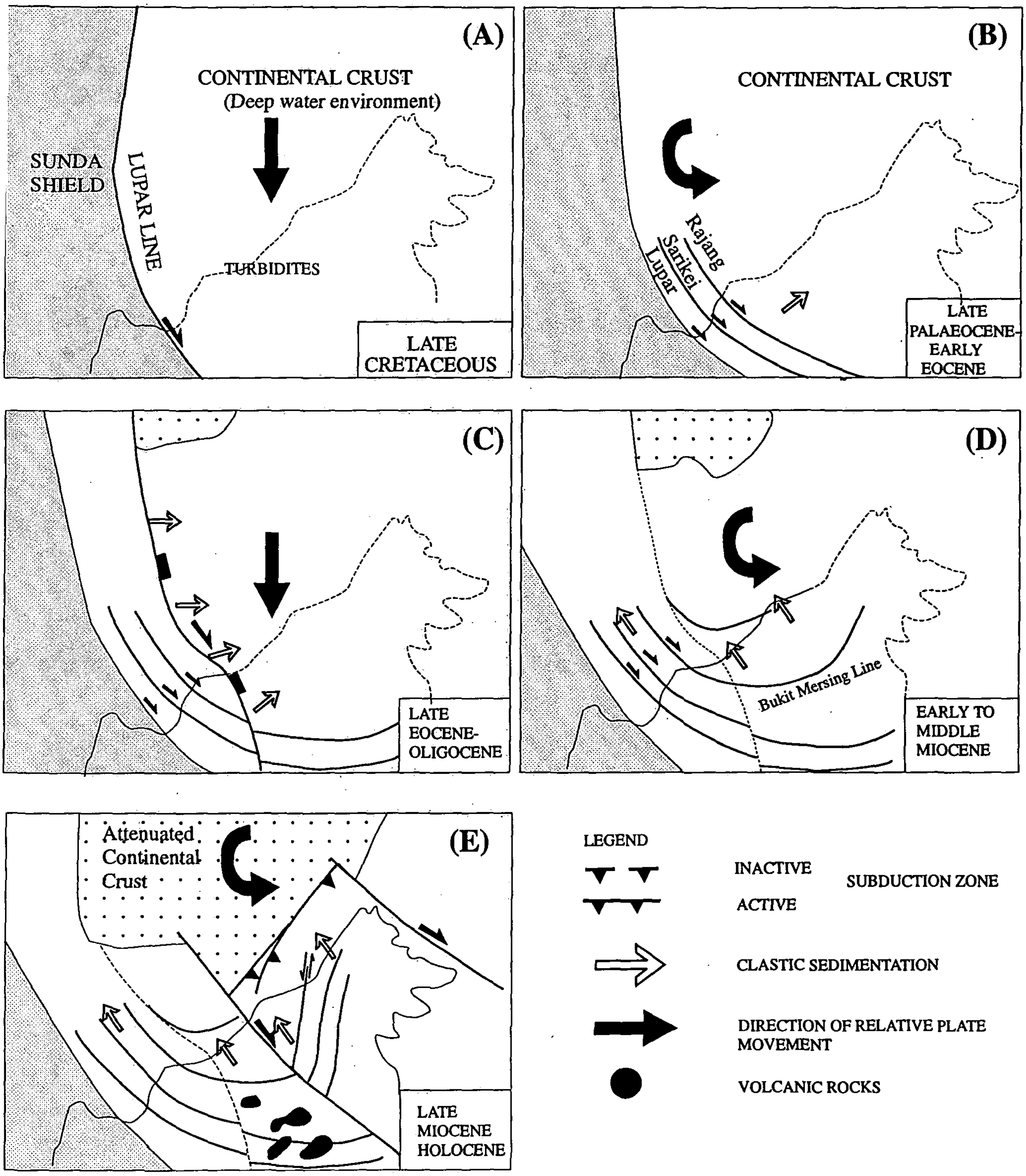


Figure 6.20. Proposed tectonic evolution model for northern Borneo based on this study.

Sarawak Basin, during Eocene to Late Oligocene times (Figure 6.20c). The encroaching of SCCP southward has resulted in the formation of NW-SE strike-slip lineament in Sarawak, represented by the West Balingian Line. The Eastern Sub-Basin of the Sarawak Basin was formed by movement along the lineament, followed by the deposition of T1S and T2S sediments with progradation to the east; the coastline coincides with the orientation of the West Balingian Line (Figure 6.20c).

