Neogene tectonics and orogenesis of Indonesia

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Abstract: The present tectonic configuration of the Indonesian archipelago is thought to have been developed during Neogene times, and shows a triple convergence, which is due essentially to interaction of three megaplates: the westward-moving Pacific Plate, the northward-moving Indo-Australian Plate and the south-southeastward-moving Eurasian Plate.

The archipelago is built up of at least 5 distinctive crustal elements including 1) **Sunda Shield (SE Eurasian Plate)** 2) **Indian (Oceanic) Plate**, 3) **Australian Craton** 4) **Pacific Plate** and 5) **Transitional Complex**. Each unit consists of several distinctive tectonic units.

This tectonic convergence was subsequently followed by the development of *orogenic belts* in most parts of the region, which kinematically can be recognized and divided into 4 types:

1. **Sunda Orogeny** in western Indonesia due essentially to a back-arc thrusting in Jawa and Nusatenggara, and transpressional movement of the Barisan Fault System in Sumatera. The orogeny gave rise the development of the Southern Mountain Ranges in Jawa and the Barisan Mountain Ranges in Sumatera, which are coincident with the fold and fault belt. In Sumatera the belt shows a typical flower structural setting.
2. **Banda Orogeny** in Sulawesi and its surroundings due essentially to the development of a Tethyan type convergence together with the transcurrent movement of the Palu-Koro Fault System, which give rise the development of mountain ranges in Sulawesi.
3. **Melanesian Orogeny** in Irian Jaya and Papua New Guinea and Sahul Platform due to the development of thin-skinned tectonics, causing the development of the Central Irian Jaya Fold and Thrust Belt coincident with the Central Irian Jaya Mountain Ranges.
4. **Talaud Orogeny** in the northern Maluku region due to the development of double arc collision coupled with the transpressional movement of southern extension of the Philippine Fault System giving rise the development of the imbricated Talaud-Tifore ridge in the form of flower structure, which is partly emerged above sea level.

INTRODUCTION

This paper presents an overview and analysis of the tectonic development and tectonic setting of the Indonesian archipelago particularly from the Neogene to present times.

During the last two decades, since the beginning of Pelita I in 1970 (the first five years of national development of Indonesia), the geology of the archipelago was intensely and systematically investigated by both government and private institutions. These include geological mapping conducted by the Geological Survey of Indonesia and Geological Research and Development Center (GRDC), partly in collaboration with the United States Geological Survey (USGS), the British Geological Survey (BGS) United Kingdom, Bureau of Mineral Resources (BMR) of Australia and JICA of Japan.

Exploration for mineral and energy resources by foreign and national companies and geological and geophysical research by both Indonesian and foreign earth scientists, has revealed more comprehensive information on the geology of the region (Simandjuntak, 1992b). These data give a better understanding on the geological and tectonic history of the achipelago.

Up to date information is provided by GRDC, Pertamina, Lipi, Lemigas, Marine Geological Institute (MGI) and other domestic and overseas institutions related to earth sciences.

This paper is part of the work carried out in conjunction with the compilation of the geotectonic map of Indonesia and the Working Group on Geotectonic Map Project of East Asia (WGGM-CCOP-NW Quadrant Circum Pacific).

TECTONIC SETTING OF INDONESIA

Based on geological and geophysical data, the Indonesia Archipelago can be divided into at least five mega crustal elements, comprising 1) Sunda Shield (SE Eurasian Plate) in the north-west, 2) Indian Ocean Plate in the south and west, 3) Australian Craton in the southeast, 4) Pacific Plate in the east-northeast and 5) Transitional Complex

in the central part of the region (Simandjuntak, 1992a). These crustal elements are tectonically bounded to each other by either active or inactive (reactivated) subduction zones or wrench and/or thrust faults (Figs. 1 and 2).

Tectonostratigraphy of Indonesia

Tectonostratigraphically, on the basis of lithological association, structures, age and/or biostratigraphy and geophysical data, each crustal element can be divided into several distinctive tectonic units (Fig. 3; Simandjuntak, 1992a).

Sunda Shield corresponds to most of western Indonesia, including Sumatera, Jawa, Jawa Sea, Kalimantan and part of the South Arm of Sulawesi. The Sunda Shield can be divided into: a) fore arcs, b) volcanic arcs and c) back arcs in Sumatera and Jawa d) platform and e) accreted zone in Kalimantan and f) magmatic arcs in the South Arm of Sulawesi.

Carboniferous meta-flysch sediments are the oldest rocks recognised in the Sunda Shield. However, core samples from east Medan, North Sumatera were dated as Devonian in age.

Indian Ocean is floored by oceanic crust of Cretaceous-Paleogene age with a cover of pelagic sediments.

Australian Craton is represented by parts of its northern margins which occur in Irian Jaya and Sahul Platform, and can be divided into 3 distinctive units, composing a) the Southern Plains of Irian Jaya, b) the Central Irian Jaya Fold and Thrust Belt and c) the Birds Head and Neck of Irian Jaya and Misool.

The oldest rocks in Irian Jaya are pelites containing fossils, *Graptolites*, of Siluro-Ordovician age.

Pacific Ocean with its floor of Mesozoic or older oceanic crust and deep sea sedimentary cover.

Transitional Complex is defined as the region that is presently tectonically active convergence, divergence/rifting, faulting (thrusts, wrenchs, block or extensional faults), and in parts is volcanically and seismically active. The complex is also characterised by the presence of Paleozoic allochthonous terranes juxtaposed with the surrounding younger autochthonous terranes. The complex consists of some 17 distinctive units, including accretional zone of the Cretaceous Eastern Sulawesi Ophiolite Belt (ESOB), Paleozoic Banggai-Sula Platform (BSP), Paleozoic Tukang-Besi-Buton Platform (BSP), Paleozoic Mekongga Platform (MP), Paleozoic Seram-Buru Platform (SBP), Paleozoic Obi-Bacan Platform (OBP), Cretaceous Sumba Platform (SP), Timor-Tanimbar-Kai Accretional Zone, Quaternary Banda Arcs (BA), Cretaceous Banda Sea Floor (BSF), Paleogene Talaud-Tifore

Ridge (TTR), Paleogene Western Halmahera Magmatic Arc (WHMA), Mesozoic Eastern Halmahera Ophiolite Belt (EHOB), Neogene Sangihe Volcanic Arc (SVA), Paleogene Sulawesi Sea Floor (SSF), Paleozoic Misool and Birds Head Platform (MBHP), Collision Zone of Irian Jaya. The accretional wedges in the western part of Sumatera and southern part of Jawa in western Indonesia may be included in the Transitional Complex.

Carboniferous metamorphics occurring in most of the micro-continents are considered to be the oldest rocks in the Transitional Complex. The metamorphic rocks are intruded by Permo-Triassic granitic rocks with Mesozoic, passive margin, sedimentary cover rocks.

The Banda Sea crust, based on identification of magnetic reversal ages, heat flow analysis, bathymetry and onland geology is thought to have been formed in Cretaceous times (Lapouille, 1985; Lee and McCabe, 1986).

Juxtaposition of the Paleozoic micro-continents with the Cretaceous oceanic crust in the Banda regions indicates that these continental slices are allochthonous in origin.

The Banda Platform geologically shows similarities with the South East Kalimantan and the South Arm of Sulawesi, in especially the occurrence of Cretaceous flysch sediments associated with volcanics and Paleogene Volcanics. The platform therefore is quite different, both in age and lithological association, from the other (Paleozoic) micro-continents described previously.

These tectonic units are always bounded by faults and thrusts from each other. Some of these faults may be reactivated at the present time.

Major Structures

Major or regional scale structures include subduction zones and thrusts and steep faults. Figure 1 shows the present tectonics and structural configuration of the Indonesian archipelago. The development of these structures is related closely to the tectonic convergences and tectonic divergences during the evolution of the regions from Mesozoic to present times.

Some of the faults might have reactivated older structures.

