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The origin of the 'circular basins' of Sabah, Malaysia

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Abstract: Surface mapping, dating and radar image study of strata in southern Sabah (northern Borneo) have made it possible to revise the stratigraphy and reinterpret the structure and tectonic evolution of the area. Early Miocene regional unconformity may be equivalent to the Deep Regional Unconformity recognised offshore, below which the succession can be resolved into an Eocene accretionary complex age overlying an ophiolitic basement, and an upper Paleogene deep-water succession which formed in a forearc. The Paleogene deposits underwent syn-depositional deformation, including the development of extensive mélanges, all of which lie below the unconformity. Localised limestones were deposited followed after a period of uplift and erosion in the Early Miocene, followed by an influx of clastic sediments deposited in delta and pro-deltaic environments in the Middle Miocene. These deltaic to shallow marine deposits form two coarsening-upward successions, mapped as the Tanjong and Kapilit Formations. The total thickness of these two formations remaining in the southern Sabah Basin amounts to 6,000 m, about half of previous estimates.

The Early Miocene unconformity is interpreted to be the result of deformation and uplift following underthrusting of continental crust of the South China Sea which terminated Paleogene subduction beneath North Borneo. Renewed subsidence led to the development of a major Miocene depocentre above the older forearc accretionary complex. A new tectonic model is proposed for southern Sabah whereby a major transpressional deformation probably occurred during the Late Pliocene and the Tanjong and Kapilit Formations were deformed into broad NW-SE-trending synclines separated by narrow anticlines. The anticlines are sub-parallel to major faults and associated with high angle reverse faults, and positive flower structures. Secondary fold-faults formed oblique to the major faults. The structural style suggests that the NW-SE trending faults acted as major left-lateral transpressional zones and possibly produced large-scale contractional duplexes. The faults may in part be reactivated basement structures. This deformation uplifted the area and is termed here the Meliau Orogeny. Renewed extension during the Quaternary caused some sequence repetition and widened the original synclines. The 'subcircular- to elliptical-shaped basins' of the Meliau, Malibau and Tidung areas are structurally controlled synclines and interpreted as remnants of a single large basin, deformed in the NW-SE trending transpressional fault zones.

INTRODUCTION

The geology of Sabah, a province of Malaysia in the northern part of Borneo (Figs. 1 and 2), has been the subject of a number of studies, some regional in nature (e.g. Hutchison, 1988; Hutchison *et al.*, 2000; Rangin *et al.*, 1990), others focused on particular areas or aspects of the geology (Clennell, 1991; Tongkul, 1995; Hutchison, 1996; Noad, 1998). Previous geological maps of Sabah (Wilford, 1967; Lim, 1985) indicate the distribution of the main rock formations.

The main tectonic elements of Sabah includes a the major fold-thrust belt trending north-northeast in the west and bending to the east and southeast towards the northeastern part of Sabah (Fig. 2). This arcuate belt consists of the deep-marine Eocene-Lower Miocene Rajang-Crocker accretionary prism related to southeasterly subduction of the proto-South China Sea (Rangin *et al.*, 1990; Tongkul, 1990; Hall, 1996). Much of the eastern part of Sabah consists of an ophiolite complex, the mélanges and broken formations. The ophiolitic rocks are considered to form the basement to the sediments of Sabah (Hutchison, 1989). Chert and other associated deep-marine sediments overlying the ophiolite are Lower Cretaceous to Eocene in age (Jasin *et al.*, 1985).

The broken formations and mélanges of Sabah show characteristics of tectonic, sedimentary and diapiric origin and were suggested to have formed in Early Miocene (Clennell, 1991; Balaguru, 2001). In the Late Early Miocene they were uplifted and shallow water sediments were deposited unconformably on the pre-Neogene rocks which are more intensely deformed. The Neogene sediments are mostly shallow marine to fluvio-deltaic and contain coal beds and have formed unusual sub-circular to elliptical shaped and fault bounded areas. They are about 20-30 km wide and known as 'circular basins' of Sabah, such as the Meliau, Malibau, Tidung, Bangan and Bukit Garam 'sub-basins' (Fig. 2). However, the detailed structural style and architecture of the Neogene sediments has not been studied before. Their structural relationships with the regional structural trend have often been simplified or not been considered. The structural controls, including timing,

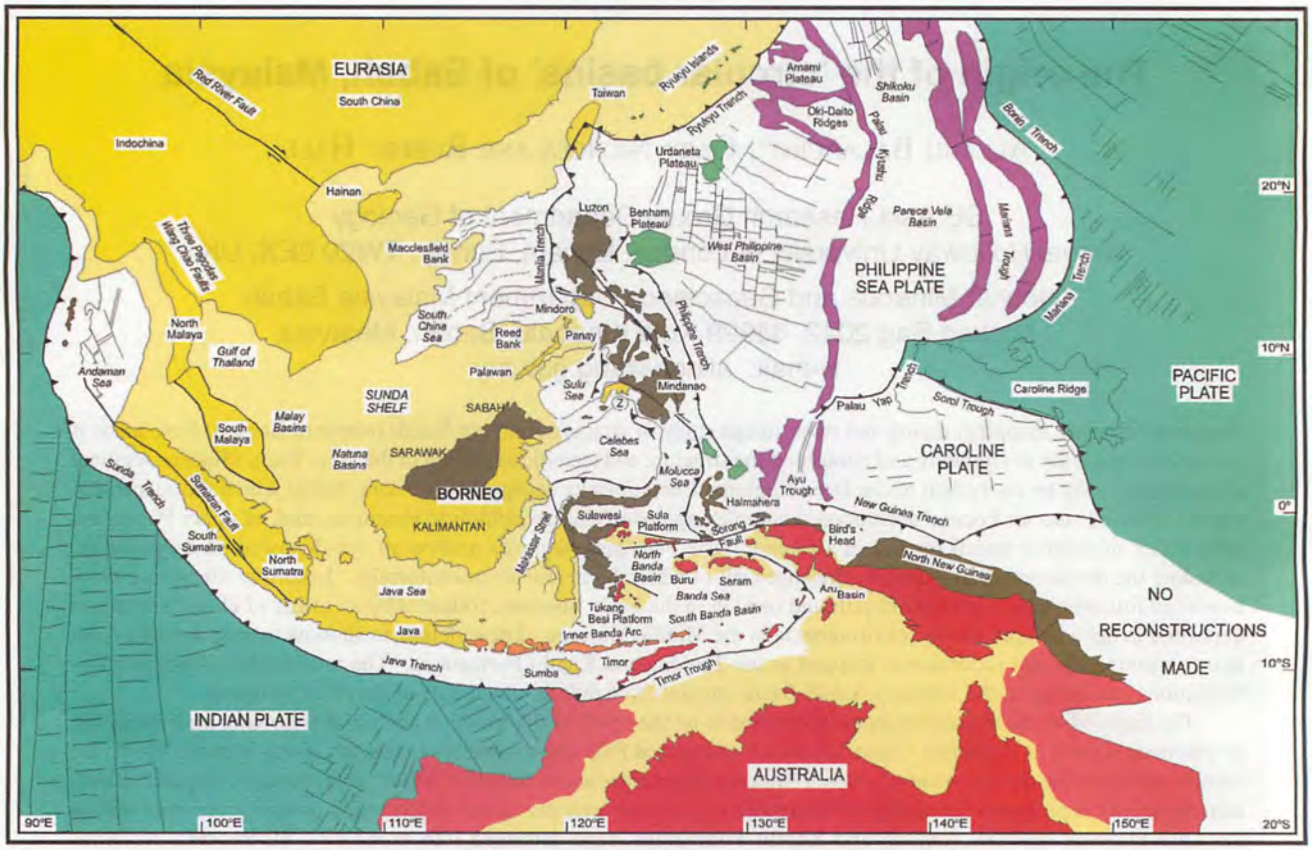

Figure 1. Simplified present-day tectonic configuration of SE Asia (from Hall, 1996) and Borneo in regional context.

