Geol. Soc. Malaysia, Bulletin 22, December 1988; pp. 135–151

Stratigraphic-Tectonic Model for Eastern Borneo

CHARLES S. HUTCHISON
University of Malaya
59100 Kuala Lumpur
Malaysia

Abstract: Eastern Borneo has been nucleated since Late Cretaceous time around the Miri Zone, whose basement appears to be a microcontinent rifted from the shelf of Vietnam and south China. The eastern margin of the Miri Zone is interpreted as an Atlantic-type margin, with down-faulted continental crust giving way eastwards to Late Cretaceous to Eocene oceanic lithosphere ('Chert-Spilite Formation' and underlying 'Crystalline Basement'), of the same age as the ocean floor of the adjacent Celebes Sea.

The NE trending Rajang Group was deposited as a Late Cretaceous through Paleogene turbidite fan directly on the Chert-Spilite Formation. Eastwards subduction of this oceanic basement resulted in the western and northern Sulawesi volcanic arc causing narrowing of the marginal sea gap between the trench and the Miri Zone microcontinent, resulting in shoaling of the infilling Rajang Group flysch to locally give carbonate reefs through the Paleogene.

By Early Miocene time, the Rajang Group had been compressed between the Miri Zone microcontinent and the Sulawesi arc-trench system into a fold-thrust collision orogenic zone. Ophiolite was obducted and it shed blocks of itself into extensive olistostrome deposits of the Dent and Segama Valley areas.

As the Miri Zone collided with the Rajang Group, thrust tectonics resulted in Late Oligocene-Early Miocene granite intrusions in the Long Laai, and Late Miocene in the Mount Kinabalu area. The tin mineralization of the Long Laai plutons is interpreted as mobilized from the underthrust Miri Zone basement.

Aulacogen-like rift arms extended outwards from the opening Makassar Straits as the northern arm of Sulawesi rotated clockwise. The rift system was filled by fluvio-deltaic sediments of the Tanjong Formation, which is oil, gas and coal-bearing in the Tarakan Basin, but unexplored for oil and gas in Sabah, although its coal deposits are well known at Silimpopon.

INTRODUCTION

The tectonic evaluation of eastern Borneo has usually been assumed to result from SE subduction of South China Sea lithosphere at the NW Borneo Trench (Hamilton, 1979; Bol and Van Hoorn, 1980). The weakness of this model is the absence of a volcano-plutonic arc, and the large Miri Zone microcontinent has improperly been excluded from consideration. The stratigraphic and tectonic evolution of eastern Borneo can only be meaningfully discussed in terms of the total framework, which includes the predominantly turbiditic Late Cretaceous through Paleogene Rajang Group, deposited upon oceanic basement ('Danau Formation' of 'Chert-Spilite Formation') and the contiguous areas which are underlain by continental crust. These include the Miri Zone, extended east to the Kelabit Highlands and north to the Luconia and Balingian provinces, and the Dangerous Grounds rifted continental terrain lying beneath the South China Sea in front of the NW Borneo Trench (Hutchison, 1984). This paper attempts to award to the Miri Zone a greater and more realistic role in the stratigraphic and tectonic evolution of eastern Borneo.

THE WEST BORNEO REGION

Northwestern Borneo has been subdivided by Haile (1974) into the West Borneo Basement, Kuching, Sibu, and Miri Zones (Figure 1). The West Borneo Block includes the first two of these zones and extends as far NE as the Lupar Line (Hutchison, 1975). The Kuching Zone is a shelf zone on the edge of the West Borneo continental lithospheric block.

The 200 km wide Sibu Zone is predominantly of steeply dipping highly deformed low grade metamorphic flysch, separated from the Kuching Zone shelf by the 30 km wide Lupar Line melange suture (Tan, 1979). The Sibu Zone therefore represents a terrain of great stratigraphic thickness, estimated to be about 15 km (Haile, 1974). It represents an accretion-

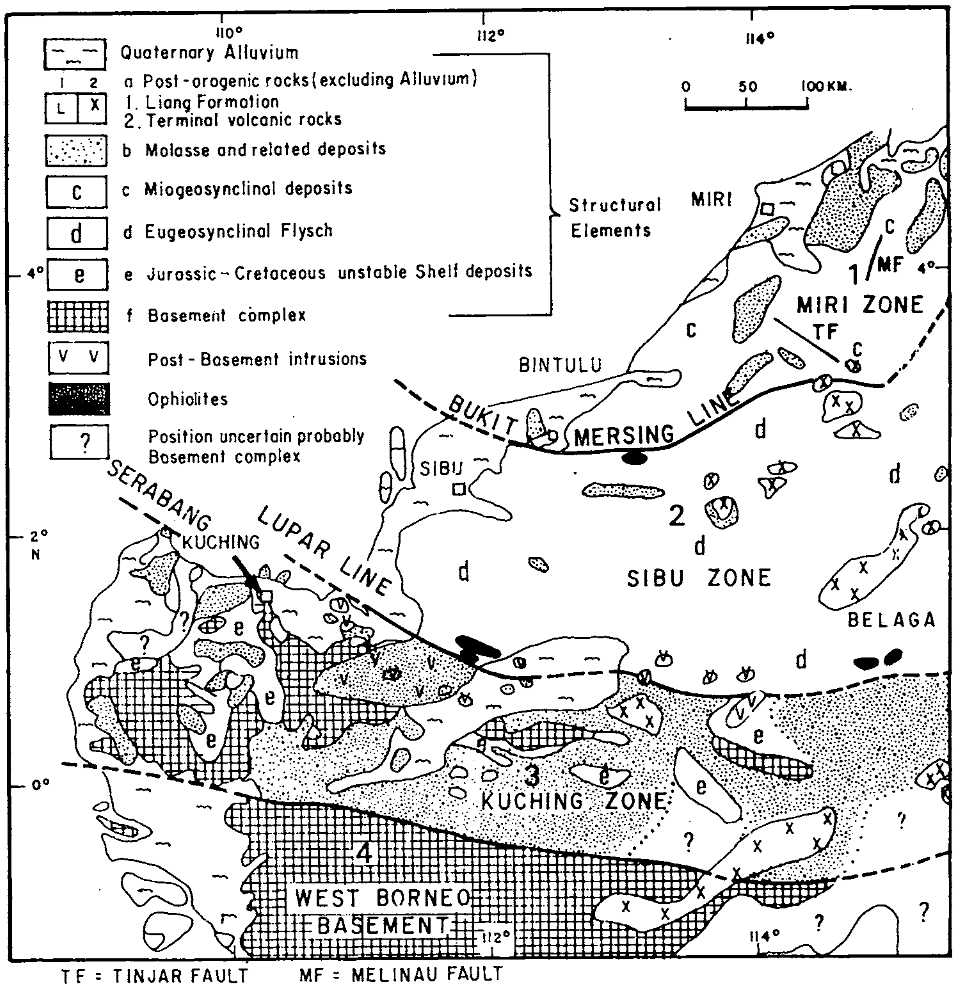

Figure 1: Structural divisions of West Kalimantan and Sarawak, after Haile (1974). Convergent tectonic activity has been documented along the Lupar and Bukit Mersing lines (Hutchison, 1975).

ary prism and other turbidite fan sediments, deposited upon Late Cretaceous oceanic crust, and subsequently compressed between the West Borneo Block and the Luconia Province (Miri Zone) continental block, which rifted and drifted south from the shelf of Vietnam-South China (Figure 2).

