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# Tectonic evolution of the NW Sabah continental margin since the Late Eocene

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**Abstract :** The NW Sabah continental margin in the northern part of NW Borneo, consists of 2 main elements: a Tertiary trench-associated sedimentary basin with up to 12 km of siliciclastic sediments and the Southern South China Sea Platform, separated by the deep and relatively narrow, NE-trending NW Sabah Trough.

The Tertiary sedimentary sequences were deposited during two main phases of basin development:

1. a pre-early Middle Miocene phase of generally deep-marine clastic sedimentation (Stages I, II and III). The sediments were subjected to strong compression to form an imbricate wedge related to the subduction of the South China plate. This was concomitant with the counter-clockwise rotation of the Borneo plate, and the relative motion of the two plates may have produced N-S wrench faults.
2. a post-early Middle Miocene phase of clastic shelf/slope deposition (Stage IV) which prograded northwestward over the underlying imbricate wedge and separated from the latter by a major regional unconformity.

On the basis of differences in structural styles and sedimentation histories, the NW Sabah continental margin can be subdivided into 7 tectonostratigraphic provinces: (1) the CrockerAccretionary Prism, (2) the Inboard Belt, (3) the Outboard Belt, (4) the East Baram Delta, (5) the NW Sabah Margin, (6) the NW Sabah Trough and (7) the Southern South China Sea Platform.

Some 90 exploration and exploratory appraisal wells have been drilled in the NW Sabah offshore. Apart from minor oil and gas shows in the pre-early Middle Miocene deep-marine sediments, all commercial accumulations discovered to date have been found in the Middle Miocene or younger clastic reservoirs in the Inboard Belt, Outboard Belt and East Baram Delta. The other tectonostratigraphic province have not been drilled to date.

The tectonic evolution of the NW Sabah continental margin occurred in four stages:

1. The Late Eocene to early Middle Miocene subduction of the South China Sea oceanic crust beneath Borneo with deposition and subsequent of deep-marine sediments into an accretionary prism.
2. The collision and subduction of the South China Sea attenuated continental crust with Borneo in early Middle Miocene which led to the regional uplift and erosion of the accretionary prism resulting in the Deep Regional Unconformity. This was followed by NW progradation over the Inboard Belt from Middle Miocene to early Late Miocene.
3. Cessation of active subduction in middle late Miocene was accompanied by major tectonic activities. The Inboard Belt was subjected to strong compressional deformation, probably associated with deep-seated major N-S shear zones. The area was strongly folded, uplifted and eroded resulting in the Shallow Regional Unconformity.

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Transtensional tectonics at the western margin of the Belt resulted in the formation of two major depocentres, i.e. the Outboard Belt and the East Baram Delta.

4. From the Late Miocene to Holocene, the Inboard Belt remained a shallow and stable area which was continuously eroded till Stage IVF times. In the Outboard Belt and East Baram Delta, a thick prograding sedimentary wedge built out towards the northwest from Late Miocene to Holocene. A Late Pliocene phase of deformation affected mainly the Outboard Belt and East Baram Delta and gentle anticlinal features with numerous crestal faults were formed.

## INTRODUCTION

The Southeast Asian region lies at the intersection of the Pacific, Philippines, Eurasian and Indo-Australian plates (Fig. 1) and comprises a number of sub-plates which were deformed internally and moved relative to one another in a complex, poorly understood pattern. The region has been and is the subject of almost continuous investigation by numerous workers since the early 1970s (Ben-Avraham & Emery, 1973; Hamilton, 1979; Tapponnier *et al.*, 1982; Wood, 1985; Daines, 1985; Daly *et al.*, 1987; Jolivet *et al.*, 1989; etc.).

The South China Sea basin is a major feature in the Southeast Asian region and the literature contains numerous models for its evolution (Taylor & Hayes, 1983; Holloway, 1981; Hinz & Schluter, 1985; Ru & Pigott, 1986, Sarewitz & Karig, 1986, Letouzey *et al.*, 1988). This paper, however, only focuses on the evolution of the NW Sabah continental margin, located in the southern part of the South China Sea basin. The model adopted as a framework is the generally accepted one comprising at least three stages of heating and rifting (Late Cretaceous, Late Eocene and late Early Miocene) and two intervening stages of seafloor spreading for the evolution of the South China Sea basin (Fig. 2), with associated counterclockwise rotation of Borneo from Late Cretaceous to Oligocene (Hamilton, 1979; Holloway, 1981; Ru & Pigott, 1986).

## REGIONAL SETTING (Fig. 3)

The geology of Sabah is complicated, reflecting the extreme kinematic complexity of the South China Sea region. Sabah is located at the intersection of two mega-tectonic trends: the NE-SW Northwest Borneo Trend and the NW-SE Sulu Trend. The NW Borneo Trend, comprising the Late Cretaceous-Early Eocene Rajang Accretionary Prism in Sarawak and the Paleocene-early Middle Miocene Crocker Accretionary Prism in Sabah, marks an imbricated terrain/melange resulting from the southwesterly and southeasterly subductions of the South China Sea plate beneath the Sunda Shield and the Borneo accreted crust. The subduction zone migrated progressively northwards (Lupar Line in Late Cretaceous - Palaeocene, Mersing Line in Early Eocene, NW Sabah Trench in Late Eocene) and became inactive in late Miocene/early Pliocene times. These subduction zones are related to the episodes of rifting and seafloor spreading in