Subduction Zones and Thrust Faults

Active subduction zones include the Jawa Trench, the New Guinea Trench and the Philippine Trench. Thrust faults include the Halmahera Thrust and Sangihe Thrust in the northern Maluku Sea, North Sulawesi Thrust, "Asmat Thrust" in Irian Jaya and Seram Thrust in central Maluku. The Flores Thrust of Nusatenggara appears to
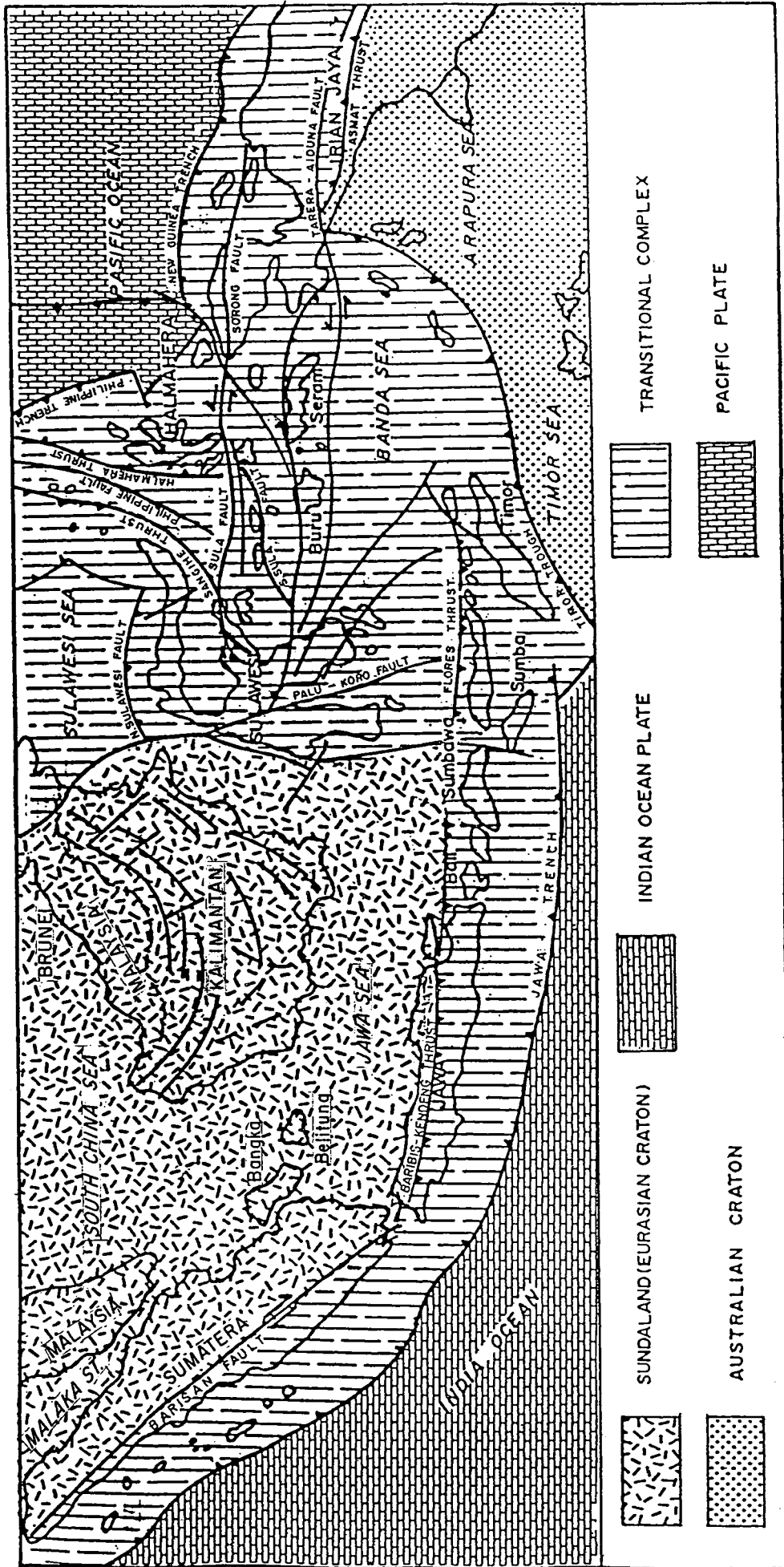
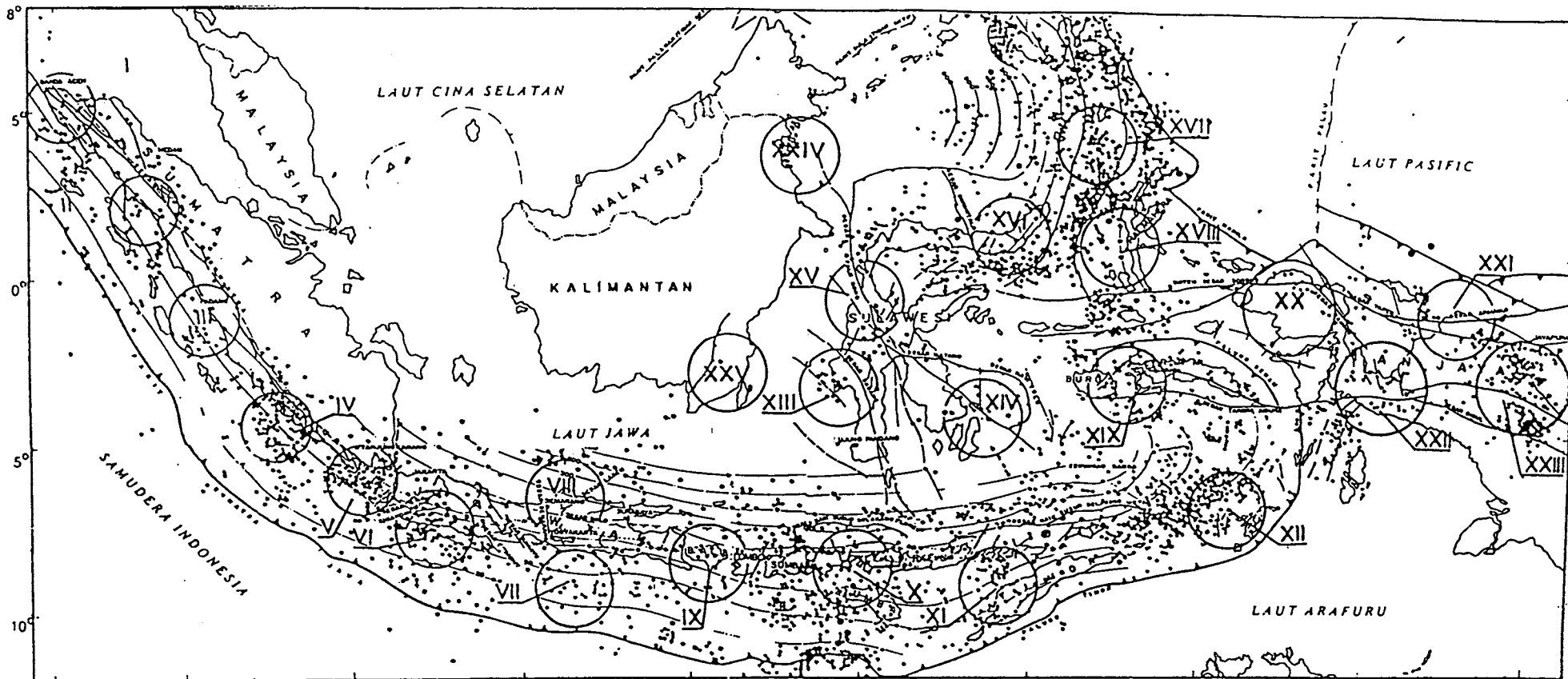Figure 1. Tectonics and structural setting of the Indonesian region.

Figure 2. Distribution of earthquake epicenters in Indonesia.

NUMBER OF REGION OF DESTRUCTIVE EARTHQUAKE

I.	Aceh	X.	Flores	XVIII.	Halmahera
II.	Sumatra Utara	XI.	Kupang	XIX.	Ambon
III.	Sumatra Barat	XII.	Yamdena	XX.	Kepala Burung
IV.	Bengkulu	XIII.	Sulawesi Selatan	XXI.	Jayapura
V.	Lampung	XIV.	Sulawesi Tenggara	XXII.	Paniai/Nabire
VI.	Jawa Barat	XV.	Sulawesi Tengah (Jayawijaya)	XXIII.	Wamena
VII.	Yogya	XVI.	Sulawesi Utara	XXIV.	Tarakan
VIII.	Lasem	XVII.	Sangir-Talaud	XXV.	Kalimantan Selatan
IX.	Bali-Lombak				

UMUR / AGE	PAPARAN SUNDA / SUNDA SHIELD	SAMUDRA HINDIA / INDIAN OCEAN	KOMPLEK TRANSISI / TRANSITIONAL COMPLEX	KRATON AUSTRALIA / AUSTRALIAN CRATON	SAMUDRA PASIFIK / PACIFIC OCEAN