The flysch is known as the Balaga Formation, and has been included by Haile (1969), together with the Crocker and other deep water formations of Sabah, into the Late Cretaceous to Early Miocene Rajang Group. The Belaga Formation has been divided by Wolfenden (1960) into four stages, which become progressively younger NE away from the Lupar Line in a fashion typical of an accretionary prism. The implication is that the trench would have progressively migrated forwards in time from the Lupar Line (in Late Cretaceous) to the Bukit Mersing Line (in Eocene time).

The sequence of events for the Late Cretaceous to Paleogene deposition of the Belaga Formation along the active margin of the West Borneo Block, to the Neogene collisional orogeny caused by the arrival of the Luconia (Miri Zone) microcontinent, is shown diagrammatically in figure 2, modified after James (1984). Subduction activity along the margin of the West Borneo Block is indicated by deformation of the Belaga Formation, the Lubok Antu melange along the Lupar Line, high pressure metamorphism, and a zone of high level subduction-related plutons in the Kuching Zone of age ranging from Eocene to Late Miocene (Tan, 1979).

The Rajang Group of the Sibu Zone is commonly metamorphosed to greenschist facies slate and phyllite containing quartz veins. This is attributed to the squashing of the Sibu Zone accretionary prism between the two continental blocks (West Borneo and Miri Zone). By contrast the Rajang Group of eastern Borneo has not been metamorphased and the deformation style is different. This diference is accounted for in the tectonic model proposed below for eastern Borneo.

During the collisional orogeny, some pillow basalt from the basement of the Sibu Zone has been uplifted along the Bukit Mersing Line (Hutchison, 1975). Rocks similar to the Lupar Line melange have been also mapped along the northern margin of the Usun Apau plateau (Figure 2). Tectonic complexities along the Bukit Mersing Line in the Tatau area between Sibu and Bintulu, and granophyre and ignimbrite occurring at Bukit Piring and Sungai Arip (Kirk, 1968), suggest very active tectonics.

THE EAST BORNEO REGION

Eastern Borneo has been nucleated since Late Cretaceous time against the Miri Zone continental margin.

The Miri Zone continues eastwards as far as Brunei and the Kelabit Highlands of the borderlands between Sarawak and Kalimantan (Figure 3). This eastern district has been identified by Hutchison (1984) as the Kelabit Highlands and Long Bawan microcontinent, continuous westwards across the Tinjar Fault with the Luconia microcontinent.

East of the Miri Zone lies the major Rajang Group turbidite flysch mobile belt, which has been folded, thrust and uplifted into a NE trending orogen, which continues towards the

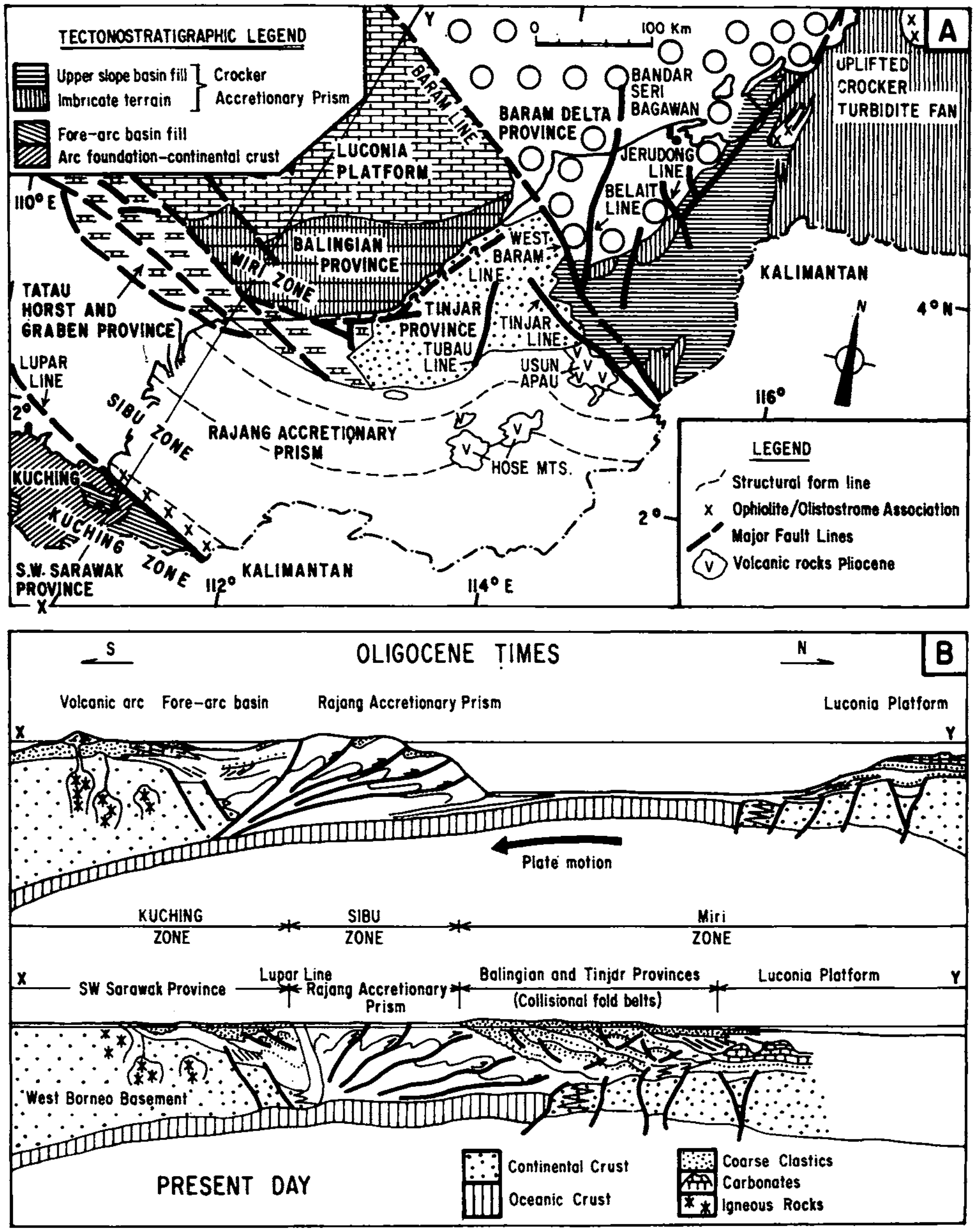

Figure 2: The tectonostratigraphic provinces of NW Borneo. B and C: Diagrammatic cross sections across central Sarawak; reconstructions for Oligocene time and configuration at the present day. Line of section X-Y (after James, 1984). The Miri Zone is composed of the Luconia Platform, Balingian, Tatau and Tinjar provinces. However it extends onshore east of the West Baram Line.