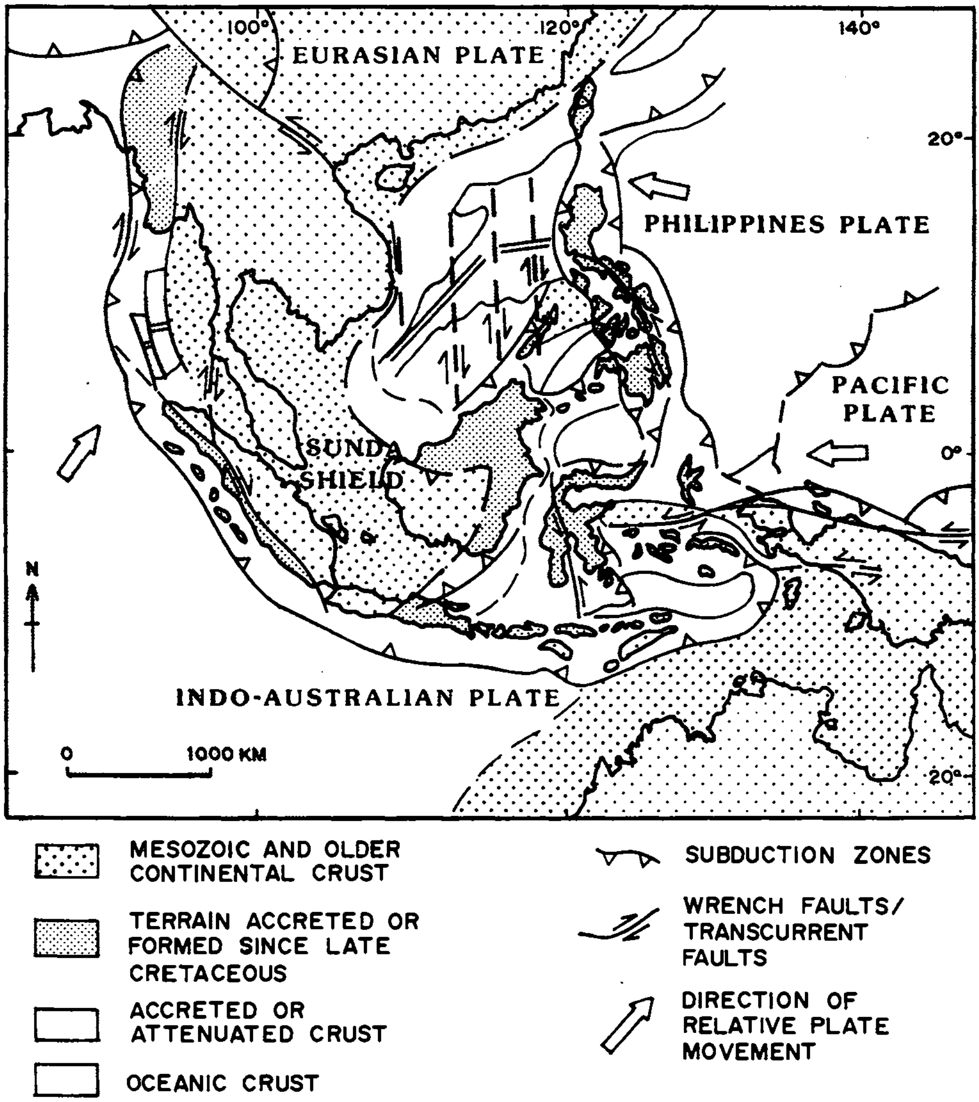


**Figure 1:** Plate tectonic elements of Southeast Asia (mainly from Hamilton, 1979; Holloway, 1981; Taylor & Hayes, 1983; Ru & Pigott, 1986)

