GEOSEA V Proceedings Vol. II, Geol. Soc. Malaysia, Bulletin 20, August 1986; pp. 97–136

Geological evolution of the Indonesian Archipelago

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Abstract: The Indonesian Archipelago consists of accretionary development of island arcs, continental blocks, rifted and drifted microcontinents, ophiolite fragments and sedimentary cover. These through a series of complicated past to recent tectonic processes form the current configuration of the archipelago. In the geological evolution of Southeast Asia, active plate margins, resulting in island arc development and accretionary terranes have played an important role since Late Triassic time.

Prior to their development, the Proto Kalimantan and Proto Sumatera continents, both including island arc were amalgamated during Late Triassic time along the Bentong-Raub suture to form the Sunda Platform. In contrast the northwestern margin of Australia has always been a passive margin. Based on palaeontology, palaeomagnetics and stratigraphy the Indonesian Archipelago is provisionally subdivided into 13 terranes. Material accreted along active margins commonly called accretionary terrane is excluded from this terrane classsification. The terranes are Proto-Kalimantan, Sumatera basement, Southwest Sulawesi, East Sulawesi Opiolite, Sumba, Seram, Timor, Buton, Banggai-Sula, Buru and Bacan.The continental fragments Sikuleh and Natal have recently been reported to occur in the southwestern coast of Sumetera. The NE margin of Australia has continued to develop as an active margin up to the present day, producing the Banda Arc. During the Paleogene southwest Sulawesi rifted away from east Kalimantan to collide with oceanic crust to the east and in the Tertiary, west Sulawesi magmatic arc came into existence.

The Sulawesi ophiolite originates from oceanic crust that was pushed westward by the migrating Banggai-Sula terrane and blocked by the Tertiary West Sulawesi magmatic arc. The terranes Sumba, Buton, Seram and Timor result from a rift-drift event affecting northwest Australia during Jurassic time. The terranes Banggai-Sula, Bacan and Buru have been formed by the Sorong Fault slicing off the northernmost portion of Irian Jaya and moving these slices westward. The northwestern Australian continent, including Irian Jaya, has acted continuously as a passive margin moving northward behind a front of oceanic crust. It collided with the northern Irian Jaya Island Arc during Oligocene time after the oceanic crust had been consumed by subduction. The polarity of the subduction changed after the collision, becoming southward.

INTRODUCTION

Recently terrane analyses have been carried out in many parts of the world and the results have been used in evolutionary geological reconstructions . There are several definitions regarding terrane, and the tectonostratiographic terrane definition by Howell and Jones (1983) is as follows "*Tectonostratigraphic terranes are fault bounded geologic entities of regional extent, each characterized by a geologic history that is different from the histories of contiguous terranes*". In practice the term "*fault bounded geologic entities*" also implies suture zones as a result of collision of terranes. Other terminologies of terranes are cratonic, suspect, allochthonous exotic and accretionary which are descriptive and self explanatory.

In the present paper, the terrane concept has been applied to Indonesia. In terrane identification the continental crust is recognized as a distinct geological entity, and it also includes rift-drift separates of continental fragments. We attempt to reconstruct the various stages of geologic evolution of the Indonesian Archipelago, especially its western part in terms of plate-tectonic accretion. Rifted/drifted parts formed by a separation of continental margins are considered as terranes; this applies mainly to eastern Indonesia where numerous continental fragments are known to occur.

Accretionary terranes as a result of island arc development of the Southeast Asian active margin, including magmatic arcs and subduction melanges, are excluded from the terrane identification. These accretionary terranes which fringe the southeast Asian active continental margin, commenced during the Jurassic, and include accretionary terranes in Sumatera (Jurassic to Recent), Java (Cretaceous to Recent), North Kalimantan (Jurassic to Late Tertiary), East Kalimantan (Jurassic to Early Tertiary), West Sulawesi (Paleogene to Early Neogene), North Sulawesi (Neogene to Recent) and Banda Arc (Tertiary to Recent). However, island arcs, that stand independently and which are not related to an active continental margin, are classified as terranes. This applies to the Tertiary island arc of northern Irian Jaya and possibly the Paleogene volcanic complex overlying the Timor terrane.

The general outline of the evolution is that the Southeast Asian region is considered as a result of an amalgamation of two continental blocks, the Indosinia and Mergui terranes, during Late Triassic time (Fig.1). Since then SE Asia has remained as an active continental margin bordered in the north by the Tethys Ocean and has advanced by island arc development until the present day. In contrast, northwest Australia is a passive continental margin bordered by the southern Tethys Ocean. This passive marginal condition prevails throughout geologic history.

PROTO KALIMANTAN (OR INDOSINIA PLATE)

As shown on Figure 2 the presence of Pre-Late Triassic sedimentary rocks in Kalimantan has been confirmed by fossils, principally fusulinid foraminifera. Van Bemmelen (1949) assumed that these rocks were deposited in a fore-arc environment as characterized by the radiolarite-ophiolite association with subordinate limestone, flysch-like sandstone and clay-slate. A volcanic facies has been recognized in West Kalimantan consisting of intensely altered basic effusives, and is associated with cherts. Further van Bemmelen recorded some hornfelses and crystalline schists in the Schwaner Mountains which he considered to be probably Permo-Carboniferous in age. Also metamorphosed limestone of possibly Permo-Carboniferous age occurs in the Ketapang Complex. Hamilton (1979) mapped undifferentiated Carboniferous through Cretaceous rocks in West and South Kalimantan. Further studies need to be done to scrutinize the ages, and at least part of it should be of Late Paleozoic age. Recently, the authors had been given a K/Ar radiometric date on foliated diorite/granite from Sanggau by the Indonesia-Australia geological mapping project in Kalimantan, which reveals two results : using biotite 201 ± 2Ma (Triassic) and using hornblende 251 ± 2Ma (Permian). It was noted that the hornblende was an earlier formed mineral and the biotite was post-deformational. The rock must therefore be at least 250Ma old (Middle Permian) while the deformation must have occured prior 200Ma ago. This has indeed heightened the suspicion that the Carboniferous-Cretaceous unit (Hamilton, 1979) should be differentiated and has confirmed the existence of an arc during Permian times.

The association of plutons, volcanics and forearc sediments suggests the existence of an arc facing north during Carboniferous-Permian time which eventually could be correlated with similar rocks from East Peninsular Malaysia. We consider that the Proto-Kalimantan terrane extends to the Malay Peninsula (east Malaya plate) and to Indochina which together form a single plate, for which the name "*Indosinia plate*" or terrane is proposed. Its origin is possibly the result of Pangaea break-up.

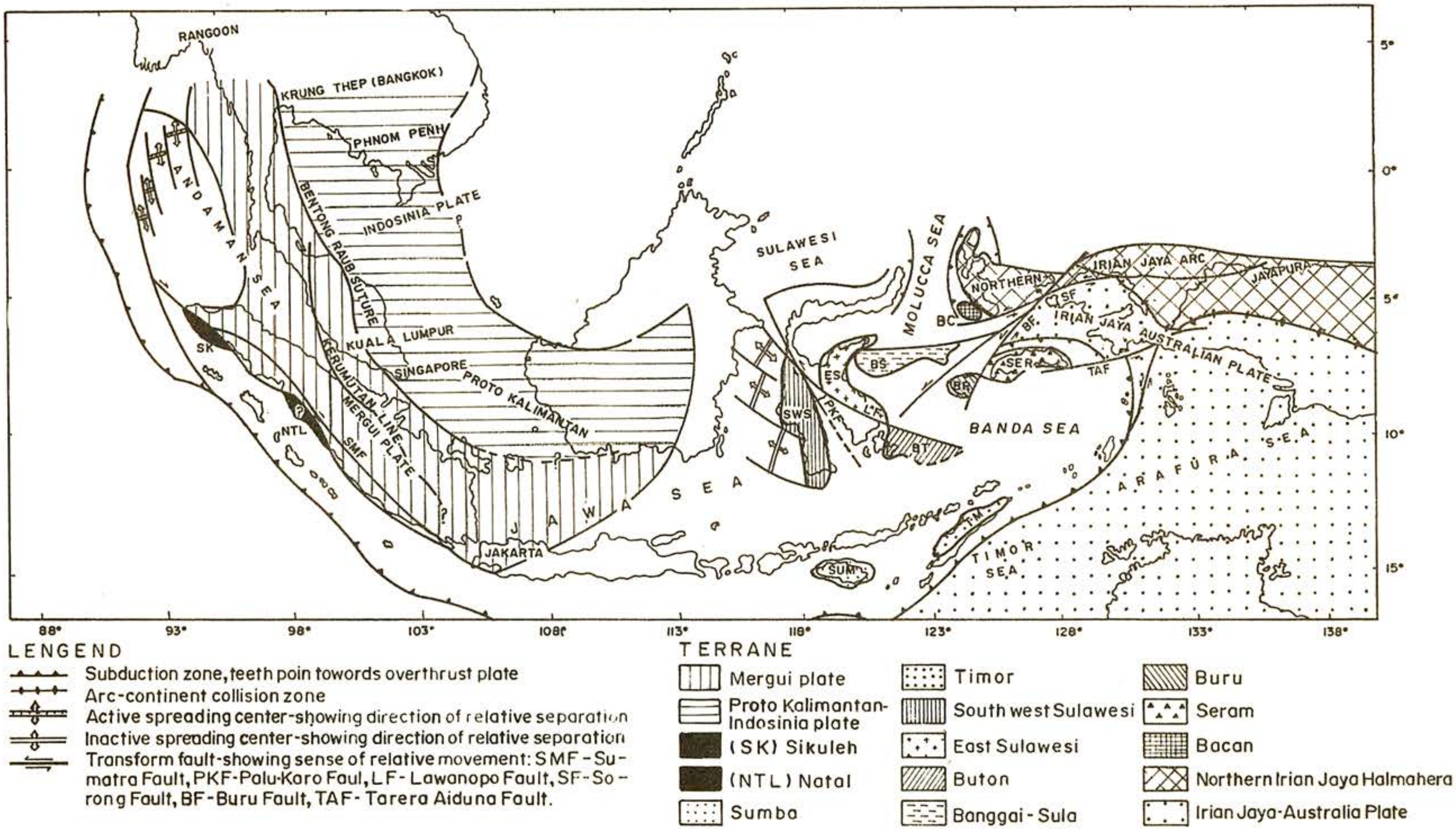

Fig. 1 Tectonostratigraphic terrane map of Indonesia with selected structural features (Hartono and Tjoknosapoetro, 1984).

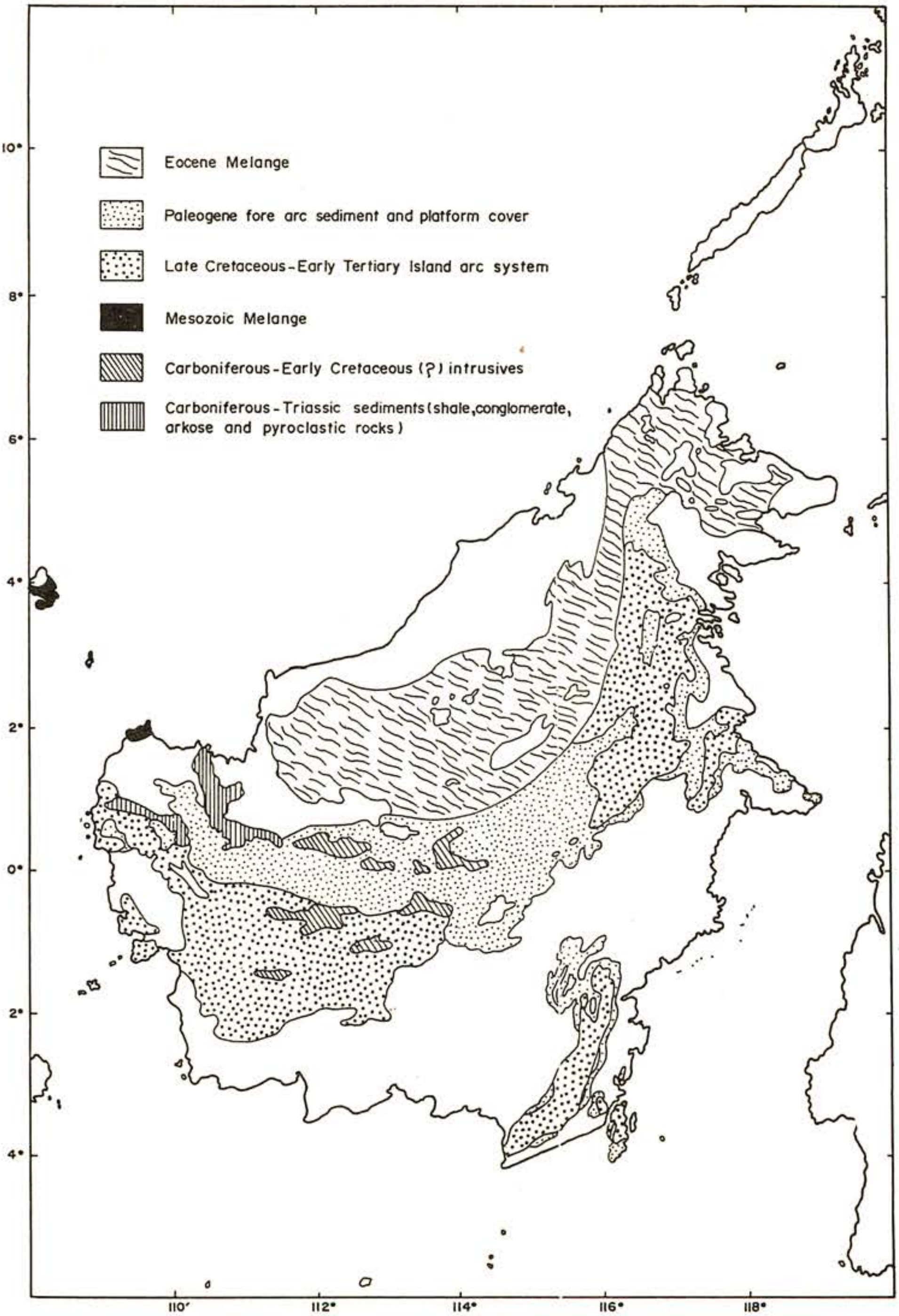

Fig. 2 Proto-Kalimantan terrane map, which includes the Pre-Late Triassic part of Carboniferous-Early Cretaceous intrusives, Carboniferous-Triassic sediments and possibly the melange of Natuna (Hartono and Tjokrosapoetro, 1984).

THE SUMATERA BASEMENT (OR MERGUI PLATE)

Cameron *et al.* (1980) and Pulunggono (1983) envisaged that the basement of Sumatera is allochthonous with regard to southeast Asia and has been derived from Gondwanaland. It occupies the island of Sumatera, the Mergui terrace in the Andaman Sea, western Peninsular Malaysia and its northern extension in Thailand (Figure 3). In Sumatera it is geologically mapped as the Tapanuli Group consisting of the Bohorok, Kluet and Alas formations, and the Peusangan Group consisting of the Silungkang and Kualu Formations. Cameron *et al.* (1980) and Pulunggono (1983) called it the Mergui plate (Fig.4)

Cameron *et al.* (1980) described the Kluet and Bohorok, Formations and mentioned that they consist of clastic rocks, with the Bohorok Formation generally coarser in grain size and containing pebbly mudstone. Overlying the two formations are lithologies with a preponderance of limestones belonging to the Alas Formation. Metamorphism has occurred with greenschist and amphibolite facies. Granite instrusion occurs with dates 257 and 207Ma Cameron *et al.* (1980) further suggest that magmatism within the Tapanuli Group was related to convergent or transcurrent motion rather than to major rifting. They attributed the magmatism as due to the Mergui platelet approaching Sundaland rather than as a result of a separation of the Mergui platelet from Gondwana.

The Silungkang Formation is clearly an island arc assemblage with intermediate to mafic volcanics. Limestone containing fusulinid fossils have been found associated with the volcanics, thus giving an indication of Permian age for the Silungkang Formation.

The Silungkang Formation is unconformably overlain by the Kualu Formation consisting of limestone, cherts and rhythmites (thinly bedded sandstones, wackes, siltstones and mudstones). The mudstones are sometimes highly carbonaceous with abundant plant remains; the occurrence of *Halobia* sp. has been reported.

Cameron *et al.* (1980) , Pulunggono (1983) and others interpret that this terrane to be of Gondwana origin having drifted northward into its present latitude. The arguments that it had a past high latitude paleogeographic position is based on the presence of pebbly mudstones, interpreted to have been deposited in a glaciomarine environment. Their lithologic characteristics are interpreted as being a result of reworking and turbiditic redeposition of ice-rafted, subglacial or fluvioglacial debris. However, there are constraints in the reconstruction because during the Permian, Gondwana's latitude was quite low as is evident from the occurrences of warm water fusulinids and corals (Fontaine,1985) . This paper is in agreement with the existence of a Mergui plate as a distinct geological entity, however the occurrence of Permian warm water fauna contradicts the interpretation that the pebbly mudstone originated from glacio marine conditions.

