Sedimentation and tectonics of Paleogene sediments in central Sarawak

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Abstract: The deposition of the Paleogene sediments in Central Sarawak occurred in four successive stages, its axis of depocentre generally advancing and younging to the northeast in response to progressive southwest subduction-accretion of a Mesozoic oceanic lithosphere and its sedimentary cover under West Sarawak. The younger sediments were deposited on top or in front of an older accreted sediments. The timing of deposition and accretion is uncertain due to lack of precise age indicators. However, based on regional considerations, the accretion is interpreted to have occurred sometimes during the Early Paleocene, Middle Eocene, Upper Eocene and Upper Oligocene, respectively, along major fault zones, producing four tectono-stratigraphic units. The older sediments were subjected to polyphase deformation as younger units were accreted.

INTRODUCTION

I was first introduced to the rocks of Sarawak during the 1991 GSM post-conference field trip, from Batang Lupar to Miri town. At that time the exposures were excellent and I was really determined to do some work in this region. Unfortunately, due to other commitments, I was unable to do much fieldwork, until 1993. For the past two years, I have visited and studied the good exposures, mainly along the north-south Sri Aman-Bintulu Highway, totalling about 20 fieldwork days. Fieldwork along the Balui River, a major tributary of the Rajang River, totaling 10 days was also carried out to have some kind of lateral comparisons with those rocks exposed along the highway. As part of the regional study, 4 undergraduate students (Jaul, 1996; Lim, 1996; Freddy, 1995; Lau, 1995) were assigned to map in detail critical areas along the N-S highway to understand the stratigraphical relationships of the rock units, their depositional environments and tectonic history (Fig. 1). The field survey was also supplemented by regional structural study of Central Sarawak using high resolution synthetic aperture radar (SAR) imageries, kindly made available by PETRONAS.

This paper presents an overview of the main findings of the study. Although there still remains a lot of work to be done, an attempt has been made to show the sedimentation and tectonics of the Paleogene sediments, based on plate tectonic concepts of subduction-accretion.

TECTONIC AND GEOLOGICAL SETTING

Central Sarawak, occupying the northwestern part of Borneo lies at the intersection of three major plates, the Eurasian, Indo-Australian and Philippines located to the north, south and east, respectively (Fig. 2). The movement of the three major plates relative to one another in a complex and poorly understood pattern has resulted in the accretion of terranes and creation of marginal basins since early Tertiary times. Central Sarawak represents part of an accreted terrane, lying adjacent to an extended continental margin to the north. The continental margin, presently occupied by the Luconia and Dangerous Grounds Platform is believed to have rifted from the southeastern margin of the Eurasian Plate or locally called the Sundaland Craton (Taylor and Hayes, 1983; Hutchison, 1989).

The accreted terrane in Central Sarawak and Sabah, commonly referred to as the NW Borneo fold-thrust belt or NW Borneo subduction complex (Hamilton, 1979) extends over a distance of more than 1,000 km along strike and reaches a width of over 300 km. Its northwestward margin ends somewhere along the NW Borneo Trough, whereas its southern margin lies near the international border of West Sarawak and West Kalimantan. The southern margin being marked by the presence of ophiolitic mélange (Tan, 1979; Williams *et al.*, 1986).

In Central Sarawak the accreted sediments have

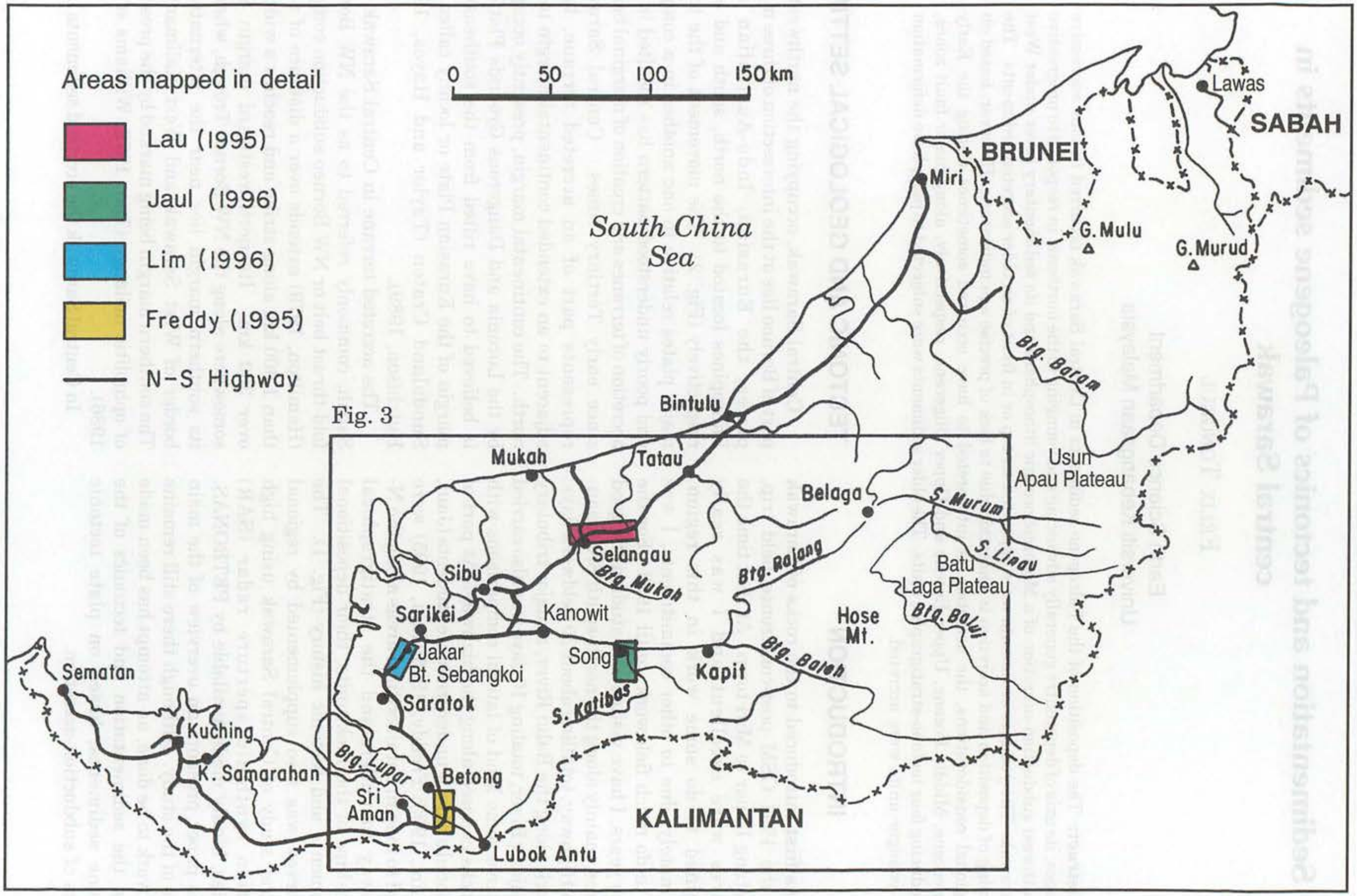

Figure 1. Map of Sarawak showing the study area.

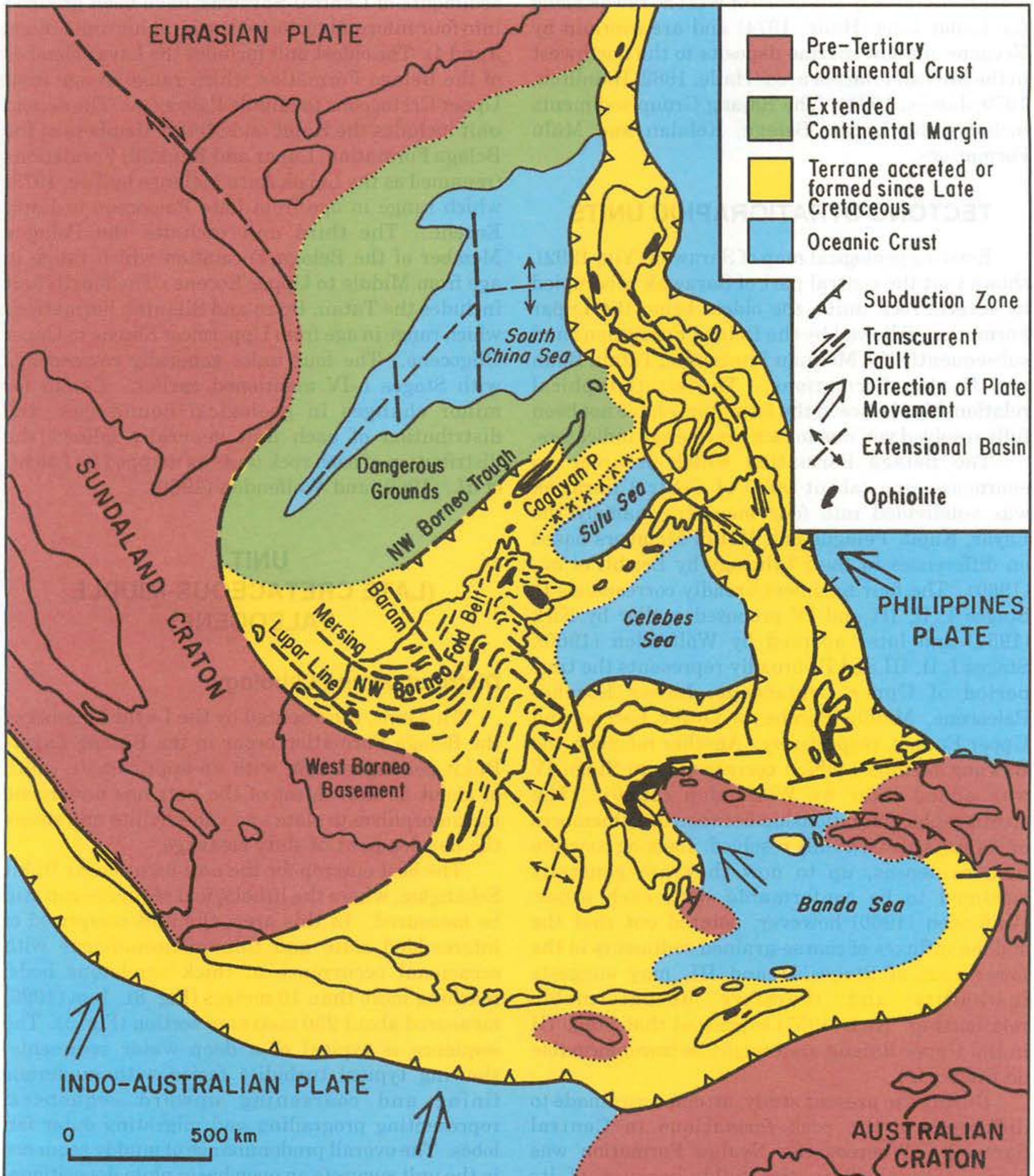

Figure 2. Geological and tectonic setting of Sarawak. Central Sarawak represents part of an accreted terrane, commonly referred to as the NW Borneo fold-thrust belt.

been mapped as the Rajang Group flysch sediments in the Sibu Zone (Haile, 1969, 1974), dated to range in age from late Cretaceous to Oligocene. The Rajang Group sediments is in faulted contact with older rocks (mostly Mesozoic) of West Sarawak along the Lupar Line (Haile, 1974) and are overlain by Neogene shallow marine deposits to the northwest in the Miri and Baram area (Haile, 1962; Hamilton, 1979; James, 1984). The Rajang Group sediments includes the Lupar, Belaga, Kelalan and Mulu Formations.