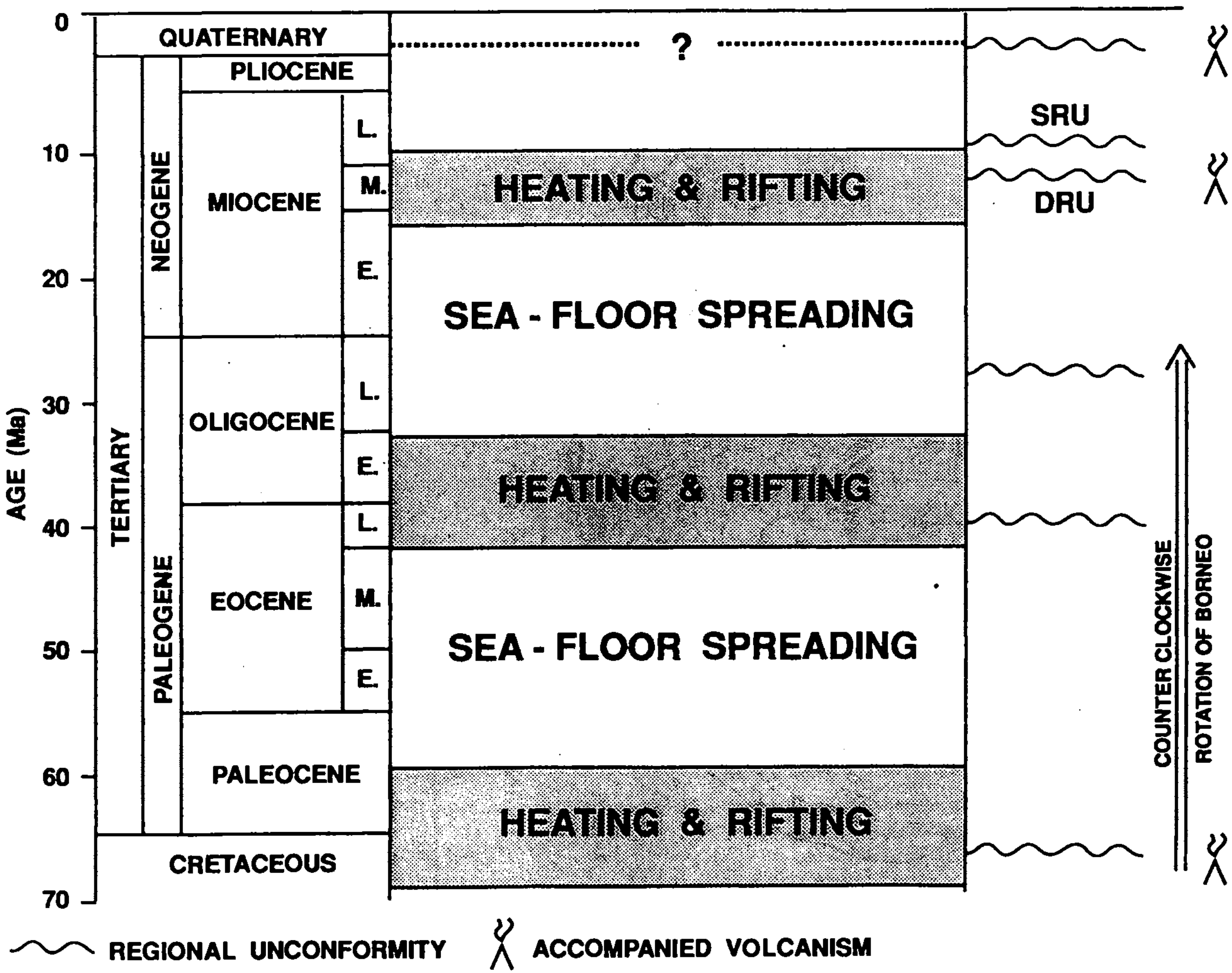


**Figure 2:** Geochronologic interpretation of episodic evolution of South China Sea (modified from Ru & Pigott, 1986).

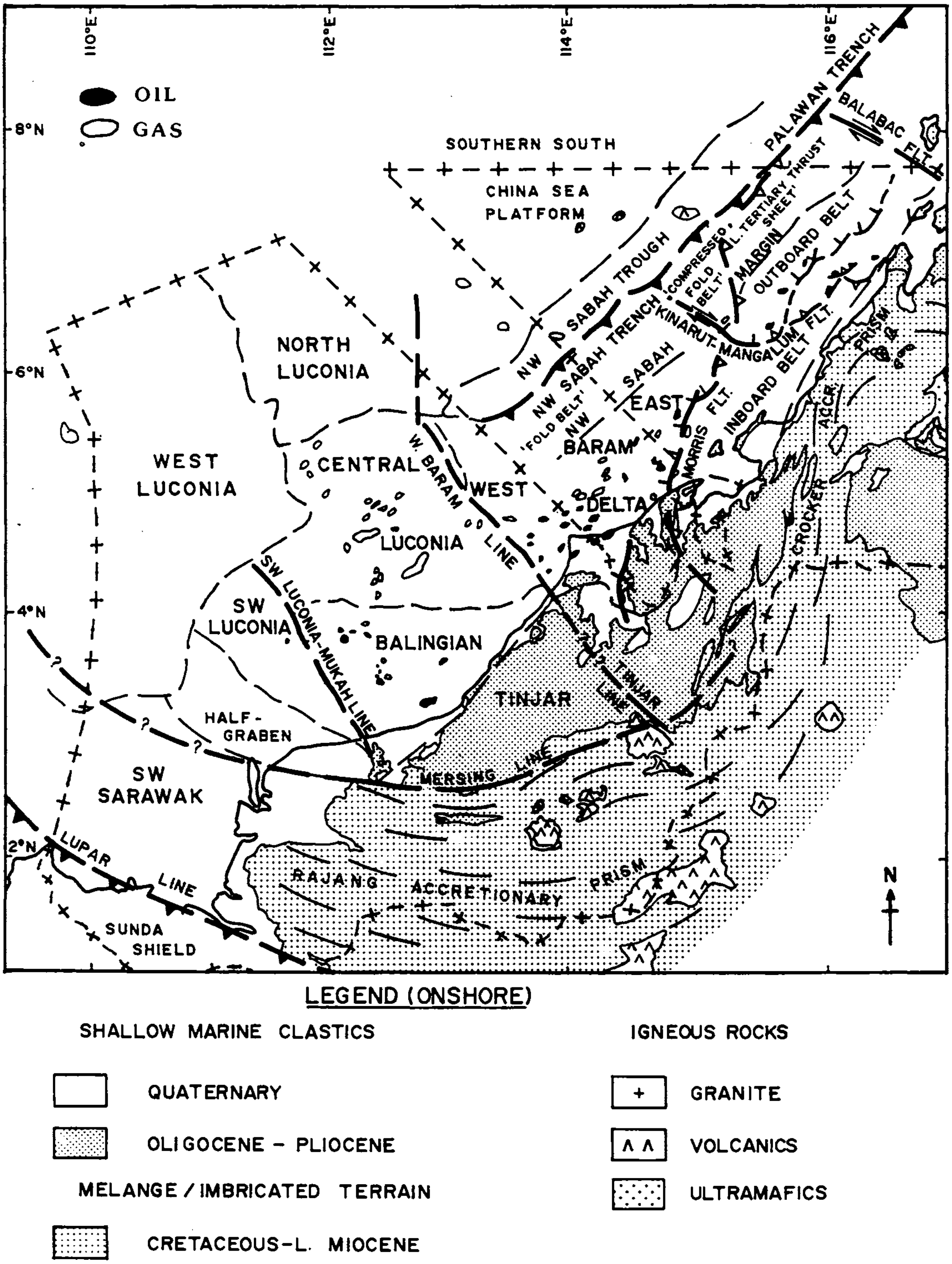


**Figure 3:** NW Borneo regional geological setting.

the South China Sea basin from the Late Cretaceous to Late Miocene. Major NW-SE and WNW-ESE trending transtensional faults (SW Luconia-Mukah Line, West Baram Line, Kinarut-Mangalum fault, Balabac fault) have been recognised and are probably related to deep-seated N-S sinistral strike-slip faults which are present in the South China Sea region (Holloway, 1981; Taylor & Hayes, 1983; Ru & Pigott, 1986). The Sulu Trend in the northeastern half of Sabah consist of melanges and broken formations of Neogene age and is probably the onshore continuation of the Sulu Arc (Hamilton, 1979). The intersection of these two trends in marked by an irregular NW-SE trending belt of radiolarites, pillow lavas and ultramafics with associated blueschists, probably marking the suture related to fossil southward-dipping 'B'-type subduction zones which were active from Palaeogene to early Middle Miocene. Hamilton (1979) suggested that the suture may be the onshore continuation of the Sulu Trench. This suture became the focus of batholithic intrusions (Gunung Kinabalu area) in Late Miocene/Pliocene.

## GEOLOGICAL SETTING (Fig. 4)

The NW Sabah continental margin consists of a Tertiary trench-associated sedimentary basin, with up to 12 km (stratigraphic thickness) of siliciclastic sediments. Immediately to the NW is the Southern South China Sea Platform, separated from the trench-associated basin by the deep and relatively narrow, NE-trending Northwest Sabah Trough.

The Tertiary sedimentary sequences were deposited during two main phases of basin development:

i. a pre-early Middle Miocene phase of generally deep-marine clastic sedimentation (Stages I, II, III) which was subjected to strong compression related to the subduction of the Cretaceous oceanic crust portion of the South China Sea plate beneath the accreted crust, and

ii. a post-early Middle Miocene phase of clastic shelf/slope deposition (Stage IV) in which progradation was to the northwest over the underlying imbricate wedge, overstepping onto the foundered and attenuated continental crust of the South China Sea Platform. These sediments are separated from the pre-early Middle Miocene deep-marine sediments by a major unconformity (the Deep Regional Unconformity) which is recognised throughout the South China Sea region. The sequence is characterised by complex tectonic attributable to oblique-slip movement occurring within a regional subduction-related compressional stress regime. The syndepositional character of the deformation was punctuated by tectonic pulses giving rise to a series of unconformities which are used to subdivide the post-early Middle Miocene sequence into 7 sedimentary units (Stages IVA to IVG) as shown in Figure 4. Typically these