KAINOZOIKUM / CENOZOIC — MESOZOIKUM / MESOZOIC — PALEOZOIKUM / PALEOZOIC

PAPARAN SUNDA / SUNDA SHIELD
(SUNDA OROGENY / OROGENESIS SUNDA)

- Qs – Sedimen Kuarter / Quaternary Sediments
- Qv – Vulkanik Kuarter / Quaternary Volcanics
- Ts – Sedimen Tersier / Tertiary Sediments
- Tv – Vulkanik Tersier / Tertiary Sediments
- Tl – Intrusi Tersier / Tertiary Intrusives
- Tm – Bancuh Tersier / Tertiary Melanges
- KTs – Sedimen Kapur Tersier / Tertiary Cretaceous Sediment
- Ks – Sedimen Kapur / Cretaceous Sediments
- Kv – Vulkanik Kapur / Cretaceous Volcanics
- Kl – Intrusi Kapur / Cretaceous Intrusives
- Km – Malihan Kapur / Cretaceous Metamorphics
- KM – Bancuh Kapur / Cretaceous Melanges
- Mzu – Ultrabasa / Ultrabasics
- Js – Sedimen Jura / Jurassic Sediments
- Jv – Vulkanik Jura / Jurassic Volcanics
- Jl – Intrusi Jura / Jurassic Intrusives
- Rs – Sedimen Trias / Triassic Sediments
- Rv – Vulkanik Trias / Triassic Volcanics
- Rl – Intrusi Trias / Triassic Intrusives
- Ps – Sedimen Perm / Permian Sediments
- Pv – Vulkanik Perm / Permian Volcanics
- Pl – Intrusi Perm / Permian Intrusives
- Cs – Sedimen Karbon / Carboniferous Sediments
- Cl – Intrusi Karbon / Carboniferous Intrusives
- Pzm – Malihan Paleozoik / Paleozoic Metamorphics

SAMUDRA HINDIA / INDIAN OCEAN
(Pemekaran kerak Samudera / MOR SPREADING)

- KQs – Sedimen Pelagos / Pelagics Sediments
- KTu – Kerak Samudra Kapur / Cretaceous Oceanic Crust

KOMPLEK TRANSISI / TRANSITIONAL COMPLEX
(Autochthonous — BANDA OROGENY / OROGENESIS BANDA — MICRO-CONTINENTS)

- Tn – (Tn)
- Qs – Sedimen Kuarter
- Qv – Vulkanik Kuarter
- Tns – Sedimen Neogen
- Tnv – Vulkanik Neogen
- Tnl – Intrusi Neogen
- Tnm – Bancuh Neogen
- Ts – Sedimen Tersier
- Tv – Vulkanik Tersier
- Tl – Intrusi Tersier
- Tm – Bancuh Tersier
- KTs – Sedimen Kapur Tersier / Tertiary & Cretaceous Sediment
- Ks – Sedimen Kapur / Cretaceous Sediments
- Kv – Vulkanik Kapur / Cretaceous Volcanics
- Kl – Intrusi Kapur / Cretaceous Intrusives
- Km – Malihan Kapur / Cretaceous Metamorphics
- KM – Bancuh Kapur / Cretaceous Melanges
- KJs – Sedimen Jura Kapur / Cretaceous Jurassic Sediments
- Js – Sedimen Jura / Jurassic Sediments
- Jv – Vulkanik Jura / Jurassic Volcanics
- Jl – Intrusi Jura / Jurassic Intrusives
- RJs – Sedimen Trias Jura / Triassic Jurassic Sediment
- Rs – Sedimen Trias / Triassic Sediments
- Rv – Vulkanik Trias / Triassic Volcanics
- Rl – Intrusi Trias / Triassic Intrusives
- PRl – Intrusi Permo Trias / Permo Triassic Intrusives
- Ps – Sedimen Perm / Permian Sediments
- Pv – Vulkanik Perm / Permian Volcanics
- Pl – Intrusi Perm / Permian Intrusives
- Cl – Intrusi Karbon / Carboniferous Intrusives
- Pz – Malihan Paleozoik / Paleozoic Metamorphics

KRATON AUSTRALIA / AUSTRALIAN CRATON
(MELANESIAN OROGENY / OROGENESIS MELANESIA)

- Qs – Sedimen Kuarter / Quaternary Sediments
- Qv – Vulkanik Kuarter / Quaternary Volcanics
- Ts – Sedimen Tersier / Tertiary Sediments
- Tv – Vulkanik Tersier / Tertiary Volcanics
- Tl – Intrusi Tersier / Tertiary Intrusives
- Tm – Malihan Tersier / Tertiary Metamorphics
- TM – Bancuh Tersier / Tertiary Melanges
- KTs – Sedimen Kapur Tersier / Tertiary Cretaceous Sediments
- Ks – Sedimen Kapur / Cretaceous Sediments
- JKs – Sedimen Jura Kapur / Cretaceous Jurassic Sediments
- Js – Sedimen Jura / Jurassic Sediments
- RJs – Sedimen Trias Jura / Jurassic Triassic Sed.
- Rs – Sedimen Trias / Triassic Sediments
- Rv – Vulkanik Trias / Triassic Volcanics
- Rl – Intrusi Trias / Triassic Intrusives
- PRs – Sedimen Permo Trias / Triassic Permian Sed.
- PRl – Intrusi Permo Trias / Triassic Permian Intru.
- Ps – Sedimen Perm / Permian Sediments
- Pl – Intrusi Perm / Permian Intrusives
- CMs – Sedimen Karbon Mesozoikum / Mesozoic Carboniferous Sediments
- Cs – Sedimen Karbon / Carboniferous Sediments
- Cl – Intrusi Karbon / Carboniferous Intrusives
- Ds – Sedimen Devon / Devonian Sediments
- Pzs – Sedimen Paleozoikum / Paleozoic Sediments
- Pzm – Malihan Paleozoikum / Paleozoic Metamorphics

SAMUDRA PASIFIK / PACIFIC OCEAN
(Pemekaran kerak Samudera / MOR-SPREADING)

- MzQs – Sedimen Pelagos / Pelagics Sediments
- Mzu – Kerak Samudra Mesozoikum / Mesozoic Oceanic Crust

Legend:
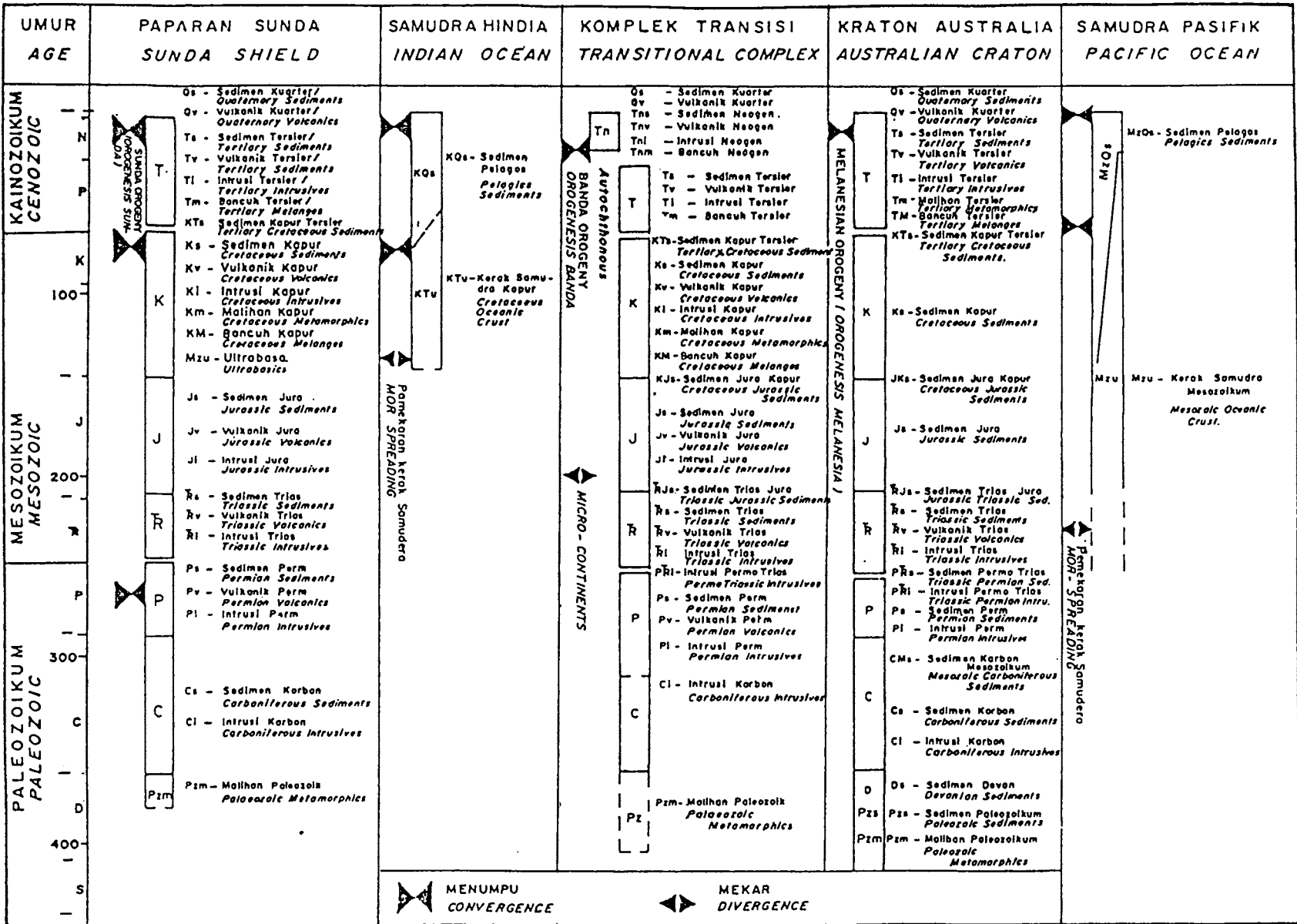- MENUMPU / CONVERGENCE
- MEKAR / DIVERGENCE