The distribution of this terrane in Northern Sumatera and its extension into Western Peninsular Malaysia and Thailand has been proposed by Cameron *et al.* (1980) The occurrences of Pre-Tertiary rocks in south Sumatera, Java and the shelf between Kalimantan and Java (Hamilton, 1979 and Bishop, 1980) suggest that the terrane may extend to these areas. This extension can only be confirmed if the Pre-Tertiary rocks indicate a Pre-Late Triassic age.

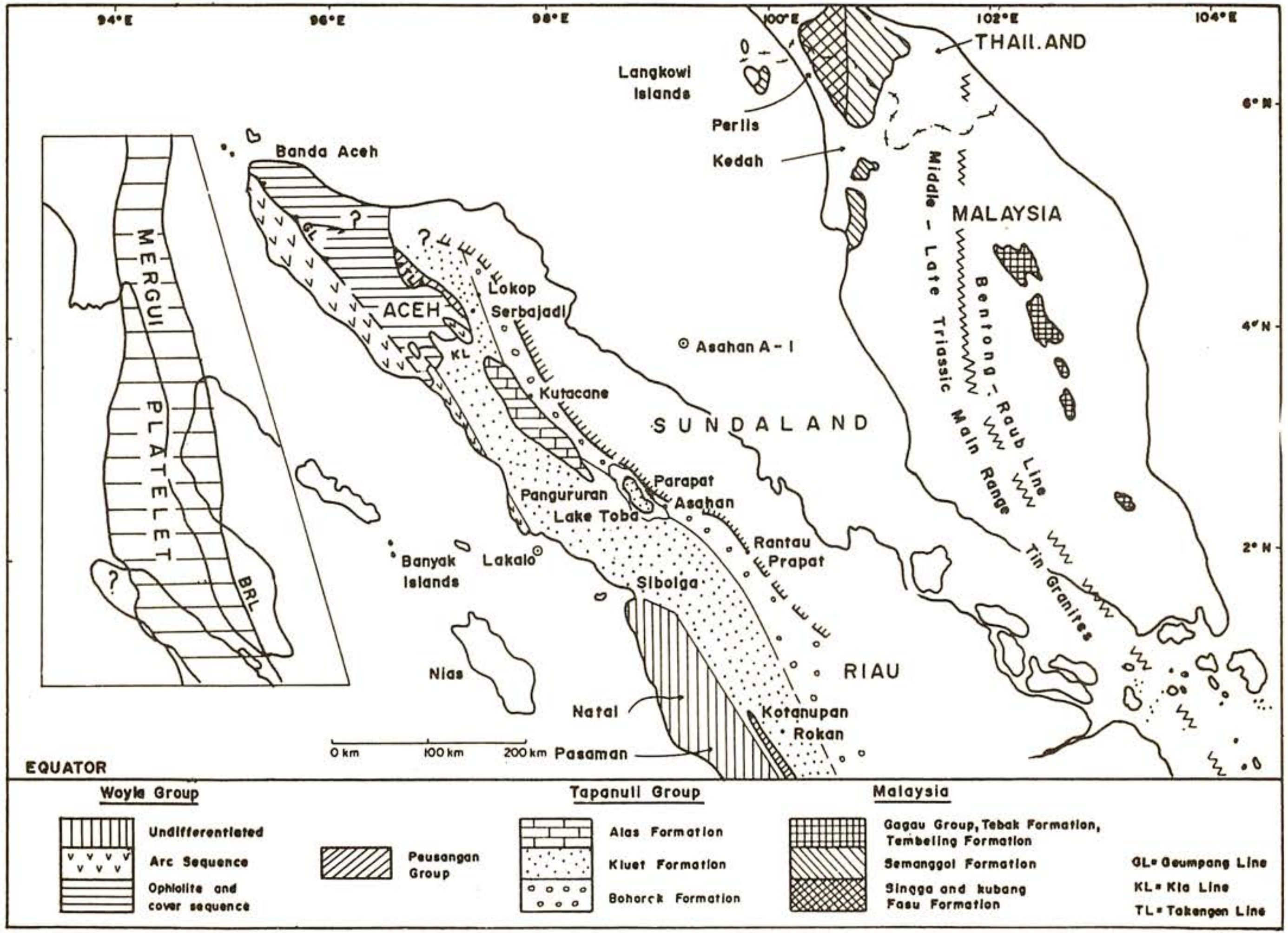

Fig. 3 Sumatera basement terrane map, which includes the Tapanuli Group. The delineation of the terrane uses the geologic map of Cameron et al. (1980).

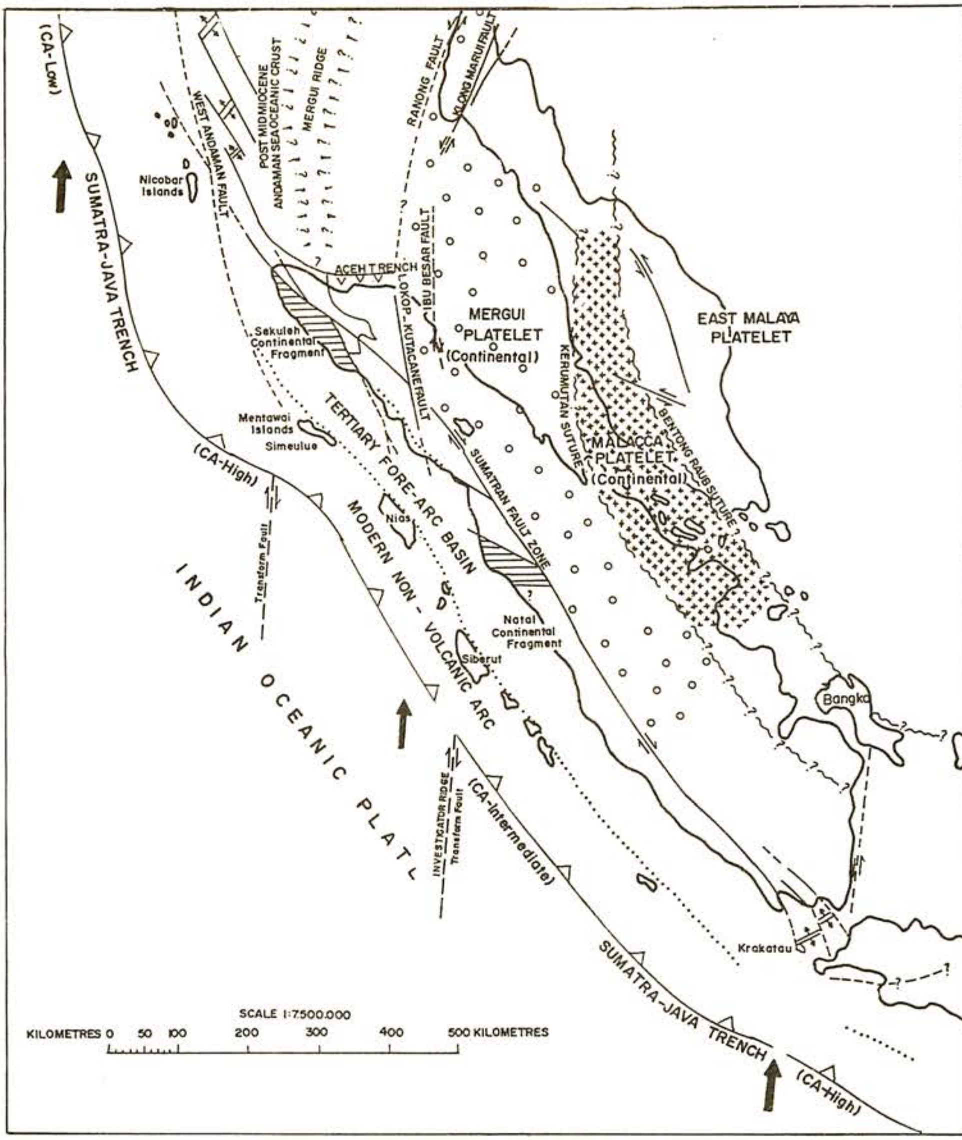

Fig. 4 Regional geological framework of Sumatera and Malaya (Stephenson *et al.* 1982).

Continental fragments (Sikuleh and Natal) have been reported by Cameron *et al.* (1980) and Stephenson *et al.* (1982) from the southwest coast of Sumatera, Fig. 3 and Fig. 4, however, their mode of emplacement to their present position is at present not clear. Further, the plate is split into two platelets, the Malacca and Mergui platelets hinged along the Kerumutan suture (Stephenson's terminology), whereas Pulunggono (1983) called it the Mutus suture.

Southwest Sulawesi

This terrane is a rift-drift from southeast Kalimantan which now occupies a position in western Sulawesi and includes geologic units in Hamilton's Tectonic Map of Indonesia

(1979); Melange (MK) , Eocene-Cretaceous sediments (TK) and Paleogene sediments (Tp). According to Hamilton (1979) the TK unit is a foreland basin deposit, whereas the Tp unit is a platform cover. Correlation of these units with the Geologic Map-Sheet Ujungpandang 1:1,000,000 (Sukamto, 1975] is given in the following table :

GEOLOGIC UNITS BELONGING TO THE SOUTHWEST SULAWESI TERRANE (ALSO SEE FIG. 6)

Based on Tectonic Map of Indonesia (Hamilton, 1979)		Based on Geologic Map Sheet Ujungpandang (Sukamto, 1975)	
Tp	Oligocene through Paleocene platform cover	TKm	Cretaceous-Early Tertiary undivided marine sedimentary rocks
		Tet	Toraja Formation (Eocene-Oligocene)
TK	Eocene through Late Cretaceous foreland basin deposit (strata deposited on cratonic side of magmatic arc)	TKmc	Cretaceous undivided marine and continental sedimentary rocks
MK	Cretaceous melange	Ksu	Cretaceous sediments
		S	Schist
		Ub	Ultrabasic and basic rocks

The Melange unit consists of largely serpentinized peridotite and basalt. The metamorphics are schist with blueschist andgreenschist facies. It also includes Cretaceous radiolarian chert, siliceous shale, greywacke and claystone. To the terrane are included Cretaceous-Early Tertiary marine and continental sedimentary rocks which consist of shale, siltstone, greywacke, arkosic sandstone, shale and pillow lava. Graded bedding and slump structure indicating turbidite deposition have been observed. Hamilton (1979) considered it as sediments deposited on the cratonic side of a magmatic arc. Other geological units belonging to the terrane are shallow sea sediments that have been deposited as platform cover consisting of shale, grey, black and red sandstone, conglomerate, limestone, radiolarian chert, tuffaceous sandstone, slate, phyllite and quartzite. These sediments could have been deposited during the break-up and rifting apart of West Sulawesi from southeast Kalimantan.

EAST SULAWESI OPHIOLITE

The east Sulawesi ophiolite consists of dunite, peridotite, harzburgite, pyroxenite, gabbro, serpentinite, basalt, and some diorite. Its age is Pre-Triassic. This interpretation is based on the occurrence of ophiolite detrital materials in Triassic sandstone and cherty limestone. The distribution is confined to the northeastern and southeastern arms of Sulawesi.

The identification of east Sulawesi ophiolite as a terrane is primarily based on structural grounds and relationship with neighbouring geological entities in which fault-bounded contacts prevail.

The Ujungpandang sheet geologic map 1:1,000,000 scale which covers northeast Sulawesi (Sukamto, 1975) and recent traverses by Mr. T. Simandjuntak (personal communication), and also Hamilton's tectonic map (1979) show that components of the Sula terrane,

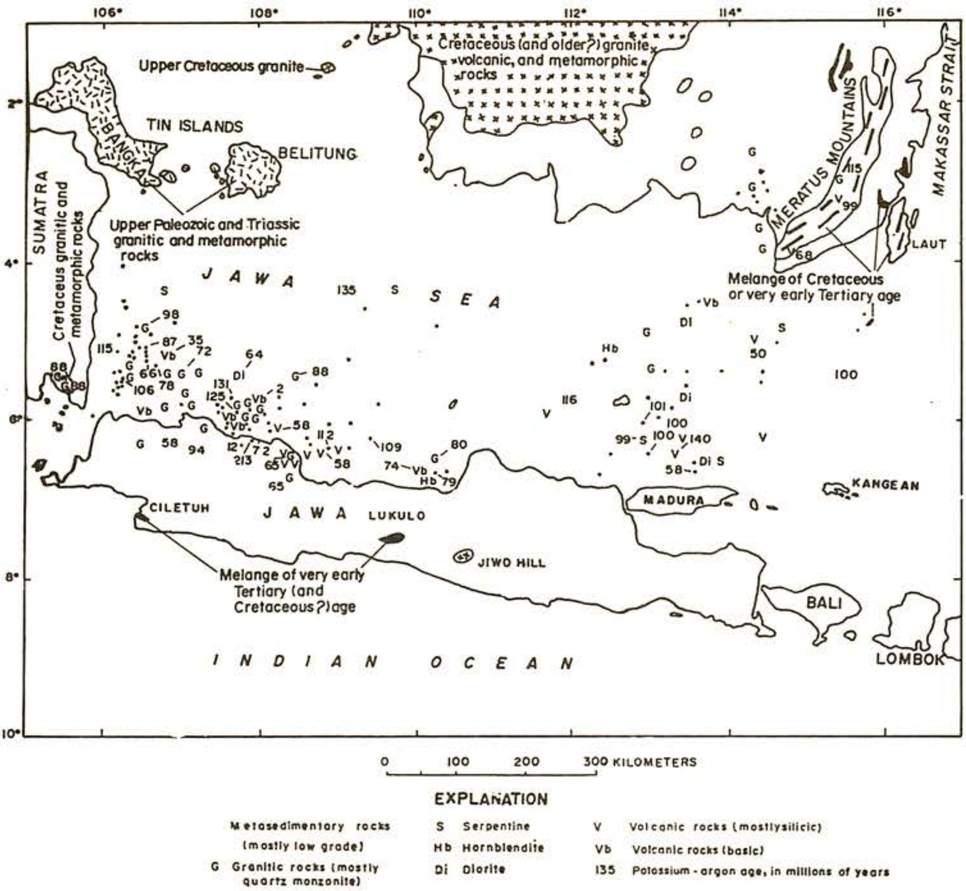

Fig. 5 Data base to support the extension of the Bentong Raub Suture to the Java Sea and the Late Cretaceous-Early island arc system to the Meratus Range in southeast Kalimantan (Hartono and Tjokrosapoetro, 1984).

namely Tertiary limestones, are thrusted under the ophiolites. The same structural feature occurs also in southeast Sulawesi in the Pegunungan Matarombeo area where Cretaceous limestones underthrusted the ophiolites. The contact between ophiolites and east Sulawesi schist is always fault bounded. In southeast Sulawesi the contact is along the Wowoni fault whereas at the boundary between northeast Sulawesi and central Sulawesi the ophiolites override the east Sulawesi schist.

