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The Southeast Sulu Sea, a Neogene marginal basin with outcropping extensions in Sabah

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Abstract: The geophysical, drill and dredge details of the Sulu Sea marginal basin allow a correlation with the Neogene geology of eastern Sabah. The basin is modelled to have resulted from early Miocene intra-arc rifting related to the SE-facing subduction system of the NW Celebes Sea.

The early stages of the opening of the Sulu Sea were characterized by explosive volcanic activity, and the rifting resulted in extensive olistostrome deposits. These events are seen onland as the Ayer and Tungku formations, and the Kuamut and Garinono formations respectively. Uplift of the Crocker Formation to the west provided the source for major quartz sands deposited in Sabah within the Tanjong Formation, and a major delta flowing northeasterly near Sandakan fed the continentally-derived turbidites of the deep Sulu Sea.

Since the ophiolitic complex of Sabah pre-dates the late-Lower Miocene opening of the Sulu Sea marginal basin, it represents the ocean floor upon which was built the volcanic arc, rifting of which gave rise to the Sulu Sea. Remnants of this early Cretaceous and older ophiolitic basement therefore underlie and outcrop within the NW margin of the SE Sulu Sea (Labuk Valley through the Cagayan Ridge), as well as along the Sulu Archipelago, extending into Darvel Day and Ulu Segama. Evidence is presented to show that the ophiolite complex was locally uplifted and eroding in the early Cenozoic.

INTRODUCTION

Marginal seas are an outstanding feature of Southeast Asia (Hutchison, 1986). Their stratigraphy and tectonic evolution have to be interpreted exclusively from oceanographic geophysical surveys, supplemented by Ocean Drilling Programme (ODP) drill sites and dredging. The Sulu Sea is an unique exception for it trends southwestwards towards eastern Sabah, where the Neogene onland geology may now be better understood in terms of the longitudinal extension of the rift.

The Sulu Sea is a small marginal basin lying between the Philippines and Borneo (Fig. 1). The early descriptions are by Marauchi *et al.* (1973) and Mascle and Biscarrat (1979). It covers approximately 260,000 km^2, and most elements of the basin trend northeast into the Philippine islands of Mindanao, Negros and Panay, and southwest into Sabah. It is composed of two basins separated by the Cagayan Ridge, traditionally named the Outer Sulu Sea (lying to the northwest) and the Inner Sulu Sea (lying to the southeast). However there is no geological merit in this terminology.

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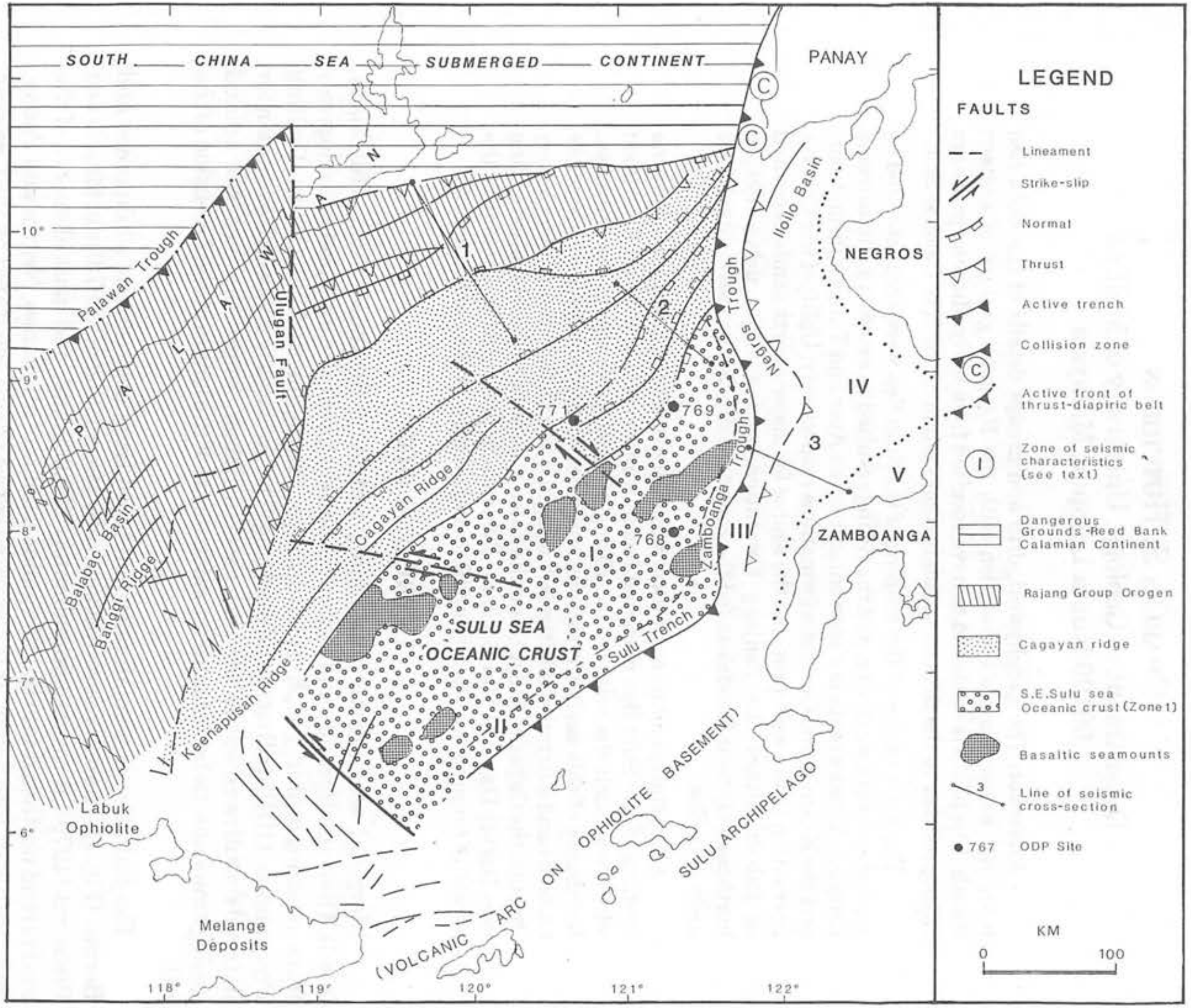

Figure 1: Main structural-geological elements of the Sulu Sea, based on Hinz *et al.* (1991) and Rangin (1989). The seismic cross sections are given in Figure 2. The zones of seismic characteristics refer to the young active Sulu Trench, shown in Figure 2, and discussed by Hinz *et al.* (1991).

A considerable amount of seismic aquisition (Fig. 2) has been reported by Hinz *et al.* (1983), Rangin (1989) and Hinz (1991). Three sites were drilled in the Southeast Sulu Sea Basin in late 1988 (Fig. 3) under leg 124 of ODP (Silver *et al.*, 1989a,b,c). The sea-floor basalts are transitional between mid ocean-ridge basalt (MORB) and island-arc tholeiite, and the oldest overlying sediments are late Lower to early Middle Miocene. The results have put to rest many previous misinterpretations, and now allow a better understanding of the geology of adjacent Sabah, where the western extension of the southeast Sulu Sea Basin can be identified. The Southeast Sulu Sea is an unique Neogene marginal basin which has onland expression. Spreading is extinct and the marginal basin lithosphere is actively being subducted eastwards beneath the Philippines at the Sulu and Negros Trench.