The opening of the South China Sea (32-17 Ma) is believed to be the driving force for the generation of the Eocene and younger strike-slip lineaments in northern Borneo despite the controversial interpretation on the driving mechanism of its opening, as to whether an effect of extrusion (Tapponnier, 1986) or independently as a back-arc feature associated with Pacific plate subduction (Taylor and Hayes, 1983). In either case, the northern Borneo area experienced further compressional effects as a result of encroaching of the SCCP into the area during the later period.

6.4.2.4. Late Miocene to Recent

As the Sundaland plate continued to rotate in a counter-clockwise direction until the Pliocene (Schmidtke et al., 1990) and the SCCP drifted further eastward and rotated in the same direction with different magnitude, the area was subjected to compression by the infringement of the SCCP which also shifted further to the east. The strike-slip movement was then taken up along the West Baram Line (Figure 6.19d) which was active during Pliocene times. This movement created the Baram Delta depression, with a great rate of subsidence followed by rapid deposition of late Miocene Baram Delta sediments in the west and compression to the east as evidenced by the broader area to the SW and narrowing to the NE of offshore Sabah (Figure 6.20e).

The southward movement of the SCCP may have stopped during this time forming the present Tertiary basin configuration (Scherer, 1980) without having a terminal collision with the mainland Sundaland plate (Figure 6.19d). This interpretation is based on the evidence that the continental fragments of the China margin never quite collided with the Sundaland plate; elsewhere subduction of South China crust beneath the Manila trench brought the Luzon arc into collision with Taiwan and north Palawan in the Late Miocene (Taylor and Hayes, 1983).

6.4.3. Plate tectonic setting of South East Asia.

The modified tectonic map (Figure 6.21) was constructed on the basis of the new understanding of the tectonic evolution in South East Asia, based primarily on Hazebroek and