Figure 3. Tectonostratigraphy of the Indonesian region.

continue westwards, off-shore, to the north of Bali and merges with the Baribis-Kendeng Thrust along northern Jawa and then terminates in the Sunda Strait at the southern end of the Barisan Fault System.

The Jawa Trench is the surface expression of an active subduction zone located off-shore along west Sumatera and stretching to south Jawa and Nusatenggara. It seems the subduction zone may be terminated off-shore to the SE of Sumba Island, on the Sumba Fracture of Audley-Charles (1975). In Sumatera the subduction zone can be classified as an oblique convergence, since the northwards-moving Indian Ocean Plate is subducted beneath the southeastward-moving Eurasian Plate.

In northern Indonesia, active subduction zones occur in a smaller scale such as along the Philippine Trench in which the Philippine Sea Plate is subducted beneath the Halmahera Islands and along the western Talaud-Tifore ridge, in which a slab of oceanic crust of the North Maluku Basin is being subducted beneath the Sangihe Islands (Figs. 4, 5). The seismicity suggests that this subduction might be continued to the Batul Thrust in the East Arm of Sulawesi, in the south, giving rise to the development of the Minahasa-Sangihe arc (Fig. 6; McCaffrey et al., 1983; Simandjuntak, 1986c; Hall

et al., 1988; GRDC, in press). The double parallel-sided subduction zones in the North Maluku Sea are still active at the present times (GRDC, in press).

In northern Irian, the New Guinea Trench in which the Pacific Plate is being subducted beneath the northern margin of Australian continent in Neogene (Hamilton, 1979; Smith, 1990). This collision is classified as oblique convergence, as indicated by the northward-moving Australian Continent against the westward-moving Pacific Plate.

The North Sulawesi Trench is the surface expression of a subduction zone, where the Eocene oceanic crust of the Sulawesi Sea is being subducted beneath the North Arm of Sulawesi in Neogene times. The subduction zone seems to have been active for a relatively short time. The present day seismicity however, suggests the subduction zone might be recently reactivated.

This subduction together with the Batui Thrust in the East Arm of Sulawesi in the south gave rise to the development of a double opposing convergences in the region in Neogene times. The seismicity and the occurrence of terraces of Quaternary coral reefs indicates that this subduction might be active at the present time
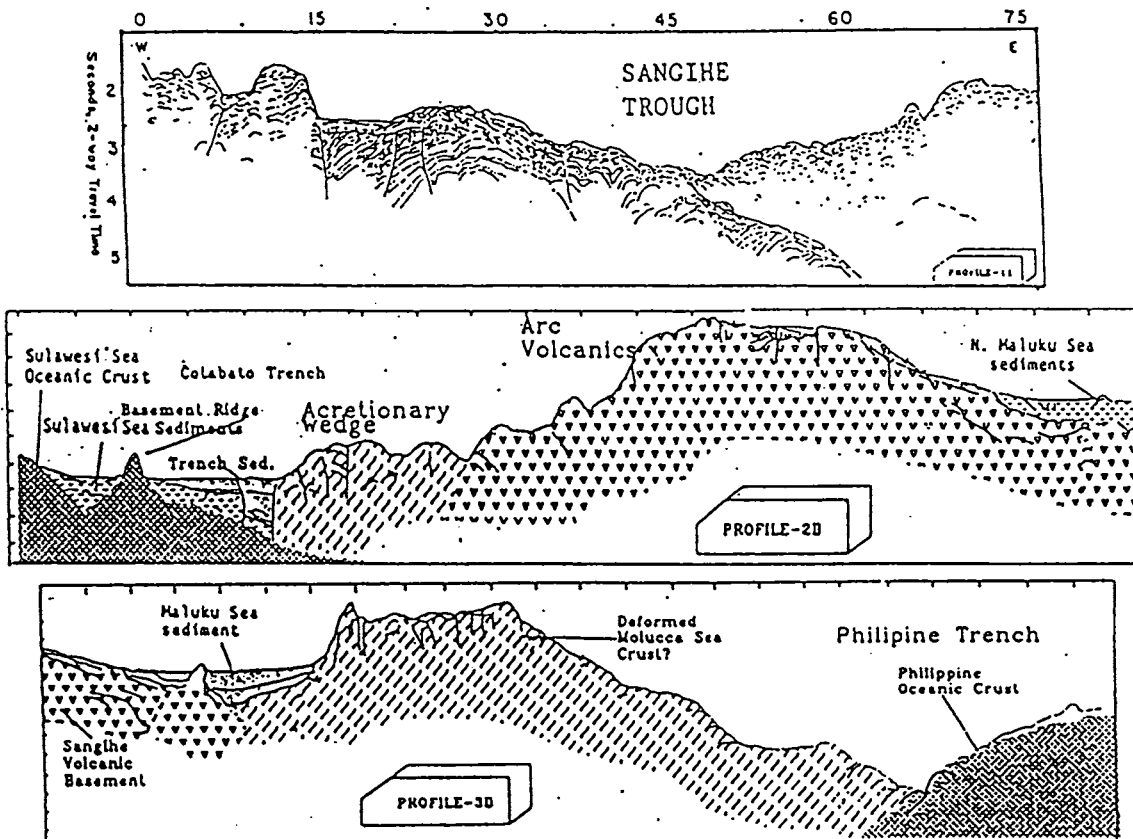
Figure 4. Seismic reflection profile of western margin of the Maluku Sea Basin (GRDC, in press).

(Simandjuntak, 1986d).

The Timor Trough-Kai Trough-Seram Trough is the surface expression of collision zones of Tethyan type, in which the NW margin of the Australian continent underplates the Banda Island Arcs. Audley-Charles et al. (1972) considered that this collision zone was active in Early Tertiary times. At present the collision might be (re)activated (Cardwell and Isacks, 1978; Hamilton, 1979; Bowin et al., 1980; Katili, 1970; Silver, 1981).

Transcurrent Faults

The main steep faults include the wrench faults of the Barisan Fault System (BFS) in Sumatera, Palu-Koro Fault System (PKFS) in Sulawesi, Sorong-Sula Fault System (SSFS) and Tarera-Aiduna-Banda Fault System (TABFS) in eastern Indonesia.

The Barisan Fault and the Philippine Fault Systems are dextral wrench faults. The Barisan Fault System (BFS) appears to have at one time been activated with a sense of transtensional movements as indicated by the presence of elongated grabens or fault bounded basins such as the Lauttawar, Toba, Maninjau, Singkarak and Ranau lakes within the fault zone of the BFS in Sumatera.

The development of the Barisan Mountain Ranges associated with the BFS, however strongly suggests that this fault was dominated by transpressional dextral movement.