BUTON

Buton terrane consists of possibly Paleozoic medium grade metamorphics and Late Triassic flysch sediments (Fig. 7). The metamorphic rocks form a basement composed of intercalations of phylite, slate, subordinate quartzite and micaceous sandstone. The sandstone contains metamorphics and plutonic fragments. It can be correlated with the low grade metamorphics in Buru (Rana Formation) and in Seram (Tehuru complex). The unit is known

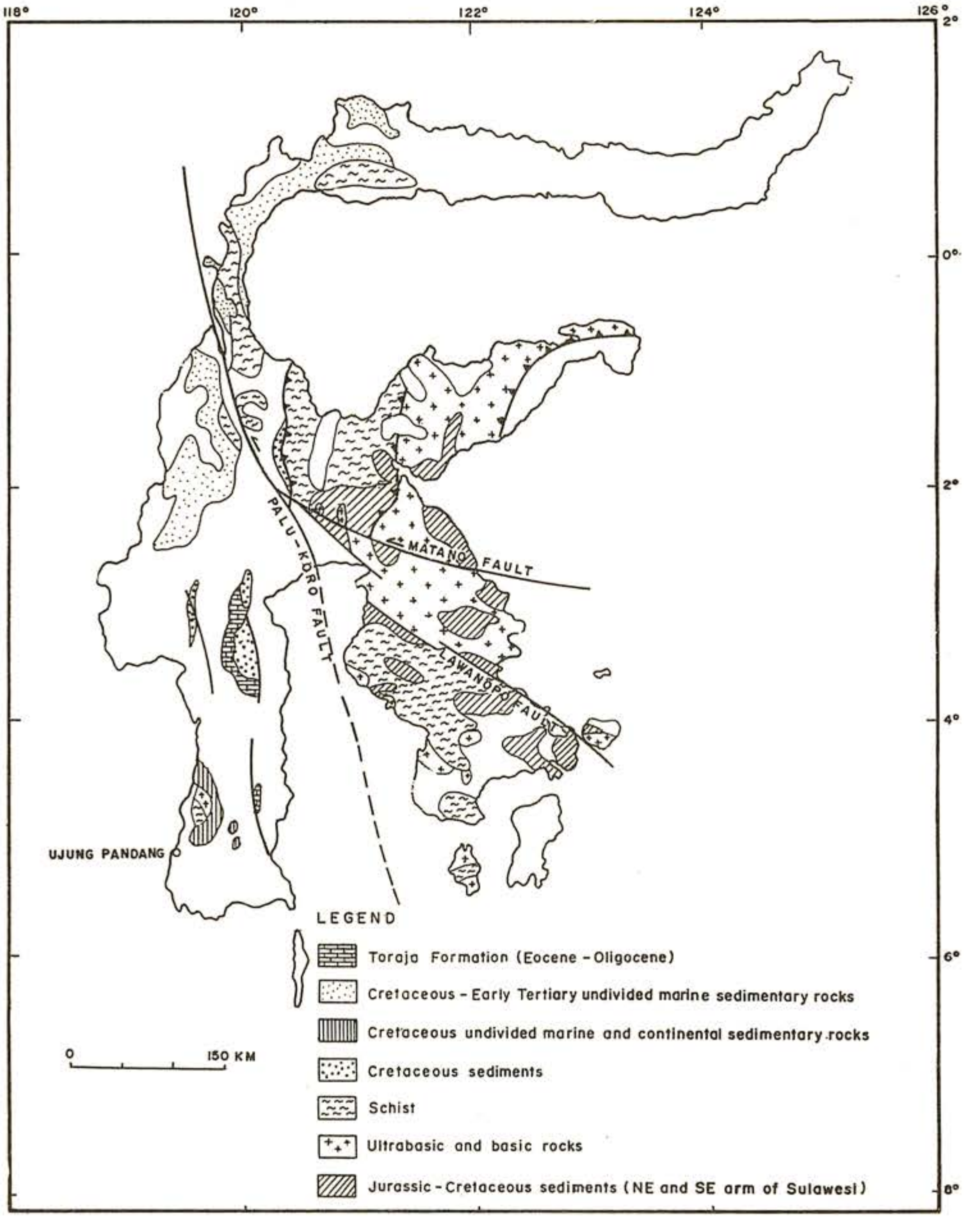

Fig. 6 Simplified geologic map of Sulawesi to show southeast Sulawesi terrane and east Sulawesi ophiolite terrane (Hartono and Tjokrosapoetro, 1984).

as the Doole Formation (Fig. 7). The Late Triassic flysch sediments consist of shale, limestone and sandstone. The proportion of the sedimentary rocks that compose the flysch is very variable; in northern Buton it consists of partly silicified limestone, whereas in the south it ranges between clastics and limestones. The unit is known as the Winto Formation. Both the Doole Formation and the Winto Formation are considered as pre-break-up sequences.

The previously mentioned sequence is overlain by deep sea sedimentary rocks —Jurassic-Eocene in age consisting of calcilutite, calcisiltite marl, mudstone and varicoloured radiolarian chert, forming a sequence known as the Ogena Formation (Early Jurassic), the Rumu Formation (Late Jurassic) and the Tobelo Formation (Cretaceous-Eocene). This sequence is considered as a break-up sequence.

The younger cover (Post Eocene) was deposited in a shallow sea consisting of conglomerate, sandstone and mudstone (Tondo Formation); and also marl and calcarenite (Sampolakosa Formation). This younger cover is a post break-up sequence.

Pigram *et al.* (1983a) who made a stratigraphic study related to Jurassic Gondwana break up on microcontinents of Eastern Indonesia, concludes that the stratigraphy fits very well with a rift-drift stratigraphic model. The model shows distinctions between pre, during and post break-up sequences.

SERAM

The Seram terrane consists of Pre-Triassic high to low grade metamorphics and Triassic sediments deposited in shallow seas.

High grade metamorphics are exposed in the central part of the island and are known as the Kobipoto and Taunusa complexes (Fig. 8). It consists of migmatite, gneiss, schist, amphibolite and quartzite. Low grade metamorphics are found and known as the Tehuru complex and Saku complex.

The Tehuru complex consists of phyllite, slate and chlorite-mica-schist. Marbles containing Paleozoic corals, algae and crinoids are found locally. Metatuff (greenstone), basalt and pyroclastics are often found intercalated in the phyllites. The Saku complex consists of glossy-slate, metawacke, arkose and limestone. The metamorphics are interpreted as a pre-break-up sequence.

The metamorphic complexes are overlain unconformably by middle-late Triassic flysch type clastic sediments, known as Kanikeh Formation. Within the clastic sediments are found andesite and dacite fragments. A Triassic limestone facies (Manusela Formation) also occurs associated with basaltic lava. The Triassic sediments are penetrated by ijolite, granodiorite and diabase dykes. These series of sediments are interpreted as a break-up sequence.

The Triassic clastic sediments and limestones grade laterally into Jurassic-Eocene deep-sea calcilutite, cherty shale and marl (Nief beds). They are interpreted as being a post-break-up sequence.

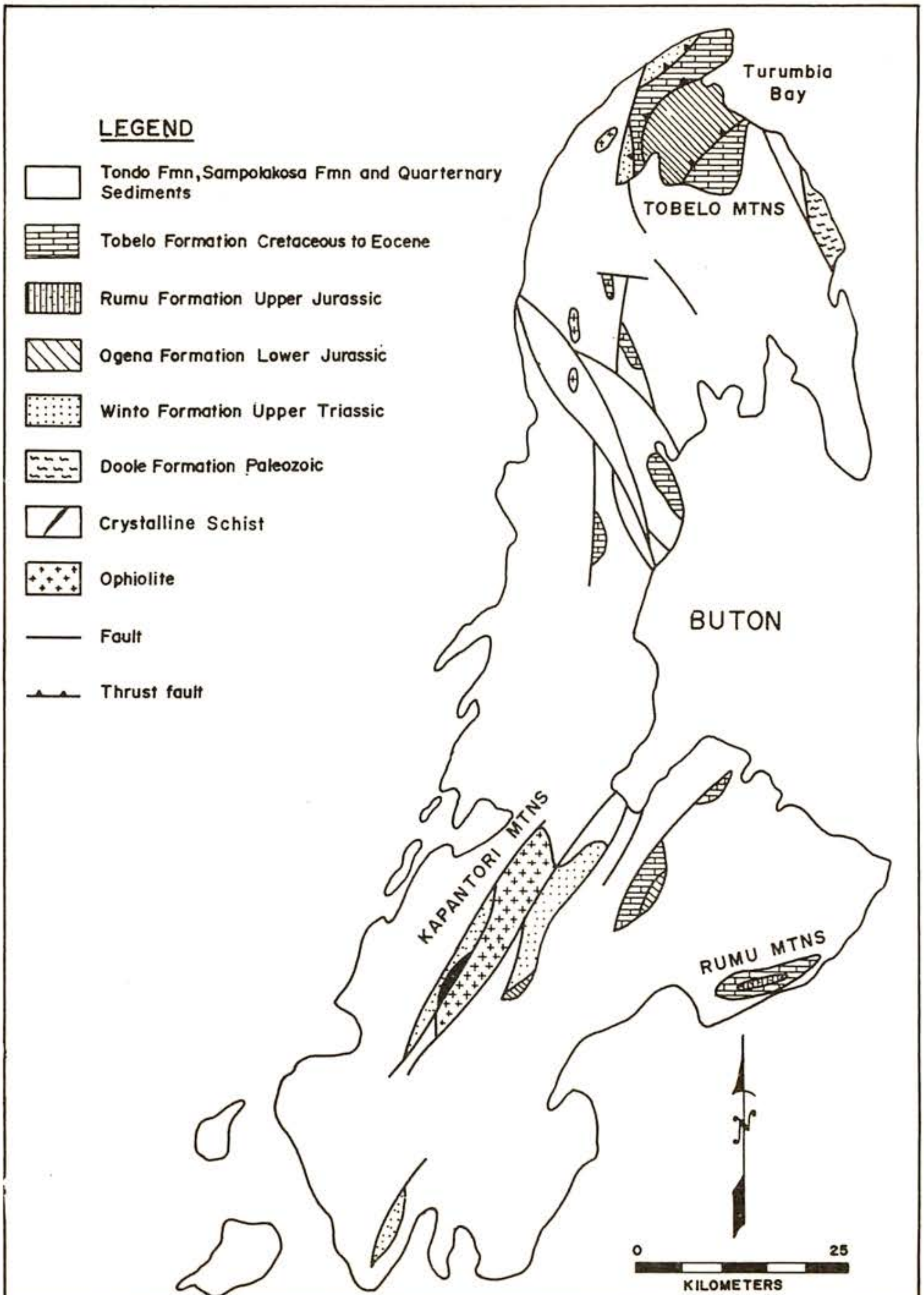

Fig. 7 Buton terrane map, which includes all Pre-Cretaceous geologic units (Hartono and Tjokrosapoetro, 1984).

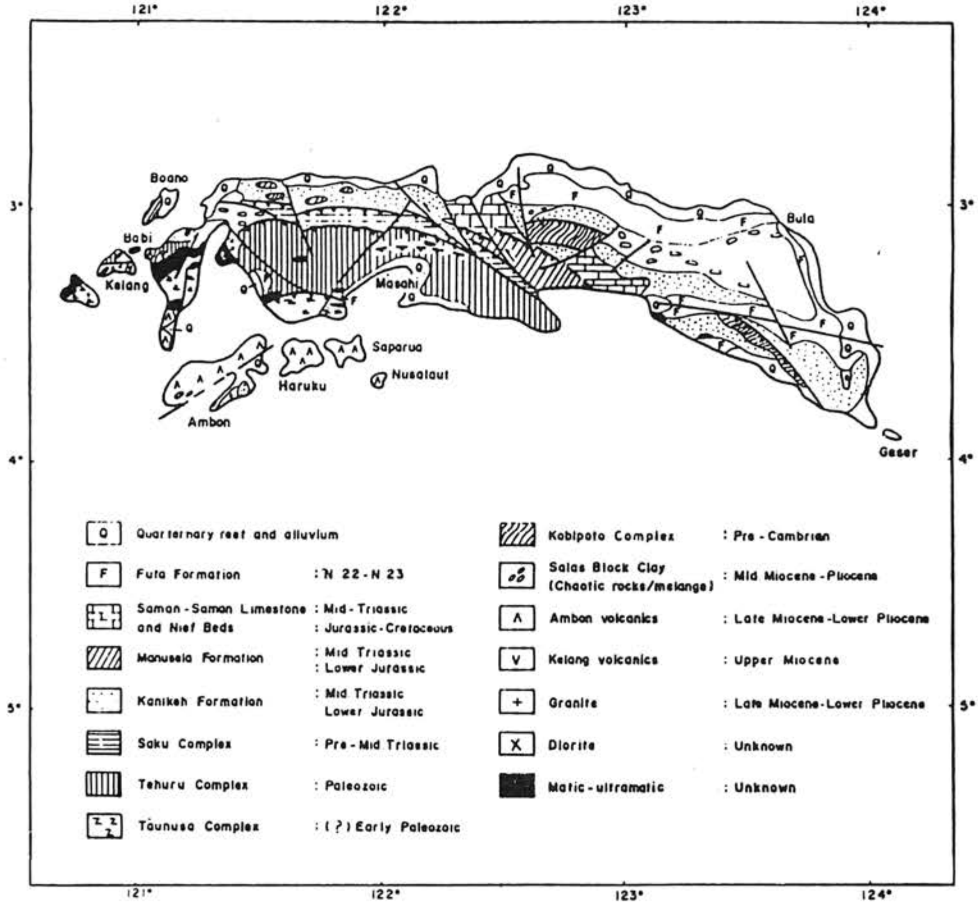

Fig. 8 Seram terrane map, which includes units belonging to the Pre-breakup and breakup sequence including the autochthonous series (Hartono and Tjokrosapoetro, 1984).

TIMOR

The Timor terrane (Fig. 10) originated from northern Australia which separated during Late Jurassic time. It reunited with Australia during Pliocene time as overthrust masses. It comprises serpentinites, high-grade metamorphics, metavolcanics, clastics, limestones and chert belonging to the Lolotoi unit (Fig. 9). It includes Permian limestone and volcanics of the Maubisse Formation and also metasediments belonging to the Aileu Formation. Additional materials have been added during the course of separation and reunion in the form of greywackes, cherts and limestones belonging to the Palelo unit and presumably also Paleogene arc volcanics.

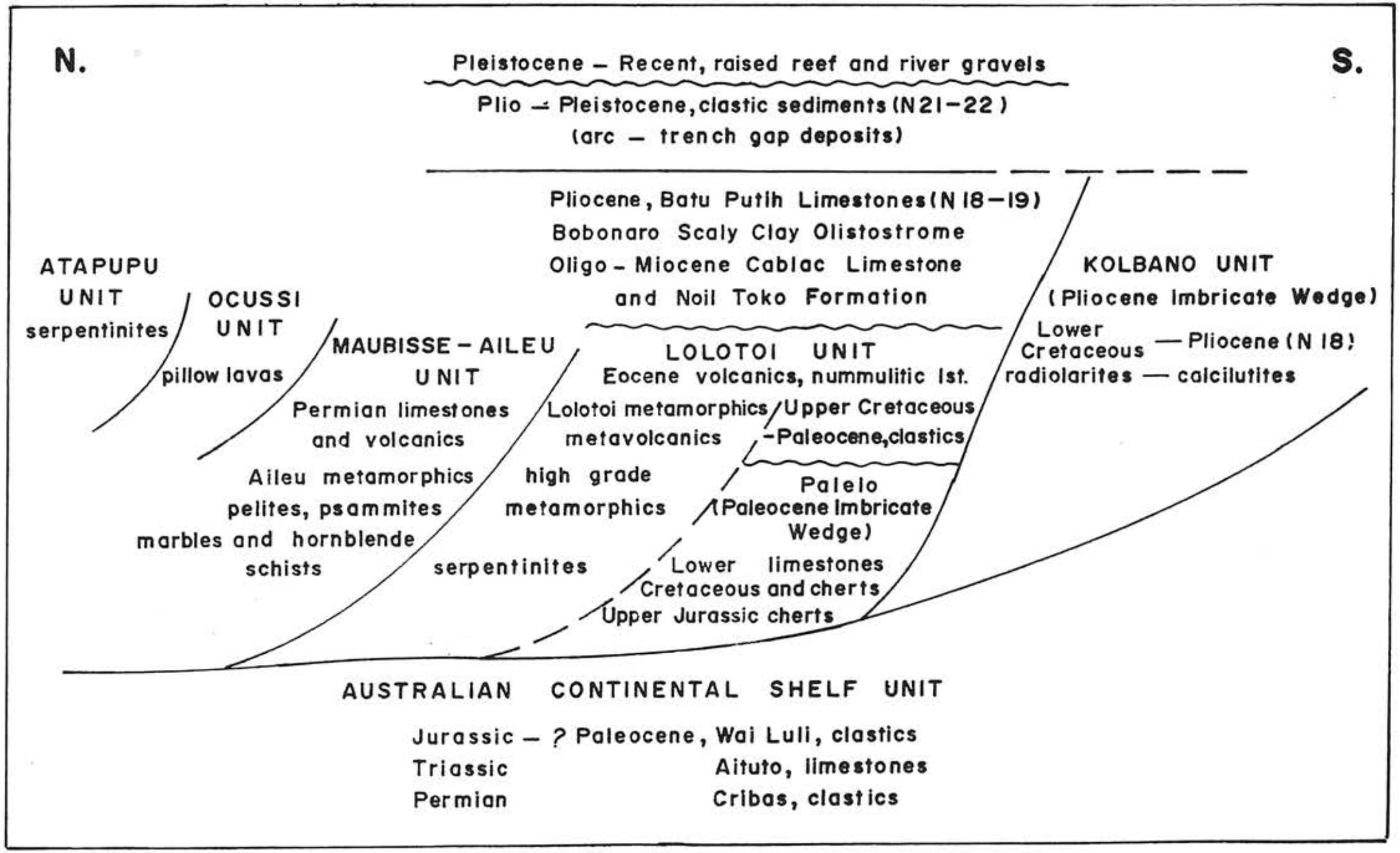

Fig. 9 A scheme to show stratigraphic relationship of geological units in Timor (Barber, 1981).