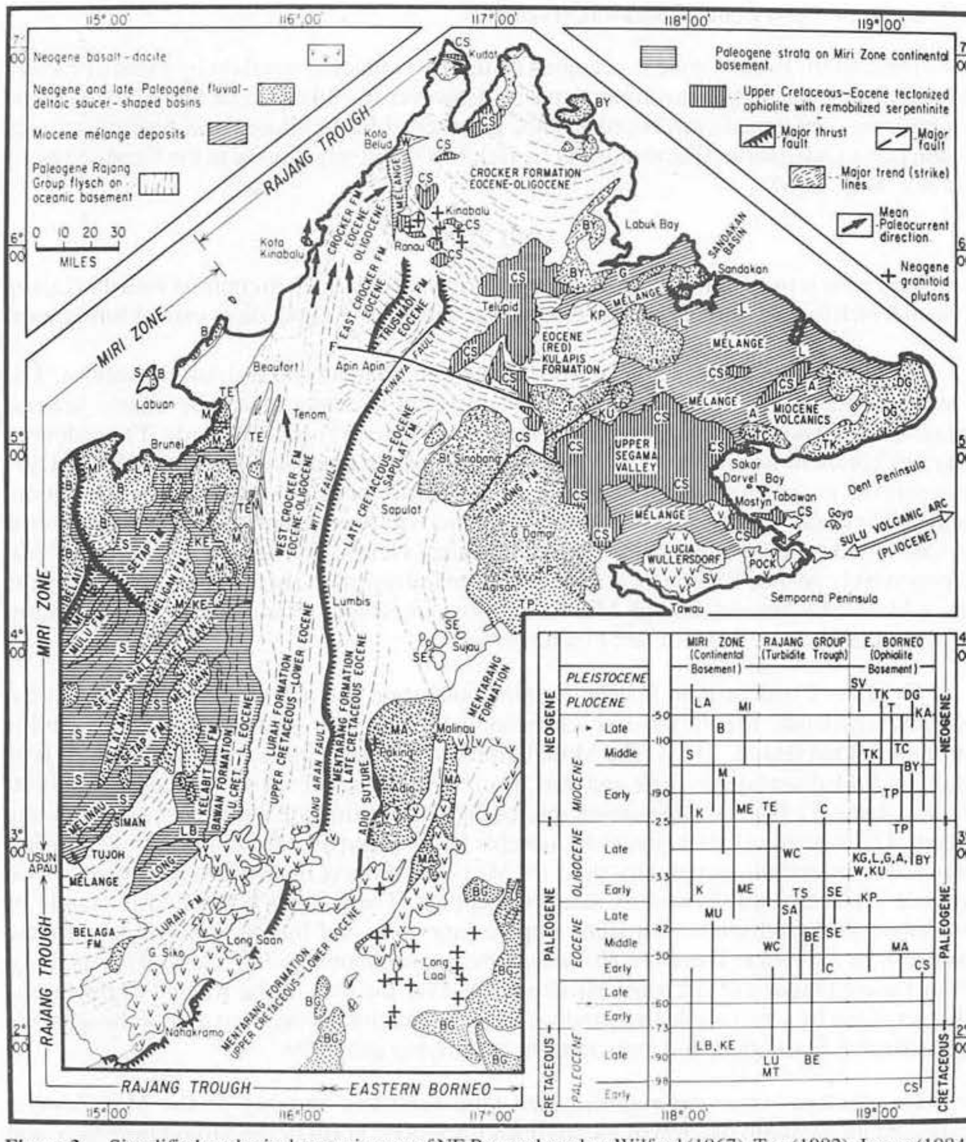

Figure 3: Simplified geological-tectonic map of NE Borneo based on Wilford (1967), Tan (1982), James (1984) and BRGM (1982), with paleocurrent directions from Stauffer (1968).
Miri Zone Formations: B = Belait, K = Kelabit, KE = Kelalan, LA = Liang, LB = Long Bawan, M = Meligan, ME = Melinau Limestone, MI = Miri, MU = Mulu, S = Setap Shale.
Rajang Flysch Zone: BE = Belaga, C = Crocker, LU = Lurah, MT = Mentarang, SA = Sapulut, SE = Sebuku Limestone, TE = Temburong, TS = Trusmadi, WC = West Crocker.
Eastern ophiolite-melange Zone: A = Ayer, BG = Bayangkara, BY = Bonggaya, CS = Chert-Spilite (with gabbro and peridotite)[Ophiolite], DG = Dent Group, G = Gariono, KA = Kapilit, KG = Kalumpang, KP = Kulapis, KU = Kuamat, L = Labang, MA = Malinau, SV = Semporna (Sulu) volcanics , T = Tanjong, TC = Tabanac Conglomerate, TP = Pempilan, TK = Tengku, W = Wariu.

SW as the the Sibu Zone of Sarawak (Figure 2).

The eastern Borneo zone is occupied by uplifted ophiolite overlain by extensive Early Miocene melange and olistostrome deposits. However it is likely to be underlain by some underthrust continental crust because of the presence of Early Miocene tin-bearing granites in the Long Laai district (Bambang and Le Bel, 1987) and rare granite in the Upper Segama Valley (Kirk, 1968).

MIRI ZONE

This zone is interpreted as underlain by continental crust and, in contrast with the Rajang Group flysch basin to the east, is characterized by predominantly shallow marine formations.

The outcropping basement is formed of the Long Bawan and Kelalan formations. The Late Cretaceous to Eocene Long Bawan Formation is characterized by coarse grained lenticular sandstone, extensive red oxidized clay (red beds ?) and coal beds. The sedimentary environment was probably fluvio-deltaic to coastal lagoonal (BRGM, 1982), and non outcropping evaporites, interpreted from the abundance of brine water wells in the region, suggest the underlying basement is a rifted Atlantic-type continental margin. It is interpreted to have rifted from the continental shelf of SE China-Vietnam in Paleogene time. It has been progressively pushed SSE by a Late Cretaceous to Paleogene early rifting phase, then by the main Middle Oligocene through Middle Miocene spreading of the South China Sea Basin (Taylor and Hayes, 1983; Ru and Pigott, 1986).

The Late Cretaceous to Eocene Kelalan Formation extends west and north from the Kelabit Highlands. It is of massive sandstone with hard grey shale and limestone, and is strongly folded (Haile, 1962). The Mulu Formation is dated Paleocene to Eocene and is of strongly folded sandstone, shale and slate. Haile (1962) interpreted it as a miogeoclinal formation. James (1984), however, reinterpreted the Mulu Formation sandstones as of turbidite origin. The formation either represents a deeper basin within the Miri Zone or its outcrop has resulted from tectonic complexity along the Miri Zone-Rajang Flysch Zone boundary which has not yet been well defined by detailed mapping. The Kelabit Formation is mainly of mudstone and sandstone, with some impure limestone and lignite. Plant fragments are common in the rocks. There are also conglomerates containing chert clasts. Fossils range from Lower Oligocene to Lower Miocene. However the area of the Kelabit Formation is characterized by water wells that produce brine, a situation identical to that of the adjacent Long Bawan Formation, and there must be underlying anhydrite.

The shallow water environment, and long persistent stability of the Miri Zone is indicated by the main outcrop of the Melinau Limestone north of the Mulu Formation, and also as smaller occurrences at Bukit Tujoh and Siman farther south (Figure 3). The Melinau Limestone has been described by Adams (1965) as a pure limestone which persisted from Upper Eocene, through Oligocene, to Lower Miocene. He concluded that the rich fauna and the limestone petrography indicate a shallow water shelf environment. However, the smaller outcrops of Keramit and Selidong have been reinterpreted as turbiditic limestone (James, 1984).

The region is then extensively overlain by the Early to Middle Miocene Setap Shale, characteristically of mudstone containing layers of siderite concretions, and Late Oligocene to Early Miocene Meligan Formation. It is a sand dominant facies deposited on a delta plain and braided river environment (James, 1984). Wilson (1964) showed that this formation extends at least from Lower to Upper Miocene. However Tate (1974) showed that deep water shales of the Temburong Formation gradually give way to deltaic sandstones and shales transitional into the dominantly sandy Meligan Formation. The Temburong Formation is therefore taken as its basinward (eastward) equivalent. Hence the base of the Meligan Formation probably extends below the Miocene and James (1984) takes it as Middle Oligocene, diachronously prograding eastwards into the Rajang Flysch basin.