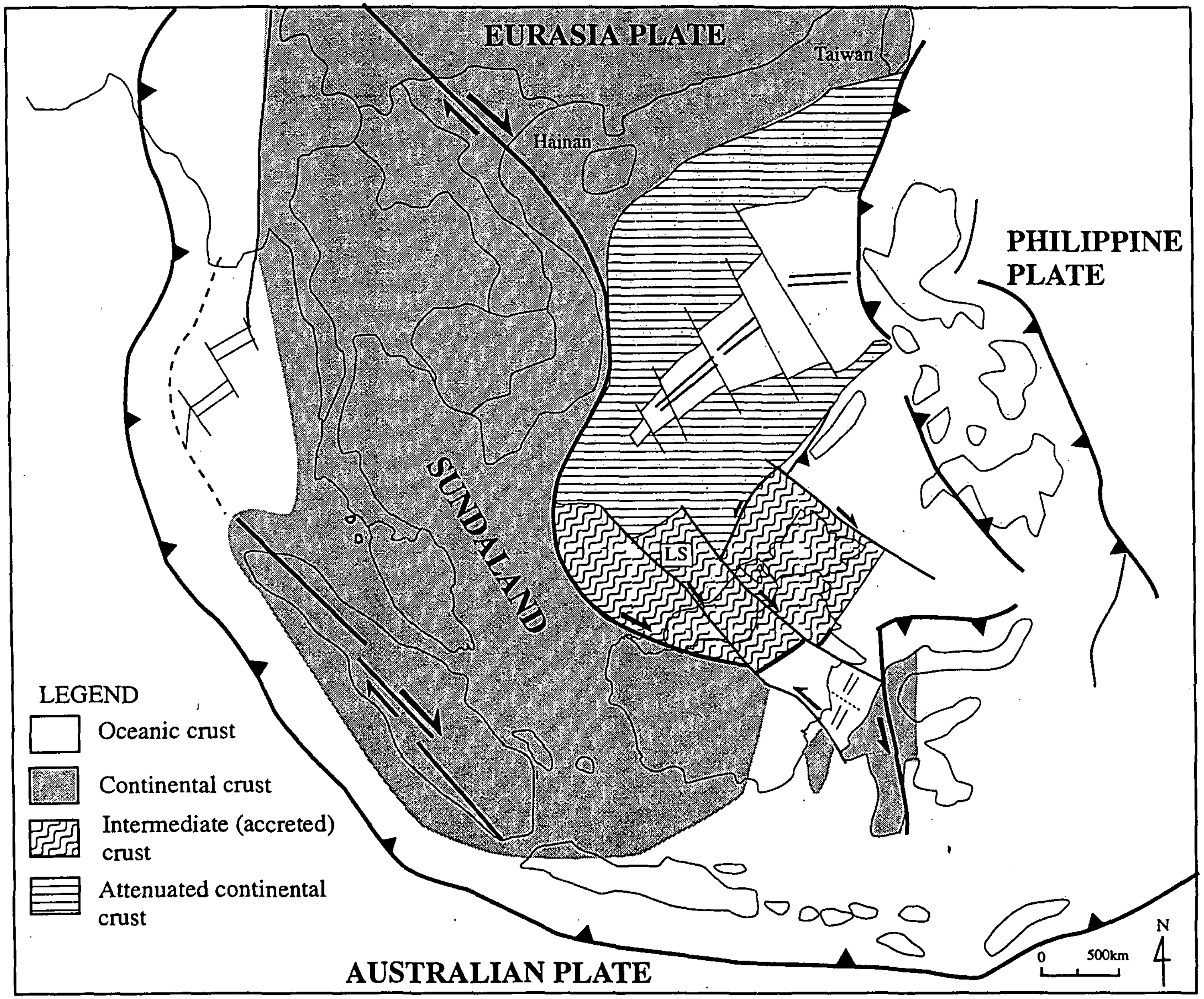


Figure 6.21. Proposed plate tectonic element of South East Asia.

Tan (1993) for the area excluding northern Borneo and the South China Sea region. The map shows that northern Borneo is separated from the Sundaland plate by a curved strike-slip lineament stretching from north Vietnam (Red River Fault) to east Borneo in a roughly NW-SE orientation and further bounded to the E-W, coincident to the location of Lupar Line which then probably terminated in the Celebes Sea.

The northern Borneo area is characterised by a series of dominant dextral strike-slip lineaments which are progressively younger eastward. Some of these lineaments offset the older lineaments as the orientations of the lineaments are different. The whole area is made up of accreted intermediate crust, interpreted on the basis that there is no concrete evidence suggesting the occurrence of oceanic crust in the area. The orientations of major strike-slip lineaments are sub-parallel to the strike-slip lineaments in west Sumatra and also sub-parallel to the offset direction in the opening of the South China Sea based on Bowin et al. (1978).

The Sabah Trough, which represents the boundary between the accreted intermediate crust and the attenuated continental crust of SCCP, was formed through the combined effects of block rotation and strike-slip movement between the two plates. Luconia (LS), however, formed as part of accreted intermediate crust, sharing the same basement that is the Belaga Formation in other areas of Sarawak. The Luconia area has undergone a similar tectonic and sedimentation history during Late Oligocene to Middle Miocene, with the other part of northern Borneo, instead of as an isolated block as previously interpreted.

6.5 Summary and conclusions

1. The whole onshore area of Sarawak and northern Borneo including Sabah and Northern Kalimantan have been subjected to the strike-slip tectonism during Tertiary times similar to the Sarawak Basin. Strike-slip tectonics were responsible for the basin formation and controlled the sedimentation and formation of structural traps and were also responsible for the deformation and the generation of the strike-slip orogenic belt of the Belaga Formation and its equivalent in northern Borneo.

2. The driving force for the strike-slip tectonism in the region may have been initiated by the lateral movement between Sundaland and the South China Continental blocks, probably due to extrusion as the result of collision between the Indian and Asian Plates during the Mid Tertiary. The strike-slip movement was later derived by the opening of the South China Sea. The end result of tectonism in the region, however, was the combination of the strike-slip movements and block rotation.

3. The findings of this study have great implications in understanding the tectonic evolution of the region whereby the Tertiary tectonic model can explain most of the unexplained geological phenomena, such as the lack of igneous activity and volcanic belt and trench sediments, which would be required in the previous subduction or thrusting tectonic models. The findings of this study will definitely contribute towards a better understanding of the tectonics of the area and the proposed tectonic model should promote a new thinking about the tectonics of the region.