TECTONO-STRATIGRAPHIC UNITS

Existing geological map of Sarawak (Yin, 1992), shows that the central part of Sarawak is occupied by several rock units, the oldest being the Lupar Formation, followed by the Belaga Formations and subsequently the Melinau Limestone, Tatau, Buan and Nyalau Formations. The stratigraphical relationships between the formations have not been fully resolved yet, due to lack precise age indicators.

The Belaga Formation which occupies an enormous area (about 90%) of Central Sarawak was subdivided into four members, namely the Layar, Kapit, Pelagus and Metah Members based on differences in their lithology by Leichti *et al.*, (1960). The four members broadly corresponds to Stages I, II, III and IV proposed earlier by Kirk (1957) and later adopted by Wolfenden (1960). Stages I, II, III and IV broadly represents the time period of Upper Cretaceous, Lower Eocene-Paleocene, Middle Eocene to Lower Eocene and Upper Eocene, respectively. Another member, the Bawang Member, which corresponds to Stage IV was added later by Wolfenden (1960). The stratigraphical relationship between each members or stages is also not fully resolved. Lacking concrete field evidences, up to now they are generally assumed to be conformable with each other. Wolfenden (1960) however, pointed out that the sudden influxes of coarse-grained sediments in the lower part of Stages II and III, may suggests instability and therefore unconformable relationship. Kirk (1957) suggested that Stage III in the Upper Rajang area might be unconformable on Stage II.

During the present study, attempt was made to differentiate the rock formations in Central Sarawak. Whereas the Nyalau Formation was easily recognized in the field, because of its distinctive lithology and simple structure, the older formations proved to be difficult to differentiate. It became even more difficult, if one were to separate each formation based on varied description of their lithologies and structures in different areas by previous researchers. It became apparent, that a regional approach using age, lithology and degree of structural deformation as a criteria for differentiation might be helpful.

Based on the above criteria, the Paleogene sediments of Central Sarawak have been grouped into four informal tectono-stratigraphic units (Figs. 3 and 4). The oldest unit includes the Layar Member of the Belaga Formation which range in age from Upper Cretaceous to Middle Paleocene. The second unit includes the Kapit and Metah Members of the Belaga Formation, Lupar and Engkilili Formations (renamed as the Lubok Antu Mélange by Tan, 1979) which range in age from Late Paleocene to Early Eocene. The third unit includes the Pelagus Member of the Belaga Formation which range in age from Middle to Upper Eocene. The fourth unit includes the Tatau, Buan and Silantek Formations which range in age from Uppermost Eocene to Upper Oligocene. The four units generally corresponds with Stages I–IV mentioned earlier. Except for minor changes in geological boundaries, the distribution of each unit generally follows the distribution of each rock units as mapped by Leichti *et al.*, (1960) and Wolfenden (1960).

UNIT I (LATE CRETACEOUS-MIDDLE PALEOCENE)

Distribution and Lithology

This unit, represented by the Layar Member of the Belaga Formation occur in the Batang Layar-Bukit Sebangkoi belt, with an approximate width of about 80 km. Most of the unit has undergone metamorphism to slate and sub-phyllite and shows the development of slaty cleavage.

The best outcrop for the unit occurs near Bukit Sebangkoi, where the lithological sequence can still be measured. In this area, the unit comprised of interbedded slate and thin metasandstone with occasional occurrence of thick sandstone beds, reaching more than 10 metres (Fig. 8). Lim (1996) measured about 250 metres of section (Fig. 5). The sequence is typical of a deep water sediments, showing typical turbidite facies with numerous fining and coarsening upward sequences, representing prograding and migrating outer fan lobes. The overall predominance of muddy sequence in the unit suggests an open basin plain depositional setting.

Towards the south near Batang Layar, the sequence commonly includes slump beds, channeled sand beds, pebbly to conglomeratic beds and vertical burrows suggesting deposition on slope settings (Freddy, 1995). The source of the sediments is

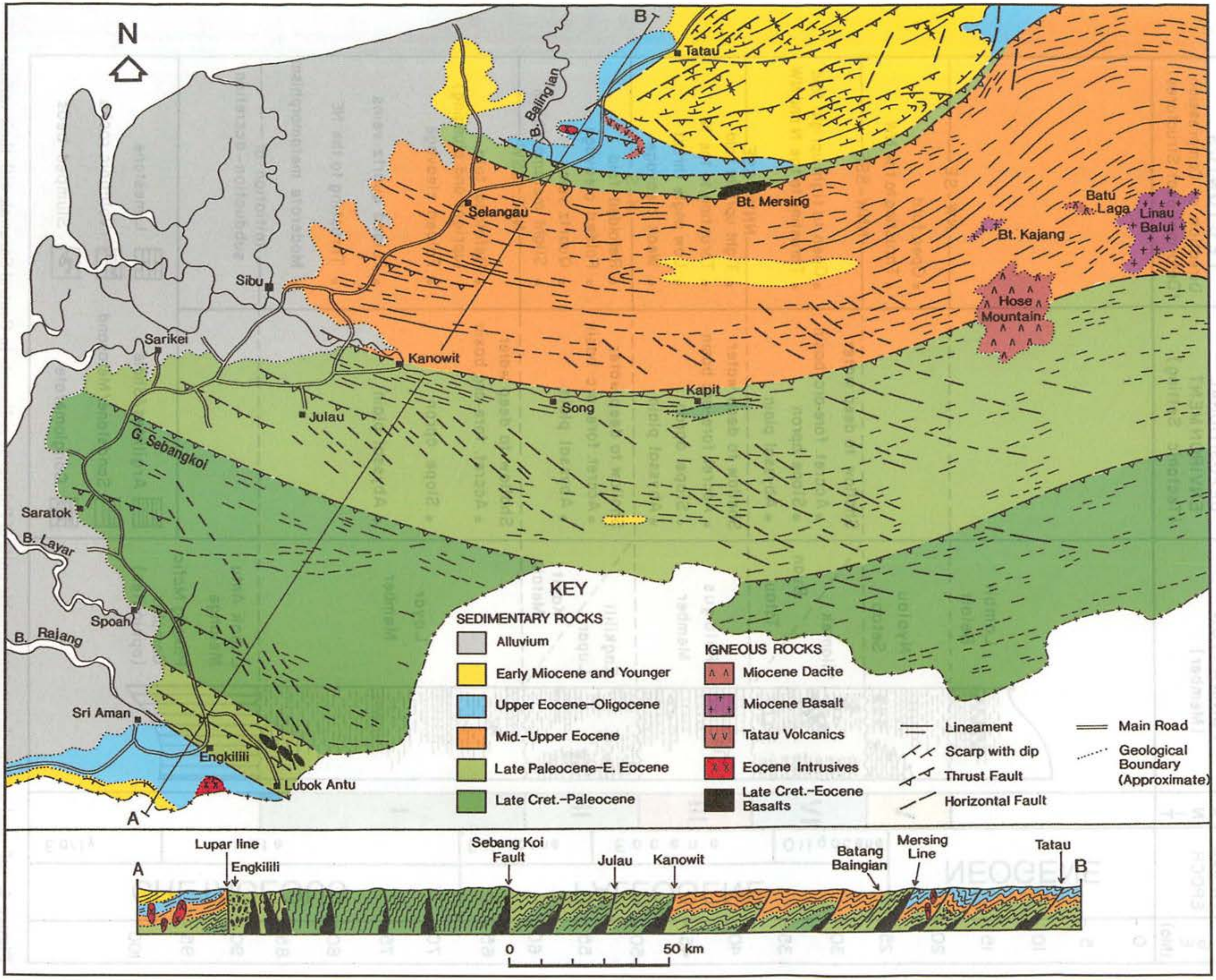

Figure 3. Geological and structural map of Central Sarawak. The regional lineaments based on SAR imagery interpretations. Geological boundaries of units extrapolated based on regional structures and on previous maps.

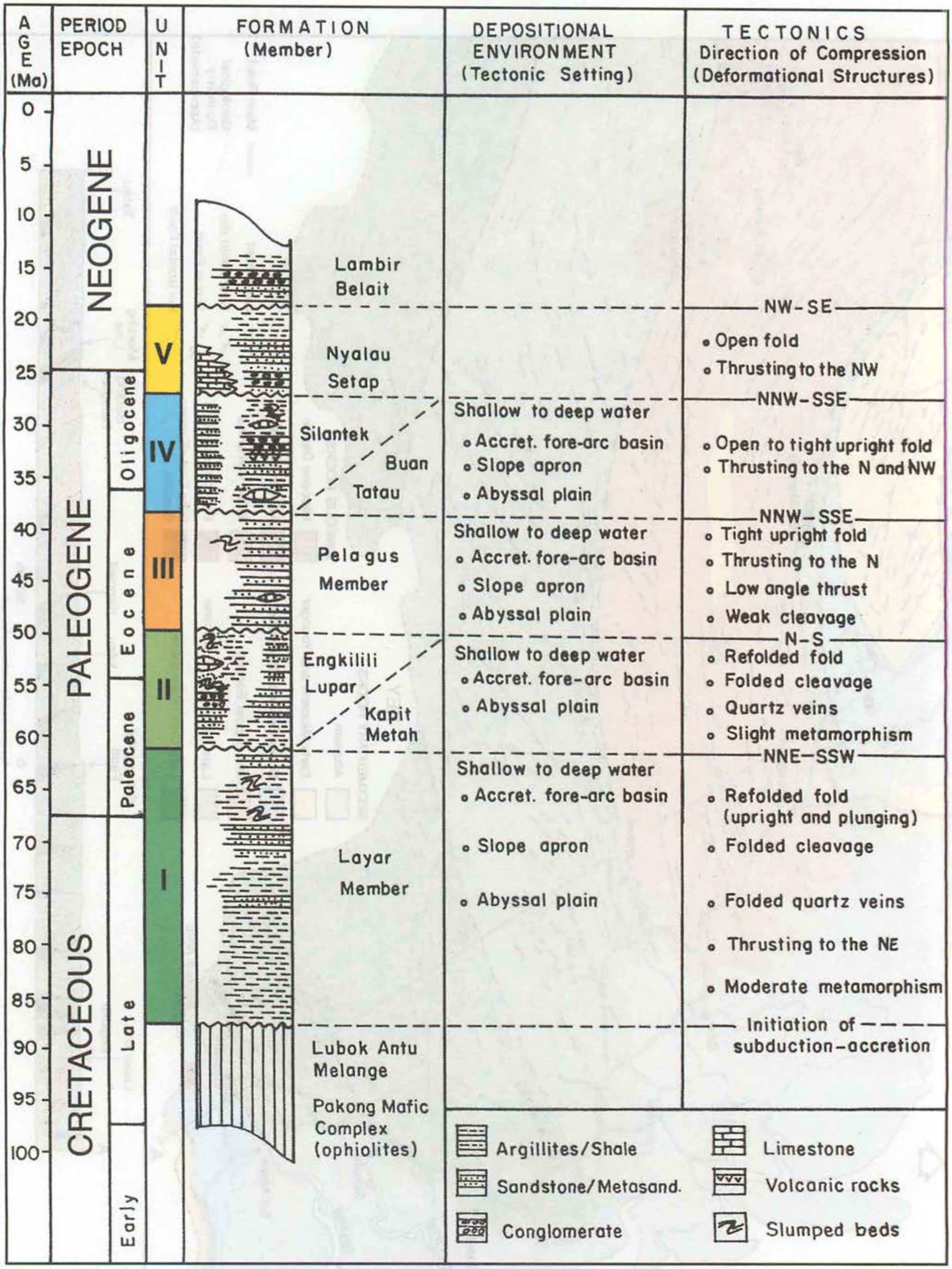

Figure 4. Informal tectono-chronostratigraphic units of Paleogene sediments in Central Sarawak with their various depositional settings and structural styles.