By contrast, the steep faults in eastern Indonesia including the Sorong-North Sula, Sorong-South Sula and Tarera-Aiduna with their western extension and then merged with the Palu-Koro Fault System in Sulawesi, are all dominated by sinistral transcurrent movement. The occurrence of the Poso, Matano and Towuti Lakes within the fault zones of the Palu-Koro-Matano Fault indicates that this fault was also at one time developed with a transtensional sinistral movement.
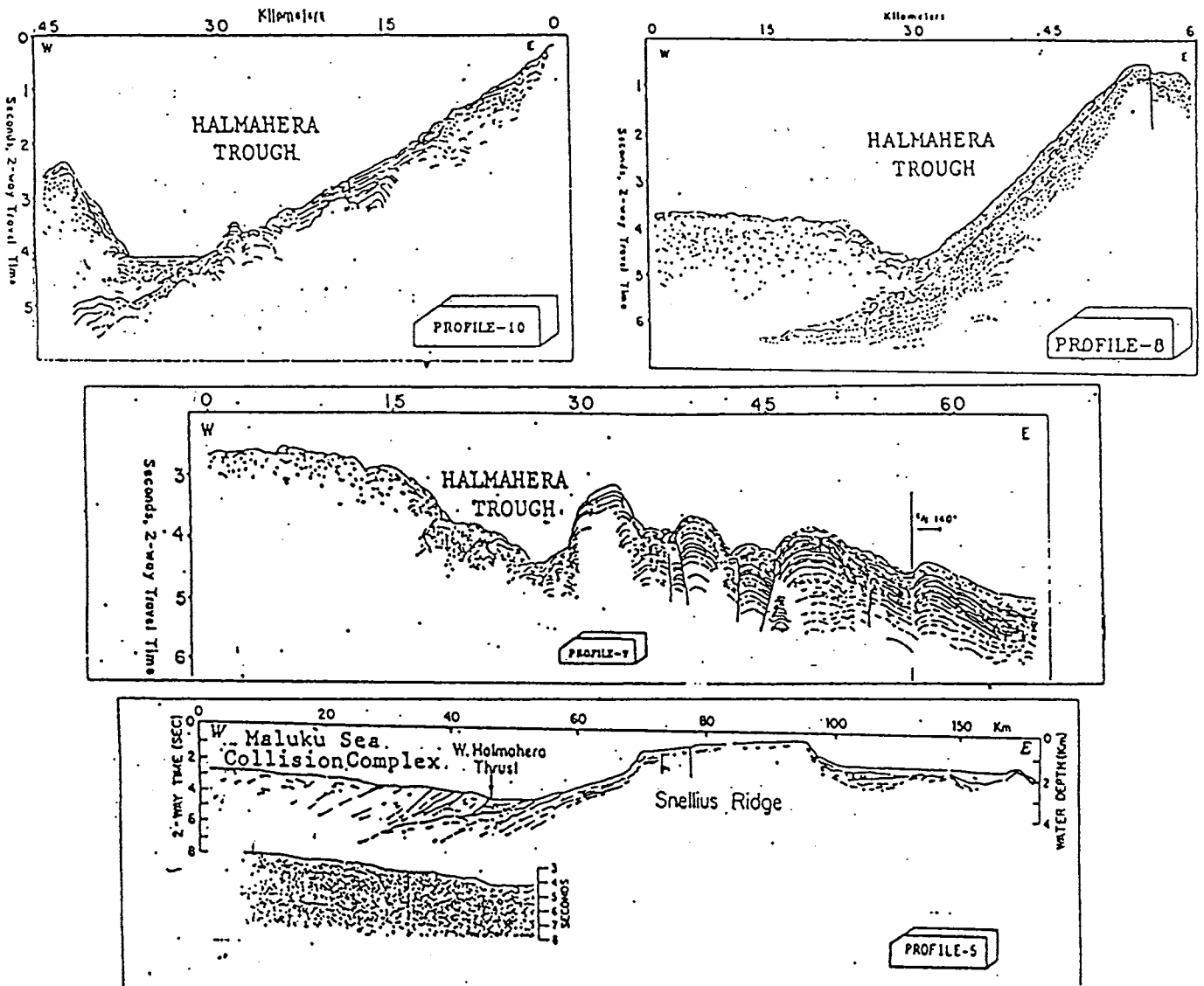
Figure 5. Seismic reflection profile of eastern margins of the Maluku Sea Basin (GRDC, in press).

Micro-seismicity analysis and the occurrence of earthquake hypocenters along the faults and thrusts, strongly suggest that most of the faults and thrusts appear to represent older structures that are reactivated at the present time.

TERTIARY TECTONIC DEVELOPMENT OF INDONESIA

The present complicated nature of the geology, structures and tectonics of the Indonesian archipelago appears to have been developed in the Neogene times, since the region developed at the center of triple convergences due to interaction of at least 3 megaplates, including the northward-moving Indo-Australian Plate, the westward-moving Pacific Plate and the south-southeastwards-moving Eurasian Plate.

The tectonic evolution of the regions is recorded by the development of both tectonic convergences and divergences and other tectonic activities. The tectonic convergences in Indonesia consist of several types including Cordilleran-type subduction, in which the oceanic crust subducted beneath the continental margins; Tethyan-type collision, in which micro-continents underplated the subduction
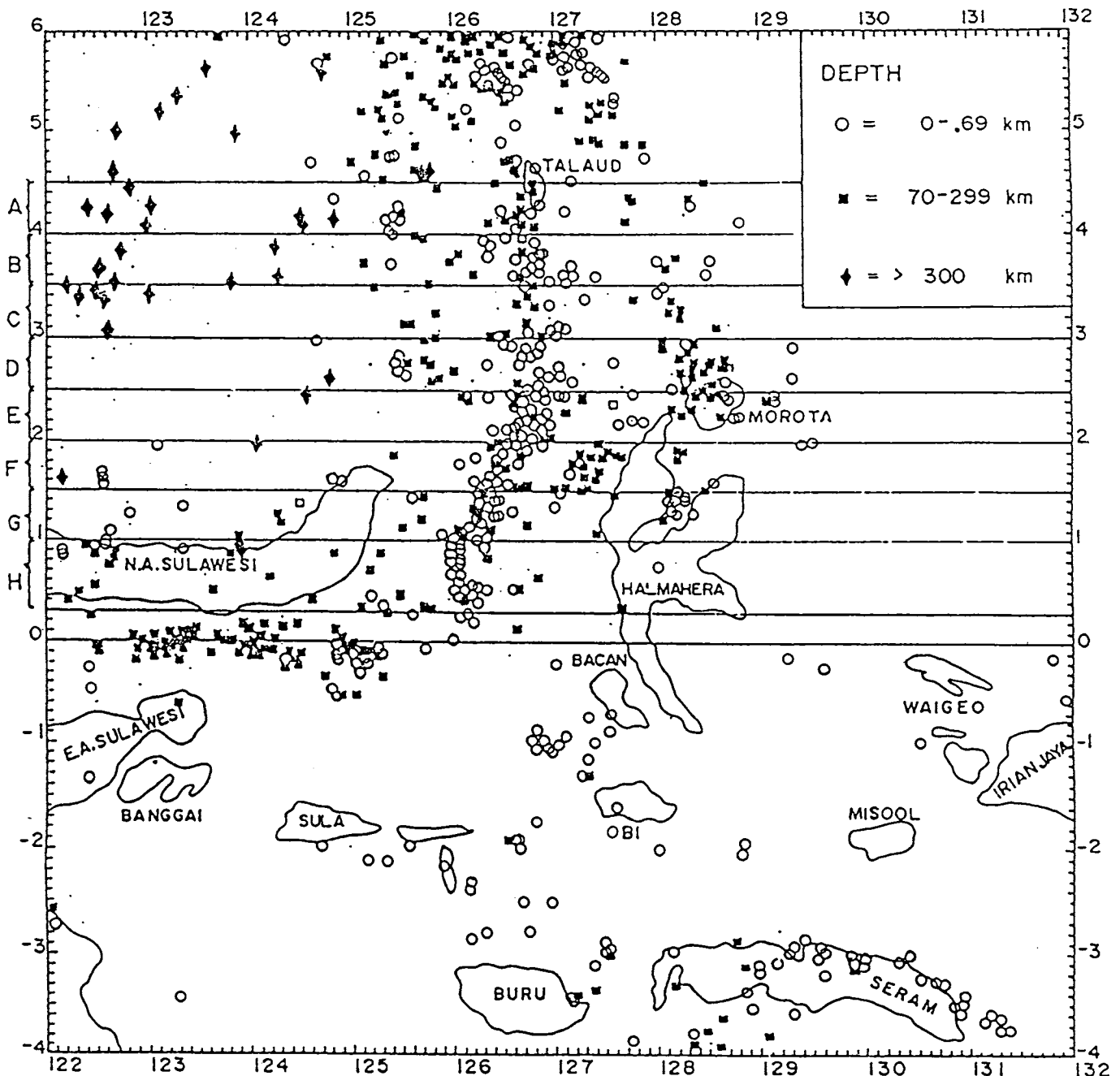
Figure 6. Distribution of earthquake epicenters during 1971–1984 in the Sulawesi and Maluku Sea Basins (GRDC, in press).

complex and island arcs and double arc collision zones.