Offshore exploration and drilling for oil in the then poorly understood Sulu Sea, both in Malaysian and Philippine waters (Bell and Jessop, 1974), was unsuccessful. The thick Miocene successions were misinterpreted by the company geologists as fore-arc basin deposits. The trend of these basins is northeasterly, unrelated to the inferred trench, which was assumed to trend northwest parallel to the east coast of Sabah (Hamilton, 1979). The Sulu Trench is now known not to extend close to Sabah (Fig. 1). The lack of understanding of the tectonic setting undoubtedly contributed significantly to the absence of success by the petroleum companies.

THE MISCONCEPTIONS

Weissel (1980) identified magnetic anomalies 18 to 20 in the adjacent Celebes Sea, trending ENE parallel to the elements of the Sulu Sea, from which an age of Middle to late Eocene was deduced. This has been confirmed by ODP drilling (Silver *et al.*, 1989 a,b,c). However Weissel (1980) deduced the age of the Sulu Sea floor by interpolation of observed ages, heat flow, and basement depths from the South China and Celebes basins, and came up with the wrong answer for the age of the Sulu Sea floor–Oligocene.

Lee and McCabe (1986) misidentified magnetic anomalies in the Celebes Sea, and made the erroneous conclusion that the basin dates back to Maastrichtian. They also identified Eocene magnetic anomalies in the Sulu Sea. This was also erroneous and demonstrates the danger of attempting magnetic anomaly identification without any direct drilling evidence of age.

Lee and McCabe (1986) made the wrong interpretation that both the Celebes and Sulu seas represent remnants of a Cretaceous-Eocene ocean which have become trapped behind younger arc-trench systems. The Celebes Sea may well represent trapped Eocene oceanic lithosphere, for its pillow basalts have typical MORB characteristics (Silver *et al.*, 1989), but the ODP data indicate an intra-arc origin for the Sulu Sea.

I also erroneously interpreted the Sulu Sea as the remnant of a former ocean trapped behind younger arc-trench systems (Hutchison, 1986), and in showing that many of the tectonic elements of the Sulu Sea continue onland into Sabah, I wrongly

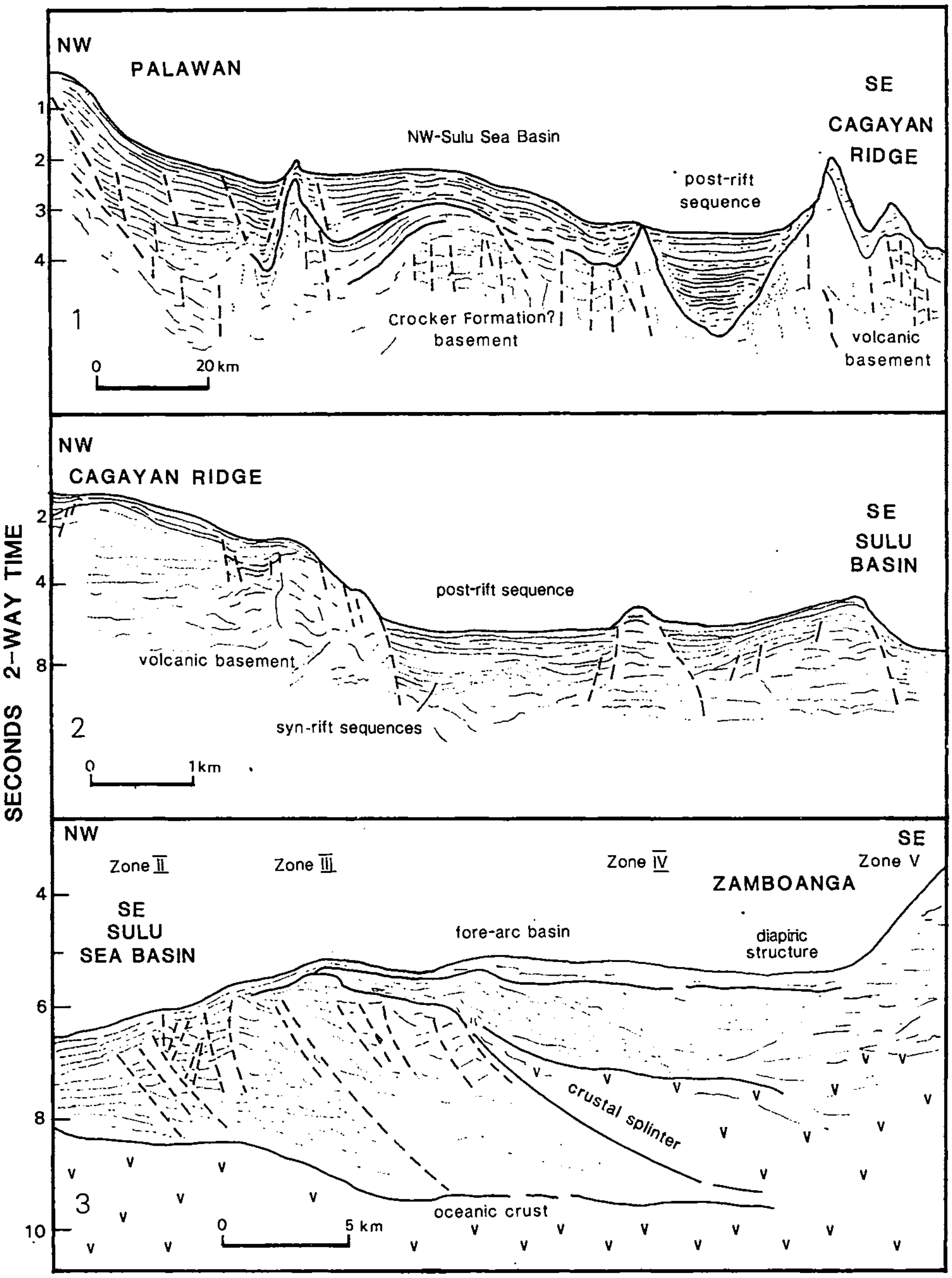

Figure 2: Selected seismic cross sections to illustrate the structure of the Sulu Sea. 1 = from Hinz (1983); 2 = from Rangin (1989); 3 = from Hinz *et al.* (1991).