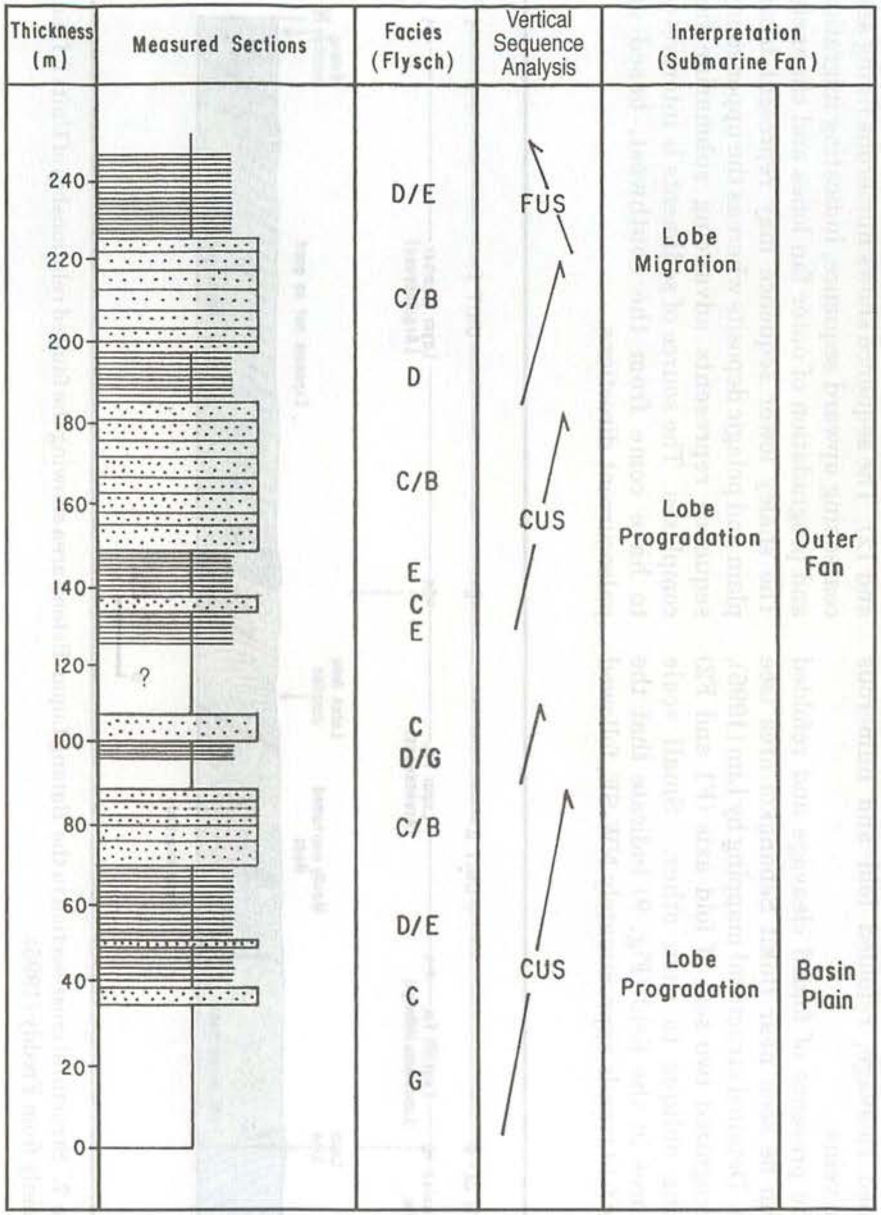

Figure 5. Measured sections of Unit I (Layar Member) at Bukit Sebangkoi by Lim (1996).

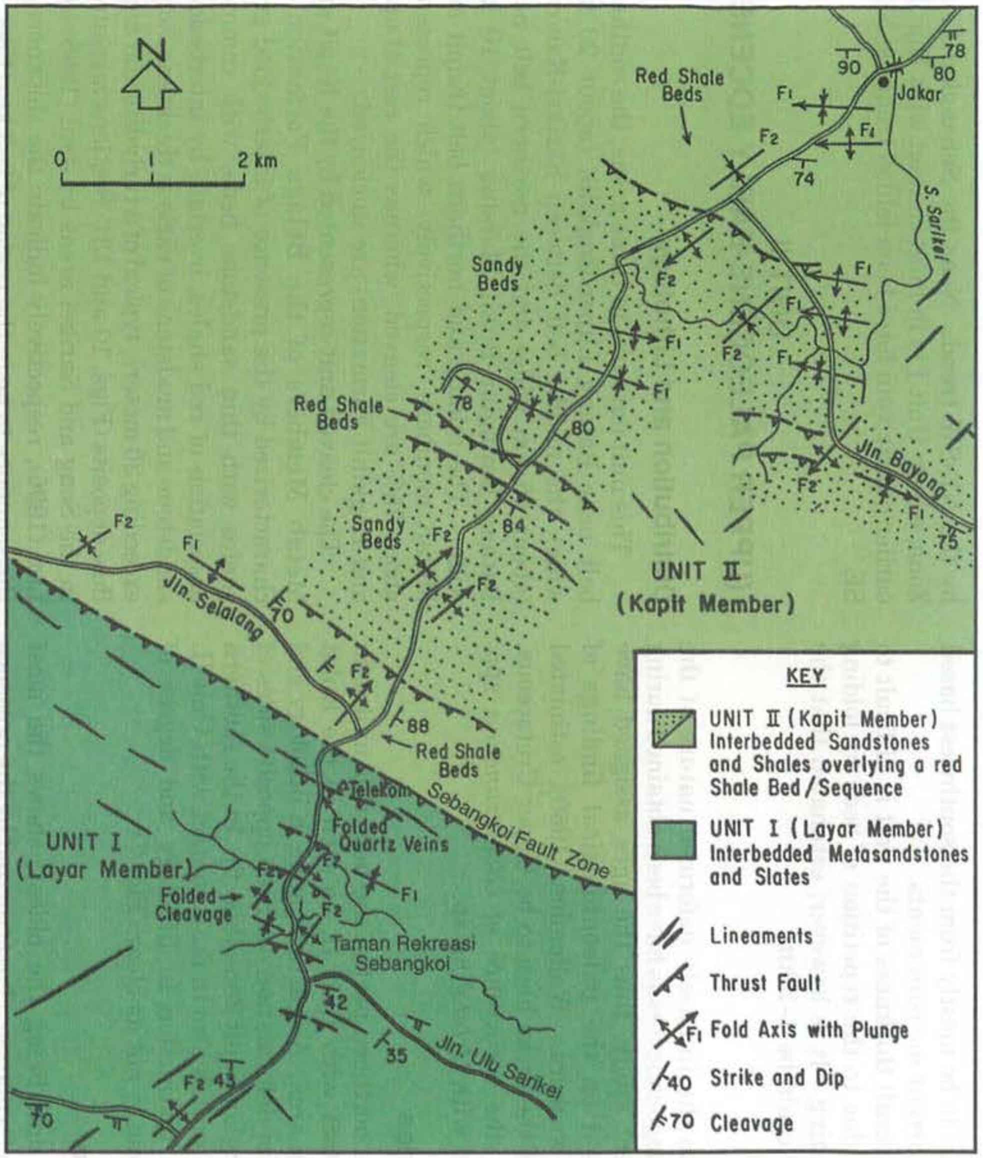

Figure 6. Geological map of the Bukit Sebangkoi-Jakar area, showing the boundary of Units I and II and the occurrence of refolded fold in both units. Mainly from Lim (1996).

interpreted to be mostly from the southwest based on paleocurrent measurements.

The overall thickness of the unit is difficult to ascertain due to the repetition of beds by folding and thrusting. It is however, estimated that the thickness could be 1–2 km.

Age

Due to the intensely deformed nature of the unit, no diagnostic fossils have been obtained during the present study, thus the ages assigned have been based on the paleontological findings of previous workers. Wolfenden (1960), estimated the age of the rocks here to be Upper Cretaceous, based on the occurrence of *Globotruncana* spp. associated with *Orbitolina* sp.

Boundaries

In the northern part of the belt, this unit is in fault contact with Unit II, as seen in the Bukit Sebangkoi area. A drastic change in lithology and intensity of deformation occur on opposite sides of the Sebangkoi Fault Zone (Fig. 6). In the southern part, this unit is also in fault contact with Unit II. Here the distinction in lithology and degree of deformation is not as clear (Fig. 7).

Structure

This unit being the oldest, shows the most intense deformation, characterized by the presence of folded cleavage, refolded fold and numerous quartz veins.

The presence of folded cleavage and refolded fold can be seen near Bukit Sebangkoi area (see Fig. 6). Detailed structural mapping by Lim (1996), has recognized two sets of fold axis (F1 and F2) trending oblique to each other. Small scale structures in the field (Fig. 9) indicate that the earlier fold trends approximately NW-SE, followed by the NE-SW trend. Near the Sebangkoi Fault Zone, where Unit I is in fault contact with Unit II, earlier quartz vein have been folded trending NW-SE.

UNIT II
(UPPER PALEOCENE-EARLY EOCENE)

Distribution and Lithology

This unit outcrops in three areas, the southern belt near Batang Lupar-Engkilili (about 20 km wide), the middle belt between Sarikei-Kanowit (about 45 km wide) and the northern belt near Batang Balingian-Bukit Mersing (about 10 km wide). The middle and northern belt (Kapit and Metah members, respectively) which represents about 75% are cleaved, whereas the rest (Lupar and Engkilili Formation) are uncleaved.

The cleaved unit represented by the Kapit and Metah Members of the Belaga Formation is characterized by the presence of interbedded grey shales with thin sandstone beds, with common association of red shales, overlain by interbedded sandstone and mudstone of various thickness, some exceeding 20 meters, typical of a turbidite and mass flow deposits (Figs. 10 and 13). Sections measured in the Song and Sarikei areas by Jaul (1996) and Lim (1996), respectively indicate the thickness of the sequence to be in the region of 2–3 km (Figs. 11 and 12). The sequence shows numerous fining and coarsening upward sequence, indicating migration and progradation of outer fan lobes and channels. The shaley lower sequence may represent basin plain and pelagic deposits whereas the upper sandy sequence represents advancing submarine fan complexes. The source of sediments is interpreted to have come from the southwest, based on paleocurrent directions.