The tectonic divergence is characterised by rifting of the NW margins of the Australian continent and then displaced westwards to the present position in the Banda Sea regions by transcurrent-transformal displacement.

Tertiary Tectonic Convergences in Indonesia

In western Indonesia a cordilleran type convergence has occurred repeatedly in Sumatera, Jawa and Nusatenggara regions since the late Paleozoic to present time (Katili, 1971). The Tertiary subduction zone seems to be intermittently active or reactivated in late Paleogene to early Neogene and then dying out or ceasing towards the end of Neogene.

In very late Neogene or early Quaternary the subduction zones migrated oceanwards with Benioff zones dipping towards the continent, in which the Indian Ocean crust subducted beneath the margin of Sunda Shield (SE Eurasian Plate). Surface expression of the subduction zone is now marked by deep trenches off-shore west of Sumatera stretching continuously to the south, through the Jawa Trench off-shore south of Jawa and terminated in the zone of discontinuity or the southern end of the Palu-Koro Fault (Jones, 1969; Katili, 1970; Hamilton, 1979; Nishimura *et al.*, 1981) and/or the so-called Sumba Fracture (Audley-Charles, 1975) in the south-southeast of Sumba Island.

During the late stage and/or subsequently after the ceasing of subduction in Late Neogene, the volcanic belt in Jawa and Nusatenggara was thrusted over the back-arc basin. Surface expression of this back-arc thrust is now called the Baribis Thrust in northern West Jawa and Kendeng Thrust in northern East Jawa (Fig. 7). In Central Jawa the thrusts appear to have been disrupted by the Cimandiri Fault, Citandui Fault and other wrench faults. For the purposes of the regional description this structure is called Baribis-Kendeng Thrust. Geophysical data show that the Baribis-Kendeng Thrust continues to the east in off-shore to the north of Bali and to the Flores Thrust, and then terminates in the southern end of the Palu-Koro Fault and/or the Sumba Fracture. To the west the thrust is terminated on the southern end of the Barisan Fault System in Sunda Strait.

During the late stage and/or the ceassion of the subduction in Late Neogene in Sumatera, the Barisan Fault System seems to be reactivated with the sence of dextral transpressional wrench movement, which is due essentially to the development of the oblique convergence in Sumatera. The Barisan Fault System appears to have been repeatedly subjected to either transtensional or transpressional wrench movement during the history of the fault since the early Tertiary times (Fig. 8).

The Sunda Orogeny therefore, has been developed during the dying out or ceassation of the Tertiary subduction zone, prior to the oceanward migration of the subduction zone and was originated by the development of back-arc thrusting along northern Jawa and Nusatenggara, and a dextral transpressional strike-slip movement of the Barisan Fault System (BFS) in Sumatera.

In eastern Indonesia the Neogene tectonic convergence appears to be more complicated due to the development of several distinctive types of convergences in the south, middle and north parts of the region.

In Irian Jaya and Papua New Guinea the Miocene tectonics convergence is marked by a south-dipping Benioff zone in which the Pacific Plate underplated the northern margin of the Australian Continent (Smith, 1990). During the late stage and/or subsequently after the ceassation of this subduction, the continental margin sequences were thrusted onto the basement of the craton in the thin-skinned tectonics manner. This period of thrust tectonics was called as the Melanesian Orogeny by Dow *et al.* (1986). The thin-skinned tectonics gave rise to the imbricated nature and the uplifting of the Central Irian Jaya Fold and Thrust Belt and its continuation to Papua New Guinea eastward. The belt coincides with the Central Irian Jaya Mountain Ranges with peaks of nearly 6,000 m above sea level. At present surface expression of this convergence is marked by a thrust front, which is herein called the Asmat Thrust. The thrust bounds the Southern Plains and the Central Fold and Thrust Belt of Irian Jaya (Fig. 9).

The Asmat Thrust continues to the east in the Papua New Guinea and to the west it appears to being extended through the Tarera-Aiduna Fault and then merges with the Seram-Kai-Timor Trough.