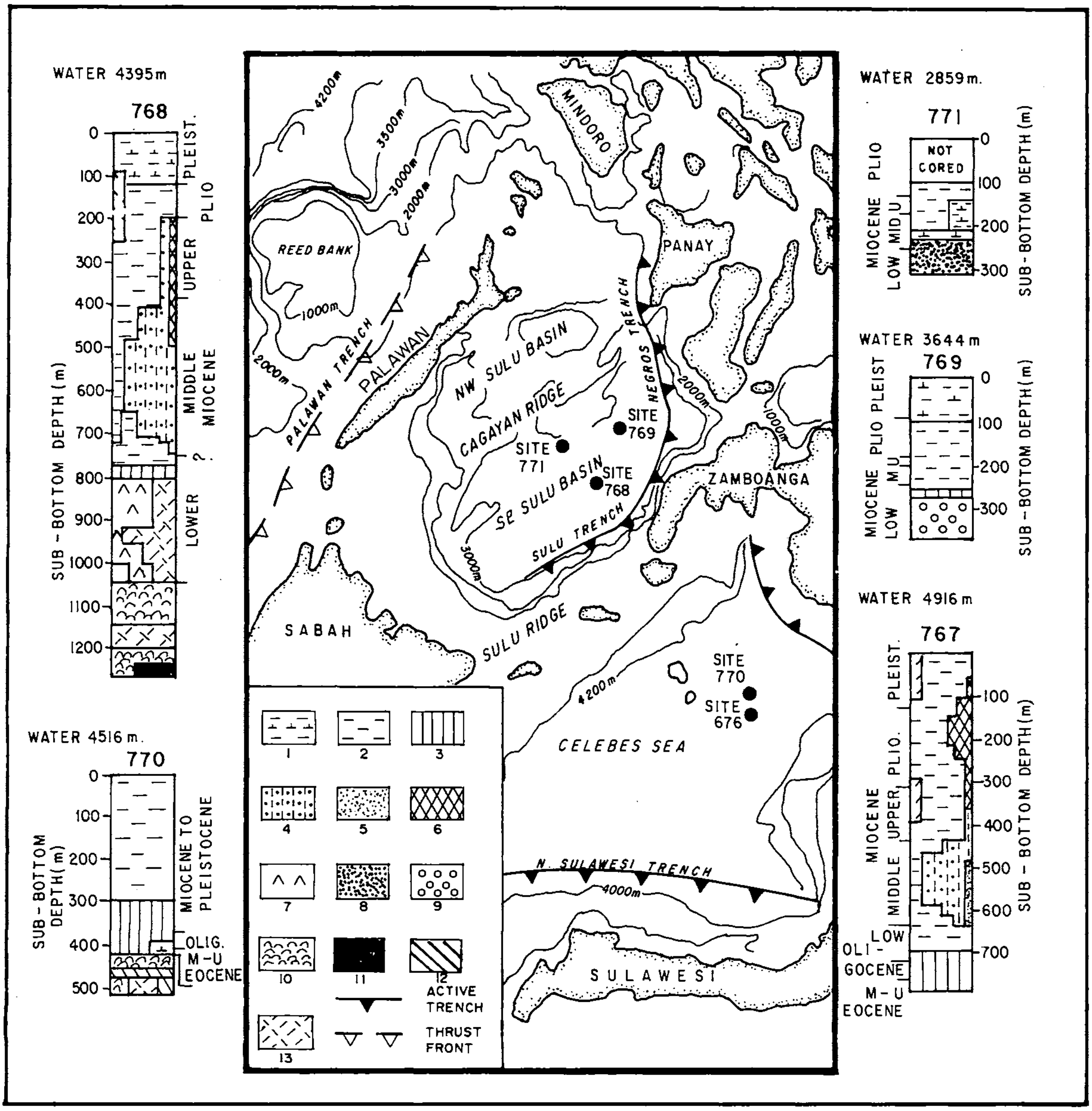

Figure 3: The Ocean Drilling Programme (ODP) drill sites of the Sulu Sea, based on Silver *et al.* (1989a,b,c). The core lithologies are as follows: 1 = nannofossil or nannofossil-foraminiferal marl; 2 = hemipelagic sediments including clay or silt (stone); 3 = pelagic brown claystone; 4 = terrigenous turbidites; 5 = quartz siltstone and sandstone; 6 = graded carbonate turbidites; 7 = fine ash tuff; 8 = pumiceous rhyolitic to dacitic coarse tuff and lapillistone; 9 = andesitic to basaltic coarse tuff and lapillistone; 10 = pillow basalt; 11 = basalt sheet flow; 12 = brecciated massive basalt; 13 = diabase sill.

presumed that the ophiolitic basement complex of Sabah represents the uplifted floor of the Sulu Sea (Hutchison, 1978). The ophiolite complex of Sabah is pre-Cenozoic, and pre-Sulu Sea in origin. This recognition allows the geology of the eastern part of Sabah to now be better understood. My former interpretation of eastern Borneo tectonics (Hutchison, 1988) did not recognize the importance of the Sulu Sea. This mistake may now be rectified.

PRESENT UNDERSTANDING OF THE SULU SEA

NW Sulu Basin

This older part of the Sulu Sea has been named the "Sabah–Palawan Orogenic Belt" (Rangin, 1989) and the "Borneo–Sulu Collision Belt" (Hinz *et al.*, 1991). It is interpreted from seismic profiles (Fig. 2) to consist of a stack of basaltic oceanic crustal slabs (like roof tiles) each overthrust towards the NW and dipping SE. These thrust sheets bring ophiolitic basement rocks to the surface on Palawan and Banggi islands. The basement is overlain by a seismically incoherent formation, interpreted by both Rangin (1989) and Hinz *et al.* (1991) to correlate with the Paleogene Crocker Formation of Sabah.

The thick overlying sub-horizontally bedded unit, of 0.5 to 3.5 s (two way time) thickness, rests with a distinct late Lower Miocene regional unconformity on the strongly deformed Crocker? Formation. The early Miocene unconformity is universally present throughout the region, named by Bol and Van Hoorn (1980) the "Deep Regional Unconformity".

The Cagayan Ridge

The seismic sections (Fig. 2), combined with the ODP cores (Fig. 3) and dredge samples (Kudrass *et al.*, 1990), suggest that the ridge represents the rifted margin of the older Borneo–Sulu Collision Belt, down faulted into the SE Sulu Sea marginal basin proper.

This rifted margin is characterized by early Miocene to early Middle Miocene lapillistone, tuff and basalt flows (Silver *et al.*, 1989a,b,c). Dredged samples include calc-alkaline basaltic andesite, dacite and rhyolite tuff (Kudrass *et al.*, 1990). The calc-alkaline volcanic arc is seen to be superimposed on tilted basement blocks and intervening half graben basins. An obvious interpretation is that the Cagayan Ridge represents an Early to early Middle Miocene volcanic arc which was actively rifting.

The SE Sulu Sea Basin

Hinz *et al.* (1991) have delineated four structural zones in the marginal sea proper (Fig. 1).

Zone I comprises the major part, 140 km wide. The igneous basement is smooth and has the seismic signature of typical oceanic crust, also characterized by several basaltic seamounts (Fig. 1). The basaltic layer is overlain by a 1 to 2 s (two way time) thick sedimentary formation. The minimum age of initiation of sea floor spreading is 19 Ma and an age of 15 Ma has been determined for ODP Site 768 (Fig. 3). The oldest sediments overlying the basaltic basement are late Lower Miocene radiolarian red clay, overlain by 250 m of acid pyroclastic tuffs, suggesting that the SE Sulu Sea basin originated as an intra-arc basin in the early Miocene.