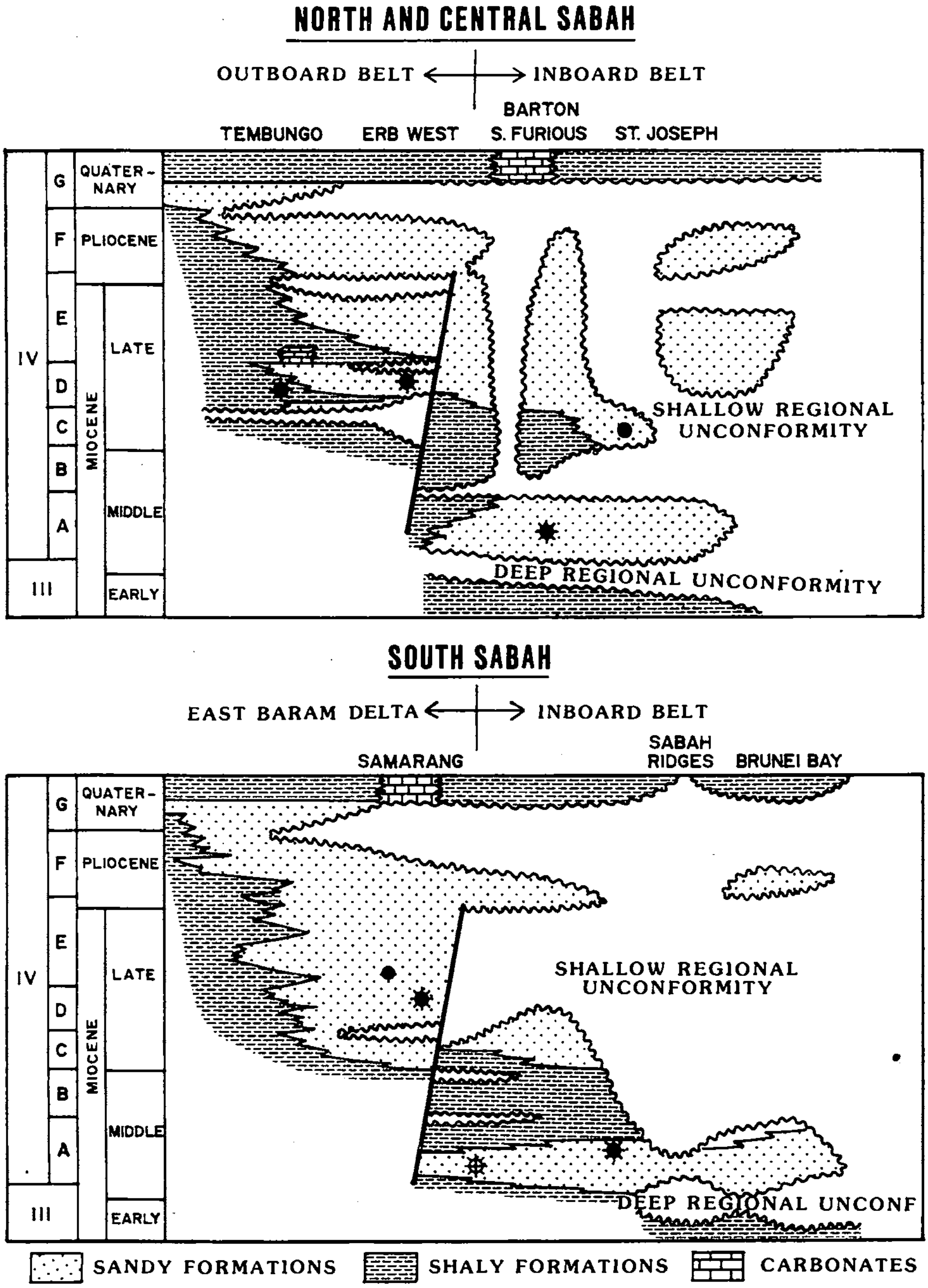


**Figure 4:** NW Sabah chronostratigraphy

unconformities pass from an erosion surface, in the southeast, to conformable horizons towards the northwest in the distal deeper water areas of the basin.

## TECTONOSTRATIGRAPHIC PROVINCE (Fig. 5 & 6)

On the basis of different structural styles and sedimentation histories, the NW Sabah continental margin can be subdivided into seven tectonostratigraphic provinces. These are:

i. ***The Crocker Accretionary Prism*** which consists of the pre-early Middle Miocene deep-marine sediments and associated mélanges (Crocker, Trusmadi, Setap Shale, Wariu and Chert-Spilite formations) and forms an imbricate wedge that crops out extensively onshore and forms the mechanical basement of a major part of the offshore. The uplifted, exposed part of the prism provided the main source of sediments for the post-early Middle Miocene clastic shelf/slope sequences offshore.

ii. ***The Inboard Belt*** is characterised by intense compressional features (the "Sabah Ridges") separated by wide, deep synclines, particularly well developed towards the western margin of the Belt. In the south, the main tectonic lineaments trend N-S and form a series of parallel, narrow wrench-related anticlines, with steep flanks and intensely faulted crest. The central part of the Belt is tectonically more complex, with both WNW-ESE and N-S trending tectonic lineaments forming domal faulted fold interference patterns. The sedimentation history in the southern and central parts of the Belt consists of an early Middle Miocene regression (Stage IVA), a late Middle Miocene transgression (mainly Stage IVB) and a Late Miocene to Pliocene regression (Stages IVC and IVF/G; Stages IVD and IVE are thin or absent). Further to the north, the Belt is characterised by NE-SW and E-W trending tectonic lineaments and the main difference in sedimentation history is a prolonged Late Miocene to Pliocene regression marked by well-developed Stages IVC, IVD and IVE sediments.

iii. ***The Outboard Belt*** occurs further offshore to the northwest and is marked by a decrease in compressional wrenching activity (represented by a few well-developed wrench-faulted features in the Tembungo-Kinarut areas) and an increase in extensional deformation marked by major N-S normal fault systems and large down-to-basin normal fault systems and large down-to basin normal faults in the vicinity of the present day shelf/slope break. The Belt is essentially a Late Miocene-Pliocene depocentre comprising Stages IVD, IVE, IVF and IVG sediments prograding northwestwards from shallow to deep marine.