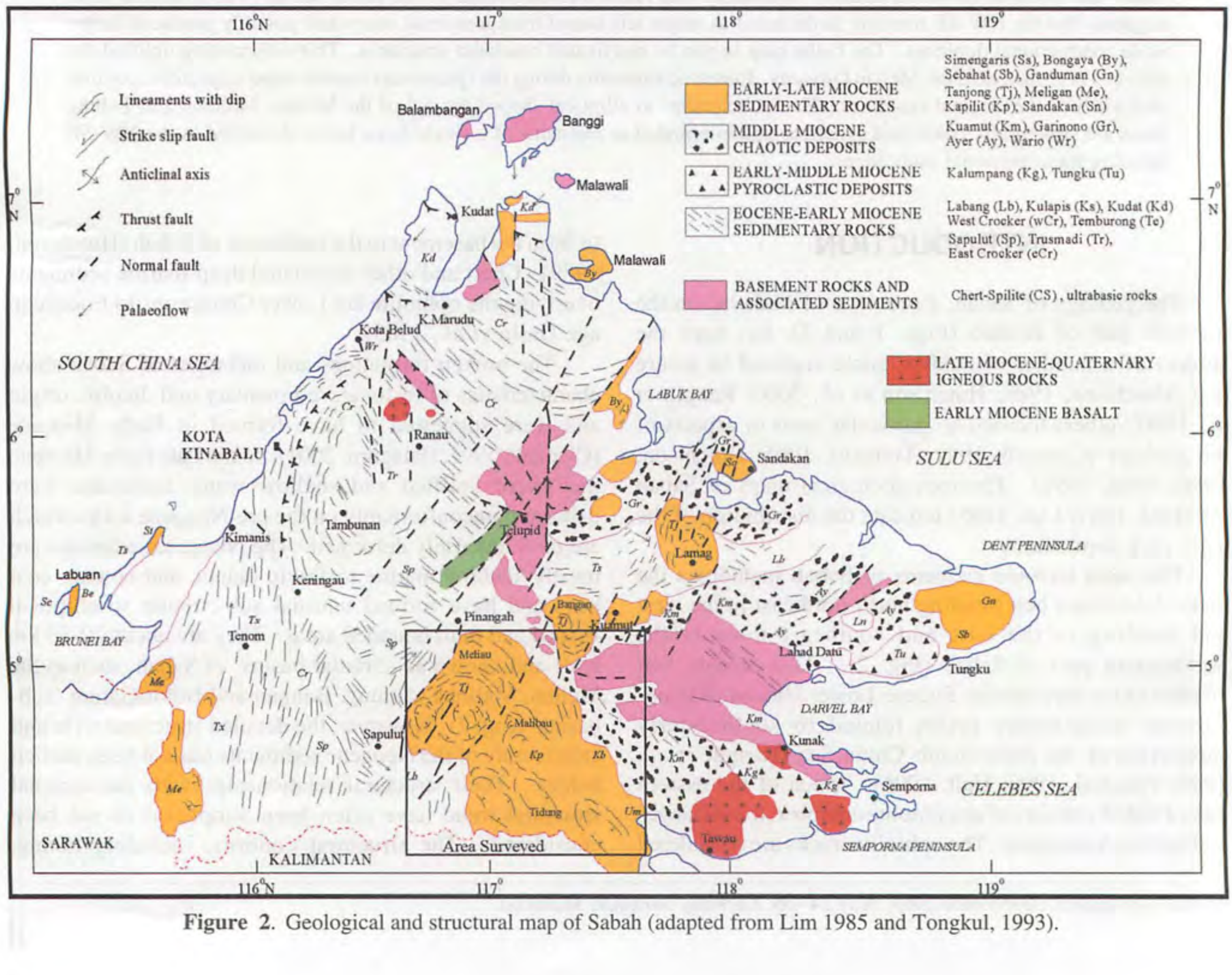

Figure 2. Geological and structural map of Sabah (adapted from Lim 1985 and Tongkul, 1993).

basement controls and fault orientation, on basin formation in the south-central Sabah basin are poorly known and described. The mechanism of how these structures developed in response to tectonic activity of this region is not fully explained.

Synthetic-aperture radar (SAR) imagery for the area has provided remotely-sensed data which are useful despite the almost permanent cloud cover of the area and enabled interpretation of the structural lineaments and morphology of the study area. Biostratigraphic dating using nannofossils has proved to be more successful than other organisms, and has made it possible to constrain the ages of the stratigraphic units and timing of events. Access to the area (Fig. 3) is provided by logging roads.

TECTONIC SETTING

The island of Borneo formed by the Mesozoic accretion of microcontinental fragments, ophiolite terranes and island arc crust onto a Palaeozoic continental core (Hamilton, 1979; Hutchison, 1989; Metcalfe, 1996) (Fig. 1). At the beginning of the Cenozoic Borneo formed a promontory of Sundaland (Hall, 1996, 2002), partly separated from Asia by the proto-South China Sea. The oceanic part of the proto-South China Sea was subducted during the Paleogene and a large accretionary complex formed along the northwestern margin of Borneo. In the early Miocene uplift of the accretionary complex occurred as a result of underthrusting of thinned continental crust in northwest (Hamilton, 1979; Taylor and Hayes, 1983; Tan and Lamy, 1991; Hazebroek and Tan, 1993). Uplift may have resulted also from shortening due to the counter-clockwise rotation of Borneo between 20 and 10 Ma (Fuller *et al.*, 1991; Hall, 1996, 2002) as a consequence of Australia-SE Asia collision. Large volumes of sediment were shed into basins, which lie offshore to the west, north, and east of Borneo, and into a Neogene basin which is currently exposed in large areas of eastern and southern Sabah (Hall and Nichols, 2002). In southeast Sabah, the Miocene to Recent island arc terranes of the Sulu archipelago extend onshore into Borneo (Kirk, 1968): the older volcanic arc was the result of SE-dipping subduction (Hall, 1996; Hall and Wilson, 2000) but the younger volcanics are likely to be the result of NW-dipping subduction of the Celebes Sea (Hall and Wilson, 2000; Chiang, 2002).

PREVIOUS STRATIGRAPHIC SCHEMES AND MODELS

The original lithostratigraphic framework of the study area (Figs. 4 and 5) was formalised by Collenette (1965) who recognised eleven formations and classified them in relation to geosynclinal development. The five oldest formations were placed in the Rajang Group, and the six youngest in the Kinabatangan Group (Table 1). He proposed that sediments of the Oligo-Miocene Kinabatangan Group were deposited in epigeosynclinal basins resting on the eugeosynclinal basement of the Rajang Group of Cretaceous to Oligocene age.

In more recent syntheses of the stratigraphy of Sabah summarised in Clennell (1996) and Hutchison *et al.* (2000) a late Eocene unconformity has been recognised which excludes the West Crocker and Kulapis Formations from the Rajang Group. A Middle Miocene unconformity was interpreted to separate the Tanjong Formation (and the related Sandakan Formation to the north) from the older, deeper marine deposits and mélanges. These schemes were based on studies of more accessible parts of Sabah to the north and west of the study area.

Collenette (1965) proposed that the Neogene sub-basins originally comprised one major basin (Fig. 4). Lee and Tham (1989) and Clennell (1991) proposed differential loading and subsidence into muddy mélange and diapirism as possible mechanism for their origin. Tongkol (1993) suggested the NE-SW trending regional strike-slip faults controlled the formation of isolated individual sub-basins.

REVISED STRATIGRAPHY OF SOUTHERN SABAH

The revised stratigraphy of southern Sabah is shown in Figure 4 and Table 1 and differences can be seen by comparing Figures 5 and 6. The important boundary between the Labang/Kuamut Formations and the overlying Tanjong (and locally the Gomantong Limestone) Formations is significant because it is interpreted to be a regional unconformity which separates a lower succession of deformed and indurated deep water sediments and mélanges from gently folded, less cemented, shallow marine and deltaic deposits above. A revision of boundaries is therefore required to ensure that the group definitions conform to general stratigraphic practice and also to reflect the stages in the basin development. The Tanjong, Kalabakan, Kapilit and Simengaris Formations are now separated from the Kinabatangan Group and are reclassified into a new group, the Serudong Group, named after the major river that cuts through the Formations.

The Labang and Kuamut Formations remain in the Kinabatangan Group and in southern Sabah are Oligocene to Early Miocene in age. In the Serudong Group, the Kalabakan Formation is now considered to be a lateral equivalent of the Tanjong Formation and not part of the mélange unit as shown in the existing geological map of Lim (1985). The Tanjong and Kalabakan Formations are dated as late Early Miocene to Middle Miocene. The Middle to Upper Miocene Kapilit Formation is now placed above the Tanjong Formation, from which it is separated by a regional erosional surface. Previously the Tanjong and Kapilit Formation were thought to be lateral equivalents of the same age (Collenette, 1965; Lim, 1985). The Simengaris Formation is unconformable above all older Miocene sediments and was deposited during the latest Miocene to Early Pliocene.

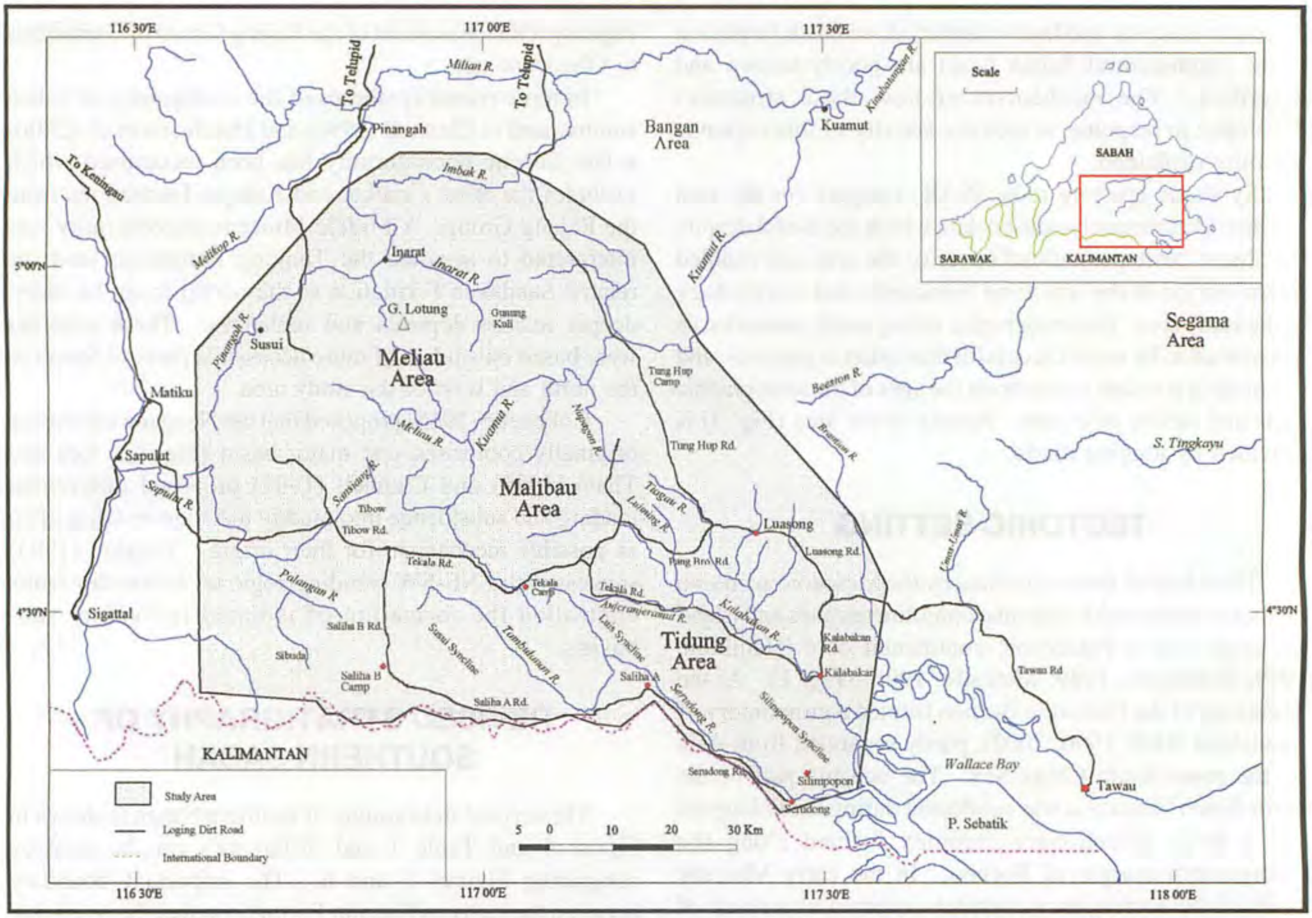

Figure 3. Map of the main rivers, logging roads and settlements in the study area of southern Sabah.