In the southern part of Central Indonesia, the plate convergence is characteristically marked by the development of a Tethyan collision zone, in which the northwest margin of the Australian continent underplated the subduction complex and island arcs. Surface expression of this convergence is now marked by the Timor Trough, which is stretches north to the Kai Trough and then curves and terminates in the Seram Trough. Audley-Charles *et al.* (1972) and Barber and Wiryosujono (1981) considered that the subduction zone along the Timor Trough was developed in the Early Tertiary. Hamilton (1979) considered the Timor Trough is an active subduction zone at the present time.
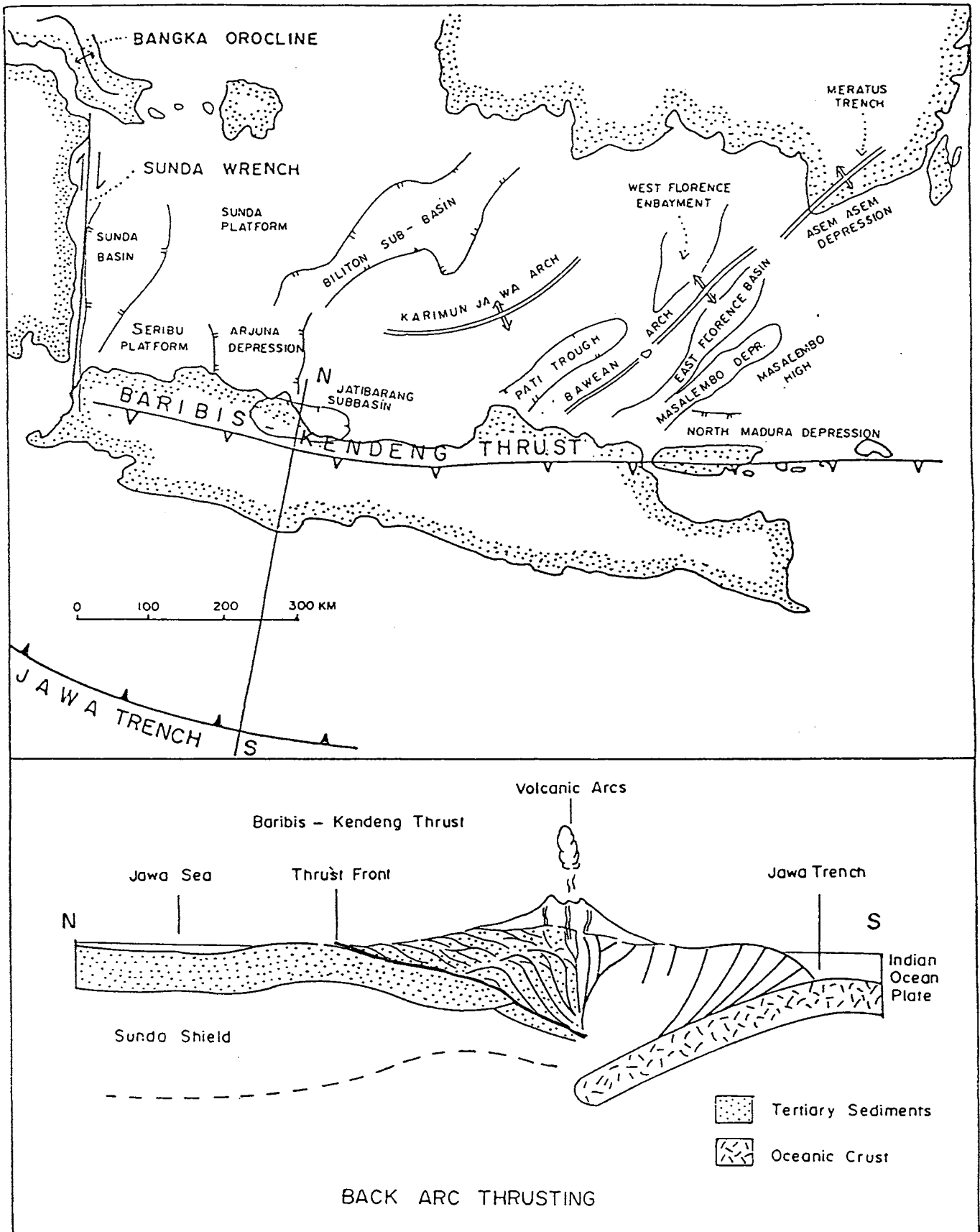
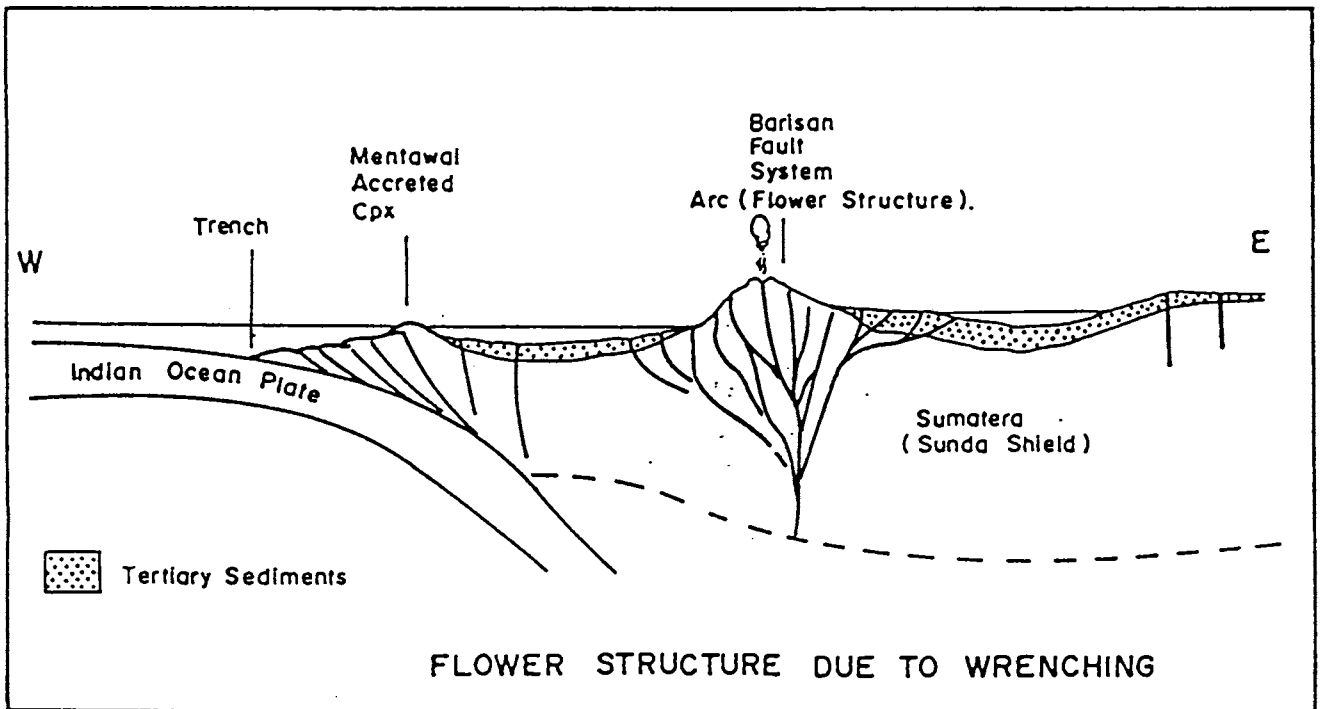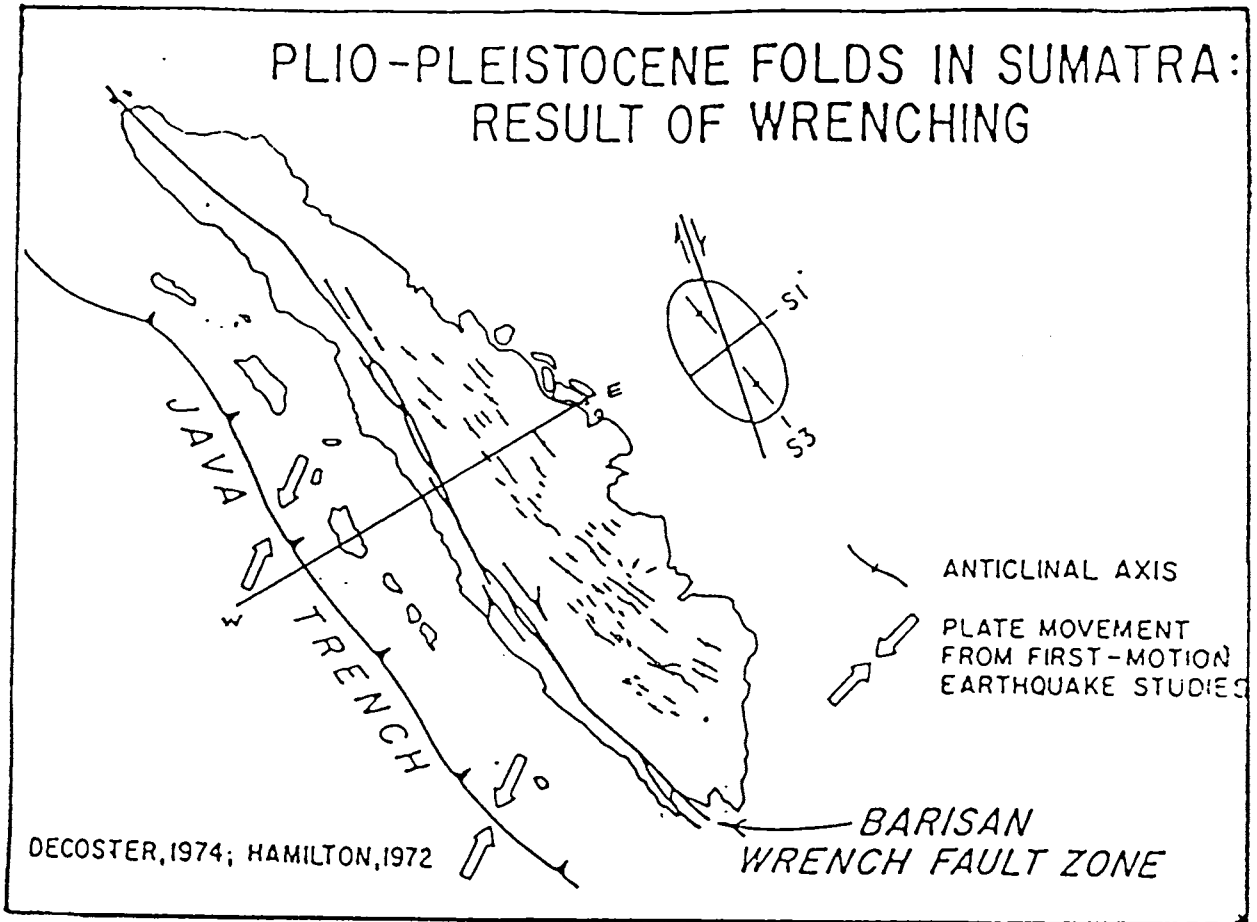**Figure 7.** Schematic tectonic profile across Jawa Trench.

Figure 8. Schematic tectonic profile across Sumatera.

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PLATFORM

CENTRAL RANGES

EXTERNAL THRUST SHEETS

INTERNAL THRUST SHEETS

MESOZOICS EXPOSED & BREACHED IN EXTERNAL THRUST SHEETS

INDURATED & CLEAVED MESOZOICS & PALAEOZOICS IN INTERNAL THRUST SHEETS

THRUST SHEETS DETACHED ABOVE MESOZOIC TARGET

THRUST SHEETS INVOLVING MESOZOIC

IMBRICATE FAN

PASSIVE-ROOF BACKTHRUST

TOPOGRAPHIC PROFILE

SYNCLINE IN ROOF SEQUENCE

UNDEFORMED FORELAND PLATFORM & BASIN

THRUST FRONT

TOPOGRAPHIC PROFILE

TERTIARY

MESOZOIC

PALAEOZOIC

BASEMENT

MESOZOIC RESERVOIR TARGET

MESOZOIC TARGET IN HANGING-WALL AND FOOTWALL

MESOZOIC TARGET IN HANGING WALL AND TERTIARY CLASTIC SOURCE IN FOOTWALL

DUPLEX OF MESOZOIC & PALAEOZOIC GIVING ELEVATION ABOVE REGIONAL

Figure 9. Schematic tectonic profile across central Irian Jaya.

During the late stage of this Tethyan type convergence, the orogenic belt appears to be developed due to thin-skinned tectonics in Timor and the Sahul Platform in Late Neogene times, where the continental margin sequences were thrust over the basement complex of the Australian Craton. This orogenesis gave rise to the development of the thrust sheet and klippe structure structures in Timor, Tanimbar, Kai and Seram Islands (Fig. 10). To the west, this thrust tectonics seem to be terminated on the eastern end of the Jawa Trench, or on the Sumba Fracture of Audley-Charles et al. (1972), or on the southern end of the Palu-Koro Fault in the off-shore area to the southeast of Sumba Island.