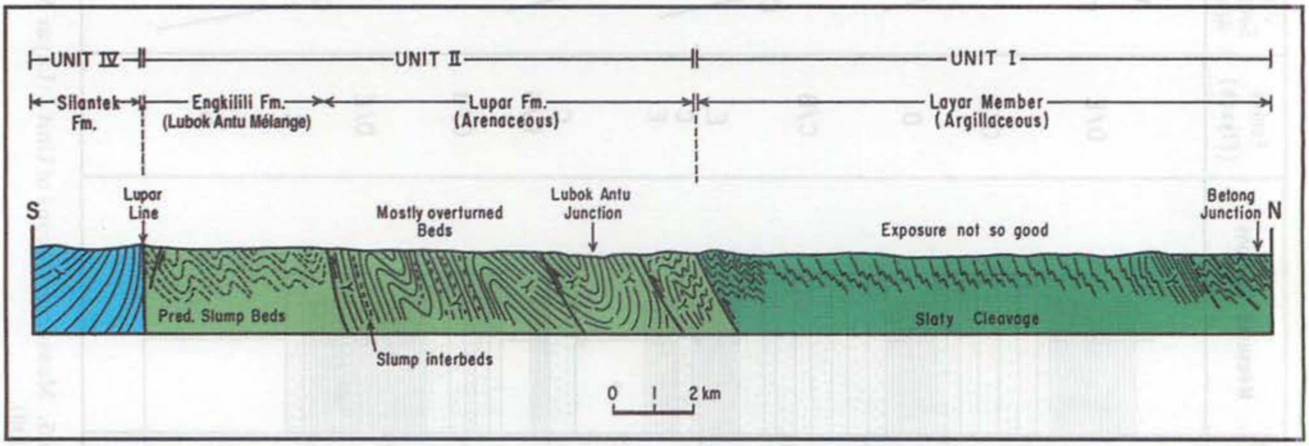

Figure 7. Structural cross-section in the Batang Lupar-Betong area showing the faulted relationship of Units I, II and IV. Mainly from Freddy (1995).

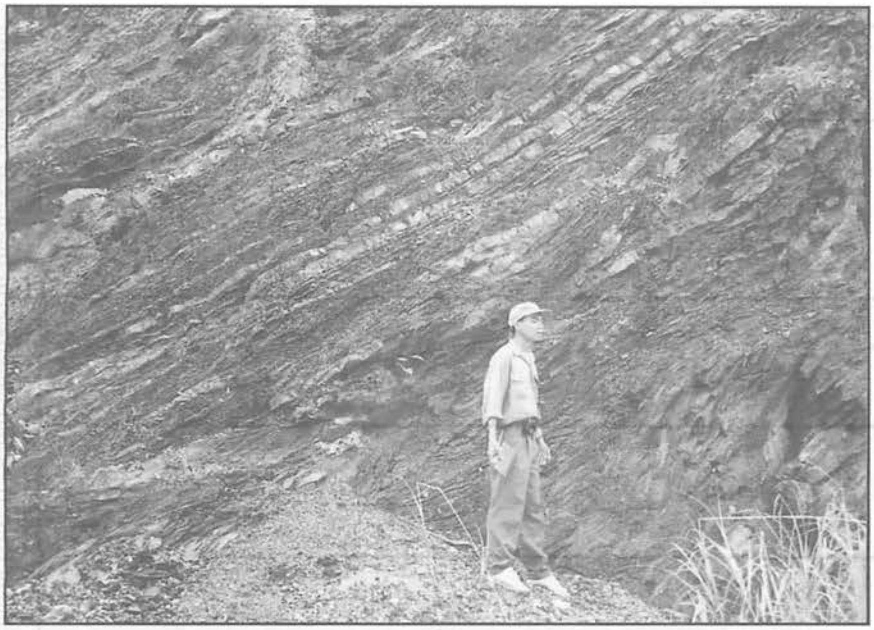

Figure 8. Dark grey slates interbedded with thin metasandstones of the Layar Member (Unit I) in the Bukit Sebangkoi area showing intense shearing and thrusting to the northeast.

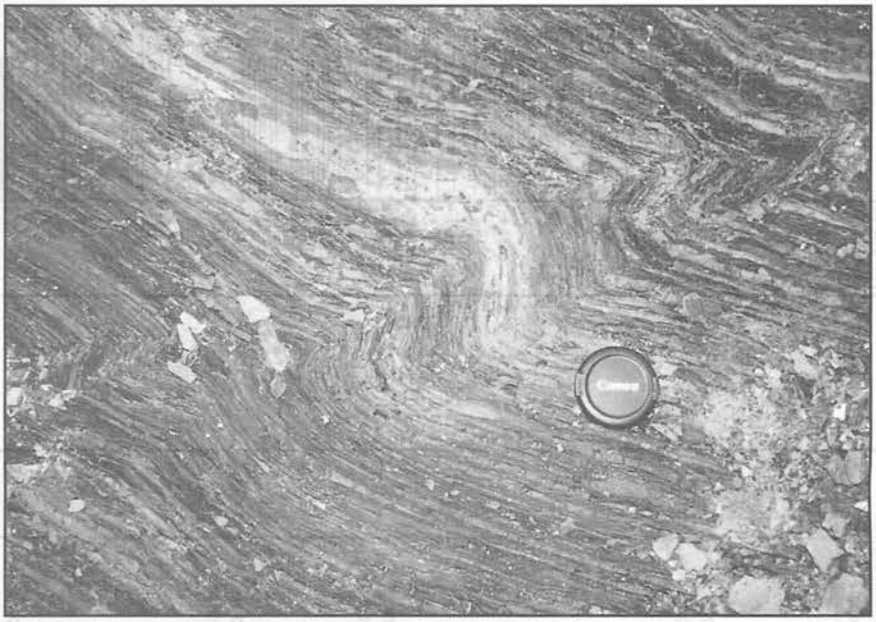

Figure 9. Small scale tight F1 fold axis trending NW-SE subjected to later folding, with its axis oriented approximately NE-SW in the Layar sediments (Unit I) in the Bukit Sebangkoi area.

Figure 10. Grey shales interbedded with thin graded sandstones of the Kapit Member (Unit II) typical of a turbidite deposit in the Jakar area. The vertically dipping sequence is accompanied by the development of cleavage.

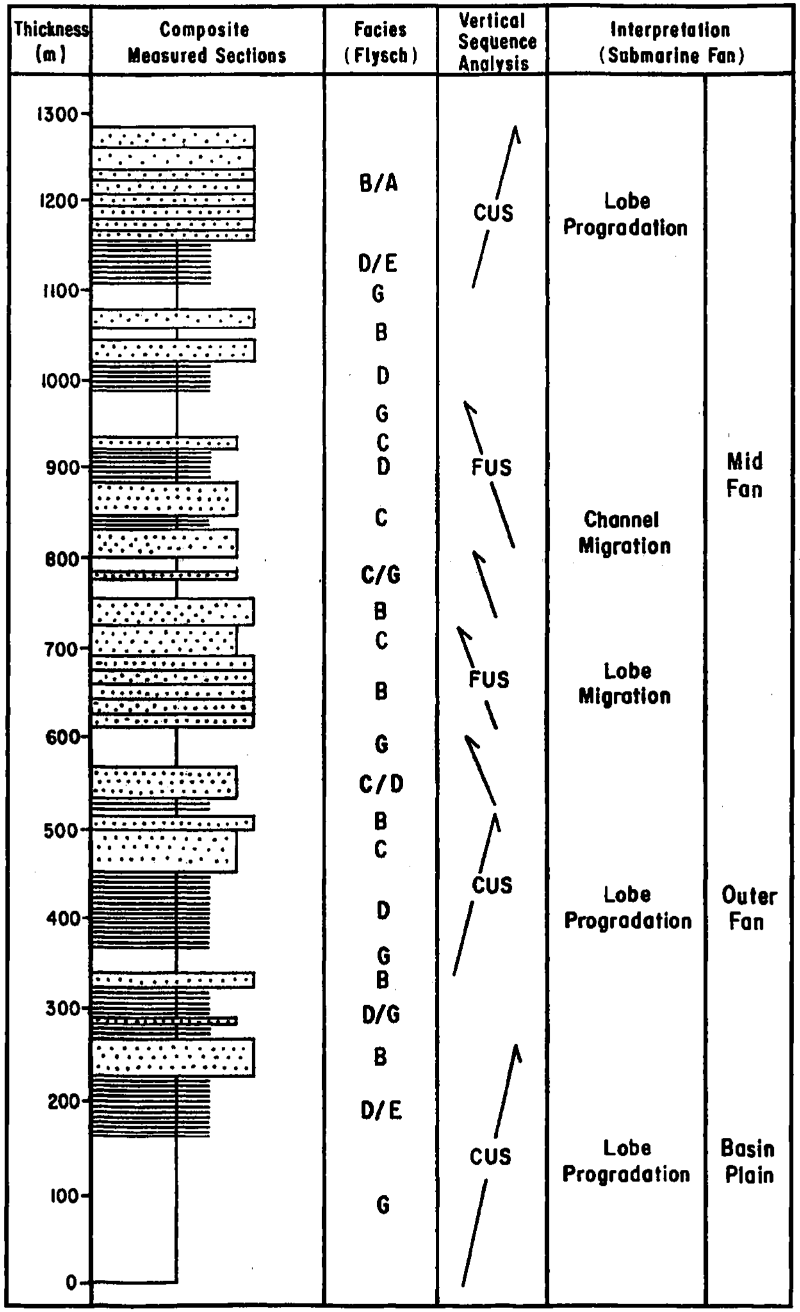

Figure 11. Composite measured section of the Unit II (Kapit Member) in the Song area by Jaul (1996).