The other Neogene formations of this region, mainly the Belait, Miri, and Liang formations, are coastal inter-tidal and fluvial deposits that contain coal and other coastal-lagoonal deposits. Both the Miri and Belait formations contain oil in Sarawak and Brunei.

A characteristic feature of the Miocene and Pliocene sand-dominant formations is that they form elliptical saucer-shaped basins, isolated one from another by narrow steep anticlines (Figure 3). They are not depositional basins but are of tectonic origin. It is suggested that they have resulted from gravity sliding of the sandstone-dominant Neogene formations westwards down a gentle regional slope from the uplifting Rajang Group anticlinorium of the Croker Formation and its equivalents. The sliding and basin formation were facilitated by decollement upon the underlying argillaceous Setap Shale Formation. Mud diapirism into the anticlinal zones also resulted in separation into individual basins by narrow steep anticlines.

RAJANG GROUP FLYSCH BELT

This great flysch belt is the eastwards continuation of the Sibu Zone Belaga Formation of Sarawak (Figure 2), which swings N and NNE along the eastern margin of the Miri Zone continental margin, to reach its best known localities in the Crocker Range near Mount Kinabalu (Figure 3). In the south it has been mapped as the Late Cretaceous to Eocene Lurah and Mentarang formations (BRGM, 1982). These continue northwards into Sabah as the West Crocker and Sapulut Formations respectively (Collenette, 1965).

KALIMANTAN

The three Late Cretaceous to Eocene formations - Long Bawan, Lurah and Mentarang - are interpreted by BRGM (1982) to represent coastal, continental margin to slope, and deep ocean basin, respectively. The Lurah Formation is predominantly of flysch-like sandstone, siltstone and argillite. Some of the argillites are purple in colour. The upper part of the succession includes micritic limestones 10 to 20 cm thick, interbedded with the argillite. The Lurah Formation also contains several coal seams at the top of the shallowing marine sequence.

The Mentarang Formation is extensively exposed, and predominantly of distal turbidite sequences of greywacke, argillite and fine siltstone. The turbidites are assumed to have been deposited upon ocean floor basalts, uplifted locally along the Adio Suture (Figure 3). There are also some intraformational jasper conglomerates and breccias. Both the Lurah and Mentarang formations are strongly folded. Slaty cleavage is displayed in the fine grained rocks (BRGM, 1982). A prominent N-S Long Aran Fault separates the Lurah from the Mentarang formations. The transition zone is strongly folded and faulted. It is shown by BRGM (1984) as a steeply eastwards dipping thrust fault and is likely to represent a fold-thrust zone.

By Middle to Upper Eocene time, the flysch trough was uplifted and the Mentarang Formation grades upwards into the Malinau Formation, of much coarser poorly bedded and sorted sandstone and thick argillite. The Malinau Formation is thrust over the Mentarang Formation along the Adio Suture, composed of greenschist, tectonite and serpentinized ophiolite, proving that the flysch formations were deposited directly on the Late Cretaceous oceanic crust, known in Sabah as the Chert-Spilite Formation (Kirk, 1968).

The Upper parts of the Lurah and Mentarang formations show indications of shallowing of the basin, and some of the limestone areas have been mapped as a separate Upper Eocene Sebuku Formation. Near Sejau, the Sebuku Formation unconformably overlies the Mentarang Formation and a basal conglomerate is followed by reefal limestone. Turbiditic sedimentation therefore appears to have been locally eliminated by tectonic uplift or infilling of the oceanic basin by Late Eocene time.

SOUTHWEST SABAH

The Mentarang Formation continues north along strike across the border as the Upper Cretaceous to Upper Eocene Sapulut Formation (Collenette, 1965). It is predominantly argillaceous with thin siltstone beds of typical distal turbidite aspect. Slump bedding occurs at several places. Shallowing of the basin is indicated by interbedded limestones and the upper part of the formation contains abundant jasper conglomerates, similar to the Mentarang Formation of Kalimantan. The Sapulut Formation is separated from the Crocker Formation on the west by the Witti Fault, which continues towards the NNE as the Kinaya Fault (Figure 3).

The West Crocker Formation in this area appears to range from Paleocene to Eocene. It is mainly of a turbidite sequence of greywacke, siltstone and mudstone, but includes rare limestone and some conglomerate.

The northwards continuation of the Sapulut Formation is known as the Eocene Trusmadi Formation, which is predominantly of argillite, with siltstone layers of distal turbidite aspect. The formation is locally metamorphosed to phyllite near fault zones and is then veined by quartz. Limestone breccia occurs locally (Collenette, 1965).

NORTHWEST SABAH

The West Crocker Formation continues northwards along strike towards Beaufort and the Klias Peninsula as the Oligocene to Miocene Temburong Formation (Wilson, 1964). It is dominantly argillaceous with thin siltstone layers and has well described turbidite features such as graded bedding and sole marks. James (1984) has interpreted it as being deposited in a basin slope environment adjacent to the deep Crocker Formation marine basin to the east and a continental shelf to the west. The time equivalent Mid Oligocene to Early Miocene Meligan Formation represents a westwards facies change onto the Miri Zone continent. It is composed predominantly of white current-bedded sandstone deposited in a delta plain and braided river environment (James, 1984).

Eastwards of the Temburong Formation, lies the main Crocker Formation. It has poor age control, but foraminifera suggest a range from Eocene to Lower Miocene. The main features of the Crocker Formation have been summarized by Stauffer (1968). It is a thick sequence of rhythmically interbedded coarse and fine clastics of complex tectonic structure. It generally has all the features of a turbidite flysch, though a few lutite beds are red or green instead of the more typical dark grey. Some of the red outcrops appear to have resulted from weathering. Primary sedimentary structures include graded bedding and sole marks. Ripple marks resulted from strong aqueous currents.

The directional primary structures were used by Stauffer (1968) to determine paleocurrent directions (Figure 3). In common with many flysch basins, the paleocurrent directions are approximately parallel to the strike of the beds and they indicate that the Crocker Formation was sedimented by N to NE directed turbidity currents flowing as a submarine fan parallel to the eastern margin of the Miri Zone continent. It might be expected that the Crocker Formation paleocurrent directions were formerly more towards the ESE, directly away from the Sundaland source, and some may have been directed away from the Brunei area of the Miri Zone. In Late Cretaceous to Paleogene times, the Miri Zone would have begun to rift along NE-SW trending faults in the early rifting phase of the Indo-China continental shelf (Ru and Pigott, 1986). It is reasonable to conjecture that the largest river of the region, the Mekong, supplied the sands to the turbidite fan. The fluvio-deltaic Meligan Formation would have represented the delta of part of the great river system, and the sands would have flowed into the Rajang Group Basin as turbidites. As the Miri Zone microcontinent was driven progressively southwards through Oligocene to Early Miocene times, ahead of the widening South China Sea Basin, the Rajang Group generally would have been progressively pushed ahead of the microcontinent and deformed and parts uplifted into shallower water environments as anticlinal areas, while other synclinal areas remained in deeper water. Thus parts of the fan appear to be older than Late Eocene, yet other parts appear to be younger. The southwards push by the Miri Zone would have caused progressive anticlockwise rotation of the Rajang Group strata in NE Borneo. Unfortunately the Crocker Formation has proved rather poor material for paleomagnetic analysis (M. Fuller, pers. comm.), but the data suggest an anticlockwise rotation as is to be expected from the outcrop geometry of the region (Figure 3).