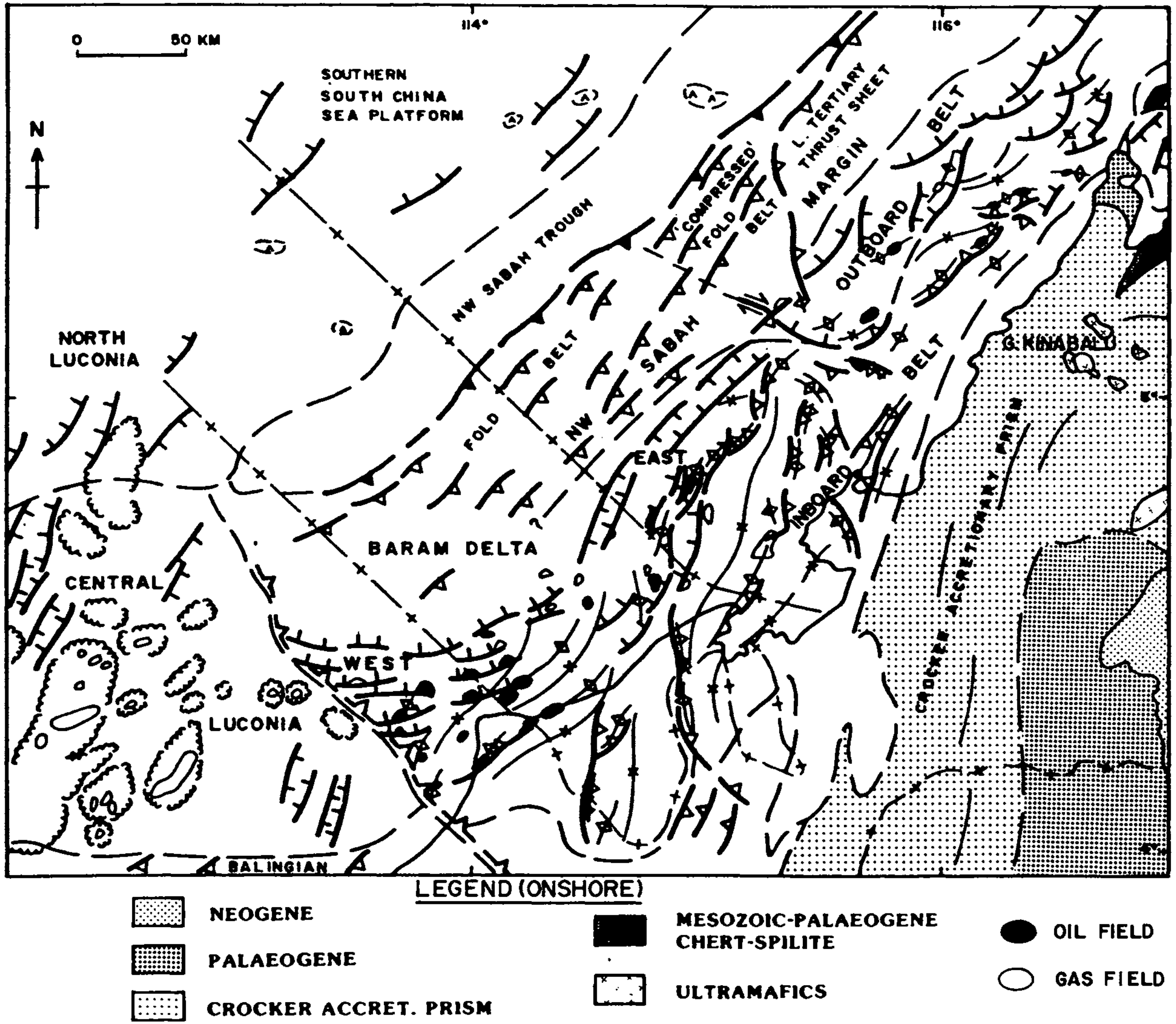


**Figure 5:** Geological setting of NW Sabah.

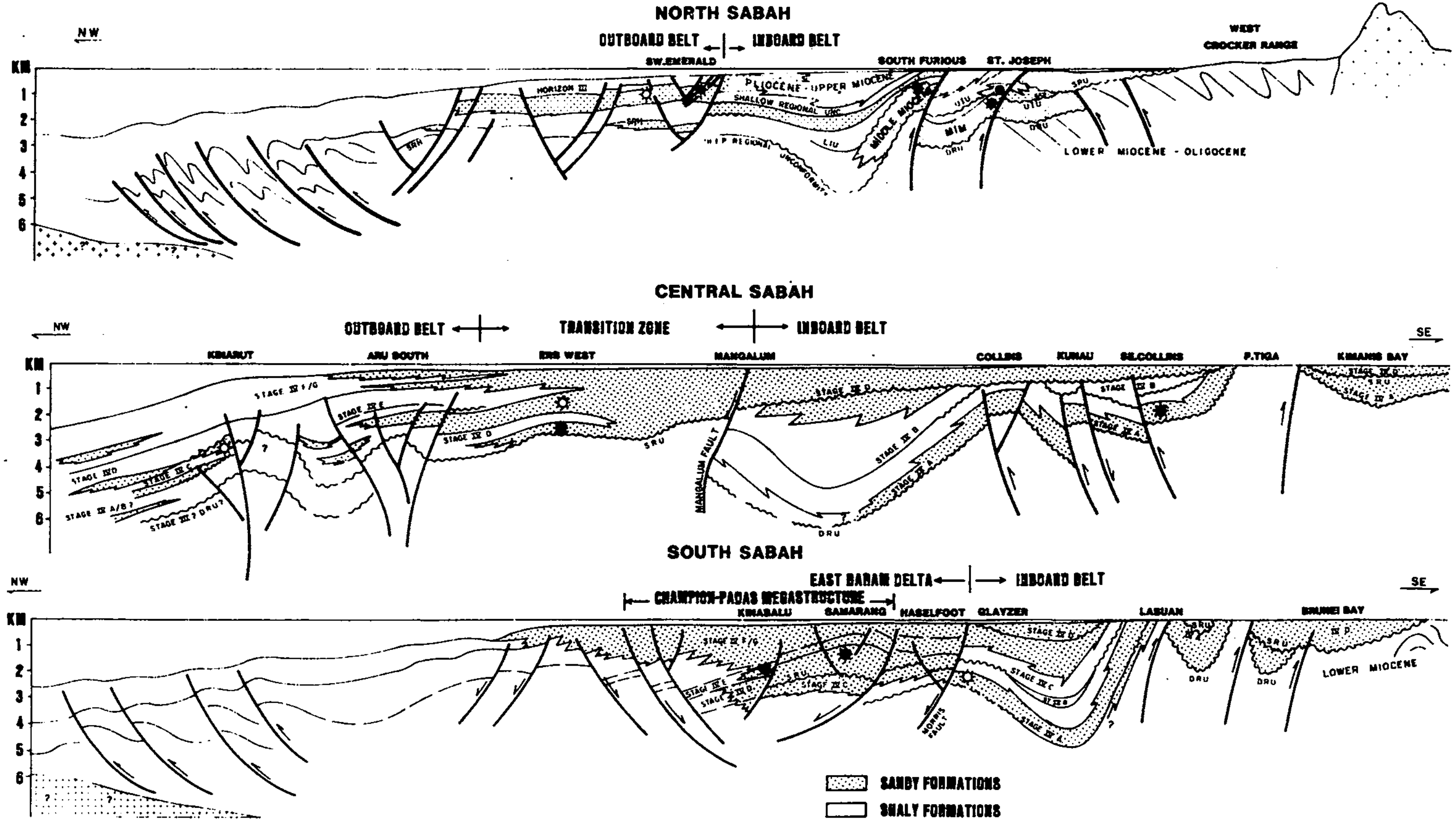


**Figure 6:** NW Sabah regional geological cross sections.

iv. ***The East Baram Delta,*** which developed in the eastern part of offshore Brunei, extends into southern offshore Sabah west of the Inboard Belt. It is characterised by typical delta tectonics, in place modified by deep-seated wrenching. The main feature is the very large Champion - Padas megastructure which, in Sabah, is made up of the Timbalai, Samarang and Padas macrostructure. These macrostructures merge downdip into a large expanding flank, bounded to the northwest by the a large counter-regional fault system. The progradational wedge passes north-westward via a series of large asymmetrical and overthrusted anticlines (possibly associated with deep-seated shale ridges) into the fold belt area in in deep water.

v. ***The NW Sabah Margin*** which can be further subdivided into 3 sub-units. In the southwest are the downdip and tow regions of the East Baram Delta extending down to the edge of the NW Sabah Trough. This realm exhibits oceanwards change of deformational styles from a zone of clay tectonics with typical clay ridges to overthrust asymmetrical anticlines which are still active. These features seem now to clearly related to massive gravity sliding along deep decollement planes induced by differential leading in the more updip parts of the delta but originally may have been subduction initiated. Along strike and further northeast the tectonic style is more compressional. Large, slightly overthrust, more closely spaced anticlines occur. This 'compressed fold belt' is probably separated from the delta toe by the eastward prolongation of the Kinarut-Mangalum fault. Further is the Lower Tertiary Thrust Sheet which is a huge allochthonous mass of imbricated sediments ('chaotic' seismic facies) reaching to the edge of the NW Sabah Trough, and separated from the 'compressed fold belt' by a major wrench fault. The allochthon probably consists of rocks of the Crocker Accretionary Prism overlain by a thin cover of younger sediments. The upper surface of the allochthon is very irregular due to the imbricated nature of the unit.

vi. ***The NW Sabah Trough*** (also referred to in the literature as NW Borneo Trench, Palawan Trough and Borneo-Palawan Trough) is a deep, relatively narrow feature where the SE-dipping Oligo-Miocene carbonates are overlain by a dominantly clayey pelagic sequence in water depth exceeding 2350 m. In the northern part of the Trough, the pelagic sediments partly rest on the Lower Tertiary chaotic unit which is thrusted over the carbonate.

vii. ***The Southern South China Sea Platform*** consists of attenuated continental crust characterised by a series of half-grabens caused by extensional (rifting) tectonics (Fig. 7). The tilted fault blocks are probably Mesozoic (Triassic to Cretaceous) sediments resting on a continental