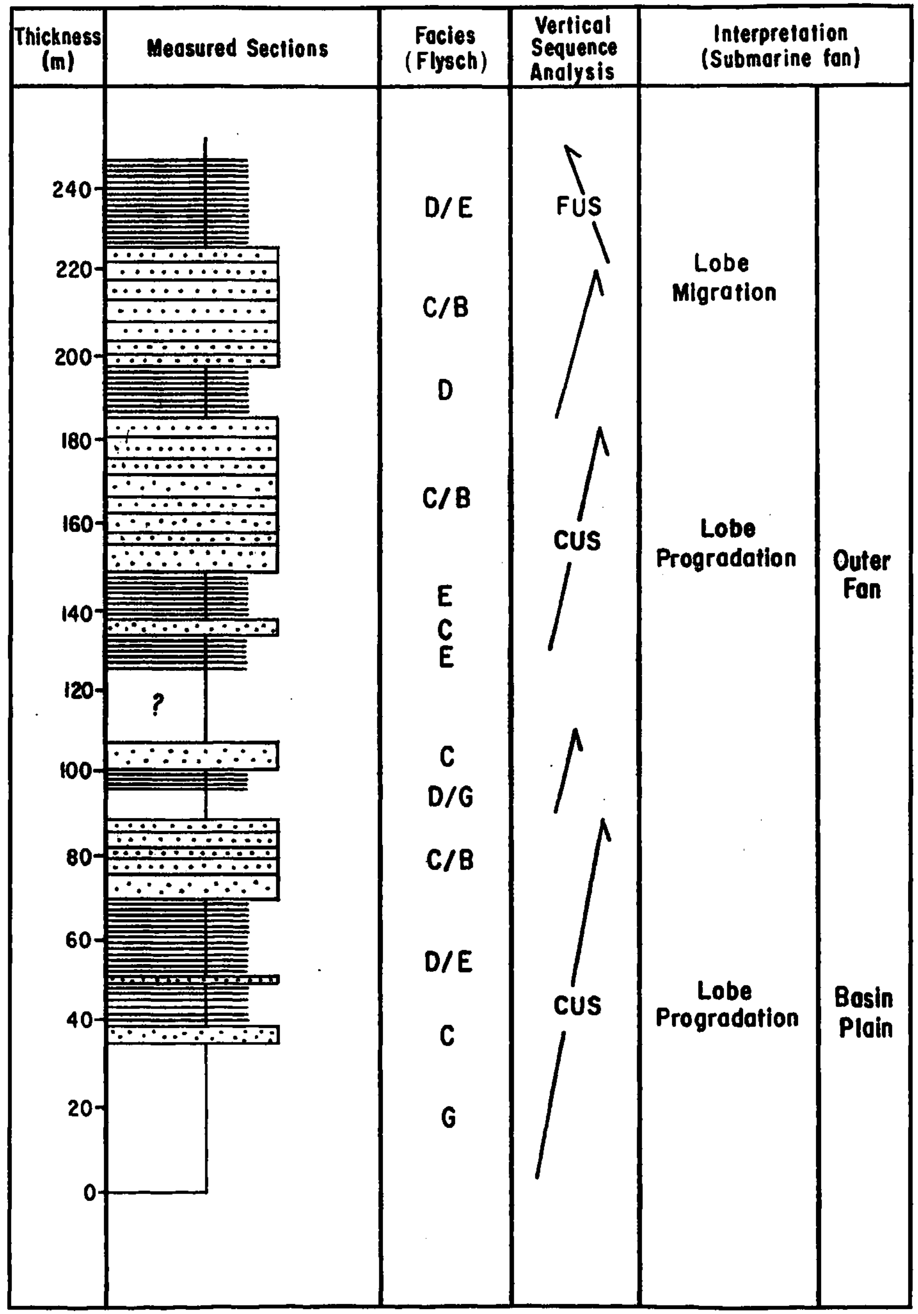

Figure 12. Measured section of Unit II (Kapit Member) in the Jakar area by Lim (1996).

The uncleaved unit, represented by the Lupar and Engkilili Formations is characterized by the intercalation of undeformed and deformed sequence. The deformed sequence is associated with primary slump structures, whereas the undeformed sequence comprise mainly of thick shales interbedded with thin to medium sandstones (Freddy, 1995). The thickness of the deformed sequence can reach up to 20 metres. The overall thickness of this unit is uncertain due to the deformed nature of the sequence. However, it is estimated, based on the exposed sections to be more than 500 metres. The unit is interpreted to have been deposited in an unstable slope environment, possibly quite shallow, as indicated by the presence of numerous vertical burrows and channeled pebbly-conglomeratic

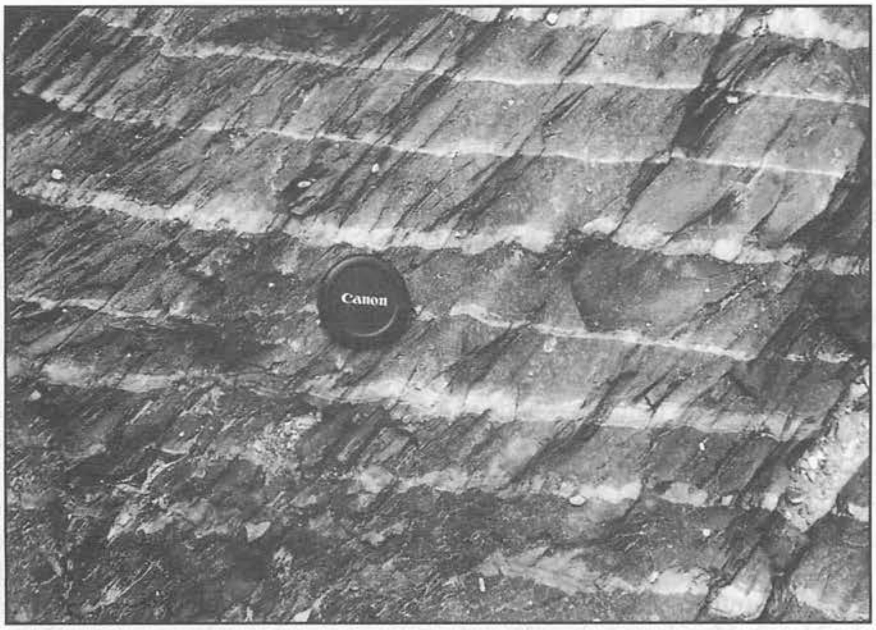

Figure 13. Red shales interbedded with thin siltstones of the Kapit Member (Unit II), interpreted as deep water basin plain deposits in the Song area. The cleaved beds represent part of a vertically plunging fold limb, with its axis trending approximately NW-SE.

Figure 14. Steeply plunging F1 fold axis trending approximately NW-SE in the thick sandstone beds of the Kapit Member (Unit II) in the Song area. The height of the hill cutting is approximately 10 metres.

sandstone interbeds in the undeformed sequence. The source of sediments is not clear due to the absence of good paleocurrent indicators.

Age

The southern belt, mapped previously as the Engkilili Formation yielded abundant microfossils, indicating ages ranging from Paleocene to Lower Eocene. However, the Lupar Formation which is conformable with the Engkilili Formation did not yield good microfossil (Freddy, 1995). Upper Cretaceous microfossils which was mostly obtained from blocks in the deformed sequence, was assumed by Tan (1979) to come from the Lupar Formation. His description of the Lupar Formation, which also shows well developed slaty cleavage is difficult to differentiate with the Layar Member. It is possible that the Upper Cretaceous age may have been derived from the latter. Tan (1979) which includes the Engkilili Formation in the Lubok Antu Mélange suggested an Upper Lower Eocene age for the matrix in the deformed beds. Tan also suggested that the limestone blocks found inside the deformed beds is of Upper Paleocene to Middle Eocene in age. An early Middle Paleocene to early Middle Eocene age was suggested by Basir and Madira (1995) for the microfossils extracted from the Lubok Antu mud matrix.

No microfossils were found on the middle (Kapit Member) and north (Metah Member) belts. Based on earlier studies, the middle belt have been dated as Paleocene to Lower Eocene, whereas the north belt as Upper Eocene (Wolfenden, 1960). Recent age determination for the Kapit sediments by Sulong (1987) shows Lower-Middle Eocene. The Upper Eocene age assigned to the Metah Formation appears to be inappropriate, considering its distinctive lithology and higher degree of deformation compared to the surrounding rocks. It is therefore assumed in the present study that the Metah member is the northern extension of the Kapit Member based on their similar lithology and structures.

Boundary

In the Batang Rajang area, the unit is in fault contact with Unit I and Silantek Formation (Unit IV) (see Fig. 6). In Sibu, Kanowit and Song areas, the Unit is interpreted to be in fault contact with Unit III. The fault is not seen in the field, but inferred from the drastic change in lithology and structure on both side of the Rajang River. For example, near Durin Ferry station, the southern side of the river is characterized by intensely sheared and tightly folded grey and reddish shale and slate, whereas on the northern side, steeply dipping, thin–medium, well-bedded carbonaceous mudstone and sandstones occur.

In the Balingian area, the Unit is in fault contact with Unit III and IV (Fig. 15). The boundary is not exposed in the field, but the sudden change in lithological and structural deformation along the road is apparent (Lau, 1995).

In the northern part of Sarawak, rocks of equivalent age, similar lithology and structure have been mapped as the Mulu Formation by Haile (1962).

Structure

This unit shows two different structural styles of deformation. The northern and central belt which are cleaved, is characterized by the presence of refolded fold and numerous quartz veins, whereas the southern belt is characterized by the presence of overturned and disrupted beds.

In the northern belt, near the Batang Balingian bridge (see Fig. 15), the unit is intensely sheared, showing tight asymmetric folding and thrusting towards the north. Kink bands are also seen in some of the foliation which are usually cut through by extensional quartz veins.

In the central belt, near Jakar (see Fig. 5), two sets of fold axis (F1 and F2) trending NW-SE and NE-SW, respectively have been mapped. In the field, the intersection of both fold axis is usually marked by a sudden change in direction of cleavage and the presence of disrupted beds, with its strike and dip in various directions (Lim, 1996). Similar structures have been mapped by Jaul (1996) near Sungai Musa in the Song area. Here the F1 fold axis shows steep plunge (Fig. 14). Along the Katibas River, the folded sequence shows approximately 1.5 km wavelength (Fig. 16).

In the southern belt, near Batang Lupar, the unit mostly shows tight asymmetric folding accompanied by steepened and overturned beds (see Fig. 6). Similar overturned rock units towards Lubok Antu have been mapped by Tan (1979). In the slumped part of the unit, rock fragments of different lithologies (mostly sedimentary rocks) and sizes (cobble to boulder) occur imbedded in a silty mud matrix. Tectonic shearing occur in places within the mud matrix. The presence of exotic blocks (igneous, sedimentary and metamorphic) in the mud matrix has led Tan (1979) to interpret them as a tectonic mélange.

UNIT III (MIDDLE TO UPPER EOCENE)

Distribution and Lithology

This unit, represented by the Pelagus Member of the Belaga Formation occur in the Sibu-Selangau belt, with an approximate width of about 60 km. The best outcrop can be seen near Sibu Town and

Near Selangau-Mukah Junction. In the vicinity of Sibu Town, the unit is characterized by a thick sequence of dark grey carbonaceous shales interbedded with thin laminated sandstones, intercalated with thicker sandstone beds. Vertical burrows are commonly seen in some of the shale interbeds, probably suggesting shallow water deposition of some of the sequence (Fig. 17).

In the vicinity of Selangau town, Lau (1995) measured about 1650 metres of section, comprising mainly of shales interbedded with sandstones of various thickness, typical of a turbidite and mass flow deposits (Fig. 20). The sequence shows several fining and coarsening upward sequence, representing the migration and progradation of a submarine fan lobes and channels over a basin plain setting. The presence of numerous primary slump structures in some of the sequence also suggests a depositional environment near a slope. In other areas, the vertical burrows in a carbonaceous mudstone with thin discontinuous sandstone beds suggests shallow water environment (Fig. 18). Paleocurrent measurements indicate a source of the sediments from the southwest.