The Long Laai subvolcanic granite instrusives have been dated by a Rb:Sr isochron at 26 Ma (Late Oligocene), supported by K:Ar determinations of 21 to 25 Ma. The initial $^{87}Sr/^{86}Sr$ ratio is low, 0.7048 (Bambang and Le Bel., 1987). However, the strong association with tin mineralization indicates a continental crustal involvement in the granitic magma genesis.

Mount Kinabalu and its satellitic granitic plutons occupy a similar tectonic setting to Long Laai, not far east of a major thrust involving Rajang Group flysch strata. Modern dating is not available, but the oldest K:Ar dates are in the range 10 to 12 Ma (Upper Miocene) (Jacobson, 1970). It is suggested that both these granitic areas are genetically related to underthrusting of Rajang Group strata. Kosaka and Wakita (1978) suggested that the Kinabalu plutons and porphyry copper mineralization are related genetically to a N-S fault system.

There is a characteristic lack of coeval volcanism. The Mamut copper mine is therefore not related to any volcanic arc, and is thus a unique plutonic porphyry copper system in this region.

EASTERN OPHIOLITE-MELANGE ZONE

The ophiolite basement of this region has been imbricated during uplift. However the igneous stratigraphy is known from the work of Hutchison and Dhonau (1971) and Hutchison (1975, 1978) in the Darvel Bay region. Upper mantle peridotite is overlain by variably metamorphosed gabbro, in turn overlain by pillowed spilite, which is overlain by red chert and other pelagic sediments. The latter is paleontologically dated Late Cretaceous to Paleocene and mapped as the Chert-Spilite Formation (Kirk, 1968). The meta-gabbro K:Ar radiometric dates as old as 210 Ma (Early Jurassic) (Leong, 1971) have to be spurious for the gabbro and meta-gabbro conformably underlie the Chert-Spilite Formation as integral layers of the same patchilly metamorphosed ophiolite. In figure 3 I have shown the ophiolite as one formation of Late Cretaceous to Early Eocene age. The Sabah ophiolite is therefore interpreted as obducted Celebes Sea ocean floor, for the ages are comparable (Lee and McCabe, 1986). Subsequent faulting has mobilized the upper mantle peridotite as serpentinite protrusions into fault and shear zones. The main ophiolite outcrops are in the Segama and Labuk valleys of Sabah, with smaller occurrences around Mount Kinabalu and Kudat. A major line of ophiolite and melange extends NE from Kudat along the Palawan arc of the Philippines.

Most of the overlying formations are of melange, probably olistostrome. They contain Early Miocene microfossils in the scaly clay matrix which contain a variety of Late Cretaceous to Paleogene lithologies of various sizes from cm to hill sized massifs. The common olistoliths are chert, limestone, gabbro, spilite, sandstone and serpentinite. Even clasts of eclogite have been described from the Dent Peninsula (Haile *et al.*, 1965). The main melange outcrops occupy most of the Dent Peninsula but extend westwards to overlie the Chert-Spilite Formation in the Segama Valley (Leong, 1974). The melange formations are known by various names, such as Garinono (Newton-Smith, 1967), Lambang and Ayer (Haile *et al.*, 1965) and Kuamut (Leong, 1974; Collenette, 1965). The melange outcrop areas are characterized by present day mud diapirism.

The fact that the scaly clay matrix contains Early Miocene foraminifera may suggest that the main period of uplift of the ophiolite basement was Late Oligocene to Early Miocene, coinciding with the Deep Regional Unconformity of offshore NW Sabah (Figure 4).

However, Newton-Smith (1967) described conglomerates and sandstones in the Bidu Bidu Hills of the Labuk Valley composed predominantly of serpentinite clasts and some of the serpentinite sandstones contain Eocene fossils. These coarse grained serpentinite clastics imply that the ophiolite was partly uplifted and eroding even in Eocene time. Unfortunately Newton-Smith (1967) assigned the serpentinite clastics to the Chert-Spilite Formation. I would rather assign them to the Eocene Kulapis Formation, with which the outcrops are contiguous. This is necessary for the Chert-Spilite Formation is now taken as the basaltic and deep water sedimentary layer of the ophiolite basement.

Lying between the ophiolitic areas of the Bidu Bidu Hills and the Upper Segama, is an extensive outcrop of Eocene Kulapis Formation (Newton-Smith, 1967). It is mapped on the basis of a predominant red colour, which taken together with the serpentinite clastics, may suggest uplift of the oceanic basement to form a landmass. However there are conflicting interpretations of the Kulapis Formation, for despite its red colouration, it has reported flysch-like characteristics in places. However the outcrops I have studied in the Telupid district have