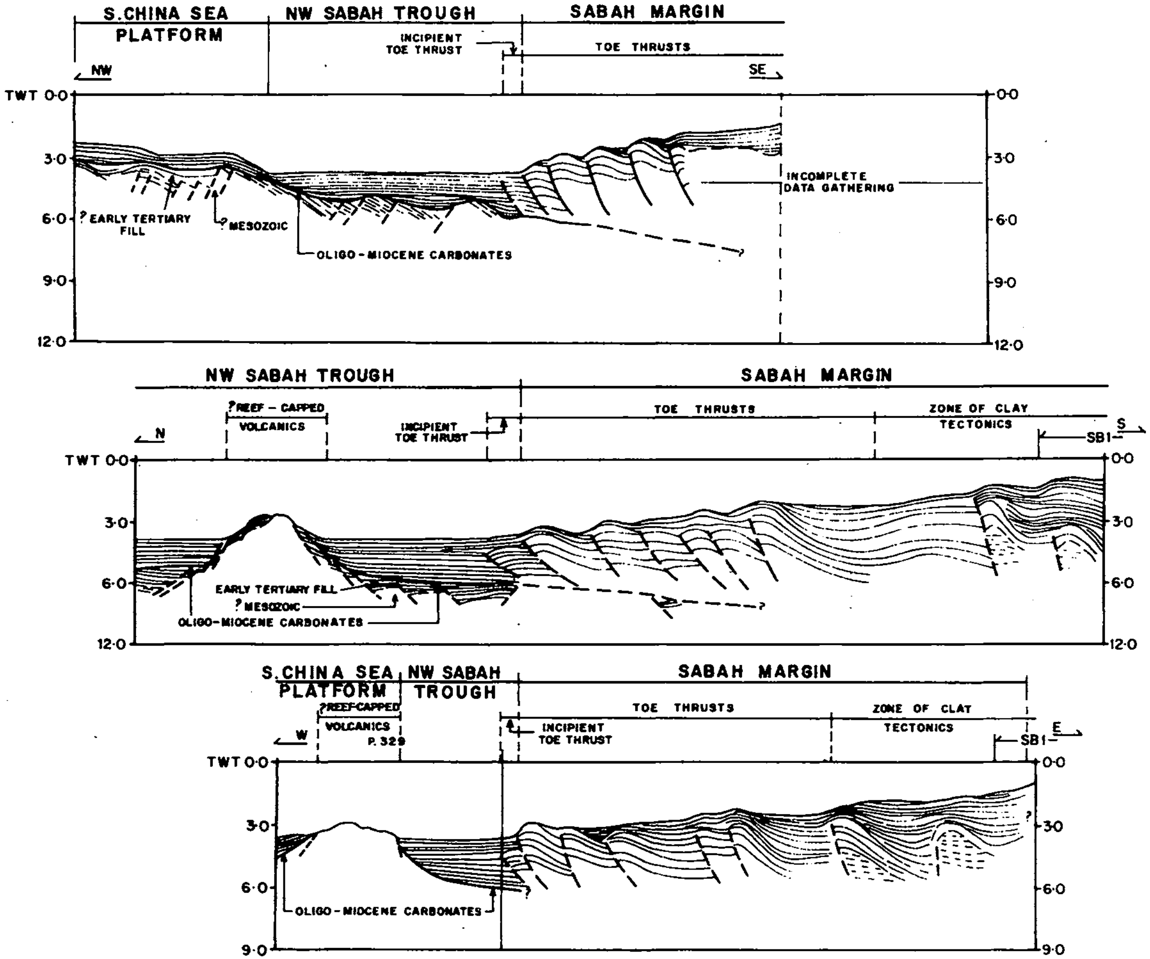


**Figure 7:** Schematic geological section across NW Sabah Trough.

basement, similar to the Read Bank and Dangerous Ground areas (Kudrass et al., 1986). The half-graben fill most probably consists of clastic sediments of early Tertiary age (Paleocene to Early Miocene). The end of the main extension and concomitant block rotation phase is marked by a strong reflector which corresponds to relatively thin, shallow water platform carbonates of Late Oligocene-Early Miocene age, as in the Palawan are (Hinz & Schluter, 1985; Kudrass *et al.*, 1986). The carbonate is overlain by well-bedded, hemipelagic to pelagic sediments which have been only mildly deformed by epeirogenic movements. On regional seismic lines this Oligo-Miocene carbonate occurs at depths of ca. 2.5-3.0 second in the Southern South China Sea Platform, plunges beneath the NW Sabah Trough to depths of between 4.5-6.0 seconds and can be traced for some distance beneath the trench-associated basin down to ca. 8.0 seconds.

The structural styles in the NW Sabah offshore were discussed by Bol and van Hoorn (1980), and the syndepositional sedimentation and significance of the regional unconformities were described by Levell and Kusumajaya (1985) and Levell (1987). Some of the oil fields has also been discussed, e.g. Tembungo (Whittle & Short, 1978), Samarang (Scherer, 1980) and Erb West (Johnson *et al.*, 1987).

## TECTONIC EVOLUTION (Figs. 8 & 9)

The NW Sabah continental margin is located in the northern half of NW Borneo and is, both tectonically and stratigraphically very different from the Sarawak continental margin to the south. The boundary between these two is the NW-trending West Baram Line. Based on regional seismic data the West Baram line extends northwestward to the edge of the North Luconia province where it is relayed into a N-S shear zone, providing evidence that the Line is a transtensional fault associated with N-S shearing.

The tectonic evolution of NW Borneo commenced in the Late Cretaceous with the first rifting of the South China Sea basin. The Late Cretaceous to Eocene evolutionary history of NW Borneo can be recognised today in Sarawak and this is discussed briefly. The Late Cretaceous to Paleocene rifting and subsequent seafloor spreading from Paleocene to Late Eocene resulted in the southwestward subduction of the pre-existing South China Sea oceanic crust beneath the Sunda Shield at a subduction front marked by the Lupar Line. The 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. The cessation of seafloor spreading and the commencement of the second rifting episode in the Late Eocene is represented by a marked unconformity of Late Eocene age in onshore Sarawak.