4. The geological model proposed by this study has significant implications for the geological related industries in the region. The proposed tectonic model could provide a general understanding for the petroleum prospectivity of the area and help in understanding structural style for hydrocarbon plays in the area. This will help the mining and petroleum companies in the acquisition of prospective exploration acreage and in carrying out of effective production plans.

Chapter 7

CONCLUSIONS

In this chapter, the overall conclusions documented in this thesis will be summarised and possible future work will also be reviewed.

7.1 Stratigraphic scheme

The regional seismic stratigraphic mapping of the Sarawak Basin has identified seven regional unconformities in the Tertiary sedimentary succession which enables subdivision into seven sequences that are later used as the basis for the stratigraphic boundaries of the new proposed stratigraphic scheme where each unit is called a Tertiary Sequence. The oldest boundary is the unconformity between the Tertiary One Sequence (T1S) and the basement rocks of late Cretaceous to Eocene age metamorphosed Belaga Formation and the youngest being the T7S of Pleistocene age. The bases of T2S and T3S boundaries are not coincident to global sea-level falls on the Haq et al. chart (1988) but other younger boundaries do coincide with the sea-level falls. However, other evidence such as the base of T4S and T5S being coincident to the major structuration in the onshore area and subsidence in the deep-water area respectively, suggests that the unconformities are probably tectonically induced rather than related to global eustatic sea-level falls.

The new proposed stratigraphic scheme is superior to the cycle concept in several aspects including that the sequence boundary can be identified on seismic and that the stratigraphic subdivision can be made before drilling. The cycle boundary in contrast can only be established after a biostratigraphic study is completed. Also the sequence boundary could be recognised by workers from other disciplines by using the information from logging tools; cycle boundaries on the other hand need to be confirmed by the biostratigrapher. Further, mapping could be carried out in all areas irrespective of the sedimentary facies whereas the cycle boundary is only accurate for marine and marine-influenced environments. Based on the fact that the main interval for the study area, i.e. the Late Oligocene-Middle Miocene sequences in the nearshore and the possible prospective sequences in the deep-water areas are predominantly made up of non-marine sediments, the application of the new proposed stratigraphic subdivision is more appropriate.

In correlating between the new proposed stratigraphic scheme and the original cycle zonation, several cycles occur within one sequence, i.e. the upper part of Cycle II, the whole of Cycle III and Cycle IV occur within the T3S. All the bases of the original cycle boundaries of Ho (1978) coincide with third-order cycles of global sea-level rise. Besides the limitation of the cycle zonation for the non-marine facies and recognition of cycle boundaries on seismic, the original cycle concept by Ho (1978) is a powerful concept of stratigraphy and therefore it should not be modified unless the meaning of the cycle is redefined. Without a new definition, it will not give any improvement to the stratigraphy but just add confusion for later workers.

7.2 Sedimentation history

From the review of sedimentation history in the Sarawak Basin, it is revealed that the palaeo-environments for the Sarawak Basin record a broad coastal plain belt with a north-south oriented coastline covering both the nearshore and offshore area including the present deep-water area during Late Oligocene to Early Miocene times. The palaeo-coastline changed to an east-west orientation during T3S (Middle Miocene) and a new depression was formed in the NW part of the Sarawak Basin during this time and was filled up mainly by T3S and T4S sediments. However, in the present-day deep-water to the north, some places remained as topographic highs until T5S (Pliocene) and were only covered by the T5S and younger sequences. These phenomena are believed to be tectonically controlled.

Deposition of carbonates in the Luconia Province began during Middle Miocene times, possibly when nutrients were supplied from a broad shelf area and away from terrigeneous influx. The carbonates grew on the basement highs and inversion areas. The termination of carbonate deposition in the Sarawak Basin during the Pliocene could be caused by several factors, including smothering by siliciclastics from the encroaching Baram delta during the late Miocene and drowning as the combined effect of global sea-level rise and the latest subsidence during the Pliocene.

More detailed study of the nearshore and onshore regions suggested that these areas experienced a similar tectonic history to the broad area of Sarawak Basin. The sedimentation in the nearshore area seems to have been mainly controlled by two tectonic lineaments, the Mukah Line and West Balingian Line. The Mukah Line separates the area without T1S and T2S sediments to the west from the area with preservation of these sequences to the east. A thick succession of hydrocarbon prolific T1S and T2S is preserved to the east of the West Balingian Line in the nearshore area. The formation of the sub-basins in the onshore area was mainly controlled by movements on tectonic lineaments and the timing of these movements were different. For example, the Lemai Fault was already in existence during T1S (Late Oligocene) while the Igan-Oya and Mukah Half-Graben formed during T3S (Middle Miocene). This resulted in a shift in the sediment depocentre through time.