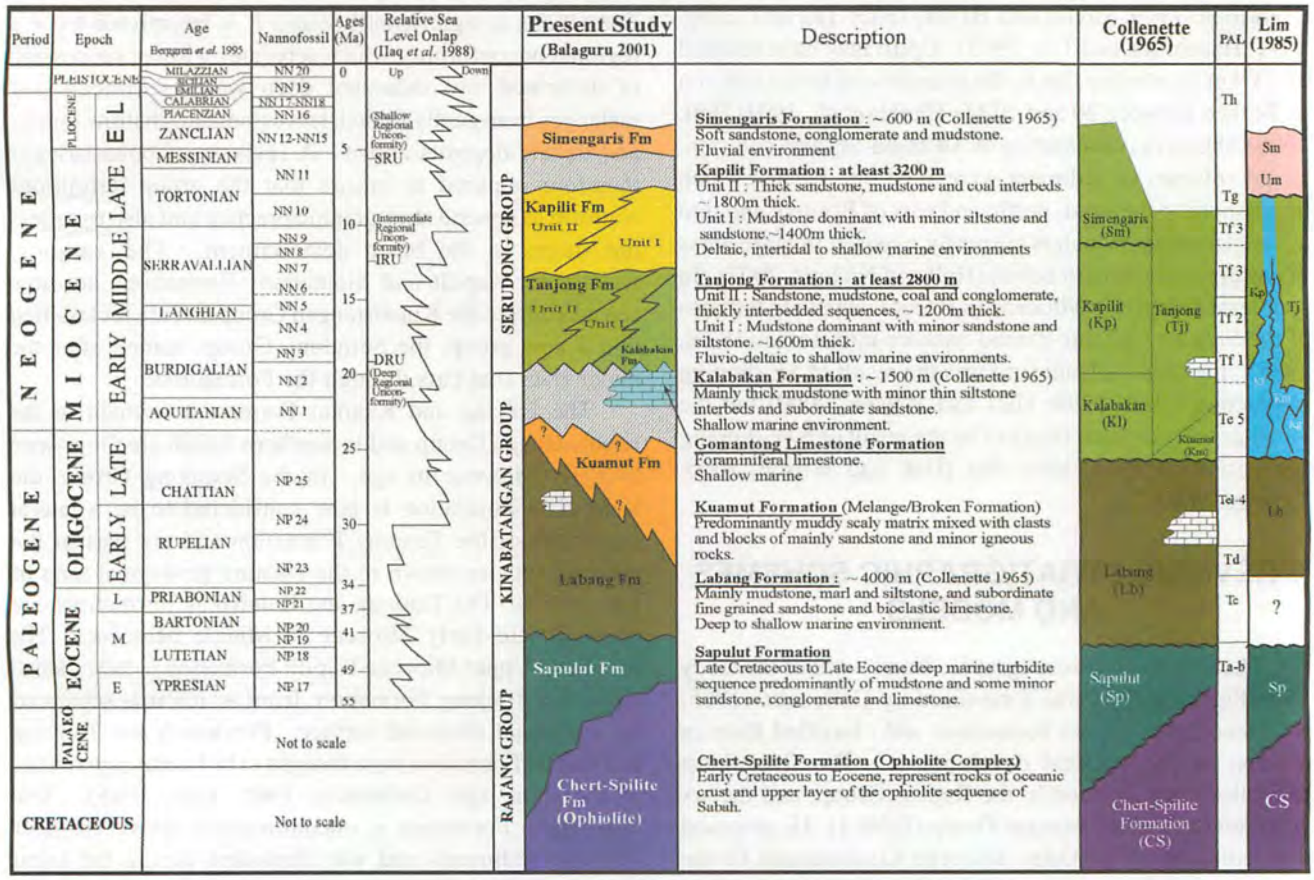

Figure 4. Revised stratigraphy of the southern Sabah area based on this study compared with previous schemes.

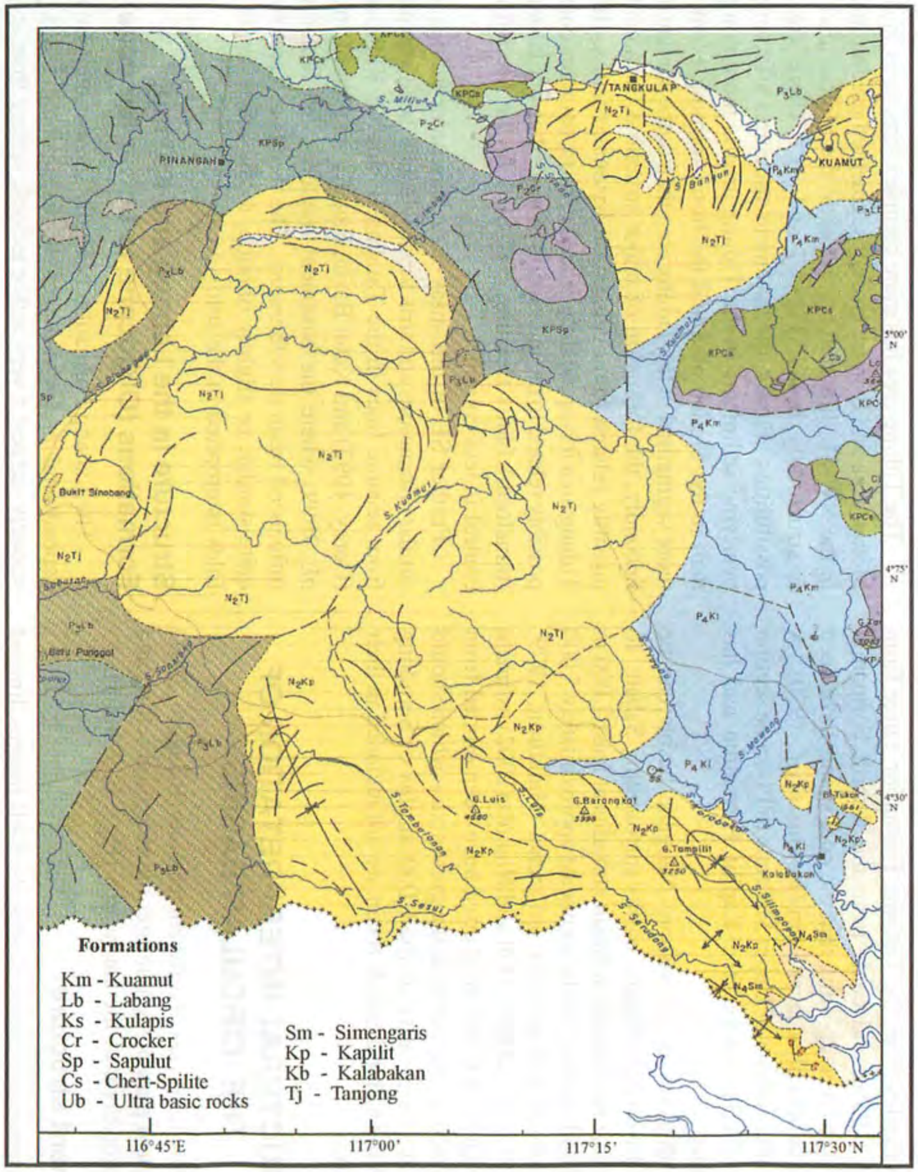

Figure 5. Previous geological map of southern Sabah (after Lim, 1985).

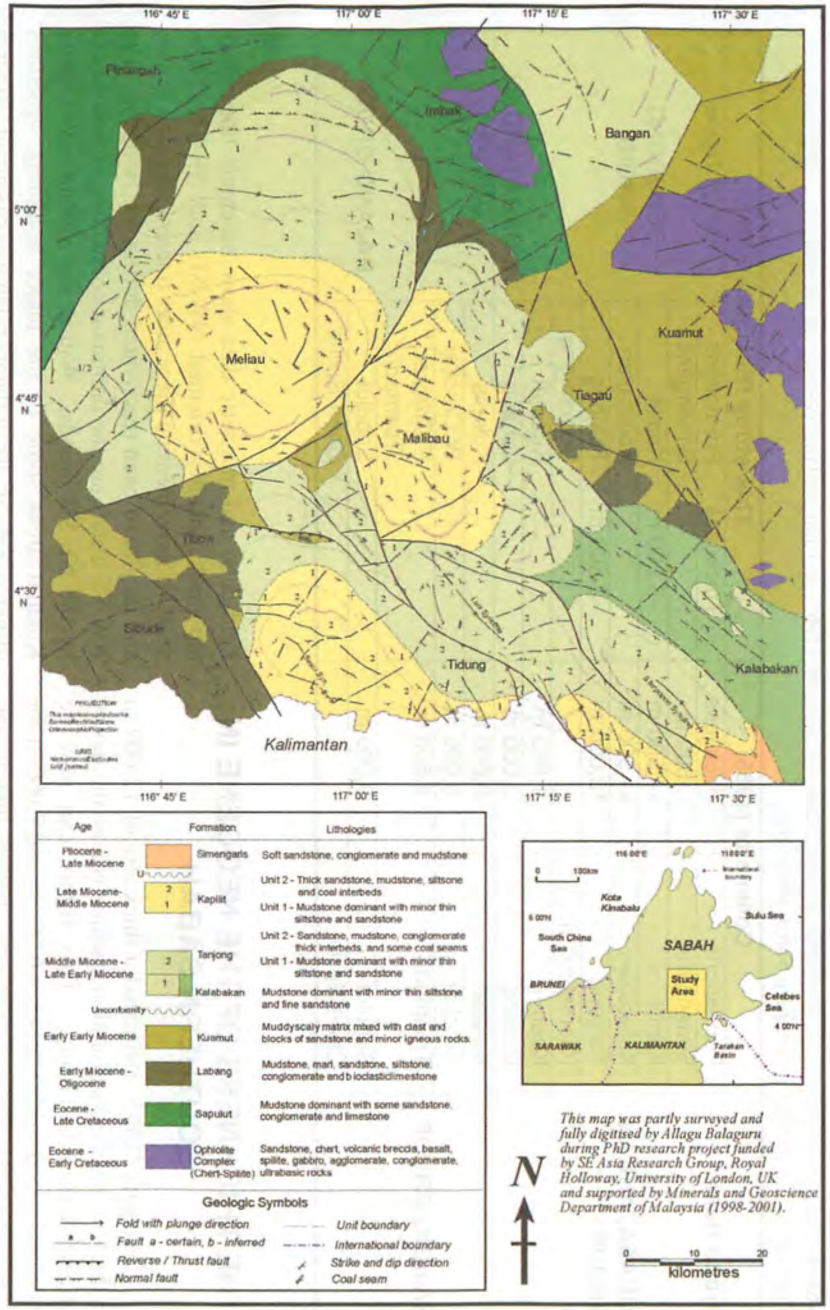

Figure 6. Revised geological map of southern Sabah, Malaysia (Balaguru, 2001).