Zone II, 7 to 25 km wide, represents the active Sulu–Negros trench. The oceanic lithosphere of Zone I descends E to SE with dips of 11° beneath zone III.

Zone III, 15 to 35 km wide, is characterized by imbricate thrust sheets (Fig. 2) typical of an accretionary wedge.

Zone IV, 15 to 30 km wide, is composed of a crustal splinter of oceanic basement which supports a narrow fore-arc basin, bounded sharply on the SE by the Zamboanga volcanic arc complex.

Thus the early Miocene SE Sulu Sea marginal basin lithosphere is presently subducting beneath Zamboanga and Negros at a very immature subduction system. It is important to note that the Sulu Trench was not responsible for the older Sulu Archipelago–Semporna volcanic arc and that the trench dies out southwesterly and has no extension into Sabah.

PRE-SULU SEA GEOLOGY OF SABAH

Progress in understanding the geology of Sabah can now be made by recognizing that a new cycle of rifting and marginal basin formation was initiated in the late Lower Miocene. All older formations therefore should be ascribed to a previous tectonic cycle or cycles (Fig. 4).

The pre-Sulu Sea basement has been rifted and imbricated, to form prominent horsts, between which the Middle Miocene and younger strata were deposited: i) extending southwestwards along the Sulu Archipelago into Sabah as the Semporna Peninsula/Darvel Bay/Ulu Segama basement horst, ii) The Cagayan Ridge, extending southwestwards into Sabah as the Bidu-Bidu Hills/ Labuk Valley basement horst, and iii) the Palawan horst, extending into Sabah as the Pulau Banggi/Kudat Peninsula high.

Together with other less pronounced horsts, they were basement highs and did not receive much Middle Miocene or younger sedimentation. The sedimentary sequences thin dramatically towards them, and turbidites in the extant Sulu Sea basin are confined to the deeps away from the basement horsts.

Paleogene and older

Extensive outcrops of an association known as the Chert–Spilite Formation[1] (Kirk, 1968) occupy the western extensions of the three major basement horsts which extend southwestwards into Sabah. The sedimentary formations which overlie the pillow basalts are predominantly ribbon chert, but also include limestone and some argillite and turbidite sandstone. These should be regarded as Layer 1,

[1]Unfortunately the Chert–Spilite Formation (Layers 1 and 2 of the ophiolite complex) was not included in the so-called "Crystalline Basement" (layers 3 and 4 of the ophiolite complex). Therefore there is no geological merit in continuing to use the terms "Crystalline Basement" and "Chert–Spilite Formation".

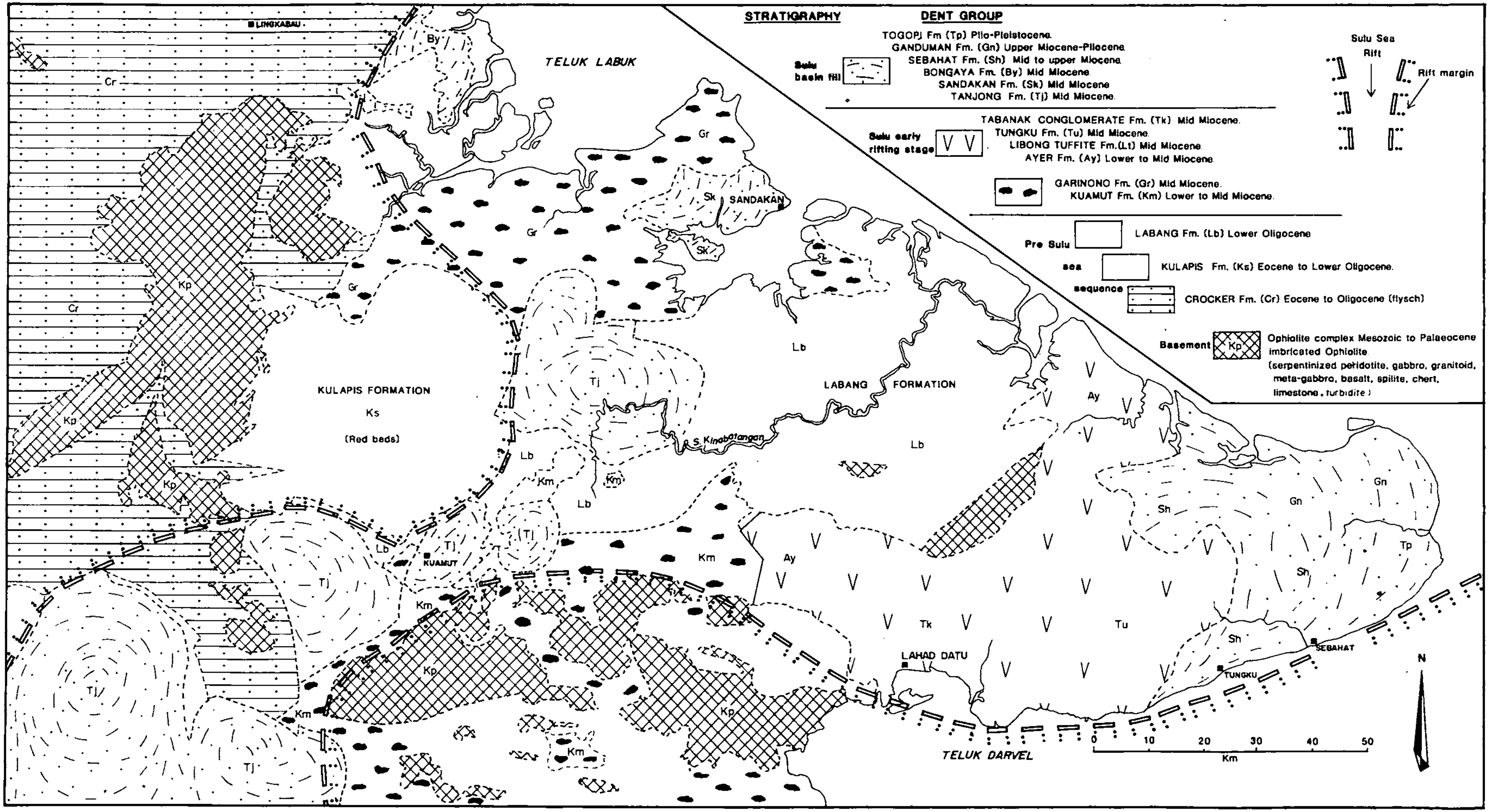

Figure 4: Simplified geological map of the Dent Peninsula of Sabah, following Haile *et al.* (1965) and Lim (1985). The margins of the Sulu Sea Rift can only be approximately drawn to encompass all mélange and basin-fill formations.

the sedimentary layer of the ophiolite complex. Radiolaria dissolved out of the cherts give a consistent age range of Barremian to Aptian (early Cretaceous) (Leong, 1977; Basir *et al.*, 1985; Rangin *et al.*, 1990). Kirk (1962) gave an age of Upper Cretaceous (Campanian) for the lower part of the Madai–Baturong Limestone, which overlies turbiditic sandstone of the Chert-Spilite Formation. This is consistent with the general Cretaceous age determined from the detailed palaeontology (Fontaine and Ho, 1989). The youngest determined age for sedimentary rocks of the Chert–Spilite Formation[1] is Paleocene to Eocene. When these sediments were laid down, the basin (presumably a marginal basin, but of pre-Sulu Sea ancestry) was predominantly below the carbonate compensation depth (CCD), so that ribbon cherts abound, but limestones, such as the Madai–Baturong Limestone, are locally significant and they suggest that the basin was later of shallower depth, above the CCD.