The Middle Miocene time marked a major change in the history of deposition in the Sarawak Basin when almost the whole area to the west was covered by the T3S sediments. This is related to cessation of movement along the West Balingian Line and the whole nearshore area behaved as one structural unit and experienced further subsidence.

7.3 Tertiary tectonics

The Tertiary tectonic history of the Sarawak Basin is best explained by interpretation of the major structures related to a strike-slip fault pattern and the wide range of structural styles is consistent with an origin by strike-slip faulting. The main conclusion for the Tertiary tectonics of the Sarawak Basin derived from this study is that strike-slip tectonism is the primary control on basin formation, deformation and sedimentation in the Sarawak Basin. Five major dextral strike-slip lineaments namely the Igan-Oya Line, Mukah Line, West Balingian Line, Tinjar Line and West Baram Line (Figure 4.42) have been identified, having characteristics analogous to well- known strike-slip faults elsewhere in the world.

The generation of the main structural traps for hydrocarbons in the nearshore area, called "faulted-fold structures", are also induced by the strike-slip tectonism. It is also believed that the formation of highs and lows in the Luconia Province and deep-water area that was subsequently followed by carbonate production and the formation of buried hills respectively, have a consistent spatial relationship to the strike-slip tectonics of NW-SE main shear orientation.

The timing of the movements along the major strike-slip lineaments in the Sarawak Basin are progressively younger in the eastward direction. However, some of the lines were reactivated in the later period. The orientations of the strike-slip lineaments are mostly NW-SE in the offshore area and shifts to an almost E-W orientation in the onshore, primarily due to the counter-clockwise rotation of the interacted blocks. The exception is the West Balingian Line and the West Baram Line that maintain the NW-SE orientation to the onshore area.

The movement along the major strike-slip lines and releasing oversteps between the lines during a particular time resulted in the formation of several sub-basins. The tectonic evolution of the Sarawak Basin is closely linked to the palaeo environment data for every sedimentary sequence. Most of the time the information derived from an understanding of the tectonic evolution provides the explanations as to why the changes happened in the palaeo environments in the depositional history of the Sarawak Basin.

7.4 Basin evolution

The results from basin modelling studies of the wells from the Sarawak Basin did not suggest any possibility that the basin was formed as a foreland basin and therefore, the basin could either be a rift basin or another type of basin with similar characteristics to a rift basin. Many of the profiles show early rapid subsidence followed by a later phase where basement subsidence is slower, indicative of rifted style of tectonic origin. Besides the subsidence pattern for the J411 well and the early phase of subsidence (37-17.5 Ma) for D411 well that agree with the McKenzie's rift model, the Sarawak Basin is characterised by a high rate of subsidence, high β values plus local episodes of compression interspersed with extension. This leaves with only one possible type of the basin that is the strike-slip related basin.

The findings of this study hence agrees with the seismic interpretations. Consequently, it can be concluded that in some instances, such as a simple pull-apart basin (J411 well), the McKenzie subsidence model is applicable for a strike-slip related basin. However, for other areas in the basin, the absence of a smooth sag phase due to thermally-controlled subsidence, the basin was subjected to polycyclic episodes of deposition and uplift, suggests that the McKenzie subsidence model is not applicable for a strike-slip related basin.

Although the subsidence data from most of the wells do not agreed with the McKenzie-type rift model, the equations for the rift basin have been used to determine the heat flow of the basin. This is because the formula outlined by Jarvis and McKenzie (1980), to test the validity of assuming the instantaneous stretching and heat flow estimations, are valid for the Sarawak Basin. The model estimates of heat flux values using the McKenzie model, are however, too low compared to the measured values with the difference in the range of 0.3 to 1.6 HFU. This is probably due to the same reasons as used in the North Sea basin (Sclater and Christie, 1980) where the higher geothermal gradient may have been caused by radioactive decay in the sediments, not accounted for by the model.