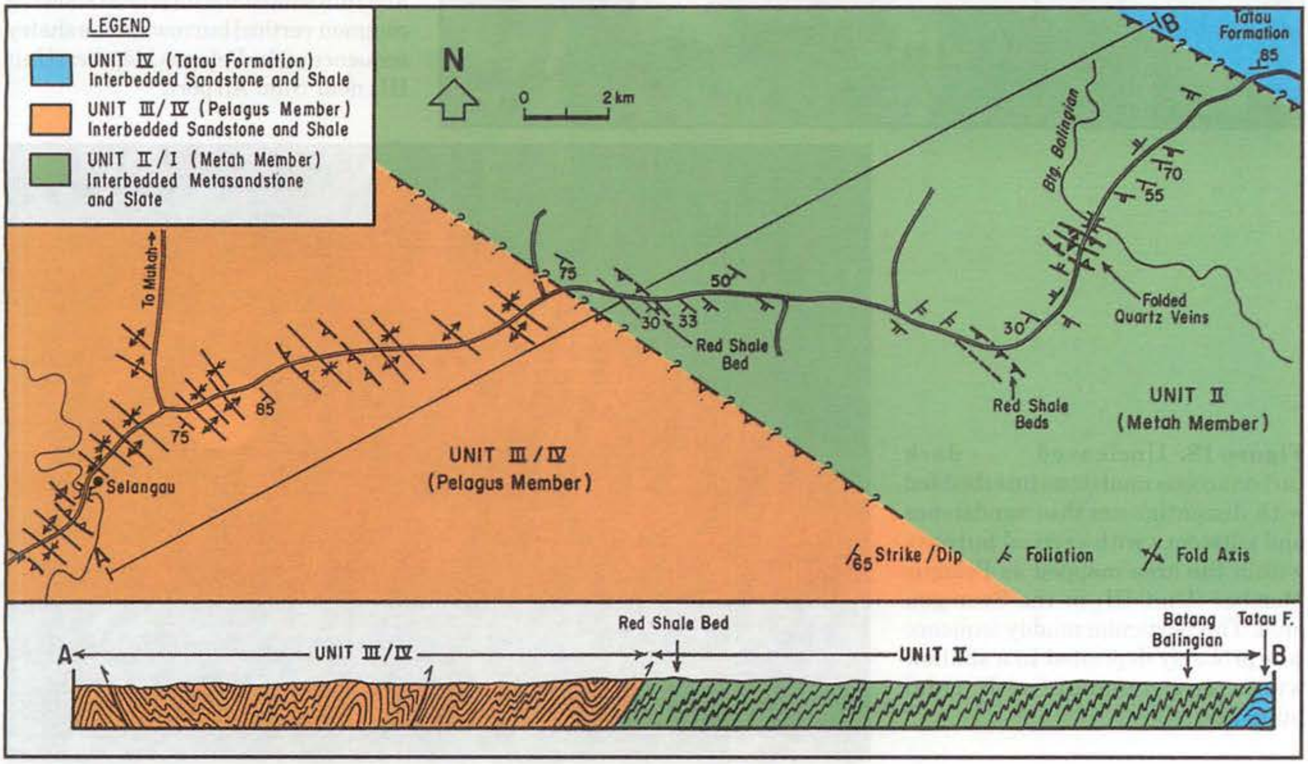

Figure 15. Geological map of the Selangau area showing the boundary of Units II, III and IV, interpreted to be faulted, as shown by the drastic change in the lithology and structural deformation. Based on Lau (1995).

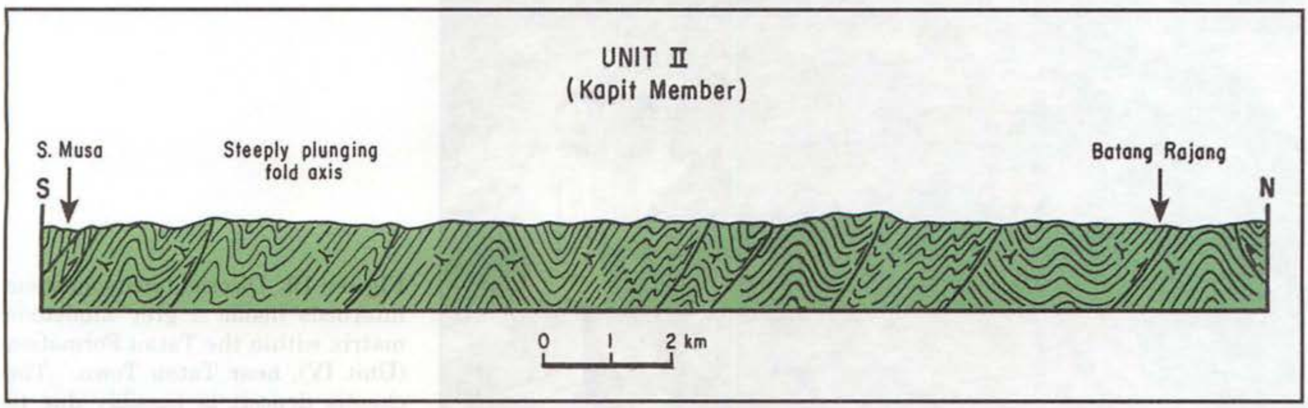

Figure 16. Structural cross-section in the Song area by Jaul (1996), showing the deformational style of Unit II (Kapit Member).

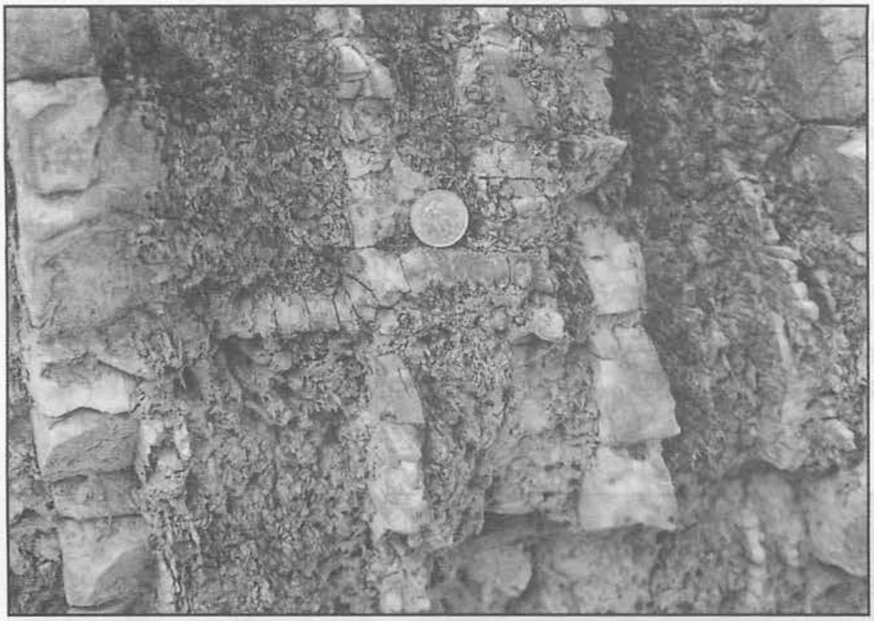

Figure 17. Uncleaved grey shales and thin sandstone interbeds showing common vertical burrows in the shaley sequence of the Pelagus Member (Unit III) near Sibu Airport.

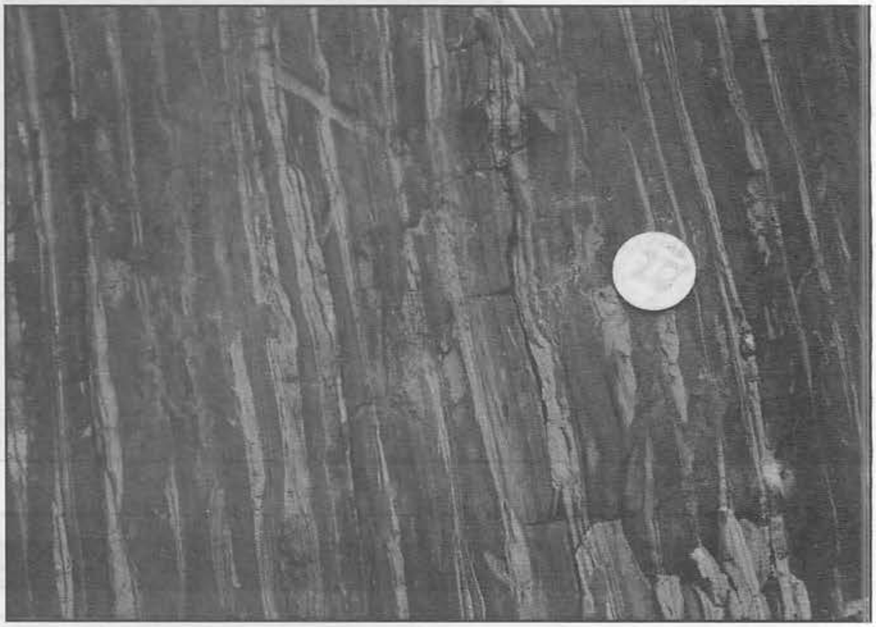

Figure 18. Uncleaved dark carbonaceous mudstone interbedded with discontinuous thin sandstones and siltstones with vertical burrows within the area mapped as Pelagus Member (Unit III) in the Selangau area. This particular muddy sequence was probably deposited in a shallow water environment with tidal influence.

Figure 19. Disorientated sandstone interbeds inside a grey mudstone matrix within the Tatau Formation (Unit IV), near Tatau Town. The chaotic deposit is possibly due to gravity sliding and reactivation by later tectonics.

Age

The shale samples in the Selangau area yielded Upper Eocene foraminifera (Lau, 1995). However, samples collected in the Sibu area was barren. The belt has been previously mapped as the Pelagus member of the Belaga Formation and has been dated to range in age from Middle to Upper Eocene by Wolfenden (1960).

Boundary

The unit is interpreted to be in fault contact with Unit II at its northern and southern margin as discussed earlier.

In the northern part of Sarawak, rock unit of similar age, lithology and structure have been mapped as the Kelalan Formation by Haile (1962).

Structure

This unit is characterized by upright, tight folding and thrust faulting with associated horizontal faults. Minor development of cleavage occur in some area.