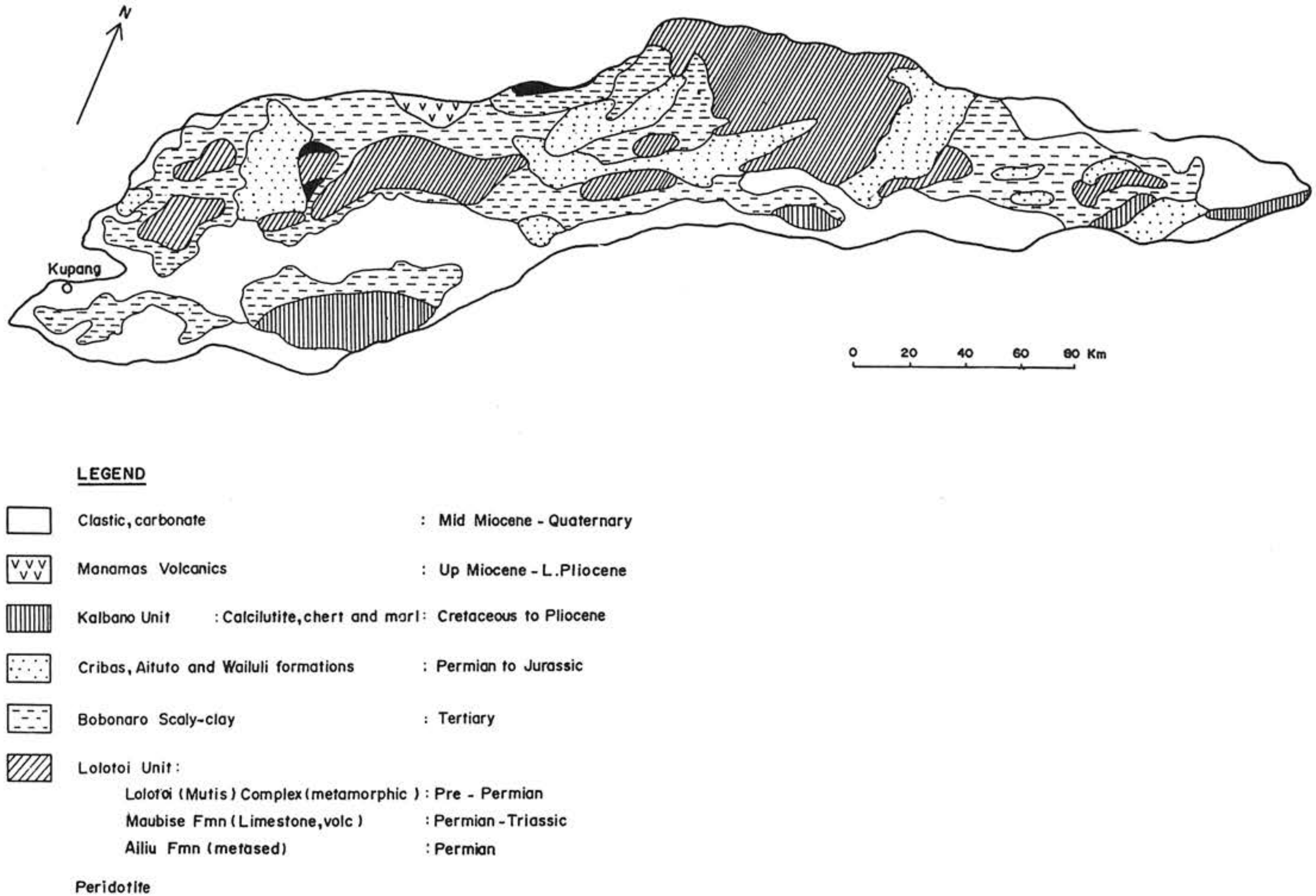

Fig. 10 Timor terrane map, which includes the Lolotoi metamorphics and Maubisse-Aileu units. (Hartono and Tjokrosapoetro, 1984).

SUMBA

The oldest rocks known from outcrops on Sumba arc of Cretaceous age. They comprise dark coloured, sometimes carbonaceous and often volcanogenic mudstones, sandstones, gravels and diamictites, pervasively intruded by andesitic and dacitic dykes and locally intruded by granodiorite plutons (Fig. 11). These sediments are siliciclastic and appear to have had a continental.provenance. They were deposited as a submarine fan and called the Lasipu Formation (Von der Borch *et al*, 1983).

Since no metamorphic basement rocks are exposed, a pre–breakup sequence seems to be absent in Sumba. It should be still buried under the known exposures. The volcaniclastic debris and volcanic dykes should be related to rift-related volcanism and hence the entire Lasipu Formation can be considered as a break-up sequence. The Tertiary Unconformably overlying cover should then be a post-break-up sequence.

There is no unanimous conclusion concerning the origin of Sumba, Hamilton (1979) and Von der Borch *et al.* (1983) considered an Asian origin, whereas Chamalaun *et al.* (1983) prefered an Australian origin. Based on a seemingly confirmed Jurassic rift-drift event in northwestern Australia we believe the origin of Sumba to be from northwestern Australia. Probably the pre-rift-drift position of Sumba was at the southwesternmost part of northwest Australia compared with pre-break-up positions of the other continental fragments now occurring in eastern Indonesia. It is also noted that more towards the southwest the break-up becomes younger.

BURU

The Buru terrane consists of low grade metamorphics of greenschist facies to medium grade metamorphics of amphibolite facies. Their ages are Paleozoic and consist of micaschist, phyllite, slate, metasandstone and marble (Fig.12). Their composition seems to reflect an origin as flysch type sediments. Further, the terrane consists of flysch type Triassic sediments (Dalan Formation) and dolomite reef limestones (Ghegan Formation).

The terrane is overlain by Jurassic-Eocene deepsea deposits consisting of calcilutite, shale and marl and Oligocene-Pliocene shallow-sea deposits. At the base, conglomerate and basic pillow lava are found. Tjokrosapoetro and Buditrisna (1982) considered Buru as a different entity from Seram based on dissimilarity of their geologic structure. Buru is less tectonized compared to Seram and its geology shows similarity to Misool located within the Australia-New Guinea continental crust rather than to Seram. On the other hand Seram possesses geological and structural affinities to Timor in having autochthonous rocks at the hase overlain by allochthonous overthrust masses. Hence Buru has been derived from the "*Birds Head*" by lateral translation whereas Seram has been derived from northwestern Australia by rift-drift.

BANGGAI - SULA

The Banggai-Sula terrane is composed of Paleozoic metamorphic rocks, Permian-Triassic granitoids and Triassic volcanics. The terrane is overlain by Lower Jurassic-Lower Cretaceous lacustrine to shallow marine clastics and Upper Cretaceous deepsea carbonates (Fig.13).

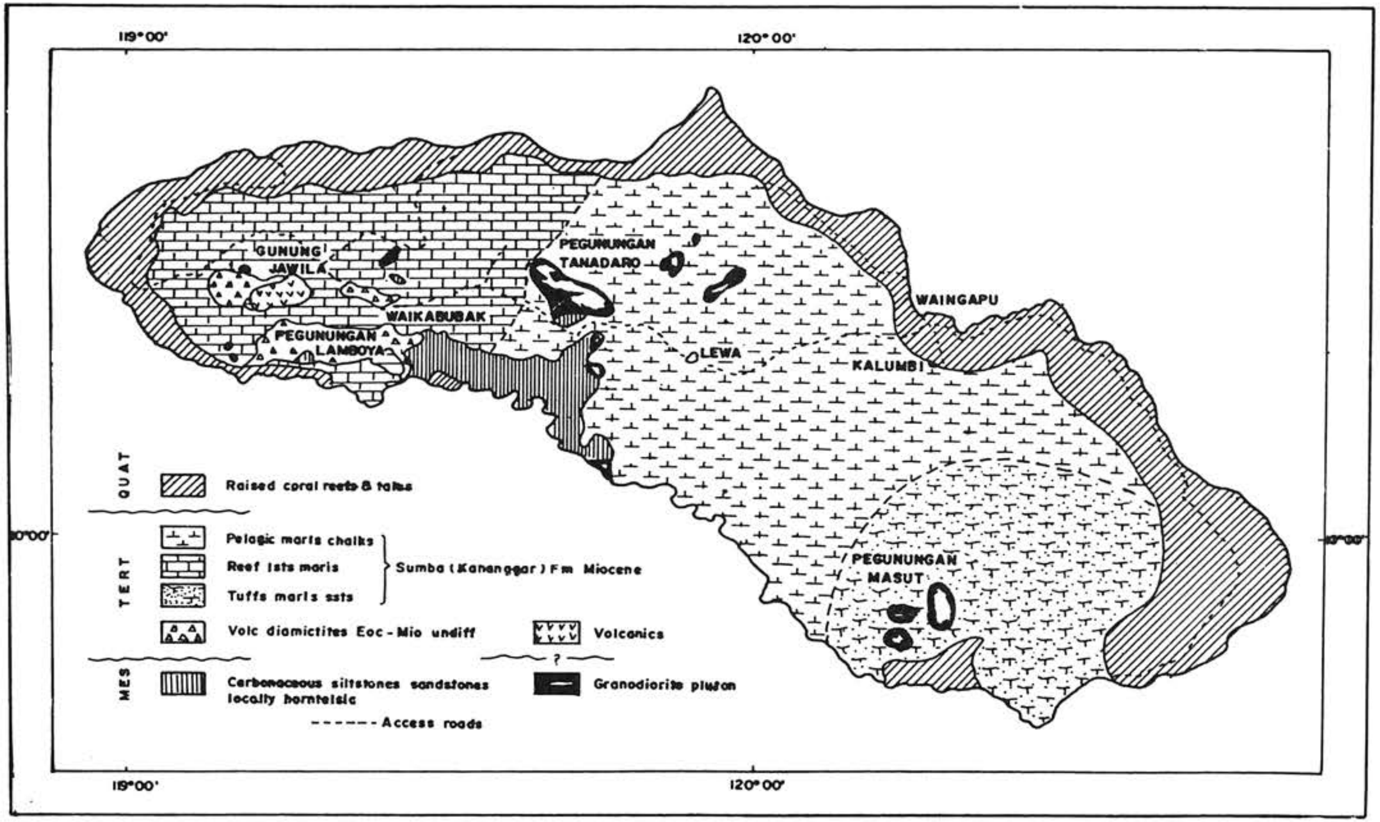

Fig. 11 Generalized geological map of Sumba (von der Borch et al., 1983) to show units belonging to the Sumba terrane.

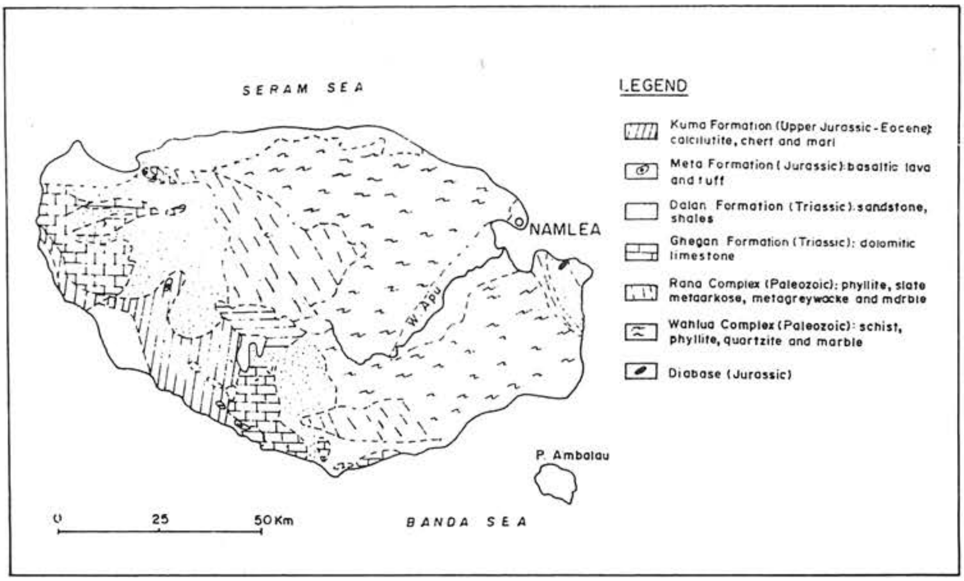

Fig. 12 Buru terrane map (Tjokrosapoetro and Buditrisna, 1982).

The metamorphics consist of silicic schist, gneiss and minor amphibolite. A K-Ar radiometric date on a mica schist from Peleng Island gave an age of 305 ± 6Ma (Sukamto, 1975).

The metamorphics are intruded by granitoids, which are composed of red granite, granodiorite, quartz-diorite, microdiorite, syenite, aplite and pegmatite. Rb-Sr radiometric dates on granites from Banggai and Taliabu islands gave ages of 235 ± 10Ma and 245 ± 25Ma respectively (Sukamto, 1975).

The volcanics are composed of rhyolite, dacite ignimbrite, lithic tuff and volcanic breccia. Two Rb-Sr radiometric whole rock dates on rhyolites from Banggai and Mangole islands gave ages of 210 ± 25 Ma and 330 ± 90 Ma. The volcanics and granitoids are comagmatic and can be considered as an island arc setting. This leads to the interpretation that the terrane could not have originated from northwestern Australia, this being a passive margin, where an island arc setting was absent. Instead it is interpreted as being derived from New Guinea where an island arc setting did exist during Permian times and which extended the whole length of northeastern Australia, including New Guinea (Parker and Gealey, 1983). Geological records on the occurrences of Permian-Triassic volcano-plutonic rocks besides the occurrences in Banggai-Sula, have also been reported from the Birds Head (Fig. 14), Western, and Central Papua New Guinea (Pieters, *et al.*,1984) indicating affinities of origin.

Lacustrine-shallow marine clastics occur in the islands Sulabesi Mangole, Taliabu and Peleng. They consist of polymict conglomerate, lithic and arkosic sandstones, carbonaceous shale and minor coal. It is very fossiliferous and Sato *et al.* (1978) identified Toarcian

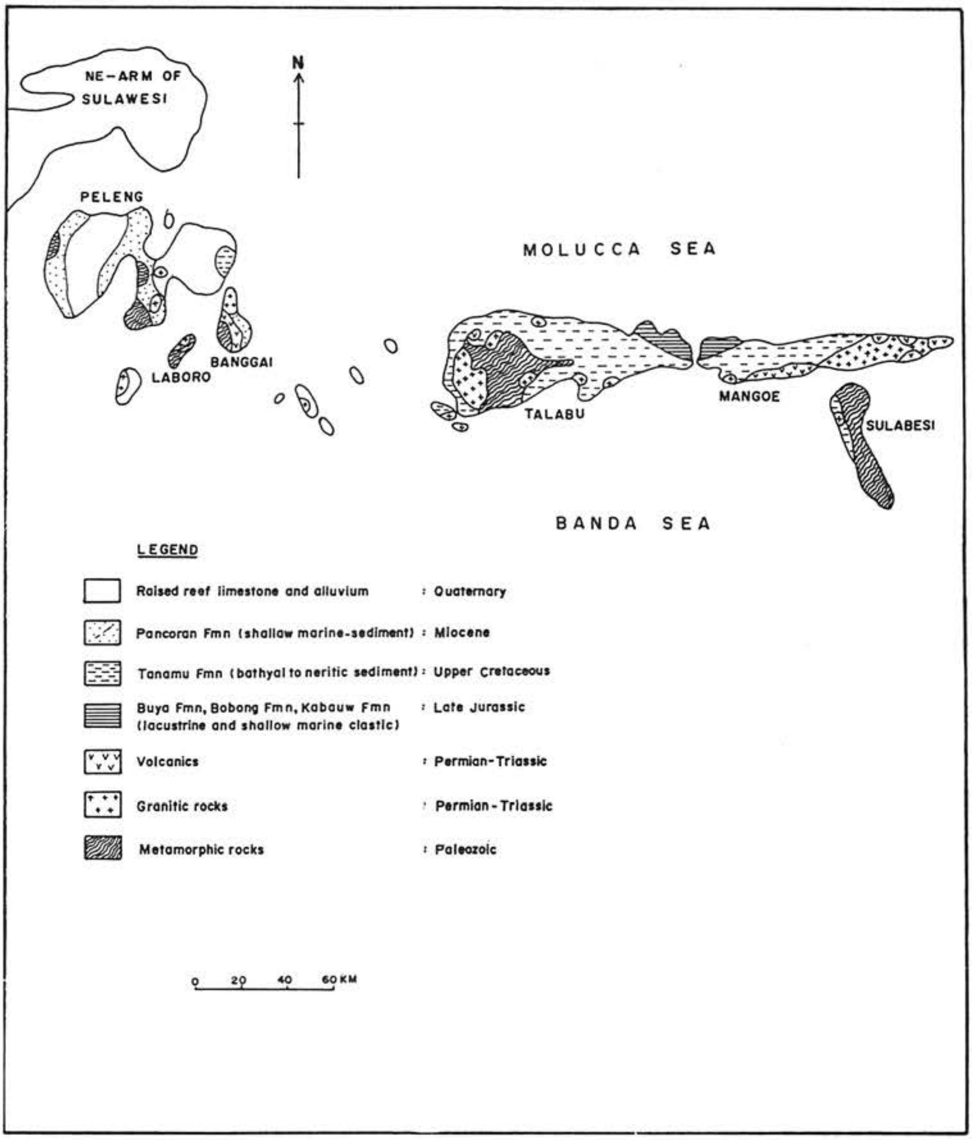

Fig. 13 Banggai-Sula terrane map (Hartono and Tjokrosapoetro, 1984).