Evidence for Paleogene uplift of the ophiolite complex

The formations which post-date the ophiolitic complex show evidence that an uplifted and eroding ophiolitic complex terrain was an important provenance (Fig. 5). These formations are briefly described:

Chert-Spilite Formation (in part): Some of the sedimentary rocks which have been ascribed to the "Chert-Spilite Formation" should not have been so included, and they belong to a younger cycle, when the ophiolite complex was uplifted and eroding. There are examples of this in the Bidu Bidu Hills of the Labuk Valley (Newton-Smith, 1967), and new roadcuts have been described by Hutchison and Tungah Surat (1991).

Sandstones of the Rumidi Estate contain clasts of altered basic igneous rock, chert, and grains of chromite and sodic plagioclase. The conglomerates contain clasts up to 3 m diameter of ultrabasic rock and spilite, in a matrix rich in serpentinite grains (Newton-Smith, 1967). This petrography indicates that they were derived in part from an uplifted and eroding ophiolitic complex, layers 1 and 2 of which are represented by the Chert–Spilite Formation. Hence these sandstones and conglomerates post-date the Chert–Spilite Formation. Plant remains are common in the sandstones, indicating that the uplifted ophiolitic complex was vegetated. Pelagic foraminifera in sandstones and interbedded mudstones are not age diagnostic. It would have been logical to include these strata in either the Kulapis Formation or the Kamansi Beds, whose outcrops are contiguous.

Kulapis Formati ι: Red, orange and pink friable sublitharenites and calcareous lithic arenites, interbedded with laminated red to chocolate-brown mudstones, are the most characteristic lithologies of the Lower Kulapis Formation (Fitch, 1958, Collenette, 1965, Newton-Smith, 1967, Yap 1976). The thick bedded sand-rich facies includes grain flow and slurry deposits, which contain shallow to deep shelf trace fossils (Yap, 1976). The oldest age-diagnostic microfossils include a calcareous nannofossil assemblage of Middle to Upper Oligocene age (Clennell, 1991).

Provenance from an uplifted and eroding ophiolitic landmass is indicated by clasts of chert and chloritized basic igneous rock and grains of ferromagnesian

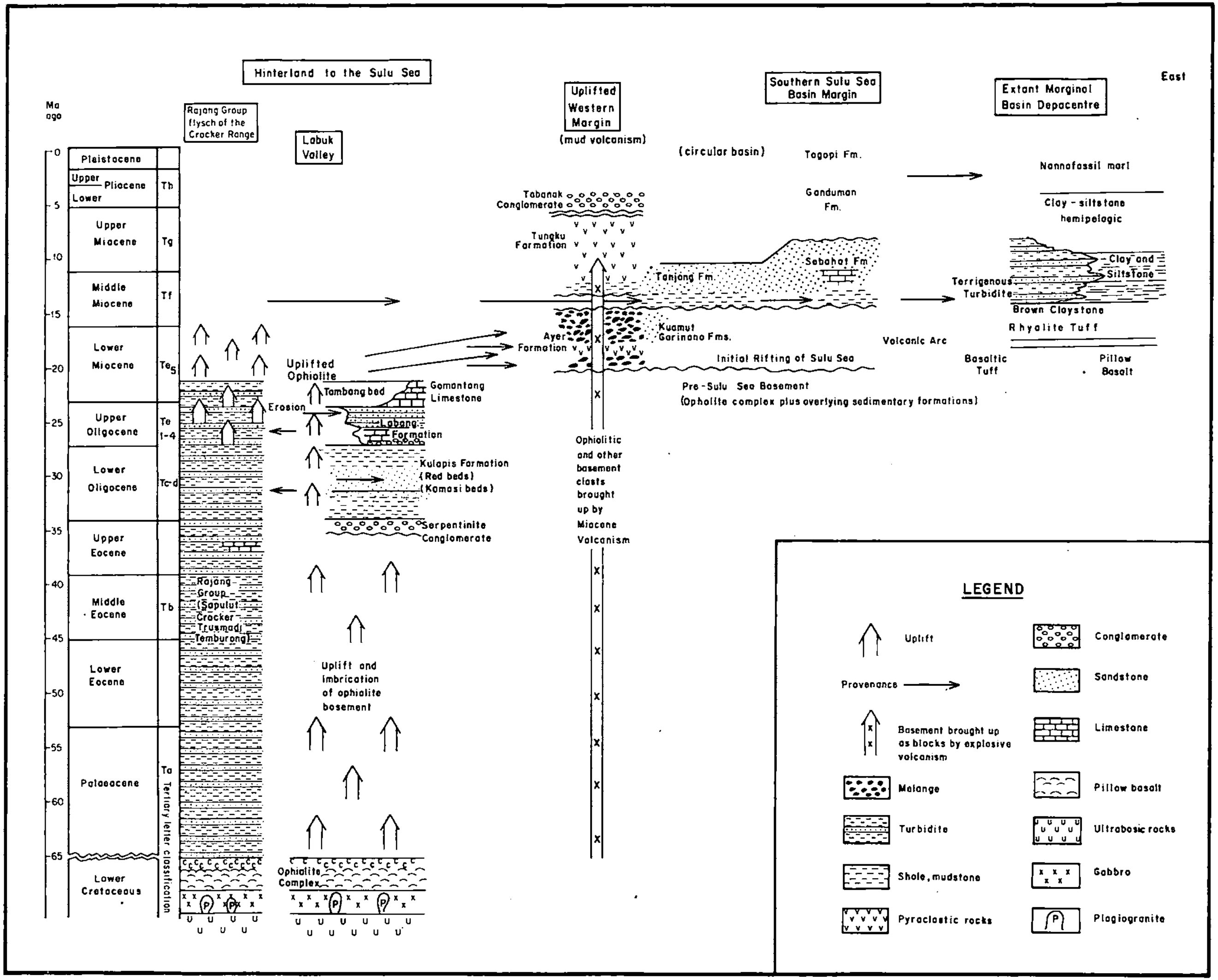

Figure 5: Schematic E-W diagram, from the Crocker Formation (left) to the SE Sulu Sea depocentre (right), to summarize the stratigraphy and major geological events. The horizontal arrows denote the direction of sediment transport from an uplifted and eroding terrain.

minerals and sodic plagioclase in the sandstones. The characteristic red colour of the marine sandstones probably indicates provenance from a nearby oxidized landmass.

Kamansi Beds: This is an interbedded sequence of grey sandstone and carbonaceous mudstone, containing similar foraminifera to the Kulapis Formation, so that Newton-Smith (1967) preferred a general Oligocene age. Provenance from an eroding landmass of ophiolitic rocks is indicated by the sandstone petrography. The coarser varieties contain clasts of chert and serpentinite. The sandstones contain grains of sodic plagioclase, olivine and epidote.