In the Selangau area, for example, numerous folds with wavelengths between 100–250 metre

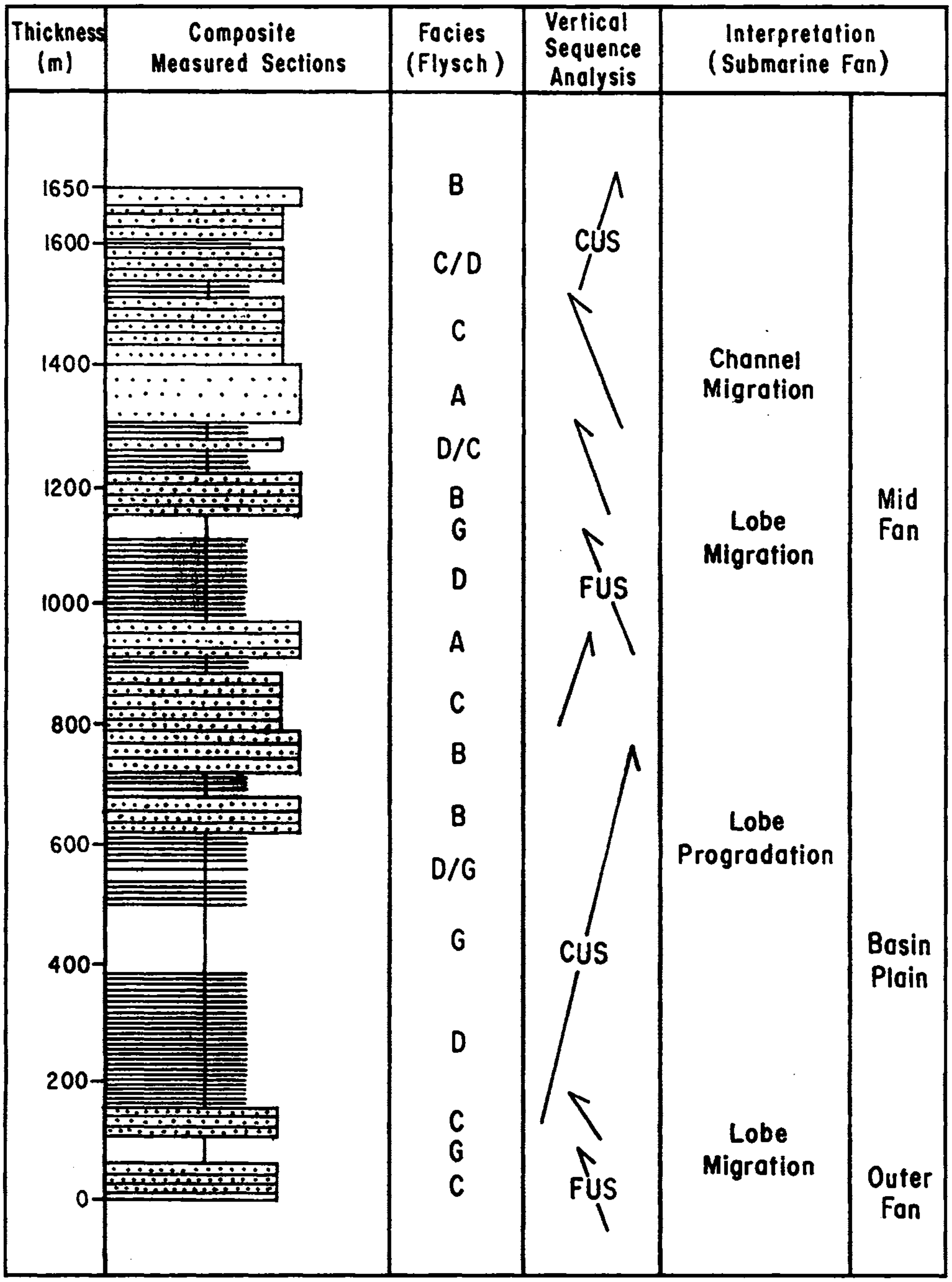

Figure 20. Composite measured sections of Unit III (Pelagus Member) in the Selangau area by Lau (1995) showing typical submarine fan sediments.

occur (see Fig. 15). These folds are possibly drag folds within a bigger fold limb, as indicated by the occurrence of fold limb with more than 1 km wavelength. The presence of numerous small scale slump folds within the fold limbs complicates the structures in this unit. The thrust faults shows transport direction both to the north and south. The steeply dipping limbs of the fold are also commonly cut through by low angle thrust faults.

Near Sibu town, at the airport roundabout, upright, tight folds can also be seen. Here the folds are so tight, that the fold limbs are nearly parallel to each other. The occurrence of slaty cleavage is restricted to the core of the fold.

UNIT IV (UPPER EOCENE-UPPER OLIGOCENE)

Distribution and Lithology

This unit outcrops in two areas, at the southern belt near Sri Aman, represented by the Silantek Formation and at the northern belt near Batang Balingian-Tatau, represented by the Tatau and Buan Formations. In the northern belt, a large part of the unit is overlain by Neogene sediments (e.g. Nyalau Formation). The unit is composed mainly of sandstones and shales, with minor occurrence of conglomerates, limestones, marls and volcanic rocks.

In the northern belt, near Arip bridge, the sediments shows common cross-beddings and vertical burrows typical of shallow water deposits. Interbeds of conglomerates, limestones, marls and volcanic rocks have also been recorded by previous workers (e.g. Wolfenden, 1960; Gasah, 1984). The sequence here have been estimated by Wolfenden to be more than 3 km.

Near Tatau Town, the sediments consists of interbedded sandstones and shales of various thickness, typical of turbidite and mass flow deposits. Some of the shale beds show vertical burrows. In the thinner sandstone and shale beds, soft sediment folding is common (Fig. 19). The occurrence of slump folds and vertical burrows suggests an unstable slope depositional environment.

In the southern belt, near Marup Ridge the unit consist of a thick sequence of grey to black carbonaceous shale and mudstone alternating with sandstones, occasionally rippled-top and cross-bedded, typical of shallow water deposits. This unit, mapped as the Silantek Formation has been well documented by Tan (1979). Tan estimated its thickness to about 5 km. Paleocurrent directions indicate a source from the north-northeast.

Age

Since the sediments in this unit is well dated, no attempts were made to do further age determination. In the Tatau area, the Tatau and Buan Formations have been dated to range in age from uppermost Eocene to Oligocene by Wolfenden (1960). The limestone lenses yielded Upper Eocene age, whereas the marl yielded Oligocene age.

In the Sri Aman area, the Silantek Formation have been dated by Tan (1979) to be possibly Upper Eocene.

Boundary

In the southern belt, the unit is in fault contact with Unit II along the Lupar Fault Zone (see Fig. 6). In the northern belt, the boundary of the unit with Unit II is interpreted to be faulted too, based on the drastic change in lithology and structure between them. The boundary of the unit with Unit III remains uncertain, due to the similarity of their lithology and structure. It is possible that some of the unit might be present within the Unit III belt.

Structure

This unit also shows two contrasting deformational style. The northern belt is characterized by the development of tight upright folds and thrust faults, whereas in the southern belt, the unit is only gently folded.

In the northern belt, near Arip bridge, numerous small to medium scale fold occur with their axis trending approximately E-W. Near Tatau Town, the beds are nearly vertical and overturned in places, indicating the presence of tight fold. The presence of numerous slump folds within larger fold limbs also complicates the structures here. Tjia *et al.*, (1987) who did a detailed structural analysis of the sediments here showed at least two main tectonic transport directions, to the north and west.

In the southern belt, near Marup Ridge the unit dips moderately to the south, forming a large syncline trending NW-SE. The dips are however, steeper near its northern margin, possibly due to the presence of the Lupar Fault Zone.

REGIONAL RELATIONSHIP OF UNITS

The relationship of the units with each other shows a systematic arrangement in terms of their distribution, age and degree of deformation. There appears also a repetition of similar depositional environment in each unit.

Except for the minor occurrence of Unit II and IV towards the north and south, the distribution of the four units generally occupies a specific belt, mostly separated by major fault zones (see Fig. 2). From the south, Units IV and II is separated by the Lupar Fault, Units I and II by the Sebangkoi Fault, Units II and III by the Kanowit-Song Fault, and Units III, II and IV by the Balingian-Bukit Mersing Faults. The age of each unit progressively youngs towards the north.

Each unit shows a variety of depositional environments, ranging from shallow marine, unstable slope to abyssal plain. The occurrence of limestones is limited to Unit II towards the south and Unit IV towards the north. The source of sediments generally comes from the southwest.

Except for the occurrence of Unit II and IV near Batang Rajang and Batang Balingian, the episode and intensity of deformation decreases as the unit gets younger towards the north (Fig. 21). The moderate regional metamorphism to slate and sub-phyllite, and the occurrence of refolded fold and numerous quartz veins is mainly restricted to Unit I and a large part of Unit II. The higher degree of deformation and metamorphism is mainly concentrated along the major fault zones. Units I and II also experienced two different compressional directions from the NE-SW and NW-SE, compared to only one in the younger units. The two contrasting deformational styles seen in Unit II and IV, are located in different areas, having different depositional settings.

DEPOSITIONAL AND TECTONIC MODEL

The difference in age, degree of deformation and lithology of each unit is difficult to reconcile with the concept that an Upper Eocene subduction was solely responsible for the deformation of the Upper Cretaceous, Paleocene and Eocene sediments in Central Sarawak. The facts are more easily explained on the assumption that deposition and deformation of the Paleogene sediments occurred progressively with time. Each culmination of tectonic events was marked by a different tectono-stratigraphic unit, irrespective of their site of deposition and style of deformation.

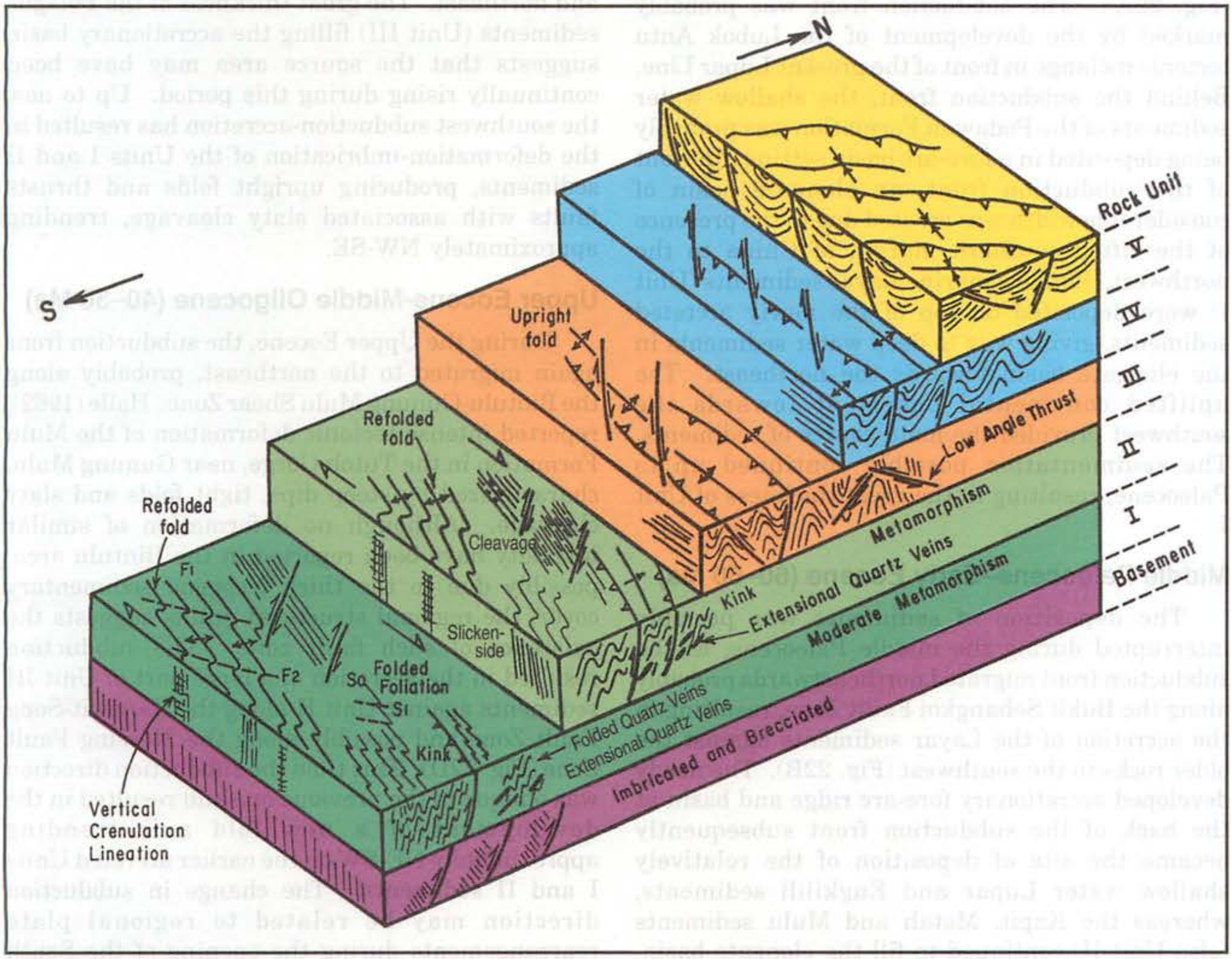

Figure 21. Summary of structural styles in the Paleogene sediments of Central Sarawak showing an overall decrease in intensity of deformation as the units get younger to the north.