Table 1. A comparison of the stratigraphic nomenclature of Collenette (1965) and that used in this study for the southern Sabah study area.
* Formations not present in southern Sabah study area.

	Collenette (1965)		This study (Balaguru 2001)		
Group Name	Formations	Thickness	Thickness	Formations	Group Name
	Simengaris	>600 m		Simengaris	
	Kapilit	>4,500 m	~3,200 m	Kapilit	SERUDONG
KINABATANGAN	Kalabakan	>1,500 m		Kalabakan	GROUP
GROUP	Tanjong	12,000 m	~2,800 m	Tanjong	
	(Gomantong)			Gomantong	
	Kuamut	1,500 m		Kuamut	
	Labang	3,000 m		Labang	KINABATANGAN
	Kulapis	3,000 m		Kulapis *	GROUP
	Crocker	6,000 m		*W Crocker* *	
RAJANG GROUP	Trusmadi	4,500 m		*E Crocker* * *Trusmadi* *	
	Sapulut	9,000 m		Sapulut	RAJANG GROUP
	Chert-Spilite			Chert-Spilite	

THE THICKNESS OF THE NEOGENE IN SOUTHERN SABAH

Collenette (1965) estimated a thickness of 12,000 m for the Tanjong Formation alone, which is now the newly defined Serudong Group. This figure can now be considerably reduced to between 6,000 m and 7,000 m for the whole of the group of Neogene shallow marine and deltaic sediments. Despite these revisions, there is evidence that much greater thicknesses of Neogene strata formerly covered the area. Vitrinite reflectance (Vr%) measurements on coal samples from the Tanjong Formation range from 0.85% to 0.93%, and coals from the Kapilit Formation 0.58% to 0.67% suggesting that the coal seams have been buried to depths of at least 3 km (Heroux *et al.*, 1979). A considerable amount of Upper Miocene to Pliocene section which formerly covered the Kapilit Formation and has been eroded.

The thicknesses of onshore Neogene basins can be compared with the offshore basins surrounding Sabah: to the northeast the Sandakan Basin contains at least 7,000 m and the Tarakan Basin to the southeast approximately 5,000 m of Miocene and younger sediments (Hamilton, 1979; Hall and Nichols, 2002). Hall and Nichols (2002) estimate the equivalent of 6,500 m of crust have been eroded from all of Borneo above 100 m at the present day which should be seen as conservative as the 6,000 m plus of Serudong Group in the Central Sabah Basin are not included in their calculations.

STRUCTURAL INTERPRETATION OF THE 'CIRCULAR BASINS'

Detailed analyses of different data sets (Balaguru, 2001) have made it possible to interpret the structural setting and deformation style of the study area (Figs. 6, 7 and 8).

Basement structure

Lineaments interpreted using the SAR images, limited field data, and magnetic data show basement lineaments are predominantly oriented NW-SE and NE-SW. The sense of movement on these older lineaments is not known and they have been reactivated during the Neogene. The NW-SE trends are the dominant controlling structures cut by the NE-SW trends. Within the Sibuda and Tiagau/Kuamut areas some of the major bounding structures oriented NW-SE are probably related to basement fractures (e.g. Sibuda and Sinoa-Brantian Faults), they probably bound the basin margins to the NE and SW of the study area.

The Tidung area has more complex structures than the Meliau area and is more closely segmented predominantly in the NW-SE direction compared to the Meliau area that is structurally broad (Figs. 7 and 8). There are two possibilities. Firstly, the basement structures affecting the overlying sediments in the Tidung area is more complex than in the Meliau area and the basin-forming event was more segmented in the Tidung area than in the Meliau area. Secondly, the formation of major structural lineaments is possibly related to movement on basement faults. In the Tidung area it is apparently related to more complex control, possibly related to the interaction of more than one basement (transform) faults trending NW-SE. In the Meliau area control is less complex.

Further SE of the study area, basement fabrics with similar orientations and structural style have been interpreted from seismic lines in the Tarakan Basin, NE Kalimantan (Dorey, 1997) and Kutei Basin, East Kalimantan (Cloke *et al.*, 1999) where the basement fractures and faults have influenced basin development. The trends at Tarakan are quite similar, or slightly oblique, to the major faults and folds interpreted in the study area.

Structure in the Labang and Kuamut Formations (Oligocene to Lower Miocene)

The Labang Formation typically shows abundant syn-depositional and syn-diagenetic extensional faults that strongly suggest a very active tectonic setting from at least

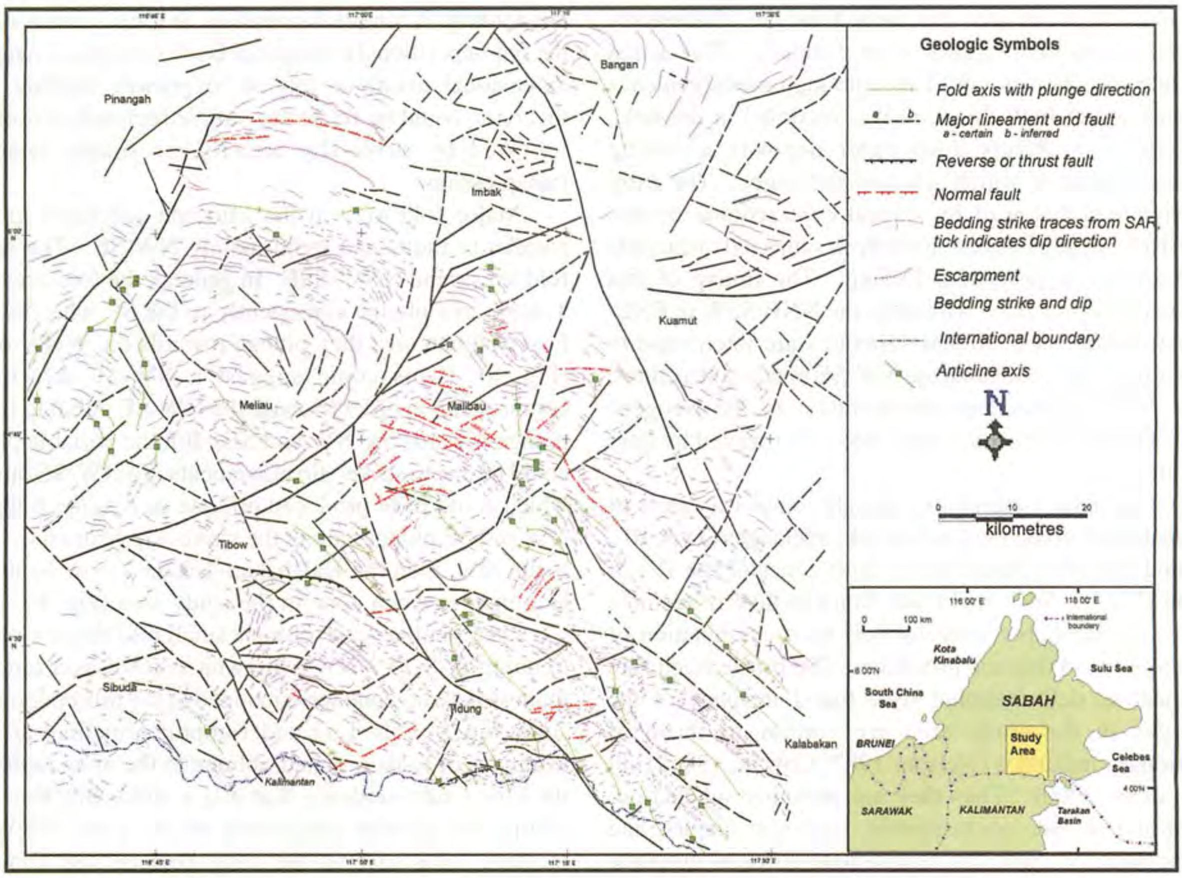

Figure 7. Principal structural lineaments based on integrated field mapping and SAR image interpretation.