Tambang Beds: This is a sequence of sandstone, calcarenite and shale. The calcarenite contains Upper Oligocene foraminifera (Newton-Smith, 1967). Provenance of the sandstones from an eroding ophiolite landmass is indicated by their content of clasts of chert and altered basic igneous rock, as well as grains of sodic plagioclase and ferromagnesian minerals.

Labang Formation: This is a sequence of sandstone and shale, with limestone and rare conglomerate and tuffaceous beds (Haile *et al.*, 1965). Many of the sandstones have been deposited by turbidity currents (Tham, 1984). Foraminifera, especially in the limestones, indicate an Upper Oligocene age. Provenance of the sandstones and conglomerates from an eroding ophiolite landmass is indicated by their content of clasts of radiolarian chert, and grains of hornblende and sodic plagioclase. The ***Napu Sandstones*** should be considered part of the Labang Formation (Haile *et al.*, 1965), and they show similar petrography.

Gomantong Limestone Formation: This limestone overlies the Labang Formation and contains Lower Miocene foraminifera (Haile *et al.*, 1965).

Crocker Formation: This thick flysch sequence of interbedded mudstones, sandstones and siltstones contains all the characteristics of a turbidite fan, deposited by currents which generally were directed towards the northeast (Stauffer, 1968). The agglutinated foraminifera are generally not age diagnostic, and an age from late Cretaceous to Eocene is generally held. Though the formation has not been stratigraphically deciphered, it is assumed to young towards the northwest, in the general form of an accretionary prism (Tongkul, 1989).

No single outcrop has demonstrated the lower contact of the Crocker Formation, but it is logical to assume that it overlies the ophiolite complex, implying that it was deposited as a turbidite into a deep marginal or oceanic basin whose pillow basaltic floor and overlying chert of the Kudat Peninsula dates back to the early Cretaceous (Basir *et al.*, 1985).

The provenance of the Crocker Formation sandstones is likely to be a distant landmass, lying to the south and west. However, there are indications of a local contributory provenance from uplifted ophilite in the Labuk Valley and Mount Kinabalu region. Kirk (1968) has listed many localities where the Crocker Formation sandstones contain clasts of spilite. He particularly mentions a locality south of Mount Mentapok, in the Labuk Valley, where contorted mudstone of the Crocker Formation contains large angular spilite blocks, and there are thin layers of fragmented spilite interlayered with greywacke. Crocker Formation sandstones to the NW of Labuk Bay contain grains of labradorite and sodic plagioclase, in addition to chert, epidote and hornblende (Wilson, 1961), which are consistent with some input from a nearby eroding landmass of uplifted ophiolite.

Trusmadi Formation: The Trusmadi Formation is considered to be a more argillaceous facies of the Crocker Formation, commonly slaty and phyllitic. Its contained foraminifera are not age diagnostic, but an age of Paleocene to Eocene is presumed from contiguous fossiliferous limestones (Jacobson, 1970).

Sandstones of both the Crocker and Trusmadi Formations in the Gunung Kinabalu region contain detrital minerals which indicate provenance from an eroding ophiolitic landmass. The rock clasts are of chert and spilite. The mineral grains are sodic plagioclase and hornblende (Jacobson, 1970).

Significance of glaucophane

The only glaucophane-bearing locality of those listed by Leong (1978), which has authenticated and in-situ outcrops, is in the Labuk Valley, along the NW-SE trending Lumau Fault in the Sungai Livadai, about 12 km NW of Telupid (Johnston and Walls, 1974). I have studied thin sections from this locality. None of the outcrops are of glaucophane schist (blueschist). Muscovite metaquartzite and metabasite contain a small proportion of euhedral porphyroblasts of glaucophane, common epidote and piedmontite. The metabasite represents the basaltic layer of the ophiolite complex and the metaquartzite represents overlying quartz-rich turbidite sandstones, which have been assigned to the "Chert–Spilite Formation". Alternatively they may represent the lower part of the Crocker Formation, which outcrops nearby.

The metamorphic assemblage puts these rocks into the glaucophane-epidote high pressure facies, leading to the unassailable conclusion that the region has been dramatically uplifted. The fact that the glaucophane is perfectly euhedral, and the rocks not schistose, precludes shearing pressure from their genesis.

EARLY RIFTING HISTORY OF THE SULU SEA

Chaotically disrupted rock units outcrop over 12000 km^2 of eastern Sabah (Fig. 4). They are predominantly mudstone-matrix mélanges and broken formations. The disrupted rock units should strictly not be given formation names and they belong to a single continuous body, which is taken to define the geographical extent of the early to Middle Miocene SE Sulu Sea rift on mainland Sabah (Fig. 4). The rifting occurred within an active volcanic arc, for pyroclastic and volcanic rocks are widespread. Active rifting created steep unstable submarine slopes resulting in widespread olistostrome deposits.

Garinono Mélange: The formation, defined by Collenette (1966), is well exposed along the newly aligned Labuk road between Sandakan and Telupid. Every gradation can be seen from coherent Kulapis Formation, through broken beds, to mud-matrix mélange in which the clasts are predominantly of sandstone and siltstone. Clennell (1991) has described similar transitions to broken Labang

Formation. Other mélange areas contain clasts of pillow basalt, serpentinite and chert. Clasts of serpentinite sandstone occur commonly in the mélange (Yap, 1976; Clennell, 1991), offering further evidence of the early Cenozoic erosional reworking of the Early Cretaceous ophiolitic complex.

In Sandakan town and in the Sungai Manila Estate, the Garinono Formation includes bedded andesite tuff and andesite agglomerate (Lee, 1970). This bedded sequence is unconformably overlain by the Middle to late Miocene fluvio-deltaic quartz-dominated Sandakan Formation. The unconformity is best seen on the coast at Tanjong Papat, beneath the new mosque.

The bedded sequence and the mélange mudstone matrix contain a range of reworked micro-fossils. The youngest (Middle Miocene) are taken to represent the formation age.

Kuamut Mélange: The Kuamut Formation (Collenette, 1965) separates the basement ophiolite complex (Chert–Spilite Formation) from the overlying Middle Miocene Tanjong Formation. It has been dated early to Middle Miocene (Leong, 1974). The clasts are of older sedimenentary formations, with a higher proportion of chert, basalt and serpentinized peridotite from the basement ophiolite.

Ayer Mélange: This strongly and irregularly folded formation comprises interlayered tuffs and mélange deposits which range from pebbly mudstone to boulder beds (Haile *et al.*, 1965).

The tuffaceous facies: The most characteristic rock type is a massive to well bedded fine grained to conglomeratic feldspathic tuff breccia. Angular to subangular fragmental plagioclase feldspar crystals form 20 to 40% of most rocks. The coarser varieties are of volcanic breccia. These tuffaceous layers are interbedded with calcareous claystone or marl. The tuffaceous facies is interlayered with and exhibits a lateral transition to the boulder-bed facies (Haile *et al.*, 1965).