(Jurassic) molluscs. The deepsea marine sediments consist of calcilutite and calcareous shale and contain *Globotruncana sp.* indicating a Cretaceous age.

BACAN

The terrane is composed of possibly Paleozoic silicic metamorphic rocks consisting of phyllite, micaschist, garnet-mica schist, kyanite-staurolite schist and granitic to quartz-dioritic gneisses. Silitonga *et al.* (1981) reported that ultrabasic rocks that occur in Bacan Island consist of gabbro, serpentinite and peridotite.

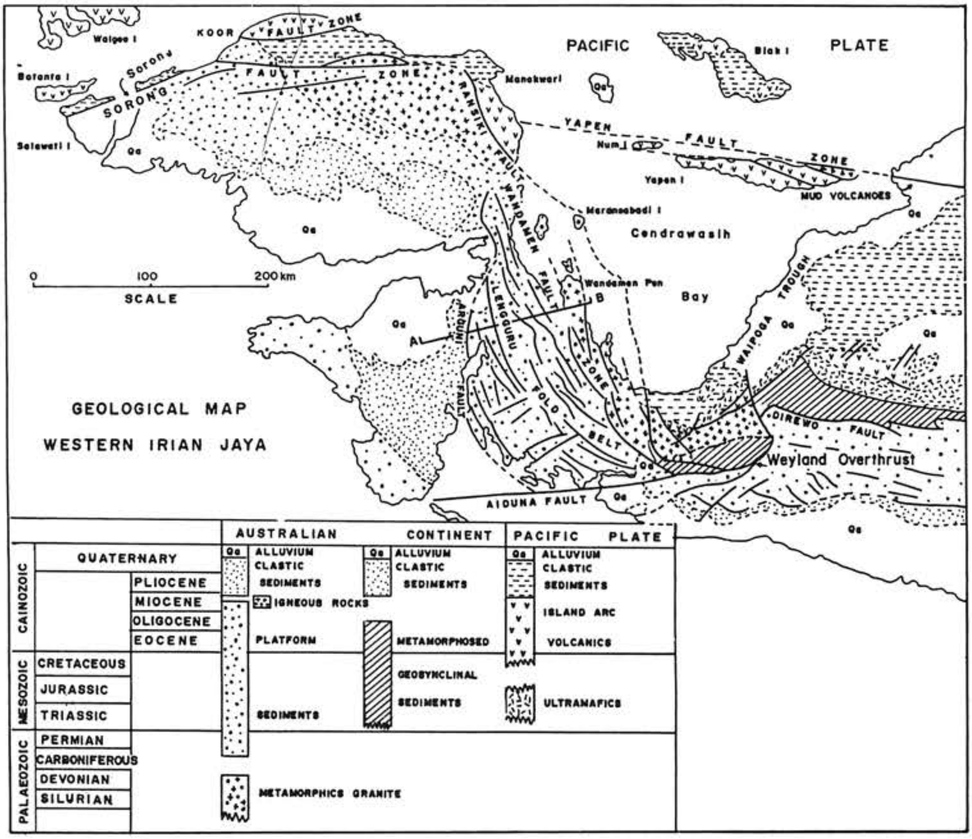

Fig. 14 Geologic map of Irian Jaya to show two distinct terranes. Australian crust and Tertiary northern Irian Jaya Arc (After Dow, in press).

Hamilton (1979) interpreted that the metamorphics were associated with plutonism and had been derived frcm New Guinea, based on their close proximity to the Sorong fault. Further their Paleozoic age is inferred from similar occurrences of rocks, possibly those from nearby Manokwari at the Bird's Head.

The ultrabasics are presently interpreted to be the same as those found in eastern Halmahera, belonging to the Tertiary island arc terrane of Northern Irian Jaya-Halmahera, therefore not belonging to the Bacan terrane.

NORTHERN IRIAN JAYA-HALMAHERA TERTIARY ISLAND ARC

This arc occupies the northern part of Irian Jaya and extends west to Yapen, Arfak Mountains, Waigeo Island, Biak Island and farther west to Halmahera. It also extends east to Papua New Guinea. It consists of oceanic ophiolite, Paleogene to early Miocene island arc volcanics, intrusives and sediments and is succeeded by Miocene limestone deposited after cessation of magmatic activity.

The ophiolites comprise dunite, harzburgite, pyroxenite, serpentinite, gabbro and pillow basalt, and are associated with minor red shale and chert. The volcanics are of island-arc type and consist of pervasively altered basic to intermediate volcanic rocks.

Island arc volcanoes were built up in Early Tertiary times over oceanic crust and locally over pelagic sediments. By the end of the Early Miocene the volcanoes were extinct and had been reduced by erosion to a platform on which coral reefs flourished. Uplift began in Late Miocene times and has continued to the present day. The products of erosion form a patchy cover of molasse (Pieters, *et al.*, 1983).

AUSTRALIAN CONTINENTAL CRUST

The extent of the crust is given in Figure 15; it extends to the southern part of Irian Jaya and the Bird's Head. Its boundary with the Banda Arc follows the inner part of the Outer Banda Arc islands. Its western limit is identified by seismic refraction data of Bowin *et al.* (1980) and also by occurrences of granitic gneisses in Fadol and Koor islands located between Seram and Kai. Australian continental crust components in the form of continental shelf sediments underthrust accretionary wedge material along longitudinal depressions along the outer Banda Outer Arc. In the Bird's Head the boundary is along the Sorong fault and Ransiki fault, and in Irian Jaya the boundary is along the collision zone between the crust and the Northern Irian Jaya island arc following the crest of Irian Jaya in an east-west

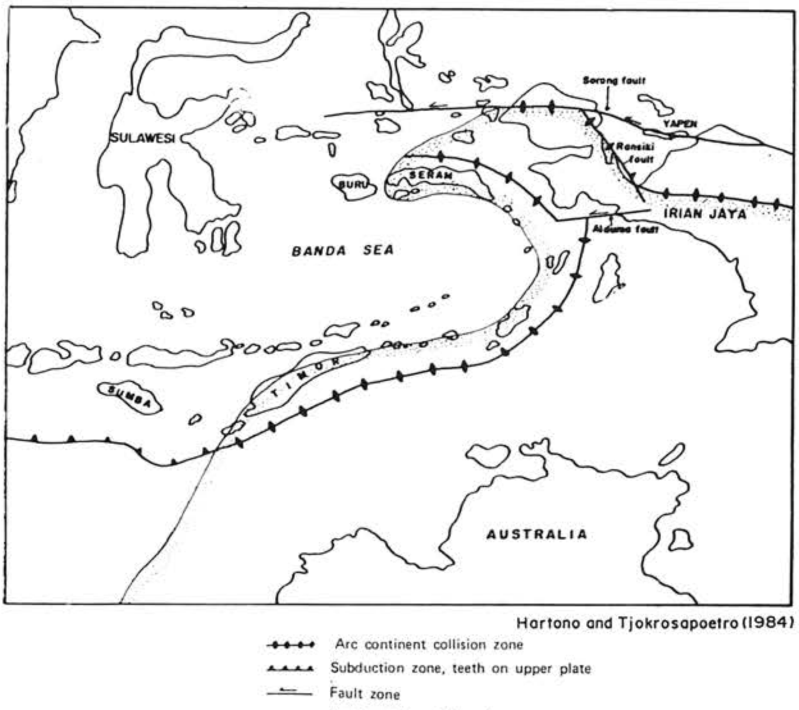

Fig. 15 Extent of the Australian continental crust terrane (Hartono and Tjokrosapoetro, 1984).

direction. It is also characterized by a foldbelt on the Australian crust side. The crust is composed of metamorphic and granitic basement and its overlying clastic sediments form a platform cover. The age of the basement is quite ancient (pre-Cambrian) since it underlies Paleozoic sediments and a recently determined radiometric date on granodiorite pebbles in a metaconglomerate from the base of Silurian-Devonian Kemum Formation in Irian Jaya gave an age 1250 m.y. (Pieters *et al.* 1983). The basement of the Arafura Sea, an intervening sea between Australia and Irian Jaya, also belongs to this crust, consisting of granitic and quartzitic basement rocks overlain by continental shelf sediments predominantly clastics with minor carbonates ranging in age from Late Paleozoic, Mesozoic and Cenozoic.

The northwestern border has always been a passive margin (Audley-Charles *et al.* 1976; Parker and Gealey, 1983), whereas the northeastern border was an active margin with an island arc setting (Parker and Gealey, 1983). The two types of continental margins are important fundamentals for the elucidation on the origin of continental fragments or microcontinents now occurring in eastern Indonesia.

EVOLUTION OF THE SUNDA PLATFORM

There are several scenarios concerning the evolution of the Sunda platform.

Katili (1981) proposed that the evolution of the Sunda platform was by development of an opposing double arc trench system from Permian until the end of the Mesozoic. The southern arc-trench system persists until the present day, whereas the northern one had become inactive during Late Tertiary (Fig. 16).

Suparka and Asikin (1981) presented a Late Paleozoic scenario, in which they believe that the double magmatic arc (Sumatera and Kalimantan) was a result of subduction from the northeast (Fig. 17). This scenario is based on trace element analysis that shows the volcanics are of calcalkaline type associated with high-alumina basalt.

Hutchison (1978) presented a scenario on arc development reconstructing the Sunda platform whereby subduction during Carboniferous and Permian time was from the east, at which time a marginal basin developed. This led to flipping of the subduction zone across the marginal basin. The life of this marginal basin was short, namely from Permian to Early Triassic time. Later on during Late Triassic the West and East Malaya Blocks were reunited along the Bentong Raub suture (Figure 18).

Pulunggono (1983) proposed the existence of a suture running approximately north-south called the Mutus Suture. This line is considered as a collision zone between the Mergui microcontinent of Gondwana origin and Proto Sunda continent. The collision took place during Late Triassic time. Pulunggono stresses the importance of the Mutus assemblage as being the basement of the oil-producing overlying sediments. The maturation of the hydrocarbon is interpreted by heatflow transfer accomodated by conductive materials of the suture basement composed of metagreywacke and phyllite. With later accretionary arc development during Jurassic and Late Cretaceous time, the volcano-plutonic arc cross-cuts the Mutus Suture as envisaged in Figure19.

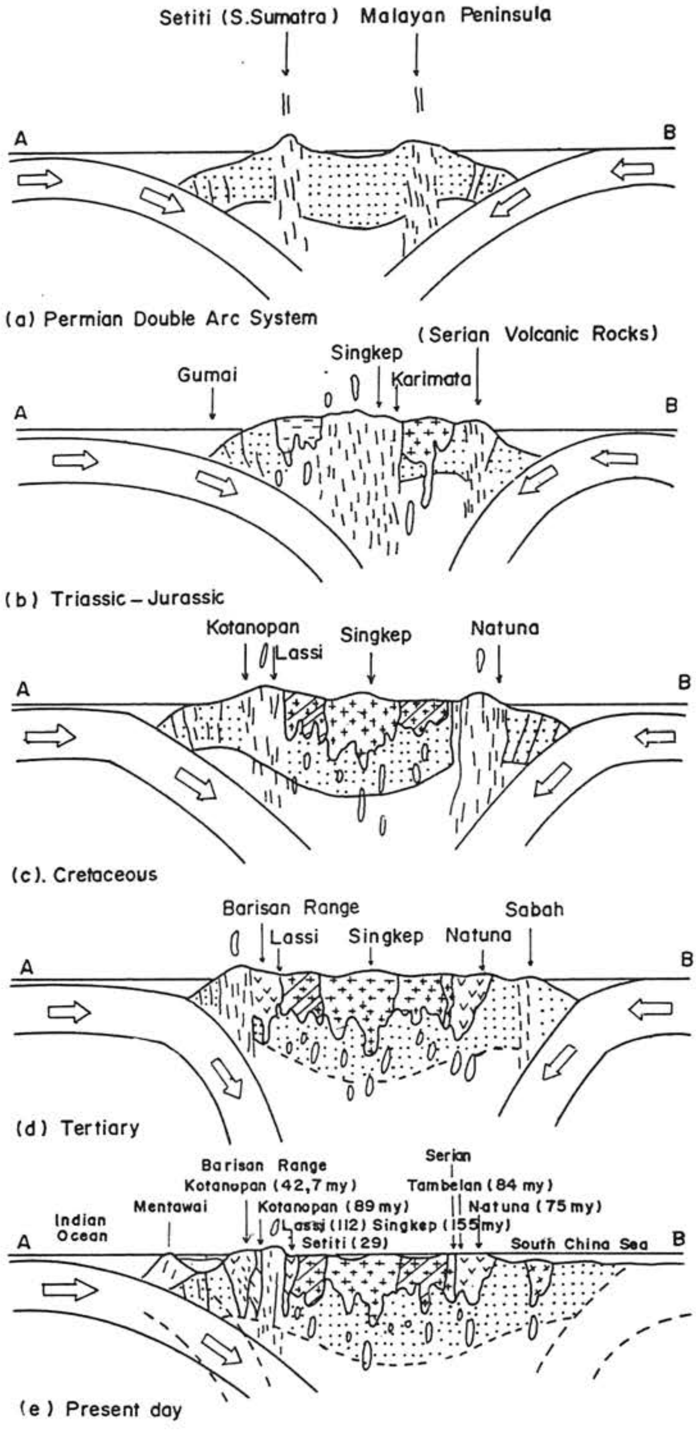

Fig. 16 Evolution of the double arc-trench system of west Indonesia (Katili, 1981).

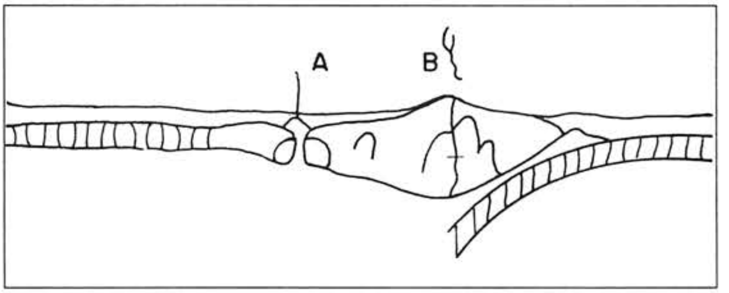

Fig. 17 NE-SW section, crossing Kalimantan and Sumatera showing arc tectonic setting during Carboniferous-Permian (After Suparka and Asikin, 1981).
A. Volcanism producing materials for the Silungkang and Palepat formations, and Karing-Salamuku-Air Kuning beds in Sumatera.
B. Volcanism producing materials for the Carboniferous-Permian volcanic facies in Kalimantan.

Ben-Avraham and Uyeda (1973) interpreted that Kalimantan had been separated away from the China mainland based on the presence of Late Paleozoic island arc setting in Kalimantan correlated with similar rocks occurring in eastern mainland China.

Anaschinda (1978) presented a scenario correlating the events in the Burmese-Thai area with synchronous events in the Malay Peninsula. The fundamental idea is that the Chiang Mai Suture, as a result of collision between Indochina craton and Burma-Malaya microcontinent (Figure 20), is drawn further south to match with the Bentong-Raub suture (Fig. 21). The obstacle in Anaschinda's tectonic development is that East Malaya is considered as a separate block from West Malaya and came into being by rifting and later on reunited during Late Triassic time. Taking into consideration the synchroneity of the event it is obvious that the East Malaya Plate is correlated with the Indochina craton, therefore it could not have been derived from two different origins.

The present paper proposes that the Sunda platform was formed by collision of the Indosinia terrane and the Mergui terrane during Late Triassic time. The Indosinia terrane includes Proto-Kalimantan, East Malaya and Indochina. The collision follows the Bentong Raub suture which is obvious in Peninsular Malaysia to Billiton, but is obscured further east by burial under tectonic cover. This suture is expected to extend under the Barito Basin in Kalimantan. This paper prefers to draw the collision zone more or less symmetrically between the opposing subduction zone as envisaged by Katili (1981), hence along the Bentong-Raub suture and its eastern continuation. Considering Pulunggono's idea (1983) that the Mutus suture is a Late Triassic collision zone in Sumatera, further studies need to be done on how it relates with the Bentong-Raub Suture. The following table shows various scenarios on the development of the Sunda platform.