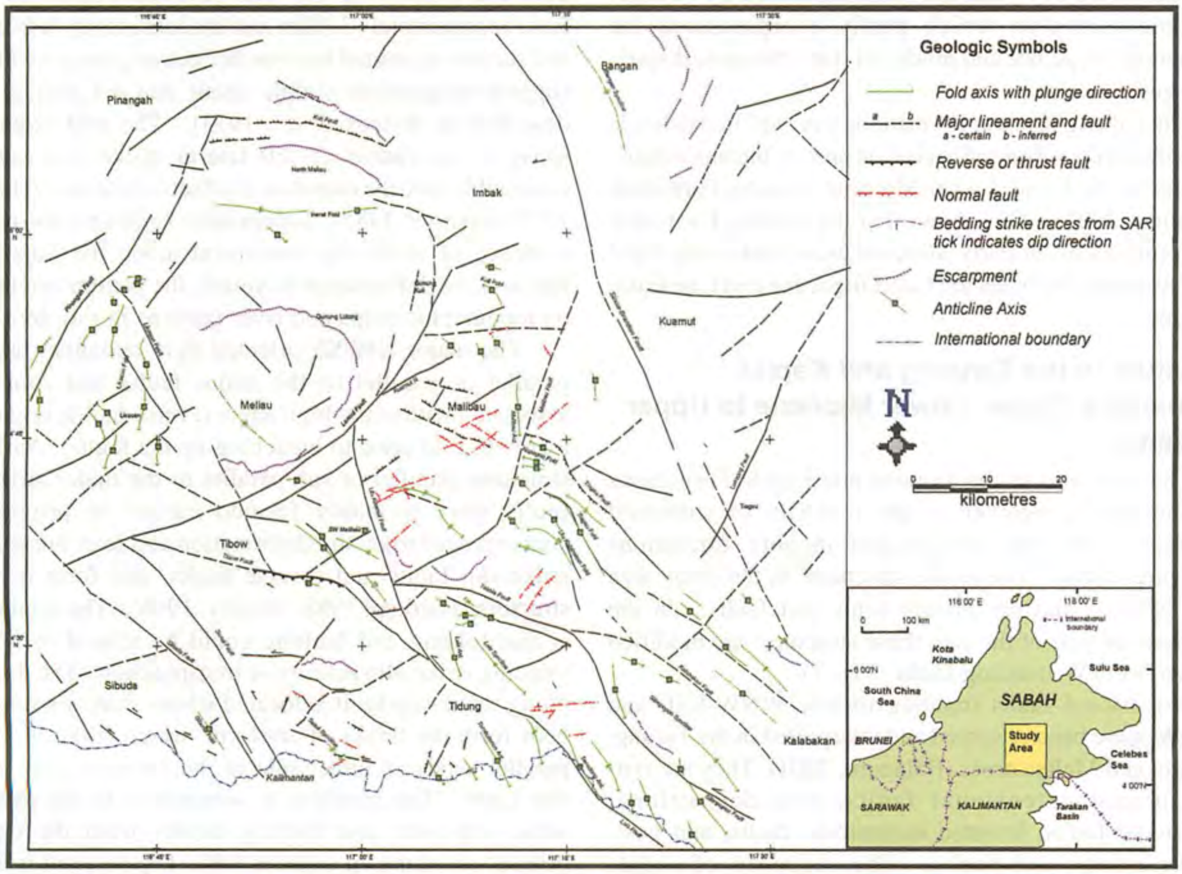

Figure 8. Orientations of major faults and folds in southern Sabah.

the Early Oligocene until the Early Miocene. Differently oriented extensional faults were formed. The actual extension direction is not clear, although some evidence for extension in E-W direction was recorded in the field. The extension affects deep-water deposits including turbidites, some of which are now mélanges. The early extension was followed by several contractional events. Overall the Labang Formation has been subjected to multiple deformation and polyphase folding. The timing of this deformation is not clear. However the NNE-SSW to ENE-WSW trending contractional structures are interpreted to be older (pre-Neogene) than the NW-SE trending structures, as the NW-SE structures are common in the Neogene rocks. The older structures have been overprinted by later structures.

The Kuamut Formation generally shows a range of chaotically deformed mud-rich blocky mélanges (Type III), and mudstone-dominated brittle fault zones (Type IV) of Cowan (1985). Such rocks are found in diverse tectonic settings and probably were formed by a combination of sedimentary and tectonic processes. The brittle fracturing and shearing deformational style found in many of the mélanges in the study area are similar to those of accretionary mélanges (Nelson, 1982; Cowan, 1985; Hall and Wilson, 2000). Thus they are probably subduction-related and include olistostromes, mud-rich diapirs, and tectonic mélanges, probably representing different structural positions in the orogenic wedge (Balaguru, 2001). The characters of older mélanges were enhanced by younger Neogene tectonism which partly overpressured the sedimentary sequence and produced some Neogene diapiric mélanges.

The Labang/Kuamut Formations were uplifted to levels where they were subjected to erosion and are unconformably overlain by the Upper Lower Miocene Tanjong Formation (Balaguru, 2001). This shows that the Labang Formation was deformed by an Early Miocene event, indicating rapid tectonic change between the Late Oligocene and Late Early Miocene.

Structure in the Tanjong and Kapilit Formations (Upper Lower Miocene to Upper Miocene)

The structures of the Tanjong and Kapilit Formations are considered together as the majority of structural lineaments observed are present in both formations (Balaguru, 2001). The major structures in the study area trend NW-SE and are mainly folds and faults. In the northwestern part of the area these structures are modified by later NE-SW trending faults (Fig. 7).

Extensional faults trending mainly WNW-ESE and NE-SW, have been observed and interpreted in the Tidung, Malibau and Meliau areas (Balaguru, 2001). They are syn-depositional extensional faults, post-depositional extensional faults, inverted extensional faults, and post-folding extensional faults. The sequence of events interpreted is: 1) syn-depositional extension, 2) inversion and folding, 3) renewed extension. It is not certain whether the syn-depositional extensional faults were due to a regional extensional event or related to growth faulting. The inversion could be related to simple regional compression followed by strike-slip activity, or simply related to transpression.

Major fold axes in the Miocene sediments are sub-parallel to faults and trend mainly NW-SE. The smaller fold axes trend NNW-SSE. In general, the fold axes in the Tidung area plunge consistently to the SE whereas in the East Malibau area they plunge towards the WNW or NW (Fig. 8). This could suggest a NW-SE direction of compression in order to cause the NW-SE trending folds to plunge towards the NW and SE. But the variable plunges could be due to strike-slip movements in a NW-SE direction which could have produced oblique *en echelon* folds with NW and SE plunges along the strike-slip fault zone. If this is the case, then the Kalabakan-Tekala-Tibow Fault Zone is a major wrench zone in the study area (Fig. 8).

On a smaller scale, oblique small fold-thrust structures trending N-S to NNW-SSE which developed along the main strike-slip zone were mapped in the Silimpopon Fault zone (Fig. 8). The Luis and Tampilit Anticlines are other examples of folds oriented oblique to the main faults. For the Luis Fault, evidence that it is a strike-slip fault is the oblique *en echelon* orientation of the many NNW-SSE trending folds such as the Luis, Poirgon and Tabulanan Anticlines. They show tight folds with fault offsets of fold axes and flanks (Fig. 8). Displacements probably range from approximately 3-9 km and are consistently left-lateral, and further supported by river deflection patterns which all suggest progressive simple shear and rotation (e.g. as described in Wilcox *et al.*, 1973). The fold orientation sense is indicative of left-lateral strike-slip faulting, compatible with the direction of offset of fold axes (Harding, 1973; Sylvester, 1985). Topographic variations also provide evidence of strike-slip movement along the Luis Fault. Because the deformation is young, the pattern can be seen on topographic maps and river patterns in this area.

The major NW-SE oriented tight anticlines are sub-parallel or parallel to the major faults and commonly associated with many high angle reverse faults, suggesting a growth fold prior to breaching by the faults. Anticlinal structures parallel or sub-parallel to the major strike-slip faults were probably formed earlier in progressive convergence strike-slip deformation and later breached by strike-slip faults and reverse faults, and form a flower structure (Harding, 1988; Dooley, 1996). The implication is that folding and faulting could be related to NW-SE trending strike-slip activity or transpression. The through-going strike-slip fault is located where sharply overturned beds form the flanks of antiform, which strike in narrow parallel bands on either side of the through-going strike-slip fault. The antiform is subparallel to the principal strike-slip zone and thereby differs from the oblique orientation of the *en echelon* fold. Dip reversal is abrupt and lack a flextural bend, and the fault architecture is not always symmetric. Stratal offsets along the fault are only apparent and the strike separation may greatly exceed the dip separation. The formation of the flower structure is promoted by convergence in the strike-slip zone by increased strike-slip displacements (Wilcox *et al.*, 1973; Harding, 1985). The large anticlines may represent deformation due to splays of a deep-seated plate-scale transform fault. The orientation of structures is consistent with those generated by transpression of Sanderson and Marchini (1984, Fig. 9). Analogue models of similar structural relationships at Confidence Hill, California were described by Dooley and McClay (1996). Convergent wrenching alters the angular relationships of the structures developed in the borderland, and structures such as folds become sub-parallel to the principal displacement zone (PDZ) at high degrees of convergence (Jamison, 1991; Ben-Avraham, 1992). Naylor *et al.* (1986) has demonstrated R1 Riedel shear angular changes due to rotation of the principal stress (Fig. 9).

The major anticlines in the study area probably represent positive flower structures in a transpressional system (i.e. uplift bounded by strike-slip faults with reverse separation, Harding, 1974, 1985) formed as 'push up' anticlines aligned sub-parallel to the strike-slip fault zones

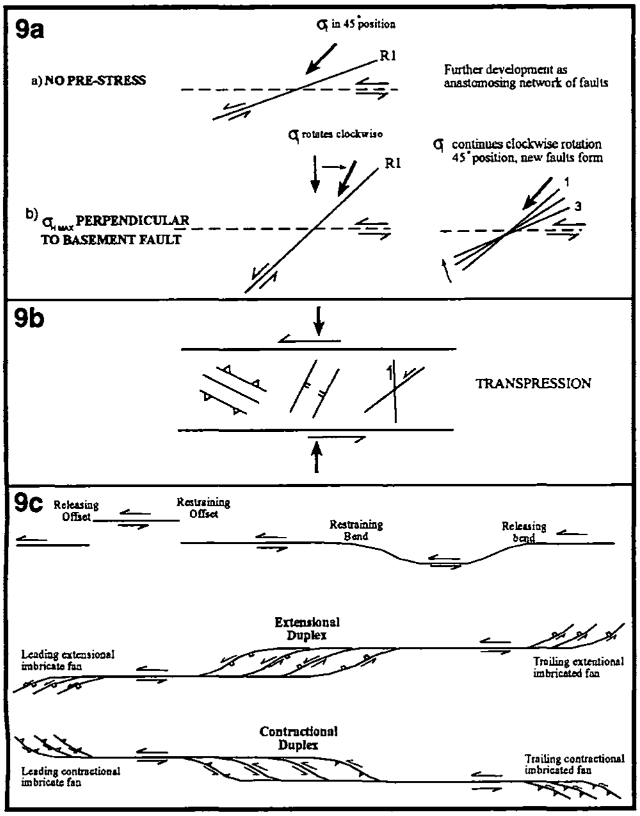

Figure 9. (a) Synoptic diagram illustrating angular change for the initial formation of R1 shears for a) pure strike-slip and b) transpression (modified from Naylor *et al.*, 1986). (b) Angular relationships of secondary features generated under transpression; redrawn from Sanderson and Marchini (1984). (c) Map view of an idealised sinistral strike-slip fault system (redrawn from Woodcock and Fisher, 1985).