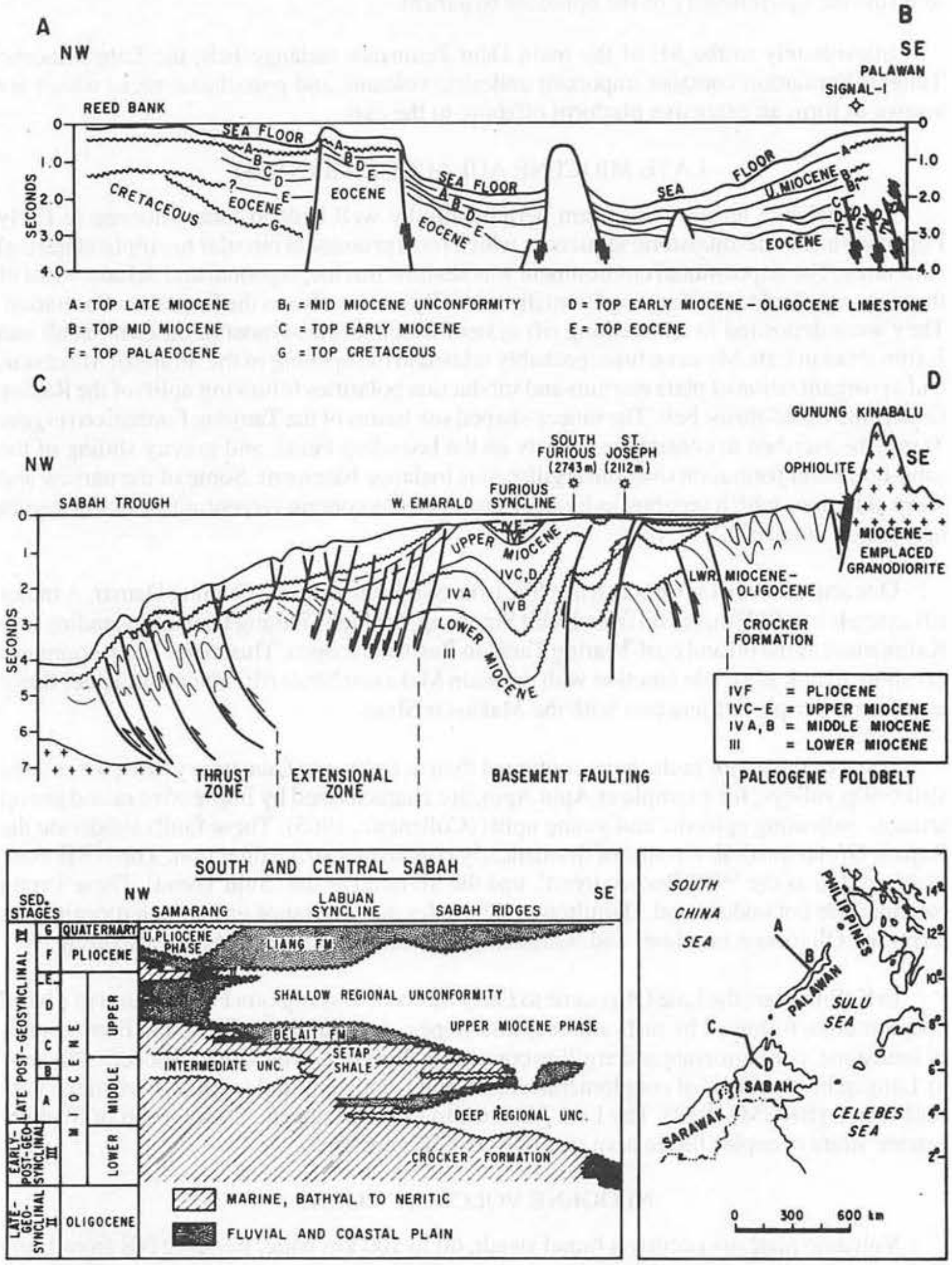

Figure 4: Northwest-Southeast cross sections across:
Top: Reed Bank to Palawan; *Middle*: Sabah Trough through the Sabah Basin to Mount Kinabalu; *Lower*: Time-stratigraphic section through Labuan, Sabah (after ASCOPE, 1981; and Bol and Van Hoorn, 1980).

definite redbed characteristics. More detailed work around Bidu Bidu Hills will be necessary to refine the uplift history of the ophiolite basement.

Immediately to the SE of the main Dent Peninsula melange belt, the Late Miocene Tungku Formation contains important andesitic volcanic and pyroclastic rock, which are known to form an extensive platform offshore to the east.

LATE MIOCENE AULACOGEN SYSTEM

The melange terrain is overlain peripherally by well bedded Late Miocene to Early Pliocene sandstone-mudstone sequences which form prominent circular to elliptical basinal structures. The depositional environment was shallow marine, lagoonal and deltaic. Most of these are ascribed to the Tanjong Formation, locally known also as the Sandakan Formation. They were deposited in a branching rift system which affected most of eastern Sabah and Kalimantan in Late Miocene time, probably related to the opening of the Straits of Makassar, and a reorganization of plate margins and subduction polarities following uplift of the Rajang Group into a fold-thrust belt. The saucer-shaped sub basins of the Tanjong Formation (Figure 3) may be ascribed to continuing activity on the bounding faults, and gravity sliding of the sand-dominant formation over the argillaceous melange basement. Some of the narrow and steep anticlines which separate individual saucer basins contain serpentinite blocks brought up by mud diapirism.

One arm of the rift system extends SW from Sandakan towards Gunung Damar. A major rift extends in a SSE direction from Bukit Sinobang, through Gunung Damar, extending into Kalimantan as the oil and coal-bearing Tarakan Basin aulacogen. This major basin continues off shore to link at a triple junction with the main Makassar Strait rift. The major Kutei Basin also forms a triple rift junction with the Makassar Strait.

Some of the major faults have continued their activity into Quaternary time, for rift and strike-slip valleys, for example at Apin Apin, are characterized by impressive raised gravel terraces indicating episodic and young uplift (Collenette, 1965). These faults subdivide the Rajang Group into sub terrains of dramatically contrasting strike direction. The NNE trend is referred to as the 'NW Borneo trend', and the SE trend as the 'Sulu Trend'. These strong rotations are not understood. Hamilton (1979) hides our ignorance under such meaningless terms as 'Oligocene orocline' and 'Oligocene arc collision'. Such ages are also unlikely.

In Kalimantan, the Late Oligocene to Early Miocene Bayangkara Formation is of a basal conglomerate followed by tuffs and reef limestones. An equivalent Tempilan Formation is of sandstone, conglomerate and argillite containing thin coals. The Upper Miocene Pliocene to Langap Formation is of conglomerate, tuffaceous sandstone and argillite, associated with coal seams (BRGM, 1982). The Late Miocene to Plio-Pleistocene Dent Group of Shallow marine strata occupies the eastern part of Sabah (Figure 3).

NEOGENE VOLCANIC ROCKS

Volcanic plateaus occupy a broad swath, 60 to 100 km wide, trending NE from Long Kelawit towards Melinau, thence NE to align with the Semporna volcanic arc (Figure 3). Some of the volcanic rocks are as old as Miocene and have given K:Ar dates in the range 10 to 25 Ma (BRGM, 1982). They have been little studied, but include a spectrum from basalt, through andesite, to dacite. The swath of Miocene to Pliocene volcanic plateaus continues westwards into Sarawak as the Usun Apau and Hose Mountains (Figure 2). It may be possible that they are related to subduction of the South China Sea lithosphere at the NW Borneo Trench. However the arc-trench gap is excessive at 400 km. Their origin is accordingly enigmatic, and worthy of intensive study in view of their potential for gold-silver mineralization.

Elsewhere (Hutchison, 1978), I have related the Plio-Pleistocene Semporna volcanic arc east of Tawau to subduction of Sulu Sea oceanic lithosphere southwards beneath the Sulu Archipelago. However the fossil trench is rather close to the volcanic arc. If the Semporna volcanic arc is indeed continuous through Kalimantan into Sarawak as a Miocene-Pliocene arc, then the Sulu Sea Trench cannot be held responsible since it has no continuation into Borneo west of the Dent Peninsula melange.

TECTONIC SCENARIO

The Existing Model

The now inactive Northwest Borneo Trench lies about 80 km offshore and parallel to NW Palawan and 170 km offshore the NW Sabah coast (Hamilton, 1979). The NW-SE cross section from the trench (Sabah Trough) through Mount Kinabalu (Figure 4) summarizes the conventional view that the evoluation of NE Borneo must be exclusively related to subduction activity at the NW Borneo Trench (Bol and Van Hoorn, 1980). Details of the offshore Sabah oilfields indicate that SE directed subduction at the NW Borneo Trench has played a significant role in the structural evolution of the region. However Mount Kinabalu can in no way be interpreted as a volcanic or plutonic arc, and its origin may not even be genetically related to the trench. There is therefore no arc associated with the NW Borneo Trench in the Sabah region, but such a possibility exists in the Sulu Sea area as the submarine Cagayan Ridge. If the offshore Sabah basins (Emarald, Furious etc.) are to be classified as 'fore-arc', then the terminology is ludicrous for no arc exists.

It is now known that the submarine terrain in front of the NW Borneo Trench (Dangerous Grounds - Reed Bank area) is of rifted and attenuated continental crust (Hine and Schluter, 1983). The terrain of the Reed Bank, extending to the NW Borneo Trench, is of Mesozoic continental crust characterized by horst and graben structures (Figure 4). This continental terrain is underthrust towards the SE beneath the rocks of Sabah and Palawan. The unconformities within the offshore basins reflect the underthrusting history. It must therefore be concluded that this underthrusting from the NW Borneo Trench has played a significant role in the tectonic evolution of the coastal zone of Sabah from Beaufort to Kudat. However it is not only tectonic mechanism and the possible greater role of the Miri Zone continental block is argued below.