MAKASSAR STRAIT OPENING

There are two main hypotheses on the opening of the Makassar Straits. Based on geologic similarities between eastern Kalimantan and western Sulawesi, Hamilton (1979) and Katili (1978) propose that the Makassar Strait was opened by rift-drift.

	SW of Bentong-Raub Suture	NE of Bentong-Raub Suture
Katili (1981)	Sumatera Permian arc with subduction from SW	Kalimantan Permian arc with subduction from NW
Suparka-Asikin (1981)	Back-arc rifting Permian volcanism (Sumatera)	Permian arc with subduction from NE(Kalimantan)
Hutchison (1978)	Fixed plate, volcanics of Carboniferous age as a result of volcanism from prior rifting	Permian volcanism in East Malaya by subduction from the NE; the arc separated away by forming of a marginal basin
Pulunggono (1983)	Mergui plate, with volca–nism as a result of subduction from SW Gondwana origin	Ancient Sundaland, with Permian volcanism in E. Malaya with subduction collision along Mutus suture from SW
Uyeda	—	Permian arc in Kalimantan originated from mainland China
Anaschinda (1978)	Burma-Thailand-Malaya Peninsula with subduction from NE	Indochina craton (passive margin)
	West Malaya	East Malaya; opening by rifting during Carboniferous -Triassic; subduction from the NE
Present paper	Sumatera basement terrane with Permian arc volcanism origin: Pangaea break-up Collision along Bentong Raub Suture	Indosinia terrane (= Proto Kalimantan terrane), with Permian arc volcanism Origin: Pangaea break-up

Hamilton (1979) proposes a Middle Tertiary opening. Reading Hamilton's tectonic map the rifted separated rocks now occurring in west Sulawesi consist of the following geologic units: Cretaceous melange, Cretaceous Eocene sediment deposited in the forearc basin of the Cretaceous arc, and Paleogene tectonic cover. These units occur both in west Sulawesi as well as southeast Kalimantan hence a Middle Tertiary opening was proposed to explain the separation.

Katili (1978) proposes a scenario of the opening of the Makassar Strait (Figure 22). During Miocene time, a magmatic arc and a subduction arc came into being in the forearc areas of East Kalimantan. By the westward movement of the Sula platform the double arcs were

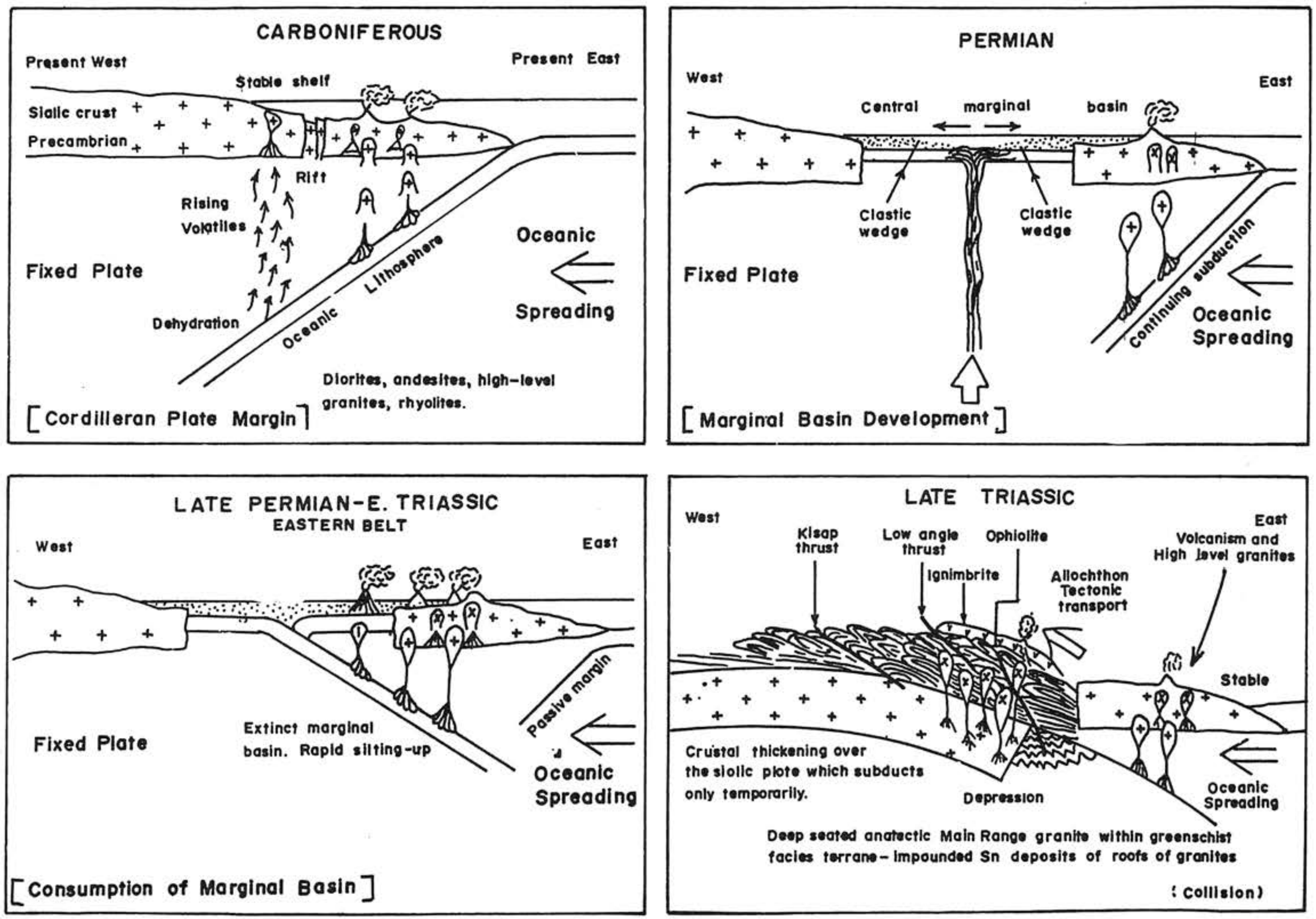

Fig. 18 Sequence of Carboniferous-Late Triassic plate tectonic development of the Malay Peninsula, (Hutchison, 1978).

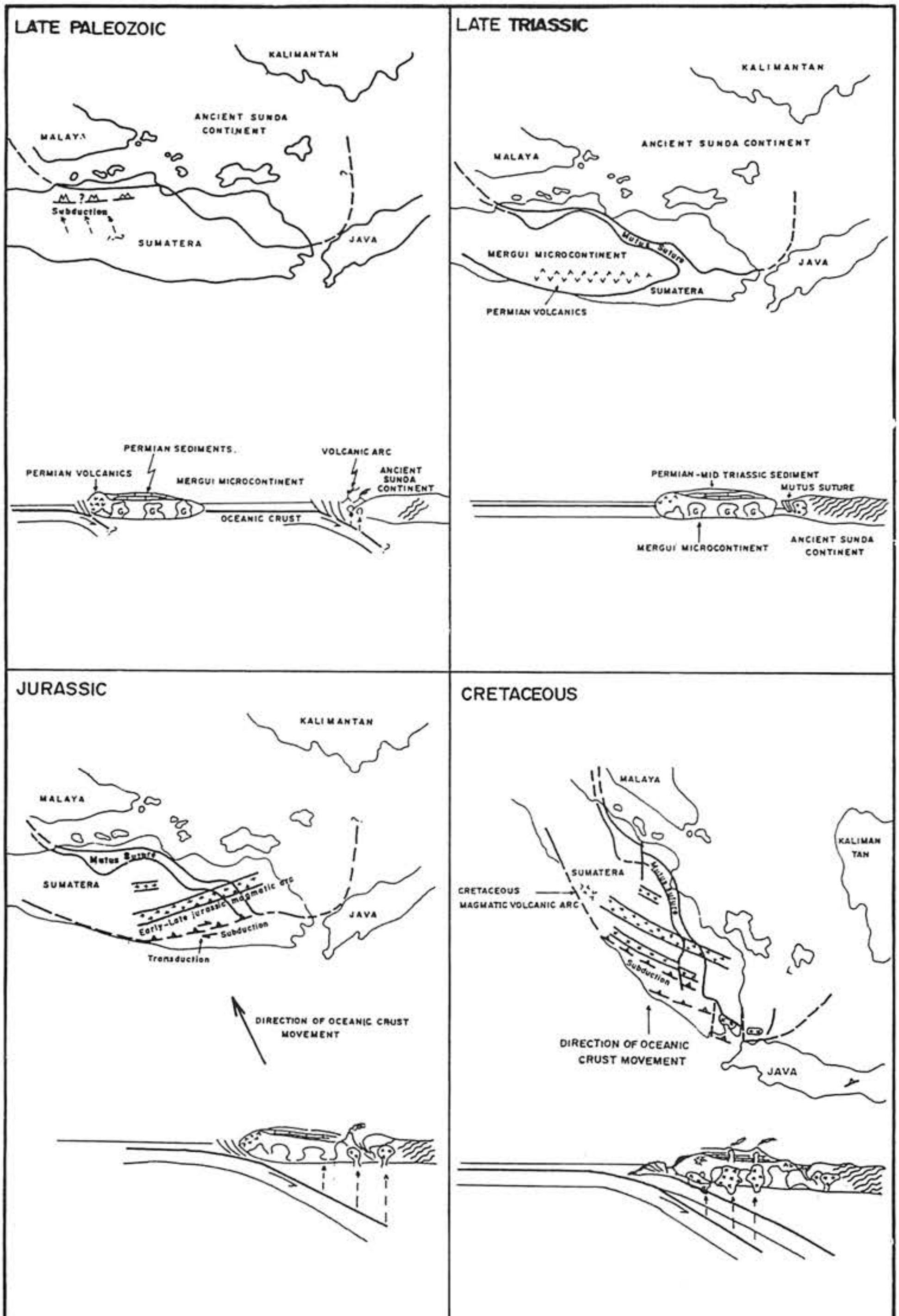

Fig. 19 Sequence of Late Palaeozoic-Cretaceous plate tectonic developments of Sumatera (Pulunggono, 1983).

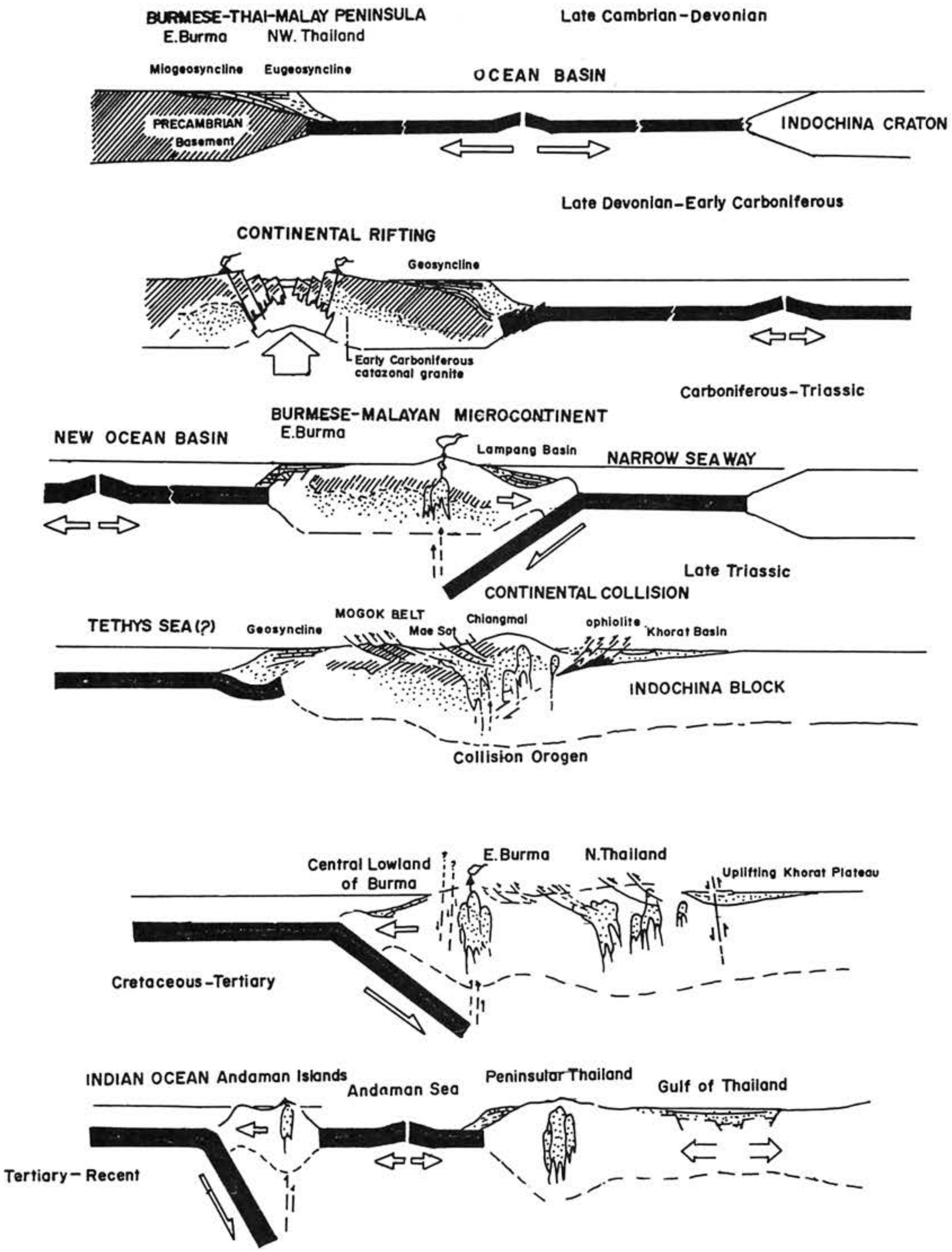

Fig. 20 Plate tectonic evolution of Thailand and Malay Peninsula (Anaschinda, 1978).

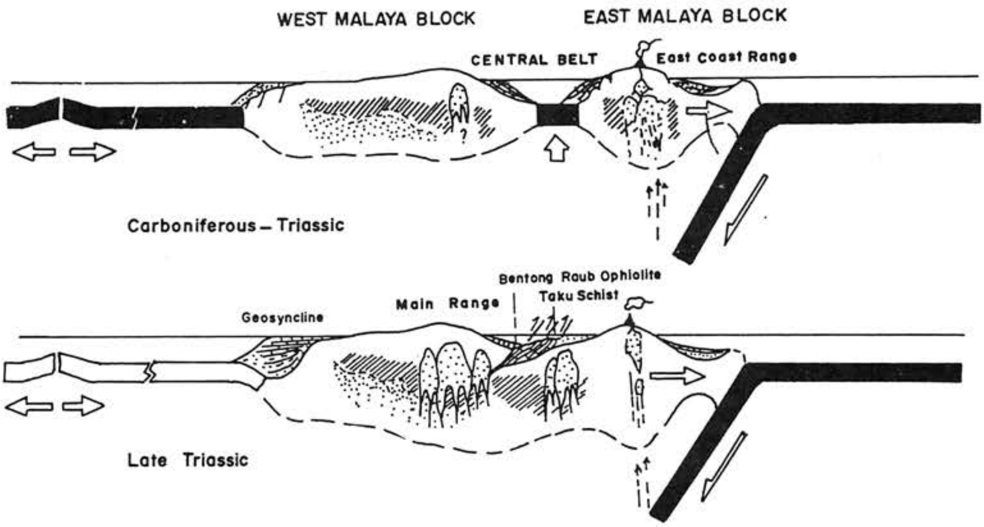

Fig. 21 Late Palaeozoic-Triassic plate tectonic evolution of the Malay Peninsula (Anaschinda, 1978).

they were detached again bringing with them some components of the Meratus Range to open the Makassar Strait.

A third hypothesis considers that the Makassar Strait is not a result of opening but merely a sedimentary basin (A.J Barber-correspondence).

The present paper follows the opening hypothesis by rift-drift and the difference with the first two hypotheses is the timing of the opening which the authors propose had taken place during Early Tertiary. The supporting evidence for this conclusion consists of magnetic and gravity data from Hasegawa (CCOP project office - oral communication), who compiled data from the Makassar Strait. He indicated that based on his compilation a rise of mantle material should have occurred in the Makassar Strait, confirming an opening. The authors of this paper are of the opinion that the timing of the opening should be Early Tertiary based on the Eocene ages of sediments in two locations (IPA, Geothermal gradient map, 1981). Paleogene volcanics occur both in the Makassar Strait and in West Sulawesi. The opening should have taken place prior to Eocene sedimentation in the Makassar Strait and also prior to Paleogene arc volcanism of western Sulawesi.