The polymict boulder-bed facies: The boulder beds range up to several hundreds of metres thickness. The matrix is of poorly bedded mudstone, slickensided around the clasts. The boulders are of tuff breccia, chert, silicified argillite, radiolarian claystone, limestone, quartzite, sandstone, pillows of spilite, serpentinite, hornblende gneiss, amphibolite, and calc-arenite.

Foraminifera in the tuffs and matrix of the mélange indicate an age extending from the late Lower Miocene into the Middle Miocene.

The depositional environment may be interpreted as unstable, with steep slopes, in the close vicinity of an active volcanic arc built on an ophiolitic basement. Active rifting of the volcanic arc would have resulted in steep slopes causing olistostromes (boulder beds) deposition into an actively opening intra-arc basin.

Libong Tuffite Formation: This formation is of well bedded tuff and rare lenticular limestones that form synclinal basins, which appear to unconformably overlie the Ayer Formation. Its sandstones and conglomerates contain clasts of andesite, chert, serpentinite, meta-gabbro and a variety of sedimentary rocks. Its sandstones may contain up to 25% hornblende, up to 35% plagioclase, and up to 15

% augite crystals. The age is Middle Miocene, and it appears to represent a similar volcanic arc environment to the Ayer Formation. This formation is unconformably overlain by the Tungku Formation (Haile *et al.*, 1965).

Tungku Formation: This Middle Miocene formation is composed of well bedded sandstone, conglomerate and plant-bearing clay. The conglomerate shows provenance from uplifted ophiolite and contains clasts of chert and metabasites. The Tungku Formation contains an important Bagahak Pyroclastic Member of andesitic boulder conglomerate and andesite breccia (Haile *et al.*, 1965). K:Ar dating of andesites along the southern coast of the Dent Peninsula has given Middle Miocene ages within the range 11 to 16 Ma (Rangin *et al.*, 1990).

Eclogite, representing subducted basaltic lithosphere, occurs as loose boulders in the Tungku Valley (Haile *et al.*, 1965). The boulders are presumed to have been brought to the surface as xenoliths within the subduction-related Middle Miocene volcanoes (Fig. 6). Once at the surface, the eclogite could have been reworked into the Ayer mélange, and in turn reworked into active mud volcanoes.

The Semporna Volcanic Arc: The Semporna Peninsula volcanic arc is predominantly of hypersthene andesite, with subordinate rhyolite and dacite. Although the volcanism was considered by Kirk (1962; 1968) to be Pliocene, superimposed by younger rift-related Quaternary basalts at Mostyn Estate, the ages have now been better constrained by Rangin *et al.*(1990). The main Semporna volcanic arc has yielded K:Ar dates within the range 9 to 12 Ma (Middle to late Miocene) and the rift-related volcanism around 3 Ma (Pliocene). Many geomorphologic volcanic features have been preserved in this arc. It became extinct when subduction ceased, but unlike the remnant arcs to the north, was not disrupted.

SULU SEA MARGINAL BASIN FILL

Formations formed dominantly of mudstone, containing important quartz-rich siltstone and medium-grained sandstone layers, which may be thick, unconformably overlie the mélange deposits. They are difficult to date because of the problem of fossil reworking, but a Middle to late Miocene age is generally accepted. Conglomerates and limestones are rare and coals are locally important. These formations are collectively known as the Tanjong Formation (Collenette, 1965), which unconformably overlies the Kuamut Mélange, and the Sandakan Formation (Lee, 1970), which unconformably overlies the Garinono Mélange. They are interpreted as fluvio-deltaic to estuarine.

A characteristic feature of these formations is that their geographical continuity has been disrupted by neotectonic processes into elliptical and circular basins. This has been ascribed to loading of the sandstones into the underlying unstable mélange deposits, and presumably occurred during uplift of the terrains on which they occur. In the Maliau Basin, for example, Middle Miocene sandstones now occupy an elevation up to 1600 m above sea level.

The Tanjong Formation of the Maliau Basin continues SSE to form the Tarakan Basin of Kalimantan (Hutchison, 1989), where similar fluvio-deltaic

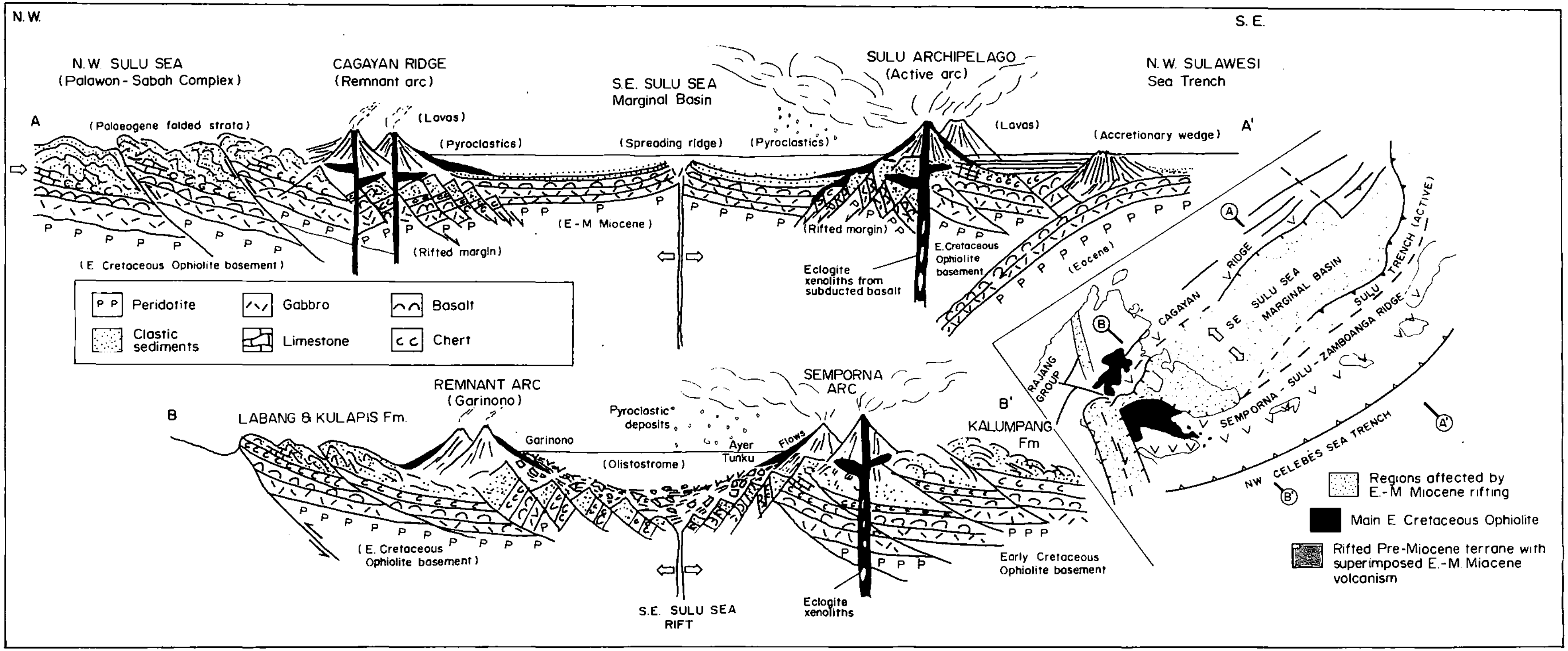

Figure 6: Schematic cross sections to illustrate the early to Middle Miocene active rifting stage of the SE Sulu Sea (A-A') and its onland extension into Sabah (B-B'). No inferred scale. Soon after this time, the Middle to late Miocene quartz-rich Tanjong and Sandakan formations built out fluvio-deltaic systems over the olistostrome deposits, feeding terrestrial turbudite flows (Fig. 3) into the main SE Sulu Sea Basin.

strata have not been uplifted, and the formation has not been deformed into elliptical/circular basinal morphology.