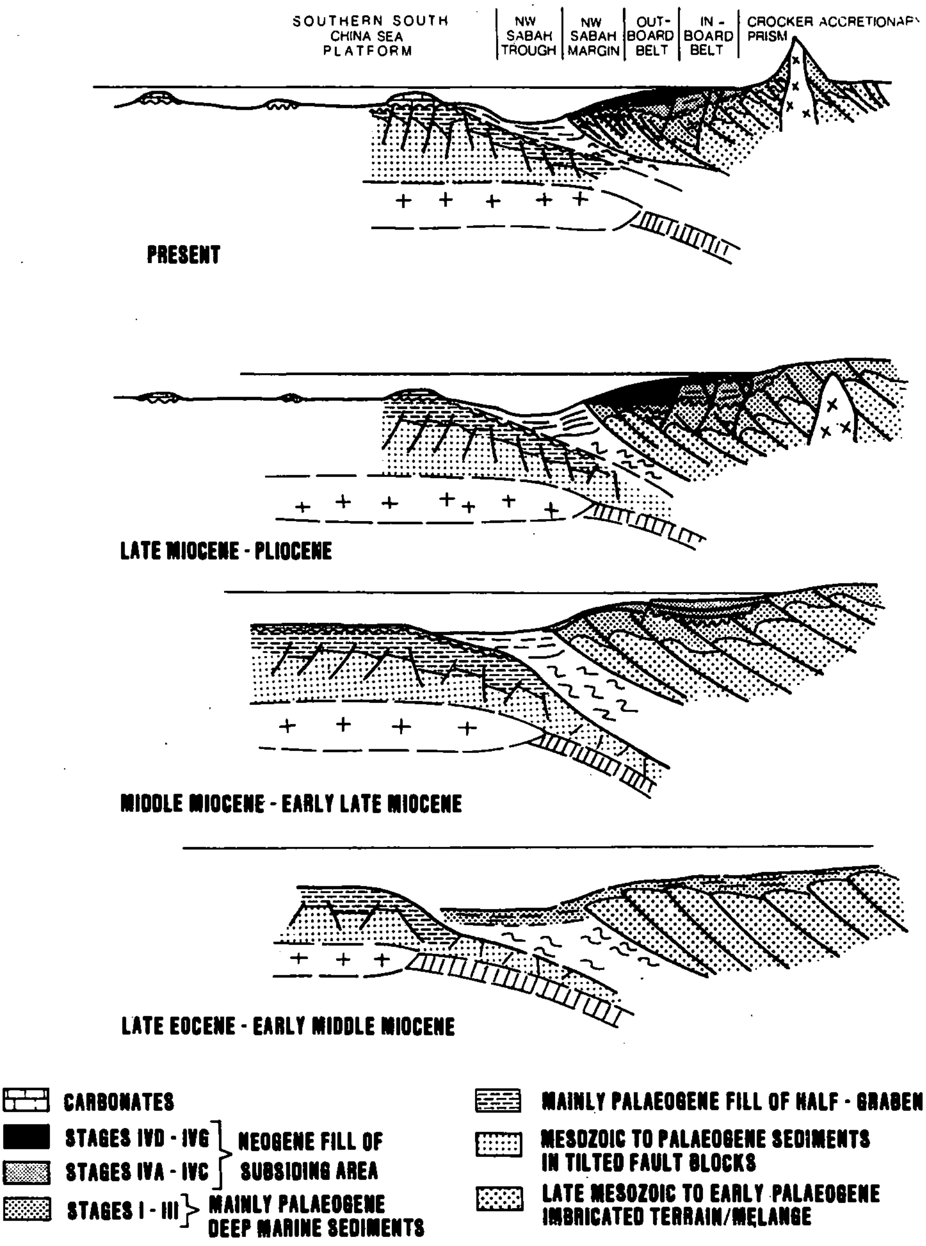


**Figure 8:** Schematic sections showing evolution of the NW Sabah continental margin

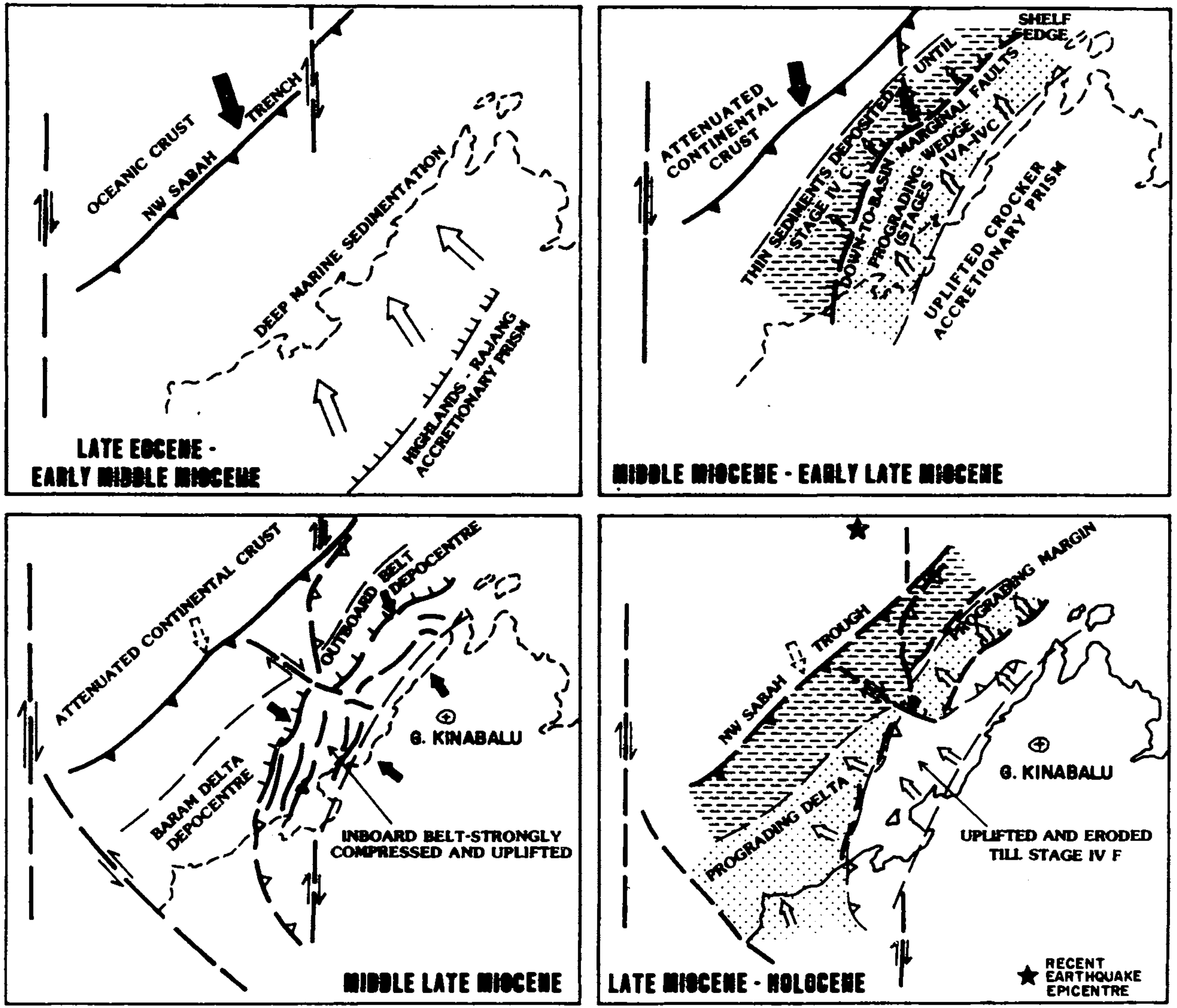


**Figure 9:** Reconstructions of the evolution of the NW Sabah continental margin from Late Eocene to Holocene.

The Oligocene is a period of major tectonic activity in the South China Sea. Crustal extension during the second rifting episode and subsequent seafloor spreading ended by the close of the early Oligocene, and probably at the same time the counterclockwise rotation of Borneo was completed (Ru & Pigott, 1986). The regional middle Oligocene unconformity is found along the entire South China Sea continental margin, including the Balingian province in offshore Sarawak, and is interpreted as a breakup unconformity.