BANDA ISLAND ARC- AUSTRALIAN CONTINENTAL CRUST COLLISION

The breakup of Gondwana and Asia in the area of present day north west Australia and Irian Jaya started in the Late Paleozoic to Triassic resulting in the birth of the Tethys ocean which prevailed throughout the Mesozoic. Later on this ancient ocean was disturbed by seafloor spreading which began in Middle Jurassic time when the northwestern Australian continent was rifted and fragmented into smaller microcontinents. These microcontinents together with Australia are moving northward at an approximate rate of 70 mm/year.

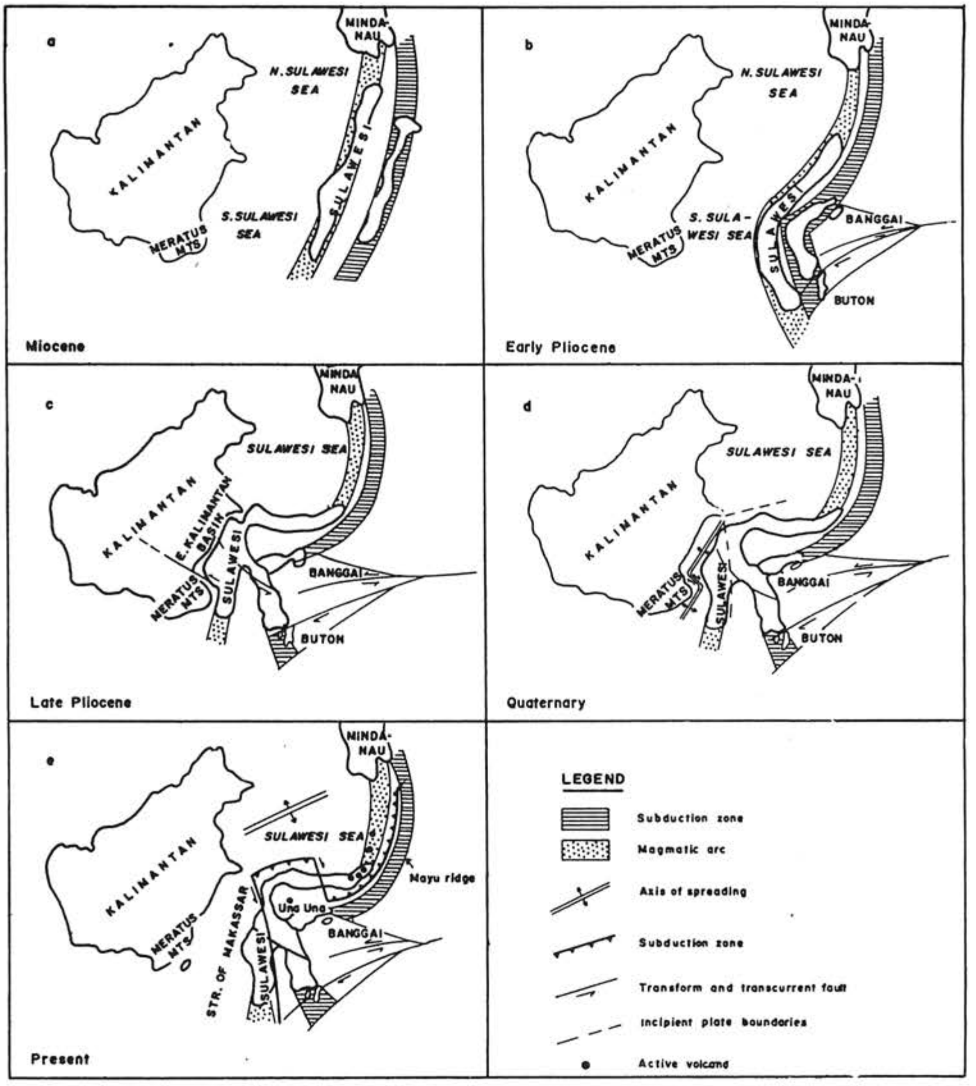

Fig. 22 Geological evolution of Sulawesi from Miocene to the present time (Katili, 1978).

Evidence of Jurassic spreading is supported by magnetic anomaly patterns in the Wharton Basin and ages of sedimentary cover in the Browse Basin, Sahul platform and Merauke platform which is Jurassic and younger in age. Continued drift is hindered by existing island arc systems: the present Banda Island Arc and the Tertiary Northern New Guinea island arc.

The present actual collision is between the South Banda island arc system and the Australian continental crust. Prior to continental crust collision, oceanic crust was subducted under the Banda Arc.

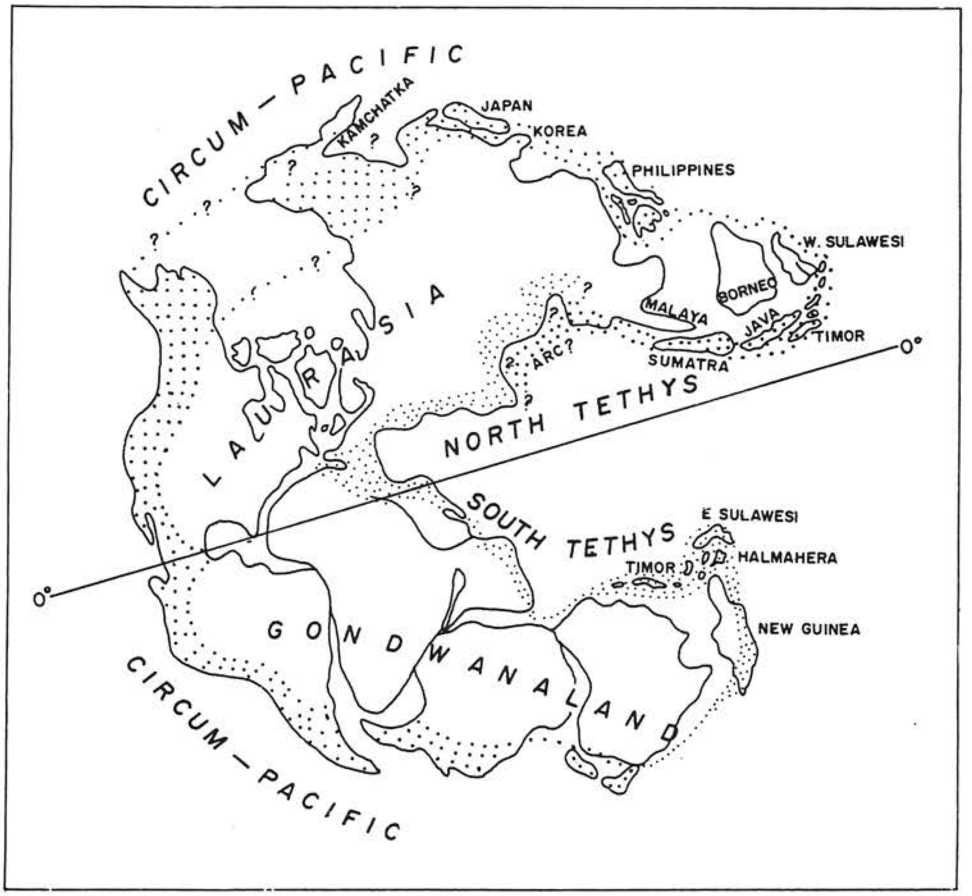

Fig. 23 Triassic paleogeographic map showing Tethys; in the north bordering with active continental margin (large dots) and in the south bordering with passive continental margin (small dots). According to Audley-Charles (1979).

An exhaustive discussion and debate on the geology of the collision complex resulting from the collision of the Banda Island Arc system and the Australian continental crust can be observed in the literature. The debates involve the position of the subduction zone which has implications for the interpretation of the origin of terranes and stratigraphic units occurring in the Banda nonvolcanic outer arc.

Based on recent data such as seismic reflection, seismic refraction, gravity and the onshore geology of Timor, we place the locus of subduction south of Timor at the trough. Timor is underlain by Australian crust with a structural break separating the Australian shelf sediments from the accretionary wedge and structurally complicated rocks now occurring in the outer Banda Arc. Audley-Charles *et al.* (1975) and Chamalaun and Grady (1978) believe that the position of the subduction is between the outer and inner Banda Arcs (between Timor and Wetar). Hamilton (1979) believes that the position of subduction is at the trench outside the outer arc. Although seismic refraction and gravity data indicate that continental crust is present beneath the Timor Trough, seismic reflection data crossing the trough show that Australian continental shelf sediments dip under the accretionary wedge of the opposing side of the trough. The position of subduction has an implication for the interpretation of the geology of the nonvolcanic outer arc ridge. The position at the trough implies that the outer arc ridge is a subduction melange, an idea held by Hamilton (1979), Katili (1974, 1975) and others. Subduction at the inter-arc positon (between outer and inner arc) implies the presence of Australian material at the outer arc ridge and the origin of the stratigraphic units as autochthonous, para-authochthonous and allochthonous series. Audley Charles *et al.* (1975) believe that the outer arc ridge is essentially a zone of Pliocene collision and the site of overthrust sheets of Asian material onto Australian basement. Chamalaun and Grady (1978) believe that over-thrusting as advocated by the previous group does not occur in Timor. Their structural interpretation is that normal faulting has occurred and whole stratigraphic units have been deposited on the Australian continental shelf.

Seismic refraction data, show that the outer-arc ridge is underlain by Australian continental crust while seismic reflection data show a down-going slab under the accretionary wedge at the trough (Jacobson *et al.*, 1978). This supports the idea that subduction is at the trough and the trough lineation represents the surface trace of a subduction zone (Fig. 24B). Later, in their interpretation of the structure of Seram, Audley Charles *et al.* (1979) reconsidered the problem of the subduction position and have two zones, A-zone at the trench and B-zone at inter-arc position (Fig. 25).

According to the imbrication model, (Hamilton, 1979), the tectonic development of the ridge of the Outer Banda Arc is an accretionary complex consisting of slices of Mesozoic and Cenozoic sedimentary rocks interleaved with clay–matrix melange. Coherent slices consist of deep to shallow water sedimentary rocks which were stripped from the down-going Australian margin and incorporated into the imbricate wedge, along with pelagic sediments of oceanic origin. The sheared, scaly–clay melange contains blocks and lenses of all sizes up to tens of kilometers long. It is considered as an integral part of the deformed accretionary wedge. According to this hypothesis, it would not be possible to distinguish and map out units of Asiatic and Australian origin. The whole thing appears as a chaotic melange as a result of collision between an island arc and oceanic/continental crust from the south.

The overthrust model (Audley-Charles *et al.*, 1975) considers that the outer arc ridge contains three principal groups of formations: autochthonous Australian-derived strata, para-autochthonous materials which originated at a distal position from the Australian continent, and allochthonous east-Asian derived strata. This model implies that the material termed "melange" is a surficial olistostrome emplaced during the Late Miocene, that forms a thin veneer over the underlying thrust sheets (Fig. 26). Based on pelagic foraminifera found in the clay matrix, the age of the olistostrome is Late Miocene. This model considers that it is possible to delineate formations within the outer arc ridge and identify the origin, whether it is of Australian (autochthonous), distal Australian (para-autochthonous), or Asiatic (allochthonous) origin.

Chamalaun and Grady (1978) consider that the outer Banda Arc belongs to the Australian continental shelf, based on similarities with formations found in the northwestern part of the

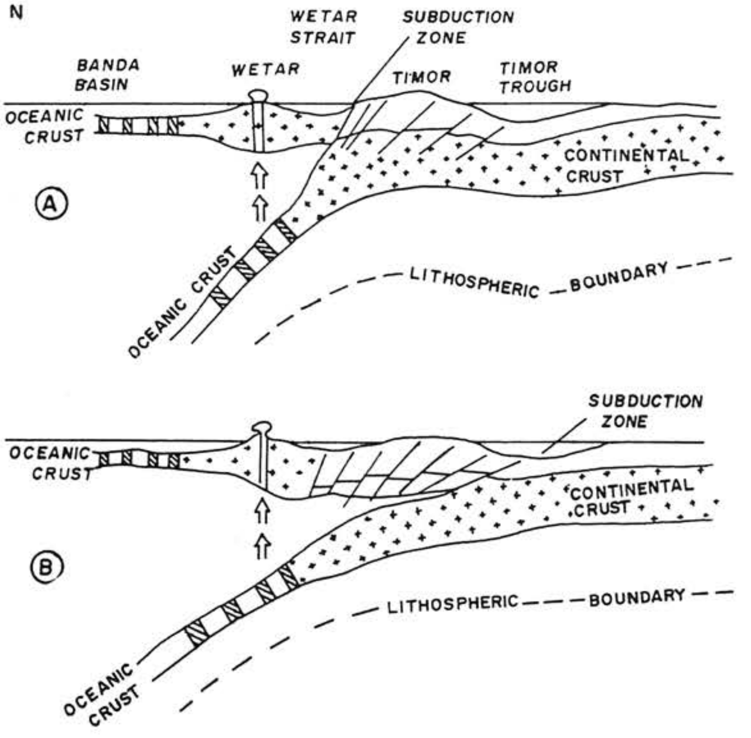

Fig. 24 A. Schematic crustal cross-section across Timor according to overthrust model (Carter *et al.*, 1976).
B. Schematic crustal cross-section across Timor with Timor trough as surface trace of subduction (Jacobson *et al.*, 1978).

Australian continent; hence, it is all considered as autochthonous. These strata entered a subduction zone at a trench located in the vicinity of Wetar Strait, later became uplifted by isostatic rebound and are now exposed in the island of Timor.

The authors of this paper are of the opinion that the Banda outer arc islands became detached from northwestern Australia during Jurassic time and formed a row of islands in the Tethys Ocean. The detached islands brought with them components of Pre-Jurassic sediments, in the case of Timor the Maubisse Formation and for Seram marmorized limestone with crinoids, associated metamorphics of the Tehuru complex, and Triassic limestone and flysch of the Manusela limestone and Kamikeh Formation. In the beginning, this row of islands was not an island arc. The island arc developed when the oceanic crust in front of the northwest Australian continent started to go under the row of islands. In Timor this event commenced during Eocene time as manifested by the occurrences of Metan volcanics and diorites. In Seram (Ambon) and other islands it commenced during Miocene time.

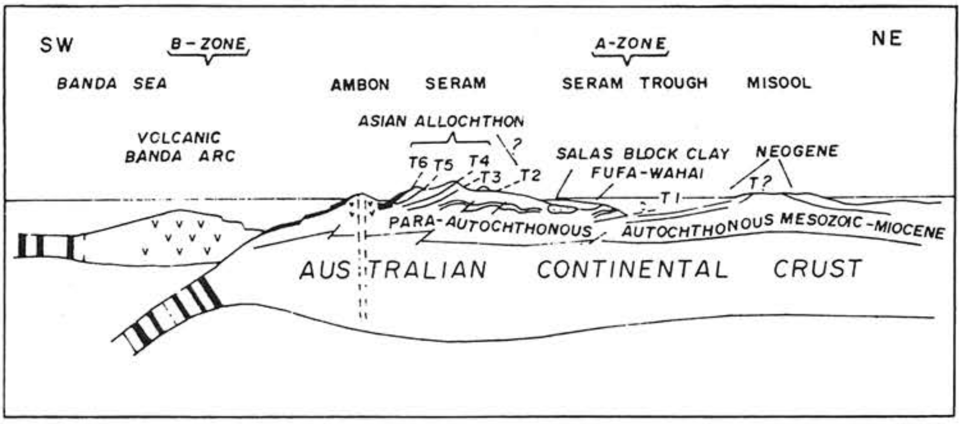

Fig. 25 Schematic cross-section through the volcanic Banda Arc, Seram to Misool; showing Australian autochthone going under Seram (A. zone) and Australian continental crust going under the volcanic Banda Arc (B. zone). According to Audley Charles *et al.*, (1979).

TERTIARY ISLAND ARC AND AUSTRALIA CRUST COLLISON IN IRIAN JAYA

Pieters *et al.* (1983) date the island arc to be Early Tertiary-Miocene. However the history of this arc dates back to the Late Paleozoic when there was an extensive island arc setting in eastern Australia. In its most northern extremities the arc separated from the continent during Cretaceous time and during Early Tertiary it developed into a double arc (Parker and Gealey, 1983). The proximal arc had a polarity of subduction northward with consumption of oceanic materials from the south forming a front of oceanic crust of the New Guinea-Irian Jaya-Australian continental crust. After the oceanic crust was consumed by subduction under the arc, collision took place and a change of subduction polarity occurred, becoming southward (Fig. 30).

The hinge between the island arc and the continental crust is a line separating ophiolites and related oceanic materials including volcanics in the north from continentally deposited clastics in the south (Fig. 15).