In Sabah another trend is NE from the Maliau Basin towards Sandakan, the SE Sulu Sea rift trend. Palaeocurrent directions show that the fluvial-deltaic Middle Miocene current directions were directed towards the Sulu Sea. Tjia *et al.* (1990) report that the long axes of pebbles and the cross beds of the sandstones and ripples indicate the transport direction was predominantly towards 30 to 70°. In the Bukit Garam District, between Kuamut and Maliau, Tham (1984) shows that the palaeocurrect directions of the Tanjong Formation were predominantly E to ESE, whereas within the Sandakan Formation, Lee (1970) has shown that the palaeocurrent directions were predominantly N-S.

Other components of the basin-fill stratigraphy have been included by Haile *et al.* (1965) in the Dent Group. It includes the late Miocene Sebahat Formation, which is predominantly of mudstone with subordinate sandstone, conglomerate and limestone, and is transgressive over the Tungku and Ayer mélanges. The Sabahat Formation is accordingly in a similar position to the Sandakan Formation.

To the north of Sandakan, the Upper Miocene Bongaya Formation, consisting of a sandstone-mudstone sequence, rests unconformably upon the Crocker Formation (Wilson, 1961).

MODEL FOR EARLY TO MID MIOCENE RIFTING

The marginal basin intra-arc rifting model of Karig (1971) has been widely accepted and developed by subsequent workers, such as Carey and Sigurdsson (1984). The details of the Sulu Sea were unknown at the time D. E. Karig wrote his paper. The Sulu Sea offers the most perfect example of the model of intra-arc rifting (Karig, 1971). It is doubtful, however, if the other marginal basins of Southeast Asia can be shown to have a similar origin (Hutchison, 1986).

The Cagayan Ridge represents a remnant arc which became extinct in the early Middle Miocene. It is represented onland Sabah in the Sandakan area by the bedded andesitic pyroclastic member of the Garinono Mélange. The Ridge is separated by the SE Sulu Sea marginal basin from the Middle Miocene active arc, to be found forming the SE margin of the Sulu Sea along the Sulu Archipelago, extending along the Semporna Peninsula as far west as Tawau (Fig. 6).

The model attributes the origin of the Sulu Sea intra-arc rifting to a SE-facing subduction system, the arc-trench system of which was migrating southeastwards. The trench should be located along the poorly known NW margin of the Celebes Sea (Rangin, 1989). The eclogite boulders and pebbles, found in the rivers of the Tungku Valley, are presumed to have been brought up to the surface as xenoliths in the subsequently disrupted Ayer and Tungku Formation volcanic arc. They were reworked into the mélange deposits.

The onland part of the SE Sulu Sea Rift is characterized by the extensive mélange deposits, interpreted to have resulted from olistostrome flows into the active rift (Fig. 6). Seafloor spreading may have extended into Sabah, but would have died out longitudinally towards the southwest extremity of the rift. However, there is no outcropping evidence of sea-floor spreading.

The extensive mélanges of eastern Sabah have been variously interpreted to have resulted from subduction-accretion (Hamilton, 1979), thrusting (Rangin *et al.*, 1990), mud diapirism (Barber *et al.*, 1986), and rifting (this paper). The absence of a sheared texture and the transition from mud-matrix mélange to broken beds favours the rifting hypothesis.

An important consideration in rejecting the thrust origin is by comparison with the great Tethyan central Asian thrust mélanges of Uzbekistan and Azerbajaan, which I have studied in the field. They are predominantly serpentinite-matrix mélanges. By contrast I have seen only two examples of serpentinite-matrix mélange in Sabah, both of minor extent, occurring near Kunak and in the Danum Valley of Ulu Segama. With so much serpentinite available in the ophiolite complex, I would expect an abundance of serpentinite-matrix mélange if they had resulted from thrust tectonics. The overwhelming mud-matrix character strongly favours an olistostrome character related to active rifting.

One cannot deny that mud volcanoes occur widely throughout the mélange tarrain of Sabah (Haile *et al.*, 1965). Nowhere in Sabah can exotically derived mud be seen pervading and disaggregating blocks of pre-existing formations (Clennell, 1991). On the contrary the mud volcanoes appear to have reworked the already mélanged rocks. It would also be impossible for mud diapirism to have originated at such great depth and to have sufficient viscosity to bring up eclogite blocks.

Very soon after the rifting and olistostrome formation, the Rajang Group to the west was dramatically uplifted to cause erosion and provide a source of the quartz-rich sandstones of the Tanjong, Sandakan and other basin-fill formations of Middle to late Miocene age. On the landmass of Sabah, they are of fluvio-deltaic and estuarine environment. The rivers and deltas fed Middle Miocene turbidite flows into the deep SE Sulu Sea and Celebes Sea basins (Fig. 3).

Tjia *et al.* (1990, p.286) discuss a tectonic scenario which takes little note of the detailed geology of the Sulu Sea and assumes that the whole of Sabah NE of the Tarakan Basin is exotic to Borneo. This is most unlikely.

Both Hutchison (1988) and Rangin *et al.* (1990) developed a model of overthrusting of the early Miocene Volcanic arc (Dent volcanics) northwesterly over the Rajang Group, resulting in a collisional orogen. The cause was considered to be the southeasterly underthrusting of the Miri Zone of Borneo and the contiguous Dangerous Grounds terrain of the South China Sea beneath the Rajang Group. Rangin *et al.* (1990) gave no satisfactory explanation for the Middle Miocene opening of the SE Sulu Sea in this model. Hutchison (1988) attributed the rifting to back arc phenomena resulting from a SE-facing subduction system in the Sulawesi region. The present paper has presented additional details of the relationships of Sabah to the Sulu Sea, which broadly fit this model. The major difficulty in understanding the tectonic evolution of this region is the rapidity with which tectonic events change. Marginal basins open along one polarity and soon thereafter begin subducting along a different polarity. Another major question remains. How much, if any, continental lithosphere was involved in the Sabah region? Hinz *et al.* (1991) have suggested that there may be continental lithosphere beneath the Cagayan Ridge. Middle Miocene granites at Long Laai are so strongly mineralized in tin as to require underlying continental lithosphere as their source (Hutchison, 1989). Yet the outcrops of Sabah and eastern Kalimantan do not suggest the existence of continental crust.

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