In fact this assumption has been mentioned earlier by Wolfenden (1960) and Haile (1962) and interpreted later in terms of subduction process by Hamilton (1979). The four stages of the Belaga Formation proposed by Wolfenden (1960) is typical of an accreted terrain according to Hutchison (1989). However, the earlier workers, in the absence of a more detailed sedimentological and structural informations was unable to elaborate on the development of the Eocene accretionary complex.

The subduction-accretion of the Palaeogene sediments is elaborated further below based on the additional informations gathered during the present study (Fig. 22). For completeness purpose, other rock units are also included in the discussion.

Upper Cretaceous–Early Paleocene (90–60 Ma)

Southwest subduction of a Mesozoic oceanic lithosphere under West Sarawak continental basement during the Upper Cretaceous resulted in the accretion of ophiolitic basement rocks and its sedimentary cover south of the present Lupar Line (Fig. 22A). The subduction front was probably marked by the development of the Lubok Antu tectonic mélange in front of the present Lupar Line. Behind the subduction front, the shallow water sediments of the Pedawan Formation was probably being deposited in a fore-arc basin setting. In front of the subduction front, an elongate basin of considerable width was created due to the presence of the rifted southern margin of China to the northwest. Shallow marine Layar sediments (Unit I) were deposited on top of the newly accreted sediments, giving way to deep water sediments in the elongate basin towards the northeast. The uplifted continental basement towards the southwest provided the main source of sediments. The sedimentation possibly continued up to Paleocene, resulting in the great thickness of Unit I.

Middle Paleocene–Early Eocene (60–50 Ma)

The deposition of sediments was possibly interrupted during the middle Paleocene, as the subduction front migrated northeastwards probably along the Bukit Sebangkoi Fault Zone, resulting in the accretion of the Layar sediments against the older rocks to the southwest (Fig. 22B). The newly developed accretionary fore-arc ridge and basin at the back of the subduction front subsequently became the site of deposition of the relatively shallow water Lupar and Engkilili sediments, whereas the Kapit, Metah and Mulu sediments (also Unit II) continued to fill the elongate basin, through the northeast progradation and migration of submarine fan lobes and channels. Shallow water carbonates may have developed along the accretionary ridge. The continued movement due to the accretionary process might have resulted in the widespread occurrence of slump structures at the edge of the accretionary ridge, especially in the Engkilili sediments. Further southwest the shallow water sediments (Kayan Formation) continued to fill the older accretionary fore-arc basin.

Middle Eocene-Upper Eocene (50–40 Ma)

At the end of Lower Eocene, the subduction front again migrated northward probably along the Bukit Mersing Fault Zone, resulting in the accretion of a large part of Unit II sediments against Unit I along the Sebangkoi Fault Zone (Fig. 22C). Due to the subduction process, a large part of the previously accreted Unit I sediments was probably uplifted and exposed to weathering and erosion at this time, supplying coarse-grained sediments to the newly formed accretionary fore-arc basins and the narrowing elongate basin to the northeast. Towards the southwest, the older fore-arc basins continued to be filled by sediments both from the southwest and northeast. The great thickness of the Pelagus sediments (Unit III) filling the accretionary basin suggests that the source area may have been continually rising during this period. Up to now the southwest subduction-accretion has resulted in the deformation-imbrication of the Units I and II sediments, producing upright folds and thrusts faults with associated slaty cleavage, trending approximately NW-SE.

Upper Eocene-Middle Oligocene (40–30 Ma)

During the Upper Eocene, the subduction front again migrated to the northeast, probably along the Bintulu-Gunung Mulu Shear Zone. Haile (1962), reported intense tectonic deformation of the Mulu Formation in the Tutoh Gorge, near Gunung Mulu, characterized by steep dips, tight folds and slaty cleavage. Although no deformation of similar intensity have been reported in the Bintulu area, possibly due to the thick Neogene sedimentary cover, the regional structural grains suggests the existence of such fault zone. The subduction resulted in the accretion of a large part of Unit III sediments against Unit II along the Kanowit-Song Fault Zone and possibly along the Mersing Fault Zone (Fig. 22D). This time the subduction direction was oblique to the previous one and resulted in the development of a new fold axis trending approximately NE-SW on the earlier accreted Units I and II sediments. The change in subduction direction may be related to regional plate rearrangements during the opening of the South China Sea basin at this time. The subduction process also resulted in the extrusion and intrusions

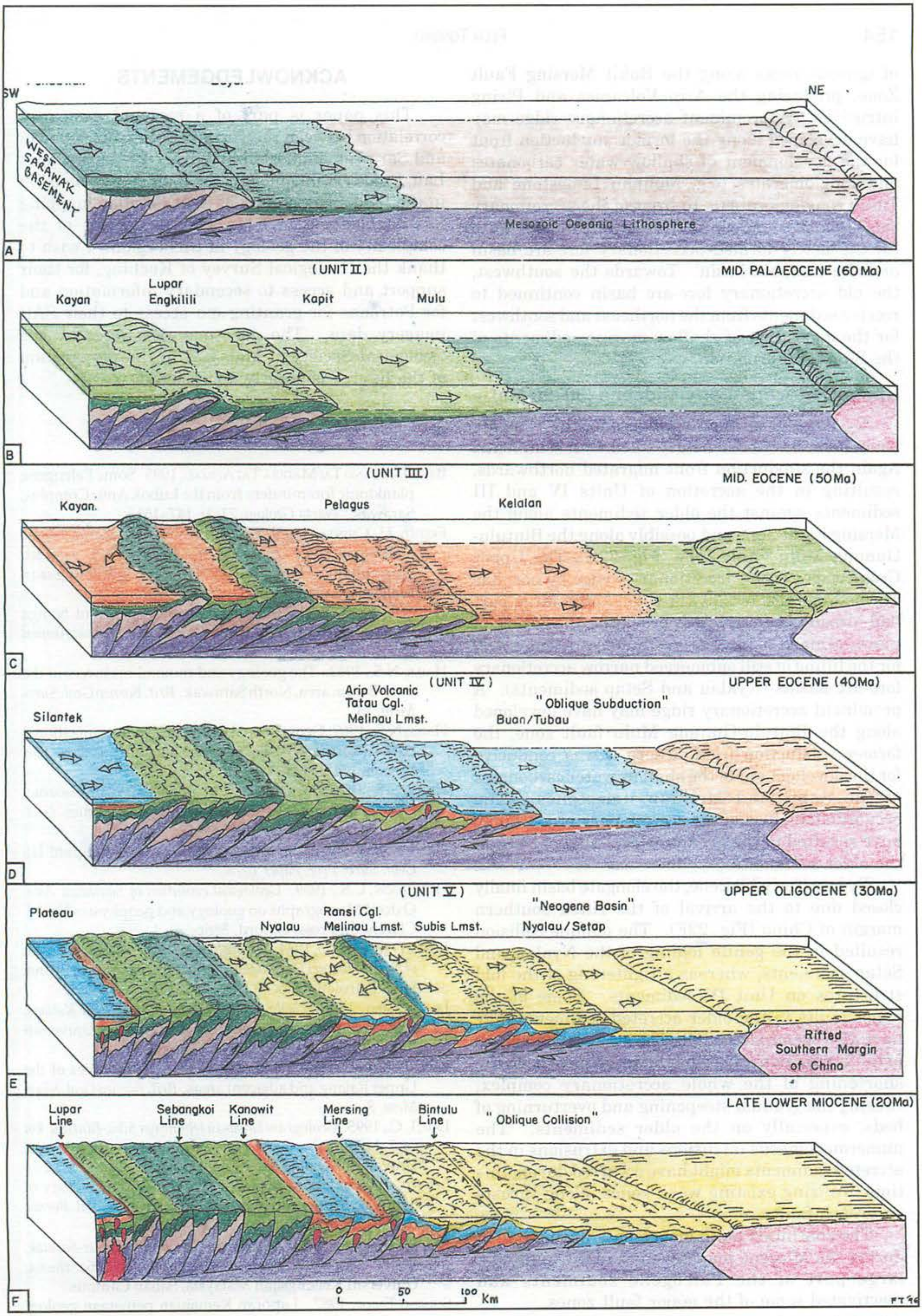

Figure 22. Schematic sedimentation and tectonic model for the Paleogene sediments of Central Sarawak involving subduction-accretion processes. The model is based on the assumption that deposition and deformation of the sediments occurred progressively with time as the subduction front migrated northwards. See text for further discussion.

of igneous rocks along the Bukit Mersing Fault Zone, producing the Arip Volcanics and Piring intrusives. A prominent accretionary ridge may have developed along the former subduction front for the development of shallow water carbonates and conglomerates (e.g. Melinau Limestone and Tatau conglomerates). In front of the accretionary ridge, shallow to deep marine sediments began to fill the newly formed accretionary fore-arc basin and the elongate basin. Towards the southwest, the old accretionary fore-arc basin continued to receive sediments from the northeast and southwest for the deposition of shallow marine sediments of the Silantek Formation.

Upper Oligocene-Early Miocene (30–20 Ma)

By the end of Middle Oligocene, the elongate basin must have been nearly filled with sediments. Again the subduction front migrated northwards, resulting in the accretion of Units IV and III sediments against the older sediments along the Mersing Fault Zone and possibly along the Bintulu-Gunung Mulu Fault Zone (Fig. 22E). The Upper Cretaceous-Eocene accretionary wedge by now has reached more than 200 km wide, and a large part had already been uplifted, providing the source of coarse-grained sediments (e.g. Ransi conglomerates) for the filling of still submerged narrow accretionary fore-arc basins (Nyalau and Setap sediments). A prominent accretionary ridge may have developed along the Bintulu-Gunung Mulu fault zone, the former subduction front, where it was conducive for the development of the shallow water carbonates of the Subis and Melinau limestones. The accumulated effect of the accretionary process may have resulted in the gradual steepening of beds on the older sediments.

By late Early Miocene, the elongate basin finally closed due to the arrival of the rifted southern margin of China (Fig. 22F). The oblique collision resulted in the gentle folding of the Nyalau and Setap sediments, whereas a tightening of the fold structures on Unit IV sediments. Some of the major faults in the older accreted sediments may have also been reactivated. The accumulated effect of the subduction and collision would have been the shortening of the whole accretionary complex, causing the gradual steepening and overturning of beds, especially on the older sediments. The numerous igneous intrusions and extrusions in the accreted sediments might have occurred during this time, utilizing existing weak zones, along thrusts or wrench faults.

The continued plate movements in this region during the Miocene may have gradually uplifted a large part of the Paleogene sediments and reactivated some of the major fault zones.

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