The Additional Model

A preliminary synthesis is presented in figure 5, which will be refined by field data from ongoing research.

The eastern margin of the Miri Zone is interpreted as an Atlantic -type miogeoclinal continental margin, with downfaulted continental crust giving way eastwards to Late Cretaceous to Eocene oceanic lithosphere of the same age as the Celebes Sea marginal basin (I, Figure 5).

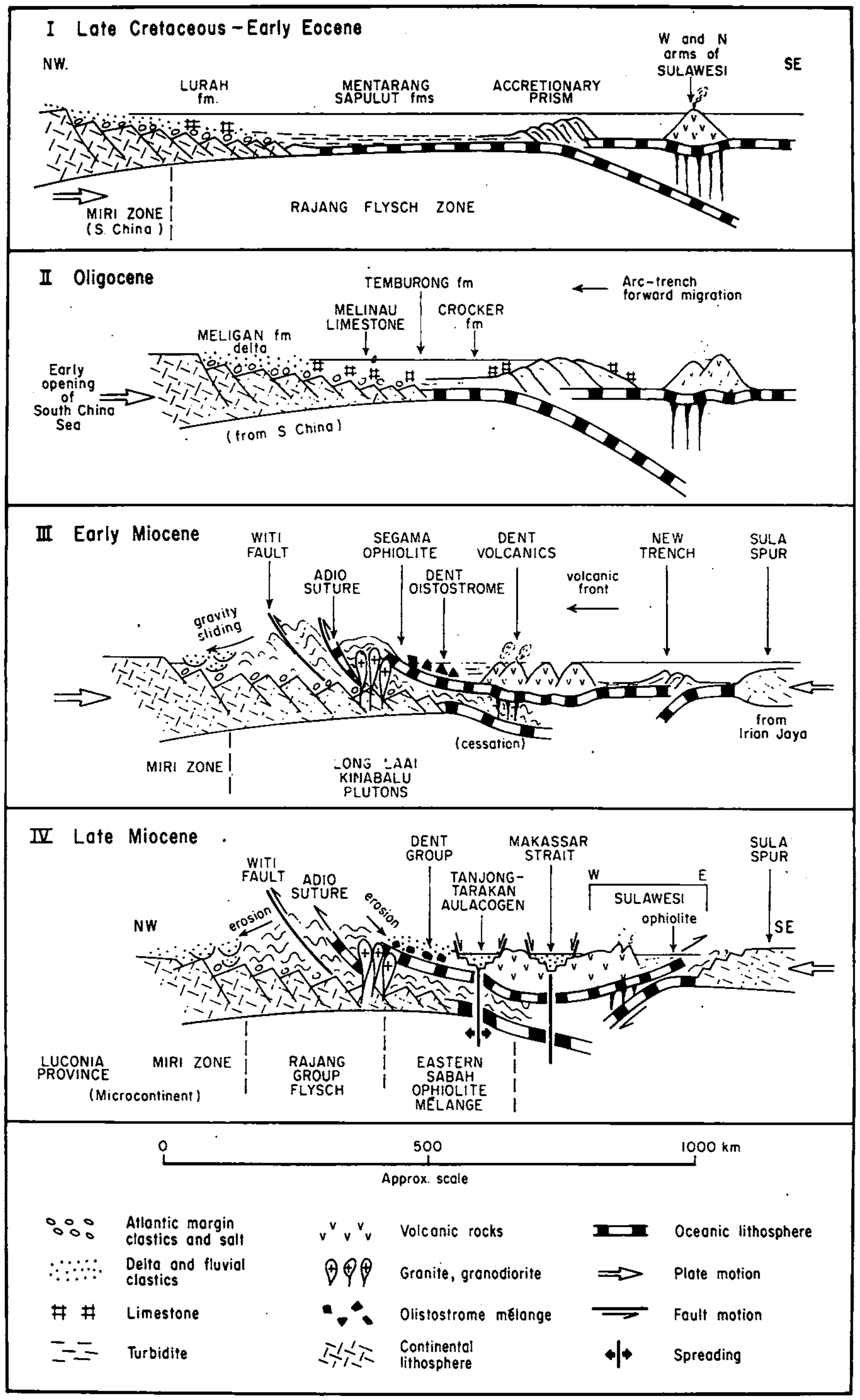

Figure 5: Schematic NW - SE cross sections across the Miri Zone from Brunei in the west to eastern Borneo and Sulawesi. The Late Cretaceous to Paleogene sedimentation pattern infers a continent on the west (Miri Zone), deepening to a turbidite fan eastwards (Rajang Group Flysch Zone). Major orogenic folding and faulting of the flysch and ophiolite obduction is dated by the Miocene granitoids at Long Laai and melange in eastern Sabah.

The abundance of salt water wells in the Long Bawan and Kelabit Highlands is interpreted as buried anhydrite deposits in the lower rift sequence . The Lurah Formation grades eastwards into the main turbidite fan of the Rajang Group flysch belt, deposited directly upon oceanic crust (Chert-Spilite Formation).

Eastwards of the turbidite fan, subduction is held responsible for the western and northern volcanic arms of Sulawesi. The northern arm was formerly in line with the western arm, for paleomagnetic data have proved a post Miocene 90° clockwise rotation of the northern arm (Nishimura and Suparka, 1986).

Continuing subduction narrowed the marginal sea basin, increased the accretionary prisms in width and height, and caused the trench and volcanic front to migrate forwards (II, Figure 5). The local shoaling of the infilling flysch basin led to turbidite sedimentation locally giving ways upwards to carbonate platforms and reefs.

By Early Miocene time, the Rajang Group flysch basin had been compressed into a fold-thrust orogenic zone, resulting from collision of the SE migrating Miri Zone microcontinent with the Sulawesi volcanic arc (III, Figure 5). Ophiolite was obducted and it shed blocks of itself and overlying pelagic sediments into extensive olistostrome deposits in the Dent and Segama Valley areas of eastern Sabah (III, Fig 5).

Thrust tectonics within the orogenic belt resulted in Late Oligocene-Early Miocene granite intrusions in the Long Laai area, and Late Miocene in the Mount Kinabalu area.

The delta and fluvial molasse formations of the Miri Zone were deformed by westwards gravity sliding away from the uplifted flysch zone of the orogen.

Subduction was caused to jump east of the now completed collisional orogen to east of the west (and north) Sulawesi volcanic arc, and to reverse polarity (III, Figure 5).

In Late Miocene time, the western driven Sula Spur microcontinent collided with the western volcanic arc of Sulawesi causing obduction of the ophiolite, and back-arc rifting occurred widely in Sabah and eastern Kalimantan. The Makassar Strait is the main rift, with several aulacogen-like arms branching from triple points along it. The main arms are the Kutei Basins, and the Tarakan Basin, which itself has a branch extending NE through Sandakan.

Fluvio-deltaic formations (mainly the Tanjong Formation), deposited by prograding rivers and deltas in the rift depressions, became progressively deformed into characteristic saucer-shaped basins as uplift continued on the aulacogen bounding faults,causing instability of the sand-dominant formations which rest on an argillaceous matrix melange basement. In some cases the narrow steep anticlines between individual saucer-shaped basins are characterized by mud diapirism which has brought up serpentinite blocks from the underlying melange. Active faulting continued in Sabah into the Quaternary, resulting in uplifted valley sides with terrace gravels.