The geothermal gradient for the Eastern Sub-Basin shows a linear relationship with the value of stretching factor. The central part of this sub-basin which was subjected to a higher stretching factor is characterised by a higher geothermal gradient than the area at the fringe of the basin in the north and south. However, this same relationship does not hold for the shallow basement area to the west.

In conclusion, the evaluation of stretching factors and heat-flow for the Sarawak Basin are consistent with the origin of a basin dominated by strike-slip tectonics. This conclusion challenges earlier models for a subduction-related origin for the basin.

7.5 Tertiary tectonics of northern Borneo

The findings of this study suggest that the whole onshore area of Sarawak and northern Borneo, including Sabah and northern Kalimantan, were subjected to strike-slip tectonism during Tertiary times, similar to the Sarawak Basin. The strike-slip tectonics have been responsible for basin formation and sedimentation, and the formation of structural traps in the Sarawak Basin and for the deformation and the generation of the strike-slip orogenic belt of the Belaga Formation and its equivalent in northern Borneo.

The driving force for the strike-slip tectonism in the region may have been the lateral movement between Sundaland and the South China Continental blocks, probably due to extrusion as the result of collision between the Indian and Asian plates during middle Tertiary times. The strike-slip movement was later produced by the opening of South China Sea. The end result of tectonism in the region, however, was the combination mainly between strike-slip movement and block rotation.

The findings of this study are also believed to have great implications in understanding the tectonic evolution of the region, whereby the Tertiary tectonic model derived from this study could explain most of the unexplained geological phenomena, such as the lack of igneous activity, such as large-scale batholithic intrusives, an extrusive volcanic belt and trench-origin sediments, which would be required in the previous subduction or thrusting tectonic models.

It is believed that the findings of this study will be able to contribute towards a better understanding of the tectonics of the area and the proposed tectonic model should, promote a new thinking about the tectonics of the region. It is also believed that the findings of this study, together with the proposed tectonic model of northern Borneo, have significant implications for the geological-related industries including oil exploration and production, by helping to understand the structural style and traps for hydrocarbon plays in the area. This will help the mining and petroleum companies in the acquisition of prospective exploration acreage and in the carrying out of effective field production plans.

7.6 Recommendation for future works

This study, that developed as a pilot project in understanding the tectonics of the whole Sarawak Basin using the reprocessed regional seismic lines, has established a better understanding of the tectonic and sedimentation history of the region which should contribute toward a better understanding on the hydrocarbon plays in the region. However, more work should be carried out in order to confirm the findings of the present study, and could involved three main approaches:

1. Seismic studies for the offshore Sarawak Basin
2. Field studies for the onshore area, and
3. Satellite imagery studies.

1. The main structural lineaments identified from this study could be delineated further using a closer grid of seismic lines which has a similar or deeper depth of penetration whereby the characteristics and the tectonic overprints of the basement rocks can be seen more clearly. The study can be done by using another set of reprocessed data generated in the later years than the data used in this study or newly acquired lines.

The newly acquired seismic lines are the preference, if the budget is permitted, since compared to the reprocessed lines, new and better acquisition parameters can be added through using longer cables and a stronger source and, further, the acquisition orientations can be planned in the manner to optimise the resolution for the structural delineation.

2. This study has seen the occurrence of igneous bodies along the major strike-slip lineaments such as Hose Mountain along the interpreted Rajang Line and the Usun Apau along the interpreted West Baram Line and Bukit Mersing granite along the Mukah/Bukit Mersing Line. However, this study could not determine the origin of the rocks because of the unavailability of geochemical data and the last known geochemical studies were conducted by Wolfenden (1960). It should be understood that a great effort is required to conduct fieldwork in the area because of the remoteness and heavily-forested nature, but further detailed studies which include trace element analyses will help in determining the origin of the source material and further contribute towards the understanding of the geology of the area.

3. This study has also identified several lineaments that have been interpreted to extend across onshore Sarawak, Sabah and northern Kalimantan. However, the interpretations are made mainly based on the linear nature of the geological features and other physiographic features seen on the limited data, without any support of imagery data. It is believed that the

identified lineaments could be confirmed further by using the most recent landsat images such as the extension of the West Balingian Line to the onshore area coincident with the lineament identified by Kang and Kadir (1990). Imagery data for the onshore Sarawak is known to be available.

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