(e.g. Susui, Luis, Silimpopon and Kalabakan Faults). Seismic lines across the Silimpopon and Likasan Faults support the interpretation of flower structures (Fig. 8). Juxtaposed dissimilar stratigraphies along the faults are commonly observed during surface mapping (Fig. 6). Abrupt changes in facies across the faults are consistent with strike-slip juxtapositioning of beds. These features provide convincing support for strike slip faulting (Harding, 1973; Sylvester, 1988; Dooley, 1996).

The folding and faulting events have affected both the Tanjong and Kapilit Formations. This indicates that the folding and faulting events are at least post-Miocene. Strike-slip faulting, possibly overprinting some of the pre-existing extensional faults, indicates that some of the post-depositional extensional faults were reactivated as strike-slip faults. For example, the Lonod and Malibau Faults, which were originally an extensional faults, are interpreted to have been reactivated as a strike-slip fault. The Lonod and Pinangah Faults are major NE-SW trending lineaments that may reflect orientation of the basement fabric. The Lonod Fault has a sinistral sense of movement post-dating the folding event.

Post-folding extensional faults are oriented mainly WNW-ESE, E-W and NE-SW. The E-W trends are probably tension fractures related to strike-slip fault movements. The other trends probably indicate a period of relaxation and renewed extension. These extensional faults are important features as they have caused sequence repetition in the Tanjong and Kapilit Formations especially in the Malibau and Meliau areas (Figs. 6, 7 and 8). Previously it was thought that the complete undisturbed Tanjong section was preserved in this main depocentre (Tjia, 1990). This indicates a period of relaxation and renewed extension which post-dates folding event at least during the Pliocene.

In summary the structural orientations of the Southern Sabah Basin indicate that the basin has gone through a complex structural evolution. The fold-fault relationship, cross cutting and related timing of faults can be explained in terms of strike-slip tectonics and the relationships observed are quite significant in the Tidung area of southern Sabah. The NW-SE trending Kalabakan, Silimpopon, Luis and Sesui Faults are the major strike-slip faults in the study area. The principal elements of strike-slip patterns observed are: 1) *en echelon* folds inclined at low angles to the strike-slip or wrench zone; 2) conjugate strike-slip faults, including synthetic faults inclined at low angles to the strike-slip zone but in opposite directions to the folds, and antithetic faults nearly perpendicular to the strike-slip zone; 3) normal faults or tension joints oriented perpendicular to the fold axes (Wilcox *et al.*, 1973). Bedding strike orientations defining an apparent sub-circular feature indicate significant amounts of rotation of bedding strikes, which are quite common in strike-slip deformation (Wilcox *et al.*, 1973; Harding, 1988). Recognition of these structures, especially in the Tidung area, suggests that the major NW-SE trending faults exhibit evidence of the latest left-lateral transpressional movement.

LATE PLIOCENE MAJOR STRIKE-SLIP TECTONIC ACTIVITY AND UPLIFT

The latest phase of major tectonic event deformed the study area into NW-SE trending narrow faulted anticlinal zones with intense deformation separated by broad synclinal areas with gently folded strata. These structures are interpreted to be related to major strike-slip faulting and transpressional fault movement in this region. Figure 10 shows the proposed tectonic evolutionary model for southern Sabah which can explain the progressive structural development of the subcircular- to elliptical-shaped 'basins' in Sabah.

Structural style and development

The complex structural style of southern Sabah has involved extension, inversion, strike-slip activity and renewed extension during the Middle Miocene to Pliocene. The present day outcrop pattern of the 'circular basins', Miocene rocks are remnants of a single larger basin. The complexities and variation in structures observed in the surface of southern Sabah cannot be explained by a simple deformation mechanism. The structural style is non-cylindrical and multidirectional suggesting superimposition of different deformation events. These were extensional, transtensional/transpressional and compressional at various stages.

The structural development is possibly best described as a result of a complex interaction between deltaic growth faulting ('thin-skinned') and basement rooted tectonic ('thick-skinned') structures. The intricate overprint relationships of such structures are well documented in Brunei Darussalam (Sandal, 1996; Schreurs, 1997; Morley and Crevello, 1997) and may replicated in the study area.

The thin-skinned type of deformation was essentially extensional and syn-depositional, driven by gravitational sliding and differential loading or compaction in a deltaic system developing over a continental margin (Bruce, 1973; Crans *et al.*, 1980; Schreurs, 1997; McClay *et al.*, 1998). The thick-skinned type of deformation was essentially rooted in the upper crust and controlled by the regional

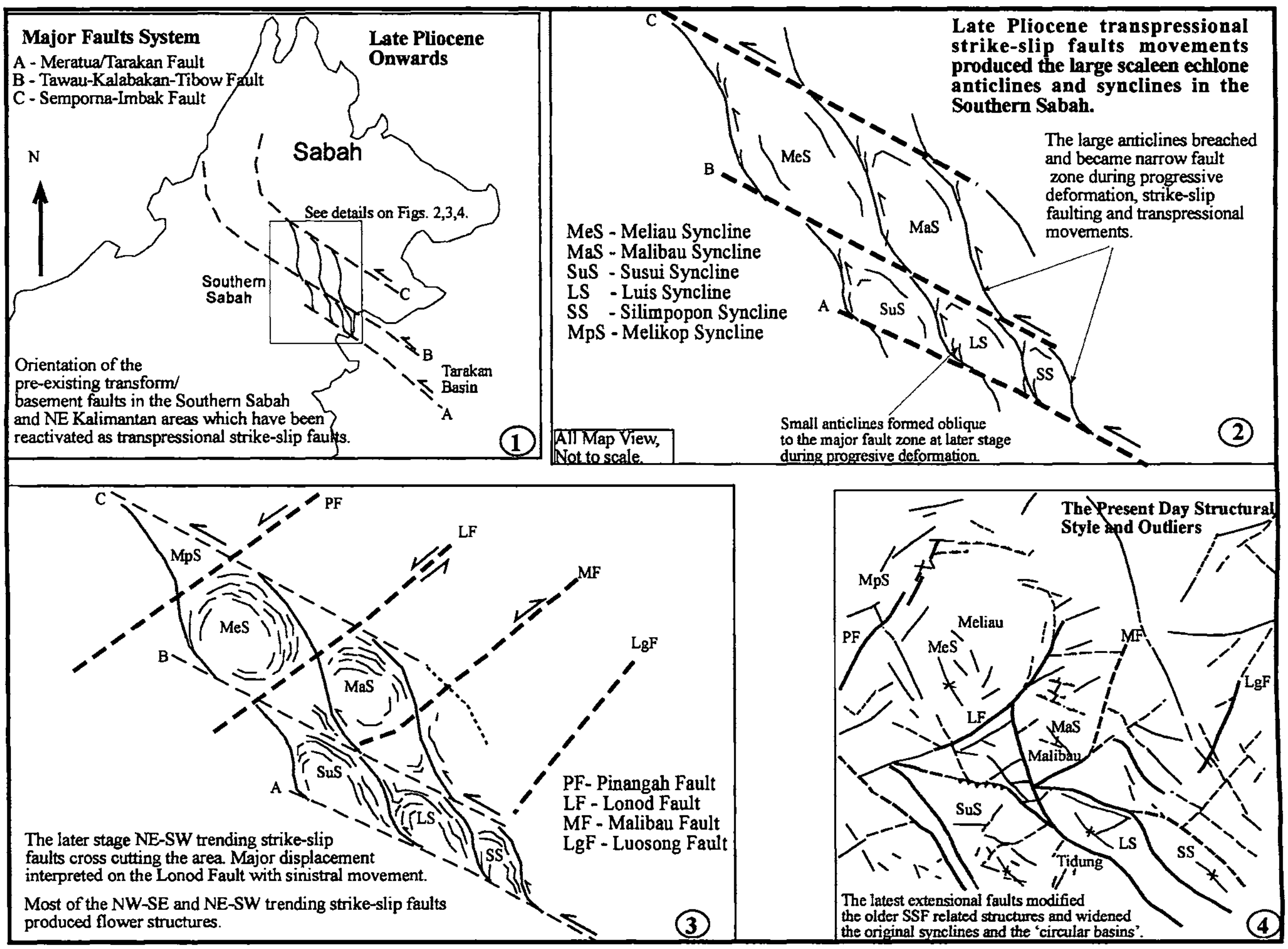

Figure 10. Proposed tectonic model of southern Sabah from Late Pliocene onwards showing the mechanism of development of the Neogene 'circular basins' of Sabah in transpressional strike-slip fault zone. The present day outcrop pattern of large subcircular- to elliptical-shaped synclines separated by narrow faulted anticlines are remnants of a single larger basin.The latest extensional faults have modified and widened the original synclines.

stress field. Related structures in the deltaic overburden were syn-depositional and/or post-depositional, and were partly related to wrench tectonics (cf. Schreurs, 1997). Transfer of the shear strain from the controlling 'basement' to the deltaic overburden occurred through mobile and undercompacted shale (Richard *et al.*, 1995) underlying the Unit II regressive deltaic successions of the Tanjong and Kapilit Formations. The shales would have caused an overall upward splay and widening of the basement-induced faults. In addition, strike-slip movement on the basement faults could be manifested in other ways, such as development of the narrow NW-SE trending faulted anticlines seen in the study area.

Basement-influenced overburden structures interpreted in the study area are described in detail in Balaguru (2001). Basement influence is most clearly represented by wrench-related structures in the deltaic overburden (Sandal, 1996; Schreurs, 1997), such as *en echelon* oblique fold-fault alignments, occasionally accompanied by reverse fault and dip reversals along individual faults, conjugate fault systems (synthetic and antithetic), local pull-apart structures, push-up blocks and ridges, and curved horsetail configurations. The large-scale structural architecture of the Miocene overburden is not cylindrical but rather an intricate pattern of large subcircular and elliptical patterns of synclines (sags) separated by narrow faulted anticlines (domes), which possibly represent a large contractional duplex developed in the major transpressional strike-slip fault zone illustrated in Figure 10.