The opening of the Makassar Strait separated the west (and north) Sulawesi volcanic arm from Borneo so that it now is part of Sulawesi island (IV, Figure 5). The exact mechanism by which the northern arm swung 90° clockwise is unclear, but is suggested by the paleomagnetic data (Otofuji *et al.*, 1982).

REFERENCES

ADAMS, C.G., 1965. The foraminifera and stratigraphy of the Melinau Limestones, Sarawak, and its importance in Tertiary correlation. *Quart. J. Geol. Soc. London,* 121, 283-338.

ASCOPE, 1981. *Tertiary sedimentary basins of the Gulf of Thailand and South China Sea: stratigraphy, structure and hydrocarbon occurrences.* ASEAN Council on Petroleum, Jakarta.

BAMBANG SETIAWAN and LE BEL, L.M., 1987. Discovery of a new tin province, Long Laai area, east Kalimantan, Indonesia. *In* Hutchison, C.S. (ed.) *Tin and tungsten granites, proc. of IGCP Project 220 meeting, Sept 1986.* SEATRAD Centre, Ipoh, Malaysia (in press).

BOL, A.J. and VAN HOORN, B., 1980. Structural styles in western Sabah offshore. *Geol. Soc. Malaysia Bull.* 12, 1-16.

B.R.G.M., 1982. Geological mapping and mineral exploration in northeastern Kalimantan 1979-1982. Final Report. *Rapport du Bureau de Recherches geologigue et minieres,* 82 RDM 0007AO, Orleans, France.

COLLENETTE, P., 1965. The geology and mineral resources of the Pensiagan and upper Kinabatangan area, Sabah, Malaysia, *Borneo region Malaysia Geol. Surv. mem.,* 12, Kuching.

HAILE, N.S., 1962. The geology and mineral resources of the Suai-Baram area, north Sarawak. *Geol. Surv. Dept. British territories in Borneo Mem.,* 13, Kuching.

HAILE, N.S., 1969. Geosynclinal theory and the organizational pattern of the Northwest Borneo Geosyncline. *Quart. J. Geol. Soc. London,* 124, 171-194.

HAILE, N.S., 1974. Borneo. Spencer, A.M. (ed.) Mesozoic-Cenozoic orogenic belts: data for orogenic studies. *Geol. Soc. London Spec. Publ.,* 4, 333-347

HAILE, N.S., Wong, N.P.Y. and Nutall, C.P., 1965. The geology and mineral resources of Dent Peninsula, Sabah. *Geol. Surv. Borneo Region, Malaysia Mem.,* 16, Kuching.

HAMILTON, W., 1979. Tectonics of the Indonesian region. U.S. *Geol Survey Professional Paper,* 1078.

HINZ, K. and SCHLUTER, H.U., 1983. Geology of the Dangerous grounds, South China Sea, and the continental margin off S.W. Palawan: results of Sonne cruises SO-23 and SO-27. *Bundesantalt fur Geowissenschaften und Rohstoffe,* 95701, Hannover.

HUTCHISON, C.S., 1975. Ophiolite in Southeast Asia. *Geol. Soc. America Bull.,* 86, 797-806.

HUTCHISON, C.S., 1978. Ophiolite metamorphism in northeast Borneo. *Lithos,* 11, 195-208.

HUTCHISON, C.S., 1984. Is there a satisfactory classification for Southeast Asian Tertiary basins? *Offshore* S.E. *Asia conf. proc.,* 5, S.E.A.P.E.X., Singapore, 6.64-6.76.

HUTCHISON, C.S. and DHONAU, T.J., 1971. An Alpine association of metabasites and ultrabasic rocks in Darvel Bay, East Sabah, Malaysia. *Overseas geol. and mineral resources,* 10, 289-308.

JACOBSON, G., 1970. Gunong Kinabalu area, Sabah, Malaysia. *Geol. Surv. Malaysia Report,* 8, Kuching.

JAMES, D.M.D. (editor), 1984. *The geology and hydrocarbon resources of Negara Brunei Darusalam.* Brunei Museum and Brunei Shell Petroleum Co.

KIRK, H.J.C., 1968. The igneous rocks of Sarawak and Sabah. *Geol. Surv. Borneo region Malaysia Bull.,* 5, Kuching.

KOSAKA, H. and WAKITA, K., 1978. Some geologic features of the Mamut porphyry copper deposit, Sabah, Malaysia. *Economic Geology,* 73, 618-627.

LEE, CHAO-SHING and MCCABE, R., 1986. The Banda-Celebes-Sulu Basin: a trapped piece of Cretaceous-Eocene oceanic crust. *Nature,* 322, 51-54.

LEONG, K.M., 1971. Progress report: East Malaysia. Upper Segama Valley-Darvel Bay area (Memoir 4 revised). *Geol. Surv. Malaysia Annual Rept. for 1969,* 186-189.

LEONG, K.M., 1974. The geology and mineral resources of the Upper Segama Valley and Darvel Bay area, Sabah, Malaysia. *Geol. Surv. Borneo Region Malaysia Mem.,* 4 (revised), Kuching.

NEWTON-SMITH, J., 1967. Bidu-Bidu Hills area, Sabah, East Malaysia. *Geol. Surv. of Malaysia Report,* 4, Kuching.

NISHIMURA, S. and SUPARKA, S., 1986. Tectonic development of east Indonesia. *J. Southeast Asian Earth Sciences,* 1, 45-57.

OTOFUJI, Y., SASAJIMA, S., NISHIMURA, S., DHARMA, A. and HEHUWAT, F., 1982. Palemegnetic evidence for clockwise rotation of the northern arm of Sulawesi. (abstract). *C.C.O.P. Paleomagnetism workshop, Kuala Lumpur, March 1982.,* U.N. Building, Bangkok.

RU, KE and PIGOTT, J.D., 1986. Episodic rifting and subsidence in the South China Sea. *Amer. Assoc. Petrol. Geol. Bull.,* 70, 1136-1155.

STAUFFER, P.H., 1968. Studies in the Crocker Formation, Sabah. *Borneo Region Malaysia Geol. Surv. Bull.*, 8, 1-13.

TAN, D.N.K., 1979. Lupar Valley, west Sarawak, Malaysia. *Geol. Surv. Malaysia Report,* 13, Kuching.

TAN, D.N.K. (compiler), 1982. *Geological map of Sarawak, first edn. 1:500,000.* Geol. Surv. of Malaysia, Kuching.

TATE, R.B., 1974. Palaeo-environment studies in Brunei. *Brunei Museum J.*, 3 (No. 2), 285-305.

TAYLOR, B. and HAYES, D.E., 1983. Origin and history of the South China Sea Basin. *In* Hayes, D.E. (ed.) *The tectonic and geologic evolution of Southeast Asian seas and islands, part 2. Geophysical Monograph,* 27, Amer. Geophysical Union, Washington, 23-56.

WILFORD, G.E. (Compiler), 1967. *Geological map of Sabah, East Malaysia, 2nd edn. 1:500,000,* Geol. Surv. Borneo Region, Malaysia, Kuching.

WILSON, R.A.M., 1964. The geology and mineral resources of the Labuan and Padas Valley area, Sabah, Malaysia. *Geol. Surv. Borneo Region Malaysia Mem.*, 17, Kuching.

WOLFENDEN, E.B., 1960. The geology and mineral resources of the lower Rajang Valley and adjoining areas, Sarawak. *Geol. Surv. Dept. British Territories in Borneo Mem.,* 11, Kuching.

Manuscript received 27 July 1987