It seems that island arc components have been upthrusted over the stable Australian crust. Major structures including a foldbelt and fault system in Irian Jaya result from convergence of the Australian crust and the northern Irian Jaya Arc.

The authors of the present paper consider that the Bird's Head is part of the Australian crust and its present protruding position northward was caused by movement along the Ransiki dextral strike-slip fault. Recently another view has been expressed that the Bird's Head constitutes a separate terrane that has been drifted from the east to its present position (Pigram *et al.* 1983b).

CONCLUDING REMARKS

1. This paper attempts to identify terranes as well as to reconstructing them geologically in relation to comprehensive geological evolution of the Indonesia Archipelago.

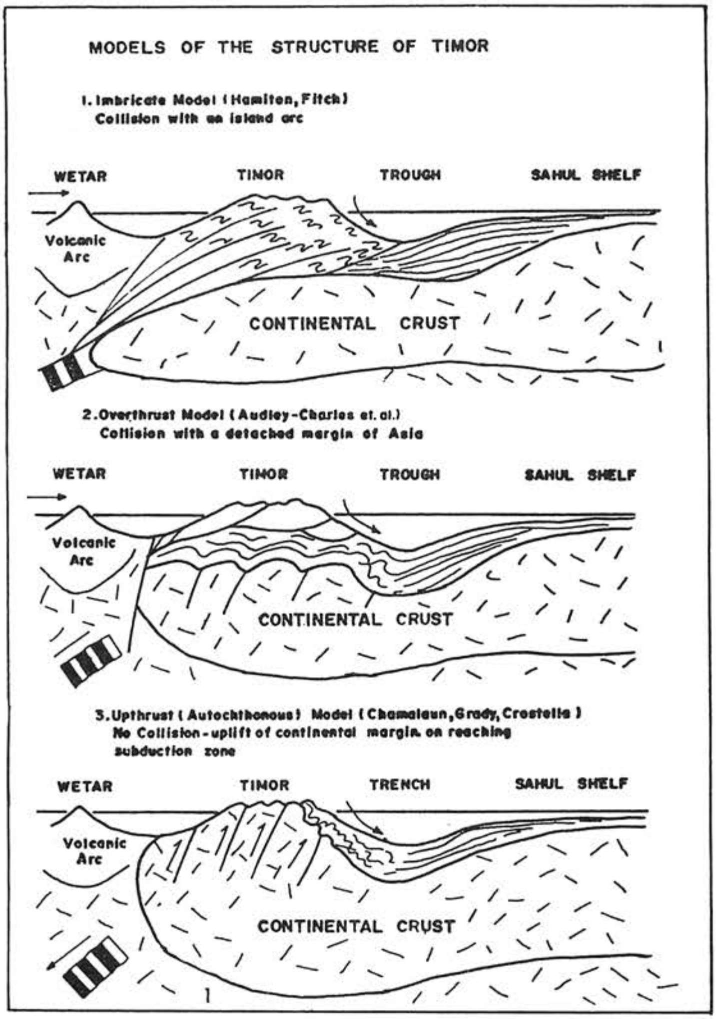

Fig. 26 Models of the structure of Timor (Barber, 1981).

2. The existence of Permian arcs in Sumatera and Kalimantan is proposed, based on findings of Permian fusulinids, existence of volcanics and associated plutons and radiometric dates. However the subduction polarities for both arcs are difficult to reconcile. The determination of these polarities could be determined by analysing the environmental condition of deposition of the sediments in relation to island arc setting and taking into considerarion also the position of volcano-plutons and oceanic materials.
3. The authors favour the Late Triassic amalgamation of the Mergui Plate and Indosinia Plate. The model should fit and be in harmony with the subduction polarities of the Permian arcs.
4. The interpretation of the east Sulawesi schist as a subduction complex related to west Sulawesi is a preliminary one which is mainly based on the presence of blue schist and

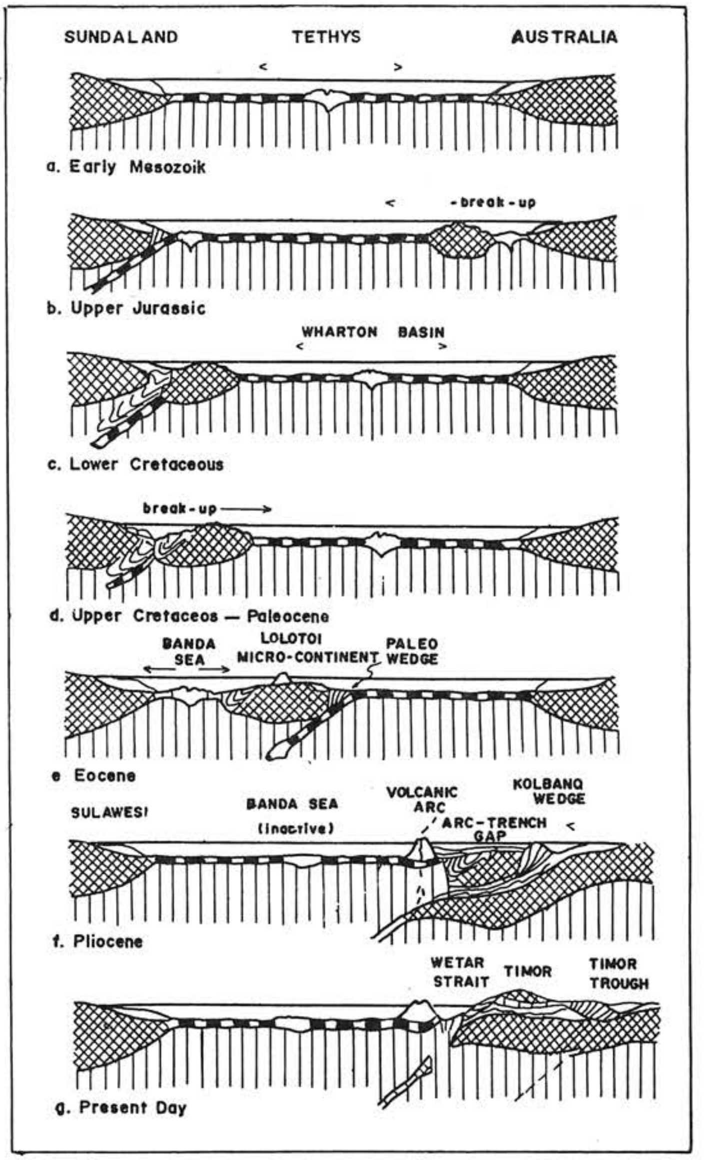

Fig. 27 Evolutionary scheme to explain the geology and structure of Timor (Barber, 1981).

green schist metamorphic facies. The extensively distributed occurrences and varied metamorphic facies of metamorphic rocks in west as well as east Sulawesi pose suspicions as to their origin.

5. The authors favour the existence of a Late Paleozoic arc in New Guinea. This is in harmony with overall geological evolution of eastern Australia, and could explain the

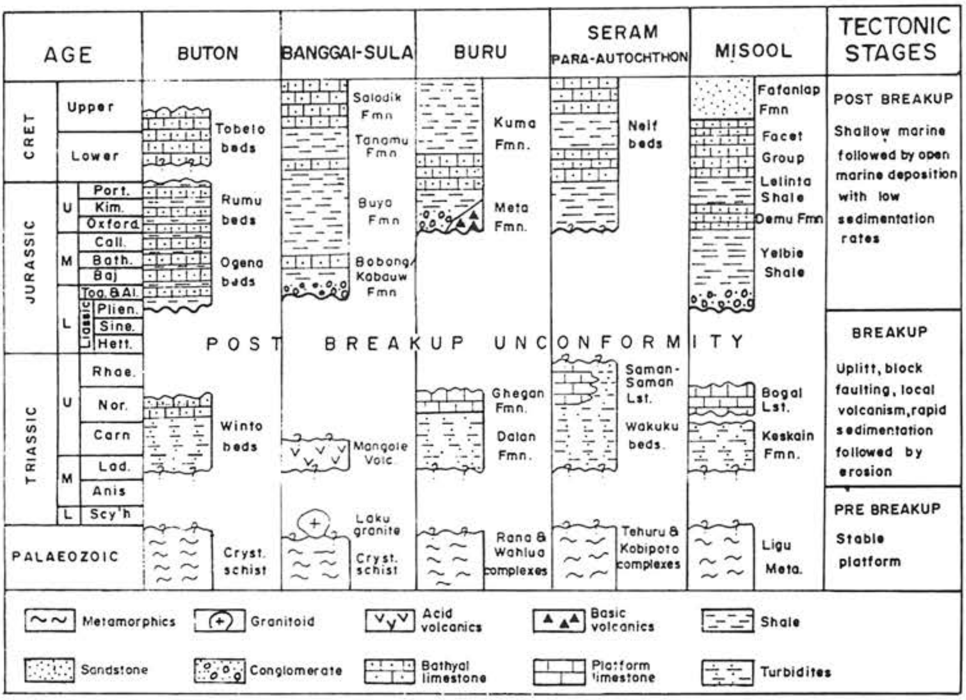

Fig. 28 Tectonic break-up stages of rift-drift sequences of Buton, Banggai-Sula, Buru-Seram and Misool (Pigram *et al.*, 1983b).

extensive development of volcanics in the Banggai-Sula terrane, which have been correlated and interpreted to have been derived from Irian Jaya-New Guinea. Irian Jaya-New Guinea is situated in the northernmost locus of this arc.

6. The consideration of the Banda Arc as not being a separate terrane follows the concept that it is the eastern continuation of the Sunda Island Arc system of western Indonesia. Several features, such as bathymetry, topography, seismic reflection profiles crossing the trough, seismic refraction data and gravity Bouguer anomaly show that there is a structural continuity from the Sunda Arc to the Banda Arc. However, there are some features that are strikingly different between the Sunda and Banda Arcs. One of the most striking is the base on which the Tertiary Sunda and Banda Arcs were built. In the Sunda Arc the base is the stabilized craton of the Sunda shelf and the back-arc basin has also the Sunda craton as basement. The Banda Arc, however, was built on continental fragments or terranes originated from Jurassic spreading of the northwestern Australia continental crust. In this paper Timor and Seram are indicated as terranes. Further the back-arc basin of the Banda Arc has an oceanic basement. If the Sunda Arc and the Banda Arc are discontinuous, the Tertiary magmatic Banda Arc including its Tertiary accretionary wedge should be considered as a separate terrane.

Clearly, a distinction should be made as to which stratigraphic units belong to the Timor-Seram terrane and which stratigraphic units belong to the Tertiary magmatic Banda Arc/accretionary wedge.

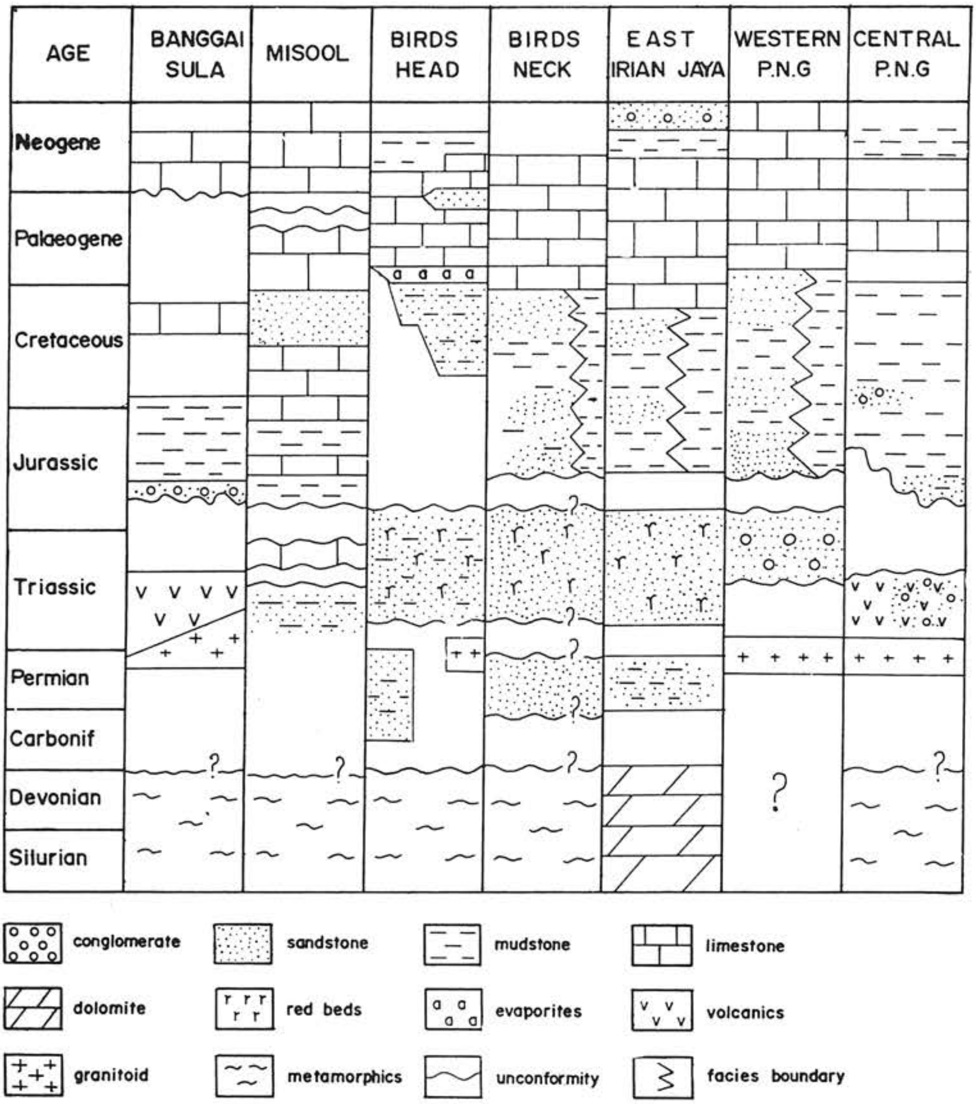

Fig. 29 Corelation chart of Banggai-Sula, Misool, Bird's Head, Birdsneck, Eastern Irian Jaya, Western PNG and Central PNG, to show mainly volcano-plutonic activity during Permian-Triassic time (After Pigram *et al.* in press).

ACKNOWLEDGEMENTS

The authors acknowledge and thank Mr. David Trail from the Indonesia-Australia Geological Mapping Project for reviewing and editing the paper. Colleagues from the Geological Research and Development Centre are acknowledged for their participation in the discussions during the preparation of this paper.

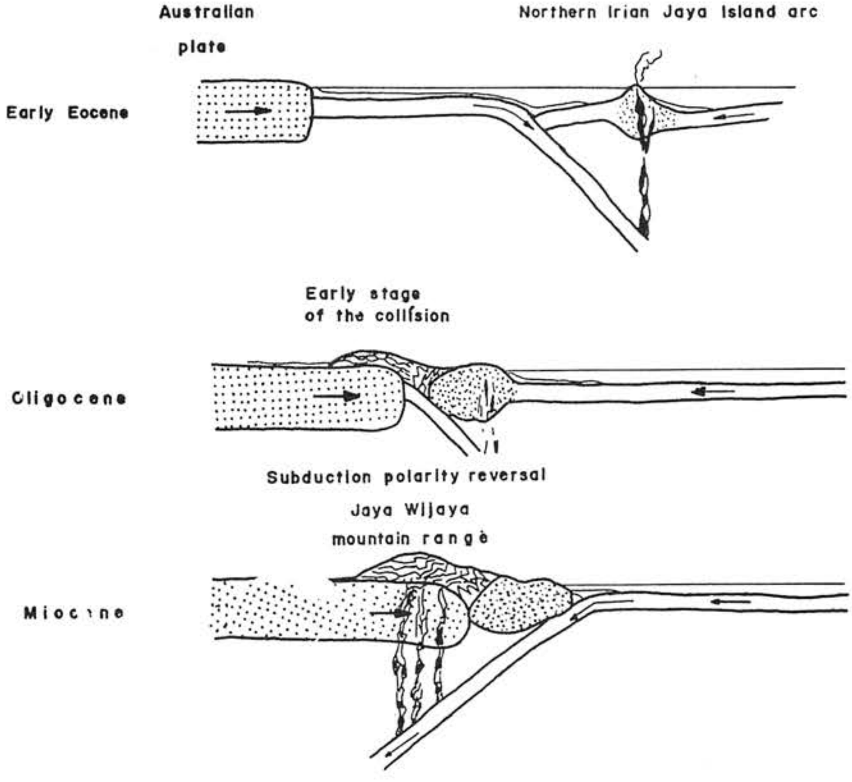

Fig. 30 Collision of Australian plate with Tertiary northern Irian Jaya Island Arc, showing change in polarity of subduction (Hartono and Tjokrosapoetro, 1984).

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Manuscript received 11th September 1984.