The main features of interpreted thick-skinned deformation are two sets of faults trending broadly 060-070° and 130-140° (Figs. 7 and 8). Neogene reactivation of these trends resulted in overburden structures either sub-parallel or slightly oblique to these trends usually associated with narrow anticlinal ridges (Kalabakan, Silimpopon, Luis and Susui Fault Zones), separating wide synclines (the Silimpopon, Luis, Susui Malibau and Meliau Synclines) (Fig. 10). The N-S trending Jerudong Fault zone and Belait Syncline in Brunei Darussalem is analogues of these structures (Sandal, 1996; Morley and Crevello, 1997; Morley *et al.*, 1998). There are conjugate sets of faults with synthetic and antithetic directions (Naylor *et al.*, 1986; Tchalenko and Ambraseys, 1970). The major NW-SE trending left-lateral strike-slip faults associated with narrow anticlinal ridges (Figs. 7 and 8) form positive flower structures (cf. Dooly and McClay, 1996 their Fig. 9) and are the most important structures in the study area. They are interpreted to be transpressional (Figs. 9 and 10). This transpressional movement produced *en echelon* minor folds and faults oblique to the major fault zones and caused inversion. Reactivation of basement faults during a period of compression caused left-lateral strike-slip fault movement along NW-SE trends. Similar motion on the Jerudong Fault zone in Brunei Darussalem formed shale diapirs and anticlines (Morley and Crevello, 1997). But in the study area there are only three localities where there is evidence for overpressured mud diapir emplacement within these fault zones.

The broadly NE-SW trending Malibau, Lonod and Pinangah Faults possibly indicate complex composites of interacting thick-skinned and thin-skinned deformation. From the displacement shown in Figure 6 movement on the Lonod Fault appear to be sinistral and of approximately 8-10 km horizontal displacement. The Malibau Fault can be demonstrated to be down-thrown-to-west on the seismic line, with subsequent possible later dextral strike-slip movement from map relationships. Cross-cutting relationships indicate the latest movements on the Malibau fault post-date the folding. These faults are interpreted to be regional and counter-regional faults that influenced deltaic shelf progradation. Counter-regional faults tend to be succeeded by later growth faults (Crevello *et al.*, 1996; Morley and Crevello, 1997). The curvature of the Malibau, Lonod and Pinangah Faults suggest they either were inverted in the initial stages of compression which developed some folds parallel to the faults, or that there was reactivation of basement faults during compression caused by left-lateral strike-slip fault movement along the NE-SW trends.

The offshore California borderland to the west of the San Andreas Fault is a possible analogue for the NW-SE trending strike-slip structural style of the study area (Allen and Allen, 1990, their Figs. 7.53 and 7.54, page 256), and the Blue Mountains of Jamaica (Mann *et al.*, 1985, their Fig. 7A page 218). In offshore California the synclinal structures are 20-50 km wide and are separated by narrow strike-slip fault zones.

Structural development of the 'circular basins' of Sabah

The present-day outcrop patterns of the Miocene sedimentary rocks (Fig. 7) resemble geomorphologically 'circular basins' (Collenette, 1965; Tjia, 1990). The circular features cover an area approximately 25 km long and 22 km wide. It is covered by virgin rain forest and is the most inaccessible and remote area in Sabah. Gunung Lotong, the highest mountain along the north-central part of the main topographical rim is between 1,500-1,800 m (5,000-6,000 feet) high. The outcrop pattern in the central Meliau is roughly circular and describes a 'basinal' morphological feature. On the SAR image, there may be some artificial topographical depression within the circular rim. The topographic map indicates the northern rim is much lower (about 150 m) than the centre of the basin (about 600 m) and the side looking SAR viewed to the south gives artificial topographic lows for areas with synclinal structures.

The Tidung, Malibau and Meliau 'circular- to elliptical-shaped basins' are interpreted here to represent fragments of a single large basin (Fig. 10). This is because across the three areas there is evidence of similar 1) basin evolution including 2) sedimentation history, 3) lithofacies distribution, 4) palaeo-environments, 5) sediment thickness, and 6) a similar pre-Pliocene structural history.

A variety of models have been proposed to explain the development of the 'circular basins' in the region

(Collenette, 1965; Tjia *et al.*, 1990; Rangin *et al.*, 1990b, Tongkul, 1993; Clennell, 1996). Most of them postulated gravitational sliding and sinking was a major factor in their structural development. However, it has been shown that the Miocene deposits of Southern Sabah have a similar depositional history throughout the Tidung, Malibau and Meliau areas, and have undergone a similar complex structural history of extension, inversion, strike-slip faulting and renewed extension (Figs. 7 and 8; Balaguru, 2001). The present shapes are remnants of a single large basin modified by post-depositional deformation and enhanced by erosion into near-circular to elliptical structures. The Neogene 'basins' are interpreted here as the product of transpressional tectonics and inversion during the Latest Pliocene (Fig. 10). Reactivation of basement faults during a period of compression caused left-lateral strike-slip fault movement along NW-SE trends. The basins generally appear now as large subcircular and elliptical synclines separated by narrow faulted anticlines which possibly represent large contractional duplexes (Fig. 10). Major NW-SE trending left-lateral strike-slip faults associated with narrow anticlinal ridges form positive flower structures (cf. Dooley and McClay, 1996, Fig. 9) and are the most important structures in the study area. They are interpreted to be transpressional (cf. Naylor *et al.*, 1986). With transpressional movement producing *en echelon* minor folds and faults oblique to the major fault zones which eventually caused inversion.

Analogous structures are present in the offshore eastern Sabah area (Clennell, 1996), onshore Brunei Darussalem (Morley and Crevello, 1997) and in the Kutai Basin of Kalimantan (Chambers and Daley, 1995, 1997; Bates, 1996; Carter and Morley, 1996). Clennell (1996) interpreted the tight anticlinal structures as diapiric in origin although he pointed out that a similar structure in the Balabac Basin was a rift structure inverted by NW-SE compression (Hinz *et al., 1991*). Inversion and wrench structures of Mid-Late Miocene age are evident in the Sandakan and Bancauan Basins (Bell and Jessop, 1974; Tamesis, 1990; Wong, 1993, and unpublished commercial data).

Regional-scale strike-slip faults and implications

Regional-scale faults with orientations similar to those in onshore Sabah extend offshore to the SE and NW (Figs. 11 and 12). The significance of these faults is discussed below.

In Northeast Kalimantan region, the prominent NW-SE trending narrow faulted anticlines in the study area extend southeastward offshore into the NE Kalimantan Basin and form several major anticlinal arches trending NNW-SSE within Plio-Pleistocene sediments (Wight *et al.*, 1993; Lentini and Darman, 1996; Biantoro *et al.*, 1996). Towards the south-southeast in younger sediments these structures become open folds with anticlinal axes which are not faulted. NW-SE trending transpressional faults were active during deposition of the Plio-Pleistocene sediments. The major arches have been interpreted as SE plunging flexures formed by left-lateral movement along faults trending NW-SE (Lentini and Darman, 1996; Darman, 1999). In contrast, Wight *et al.* (1993) favoured an interpretation of a deep thrust from the west for the formation of large 'arches' which seems unlikely as contraction during this time was related to major NW-SE trending strike-slip faulting and transpressional movement (Sunaryo *et al.*, 1988; Busono and Syarifuddin, 1999, pers. comm.; Insley, 2000). Deflected fold axes on the Mangkalihat peninsula and southern Kutai Basin from NNE-SSW to NNW-SSE trend were interpreted as related to similar transpression (Sunaryo *et al.*, 1988; Cloke, 1997).

Transpressional movement along major NW-SE strike-slip faults in this region (Fig. 12) would better explain the structural development. It probably occurred during the Late Pliocene, and is possibly related to propagation of deformation from Sulawesi towards NW Sabah. The Late Pliocene strike-slip deformation is regionally significant and occurred at a similar time to important deformation in NE Kalimantan, Sulawesi and NW Sabah. This transpressional movement is interpreted to be the cause of deformation, uplift and most recent stages of structural development in South Sabah.

In Northwest Sabah, the major structural lineaments of Sabah show a change in trend from NE-SW (the Sarawak Trend) in the northwest Sabah to WNW-ESE (the Sulu Trend) in the northeast Sabah (Fig. 12). The Eocene-Early Miocene Rajang-Crocker accretionary prism was interpreted to be originally trending NE-SW but attained the present curvature/arcuate trend as the result of later deformation. In contrast, Tongkul (1993) postulated that the change of the regional structural trend in northern Sabah was due to a change in the direction of the stress field from initial NW-SE to later NNE-SSW during the collision (north Borneo) in the Early to Middle Miocene. But the timing of collision and the stress field orientation relative to the structural development during these events are not clear.

Clearly the WNW-ESE structural trend post-dates the Miocene Kapilit Formation. The Upper Miocene Bongaya Formation in northern Sabah clearly shows WNW-ESE trending fold axes similar to the older rocks, which indicates that it was affected by the Late Pliocene tectonic activity. In this study, it is interpreted that the complex structural trends in Sabah are the result of superimposed older (Eocene-Early Miocene) and younger (Late Pliocene) structures developed during major tectonic events (Fig. 12). The fold-thrust imbricate structures of the Rajang-Crocker accretionary prism which developed during the Eocene-Early Miocene originally trended NE-SW but later attained the present curvature/arcuate trend as the result of Late Pliocene strike-slip faulting towards the NW. The faults terminate in the fold-thrust imbricate structures described by Wilcox *et al.* (1973), Woodcock and Fischer (1985), and Aydin and Page (1984) (Fig. 9c). The Late Pliocene NW-SE trending major strike-slip faults demonstrated in southern Sabah (Fig. 6) are interpreted to