The evolution of the NW Sabah continental margin, however, can only be traced back to the Late Eocene, and is discussed below:

### Late Eocene- early Middle Miocene

The subduction trench, believed to have shifted from the Lupar Line to the Mersing Line in Central Sarawak in Early Eocene times, migrated northward to the NW Sabah Trench in Late Eocene times. Subduction ('B'-type) of the South China Sea oceanic crust and its trailing attenuated continental crust beneath the Borneo accreted crust occurred during Late Eocene to early Middle Miocene. This led to the deposition of deep-marine sediments of the Trusmadi and Crocker formations (Stages I, II and III) which were imbricated into an accretionary prism.

### Middle Miocene -early Late Miocene

By early middle Miocene, the entire oceanic crust of the South China Sea appears to have been subducted beneath the Borneo accreted continental crust., and the attenuated continental crust of the South China Sea Platform collided with Borneo. The more rigid and buoyant attenuated continental crust does not bend as much and this resulted in a period of regional uplift and erosion throughout early Middle Miocene times in the South China Sea area, marked in NW Sabah by the Deep Regional Unconformity. Subsequent subsidence and sedimentation in NW Sabah during Middle Miocene to early Late Miocene times were restricted to the Inboard Belt, Based on data available to date, and is represented by progradation from coastal plain to shallow marine and deeper marine environments towards the northwest. The ancient shelf edge is probably at the present day boundary (Morris, Mangalum, SW Emerald and Bonanza faults) between the Inboard Belt and Outboard Belt and East Baram Delta. The sedimentation history consists of an early Middle Miocene regression (Stage IVA), a late Middle Miocene transgression (Stage IVB) and an early Late Miocene regression (Stage IVC). The Stage IVC regressive phase extends beyond the ancient shelf edge where it is recognised in the Outboard Belt and the East Baram Delta. Stages IVA and IVB sediments may be presents as thin sequences in the Outboard Belt and East Baram Delta but these have not been penetrated in any well.

## Middle Late Miocene

Subduction ('A' -type) of the South China Sea attenuated continental crust beneath Borneo is generally believed to have ended in the middle Late Miocene, followed by major tectonic activities. The Inboard Belt was subjected to strong, mostly compressional, deformation. Compressional strike-slip faulting was more intense in the south and was accompanied by strong uplift and erosion which gave rise to the Shallow Regional Unconformity in the area east and south of the Morris Fault, Mangalum Fault and the Bunbury-St Joseph-Bambazon Ridge. This resulted in the formation of steep, narrow anticlinal trends (the 'Sabah Ridges') separated by broad, deep synclines along the western margin. These anticlinal trends were subsequently uplifted and eroded to form the Shallow Regional Unconformity. The Kinabalu intrusion was emplaced in the middle Late Miocene (Jacobson, 1970) and is probably related to the Kinarut-Mangalum Fault in the offshore because they occur on an E-W trend at the same latitude.

During this time, a major tectonic re-adjustment occurred in NW Sabah. The western marginal faults of the Inboard Belt experienced major downthrow to the west resulting in the development of major depocentres in the north (Inboard Belt) and the south (East Baram Delta). These depocentres may be pull-apart basins associated with the major N-S strike-slip faults postulated by Holloway (1981) and Ru & Pigott (1986).

The continental collision may also explain why the NW Sabah offshore had been subjected to continuous uplifts and the resulting semi-regional tilting towards the west and northwest.

## Late Miocene - Holocene

This was a period of substantial subsidence, probably related to continued thermal contraction. By this time, the Inboard Belt in the area south and east of the Mangalum and Morris faults was a stable area of non-deposition and active erosion resulting in the strong angular Shallow Regional Unconformity which extends up to Late Miocene/pliocene Times. The erosional surface remained above sea level until Pliocene times when it was onlapped by Stage IVF sediments. In the Outboard Belt a thick progradational wedge (Stages IVD-IVG) built up towards the northwest and locally, small deltas developed (Erb West, SW Emerald and Bonanza areas), with associated extensional faulting along predominantly NE-SW and N-S trends. Progradation and outbuilding of the East Baram Delta continued throughout Late Miocene to Holocene times, with typical delta tectonic associated with growth faulting. IN the East Baram Delta and Outboard Belt, the sedimentation history consists of middle Late Miocene and late Late Pliocene regressions (Stages IVD and IVF) with late Late Miocene and Holocene transgressions (Stages IVE and IVG). A Late Pliocene phase of deformation affected mainly the Outboard Belt and East Baram Delta, with re-activation of deep-seated N-S trending wrench faults which affected the Champion-Padas trend in the East Baram Delta, and the Tembungo, SW Emerald and Bonanza areas in the Outboard Belt. Elsewhere in these two provinces gentle anticlinal features were formed.

Subduction of the attenuated continental crust of the Southern China Sea platform or lateral plate movements may have continued till at least Pliocene times. Evidence for this includes:

1. the re-activation of deep-seated wrench faults close to the boundary between the Outboard Belt/East Baram Delta and the Inboard Belt.
2. the fold belts in the NW Sabah margin which may initially be subduction related and further deformed by wrenching and/or gravity sliding at prograding front, and
3. the occurrences of two earthquakes of magnitude 6 of the Pascal scale in 1930 and 1936 at locations in the vicinity of 7° 30'N and 116°E.

## HYDROCARBON OCCURRENCES

Some 90 exploration and exploratory appraisal wells have been drilled by Sabah Shell Petroleum Company Ltd and other companies in the NW Sabah offshore. Apart from minor oil and gas shows in the pre-Middle Miocene deep-marine deposits, all commercial accumulations discovered to date are in the Middle Miocene or younger clastic reservoirs of the Inboard Belt, Outboard Belt and East Baram Delta provinces. The other tectonostratigraphic provinces have not been drilled.

The main hydrocarbon accumulations in the Inboard Belt are found in the Stages IVA and IVC lower coastal plain to fluviomarine marine sands in complex, reverse-faulted anticlines (e.g. Barton, S. Furious, Ketam). Hydrocarbon generation in the Inboard Belt is generally believed to occur prior to the Late Miocene phase of deformation, particularly in the southern part. Subsequent deformation resulted in complicated structuration and secondary migraiton. Hance the small and complicated hydrocarbon accumulations found, e.g. Ketam, SE Collins. In the Outboard Belt the main hydrocarbon reservoirs are the Stage IVD coastal to shallow-marine sands in simple faulted anticlines (e.g. Erb West) and Stage IVD deep-marine sands in reverse-faulted anticlines (e.g. Tembungo), whereas in the East Baram Delta the hydrocarbons are found in Stages IVC, IVD and IVE shallow-marine sands in relatively simple fault- and dip-closed structures (e.g. Samarang). Here hydrocarbon generation occurred before, during and after the main deformation (trap-forming) in Late Pliocene.

A significant aspect of the episodic tectonism model is in the geochemical effect of the variation of heat flow. Because of the distinct and separate heating events in the South China Sea (Ru & Pigott, 1986), the thermal maturity of sediments is greater than that expected for a classic passive continental margin of equivalent age. Therefore, the oil window can be expected to occur shallower than in a basin that had not experienced repeated heating.

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