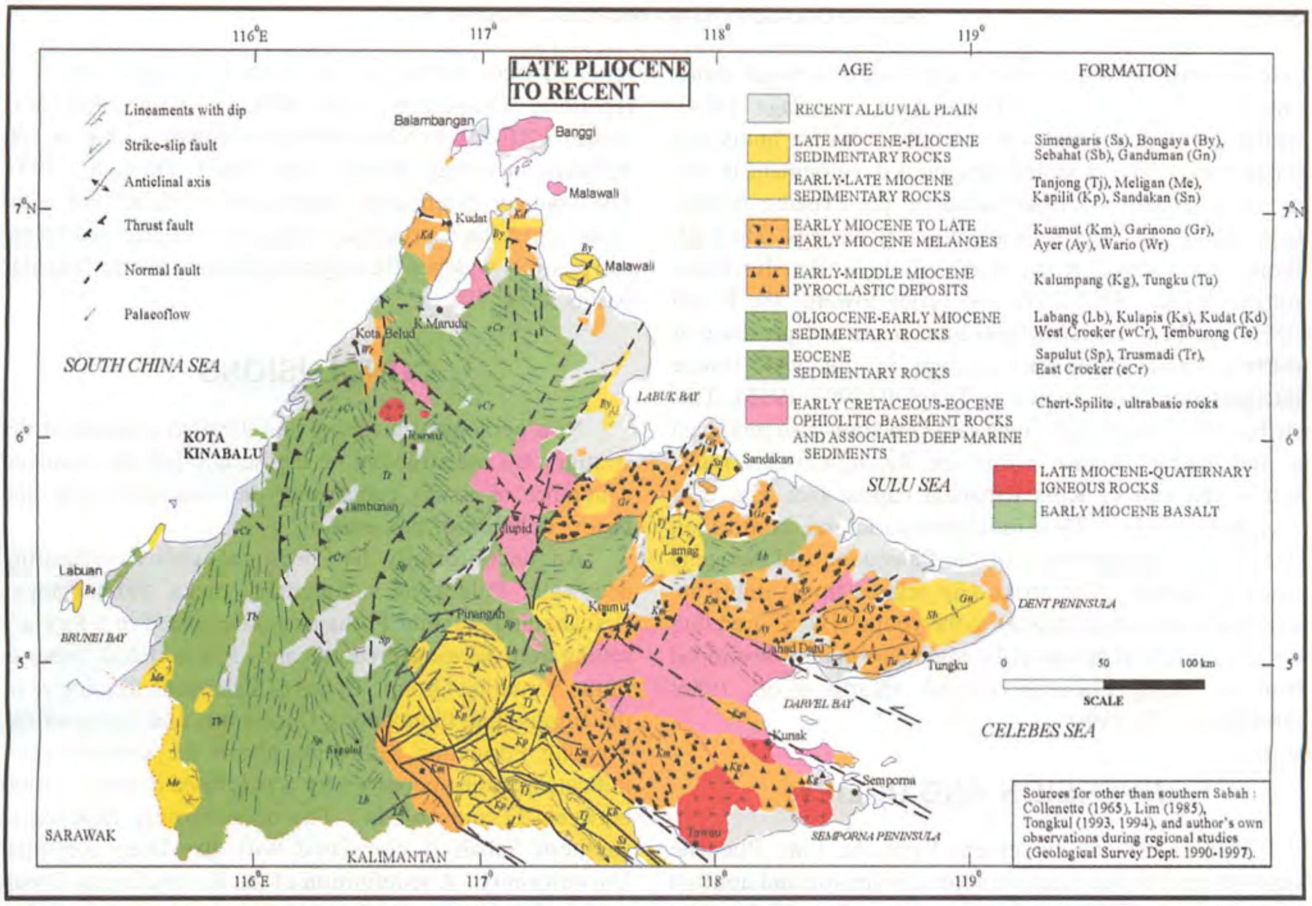

Figure 11. Structural development of Sabah during the Late Pliocene to Recent. Regional NW-SE trending strike-slip activity and transpression resulted in uplift and inversion in southern and eastern Sabah. Reverse faulting and imbrication indicate strike-slip fault termination within the previously accreted Paleogene sediments (Balaguru, 2001).

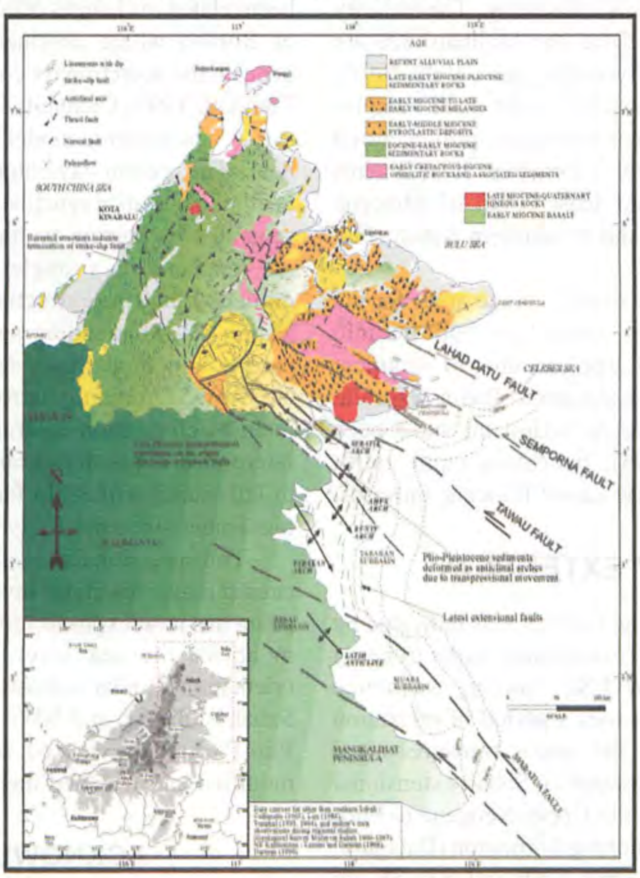

Figure 12. Tectonic framework of Sabah and NE Kalimanatan showing orientation of the major fault zones which suggest that the Southern Sabah was a major transpressional zone during the Late Pliocene onwards (Balaguru, 2001).

extend northwestward to form large-scale horsetail thrust imbricate structures (Fig. 11) (cf. Aydin and Page, 1984), which developed a series of complex reverse faults and imbrication. The complex structural development in this region is possibly further aided by pre-existing reverse faults within the Paleogene accretionary wedges. The fold/thrust belt formed at the north of the strike-slip faults roughly trends NNE-SSW and bends towards the E and ESE (Fig. 12). The structural lineaments and presence of these reverse faults are evident in the SAR image interpretation in this region by Tongkul (1993, 1995). This strike-slip related thrust-imbricate structures also produced a 'subcircular' feature within the Rajang-Crocker range just to the east of Kota Kinabalu capital (see Fig. 2 of Tongkul, 1995). This indicates structural control on 'subcircular' morphology of the Paleogene and Neogene strata of Sabah. The strike-slip related thrust-imbricate structures are also analogous to the young NW-SE trending wrench faults and thrusts in the Mindanao mainly developed from the Early Pliocene onwards (Karig *et al.*, 1986; Pubellier *et al.*, 1996).

INVERSION AND UPLIFT

Transpressional movement from the Late Pliocene onwards resulted in major structural inversion and uplifted most of the southern and eastern parts of Sabah where the Miocene strata now are exposed onland with the highest point at 1,500 m (Gunung Lotung) above the sea level. This event is here termed the Meliau Orogeny. The majority of the Miocene coal samples from the Malibau area are high volatile bituminous (A/B) type (Balaguru, 1996, 1997). Vitrinite reflectance (Vr%) values of the coal samples suggest approximately 4-5 km of structural uplift occurred since the Miocene and several kilometres of sediments were uplifted and eroded. At least 6 km of Miocene sections are now exposed onland in southern Sabah (Fig. 11).

The uplift resulted in new clastic source areas for the younger Plio-Pleistocene deltas which have built out into the present offshore areas. Large amounts of sediment have been shed into the NE Kalimantan Basin where at least 7,500 m of Plio-Pleistocene sediments have been deposited (Wight *et al.*, 1993), indicating rapid uplift, erosion and deposition from the Latest Pliocene onwards.

QUATERNARY EXTENSION

Very young extension in the study area is indicated by the presence of post-inversion extensional faults trending broadly NE-SW and WNW-ESE causing sequence repetition. The extension indicates a period of relaxation during the Quaternary after the major transpressional tectonic event and uplift. Elsewhere in Sabah extensional faults commonly occur within the Upper Neogene to Plio-Pleistocene sediments, e.g. Timohing Formation (Balaguru, 1989). Extensional faults trending NNE and NW-SE are reported from within the Sandakan Formation, causing a repetition of sequence (Noad, 1998) and extensional faults trending NE-SW to NNE-SSW are common within the NE Kalimantan basins (Wight *et al.*, 1993; Darman, 1999). The younger extensional faults have modified the older strike-slip related structures within the Neogene sediments and possibly widened the original synclines and the 'circular basins' (Fig. 10).

CONCLUSIONS

New geological mapping and detailed analysis of the stratigraphy and structure of southern Sabah has resolved a number of issues concerning the structural style and basin evolution of this area.

An unconformity has been recognised separating deepwater Paleogene sedimentary rocks and mélanges (Labang and Kuamut Formations) deposited in a fore-arc setting from Neogene predominantly fluvio–deltaic deposits of the Serudong Group. Clasts of Paleogene lithologies in the Burdigalian Gomantong Limestone, and dating of the Tanjong Formation sediments above the unconformity, indicate that the unconformity was formed during a period between 22 and 16 Ma. The unconformity exposed in southern Sabah is correlated with the Deep Regional Unconformity. A redefinition of the Kinabatangan Group is required to exclude the formations above this unconformity. The cause of this uplift and consequent change in depositional environment in the study area has been related to changes occurring along the northern margin of Borneo where continental blocks were being thrust beneath the accretionary complex (Hutchison, 1989; 1992; Tongkul, 1993; Clennell, 1996).

A new tectonic model for southern Sabah is proposed here. The present day outcrop pattern of large subcircular- to elliptical-shaped synclines (the so-called 'circular basins') separated by narrow faulted anticlines in southern Sabah are remnants of a single larger basin and the remnant outliers actually are structurally controlled large synclines. Major NW-SE trending strike-slip faults associated with narrow anticlinal ridges form positive flower structures. The NW-SE trending narrow faulted anticlinal zones with intense deformation separated by broad synclinal areas are interpreted as possibly a large contractional duplex related to left-lateral strike-slip faulting and transpressional fault movement since the Early Pliocene.

Transpressional movement since the Late Pliocene has caused major structural inversion and uplift. The Miocene strata are now exposed onland with a highest point 1,500 m above the sea level. Regional-scale faults with orientations similar to those of the study area extend offshore Sabah to the SE and NW. Renewed extension during the Plio-Pleistocene caused sequences repetition and have modified and widened the original synclines.

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