In the Banda outer arc, the collision of the northern margin of the Australian Continent seems to pre-date the thin-skinned tectonics described above, or at the least the thin-skinned tectonics are developed during the latest stages of convergences in Neogene times.

Providing a significant amount of the displacement of the northern margins of the Australian Continent occurred due to the northwards movement of the craton, the initial thrust front might be extended to the west into the presently curving Seram-Kai-Timor Trough in the form of a relatively straight line trending in an approximately east-west direction in late Neogene times.

In the northern part of Central Indonesia, the Neogene convergence was dominated by a Tethyan type collision, in which the micro-continents underplated subduction complex and/or island arc (Fig. 11). This convergence is evidenced by the occurrence of the Eastern Sulawesi Ophiolite Belt that overrides the Banggai-Sula Platform and Buton-Mekongga Platform in eastern Sulawesi (Smith, 1983; Simandjuntak, 1981, 1986a) described previously.

The most significant result of this convergence is the emplacement of the imbricated ophiolite belt as an obducted slab in eastern Sulawesi (Simandjuntak, 1986b, 1991). Similar mechanism seems to had been taken place in the emplacement of the Papua New Guinea Ophiolite Belt (Davis, 1976).

A double opposing tectonic convergence in northern Sulawesi may have been developed in Neogene time during the formation of the northwards dipping collision zone, in which the Banggai-Sula Platform under-plated the Eastern Sulawesi Ophiolite Belt. To the north an early Tertiary convergences with a south-dipping Benioff zone where the oceanic crust of Sulawesi Sea subducted beneath the North Arm of Sulawesi might be reactivated in Neogene times (Fig. 12).

The development of the Minahasa-Sangihe volcanic arc is related closely to this convergence (Simandjuntak, 1988).

In the north and northeast, two types of convergences were developed in Neogene times: i) A cordilleran type convergence occurred in northern Irian indicated by the Pacific Plate under-plating Irian Jaya-Papua New Guinea (Smith, 1990), and ii) An arc-arc collision occurred in the northern part of Maluku Sea.

GRDC (Transect VIII, in press) on the basis of geophysical and onland geological data shows that at present this convergence seems to be in the form of a double-arc collision with two separated Benioff zones dipping westwards beneath the Sangihe Arc and Halmahera Arc respectively. The initial framework, an inverted U-shaped subducted oceanic crust in this region suggested by Bowin et al. (1980), Hamilton (1979) and Silver et al. (1978), appears to have been greatly disrupted and modified during the Neogene convergence. Seismicity and earthquake analyses suggest (Fig. 13) that the double parallel-sided collisions are active (reactivated) in the North Maluku Sea (GRDC, in press).

Simandjuntak (1988) suggested that the western subduction continues to the south and joins the Batui Thrust in the East Arm of Sulawesi and then terminates on the Matano-Sula Fault. This subduction has initiated the development of the present active volcanoes in the Minahasa-Sangihe Arc.

Tectonic divergence in eastern Indonesia

The Paleozoic micro-continents occurring in the Banda regions include the Banggai-Sula Platform (BSP), Tukanbesi-Buton Platform (TBP), Mekongga Platform (MP), Seram-Buru Platform (SBP), Misool-Birds Head Platform (MBHP), Obi-Bacan Platform (OBP), and Lucipara Platform (LP). The Sumba Platform (SP) in the southern-most part of Central Indonesia is much younger than those mentioned above as it contains older than Cretaceous flysch sediments associated with volcanics.

These platforms juxtaposed with the adjacent younger terranes. Results of the seismic analysis show that the platforms are tectonically bounded with the oceanic crust of the Banda Sea. In eastern Sulawesi, the ophiolites of ESOB is underplated by the Banggai-Sula, Tukangbesi-Buton and Mekongga Platforms (Smith, 1983; Simandjuntak, 1986a; Suria-Atmadja et al., 1972).

The origin of the micro-continents in the Banda region eastern Indonesia is not clear and is still under discussion. The platforms are generally regarded as having been detached from Irian in Cainozoic times and displaced westwards along the

Sorong Fault Zone (Visser and Hermes, 1963; Krause, 1965; Hermes, 1968; Gribi, 1973; Hamilton, 1979; Silver and Moore, 1979; Smith, 1983) or from north Misool region (Audley-Charles et al., 1972).

This assumption is based on geological correlation of the micro-continents with the western Irian (New Guinea).

Pigram and Panggabean (1984) suggested that the micro-continents in the Banda region were detached from a region in Central Papua New Guinea (Irian), about 141-145 East Longitudes. They further speculated that oceanic crust developed during this Triassic rifting is no older than Early Jurassic in the east and Middle Jurassic

in the west adjacent to the newly formed continental margin of Papua New Guinea, which marked the site of separation of the micro-continents from their host Australian Continent.

Simandjuntak (1986d), based on recognition of several hiatuses in the micro-continents, discussed the tectonic evolution of these platforms. Some of the hiatuses, particularly the Early Jurassic, might be related to eustatic fall of sea-level superimposed on the tectonic divergence of northern margin of the Australian Continent. Triassic thermal doming occurring in the northwest margin of the Australian Continent appears to have initiated the rifting of the regions, followed by slicing up the continental
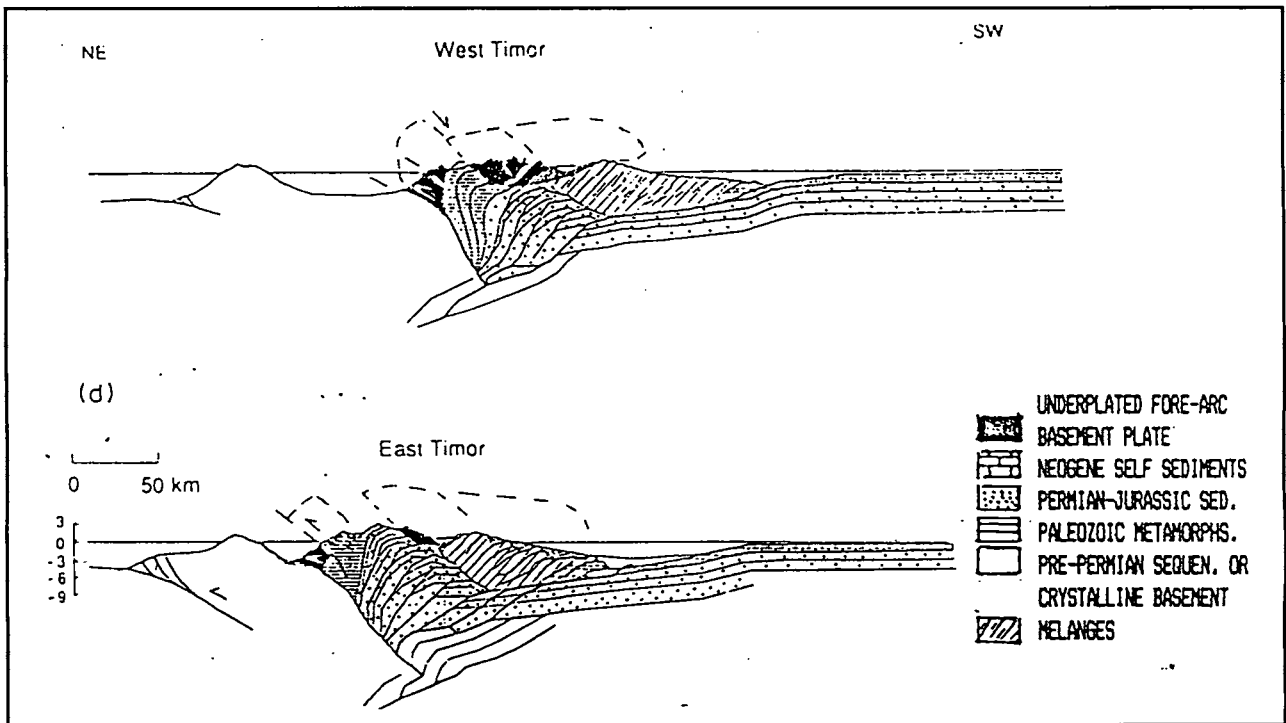
Figure 10. Schematic tectonic profile across Timor Trough, showing the development of thick-skinned tectonic (modified after Harris, 1991).
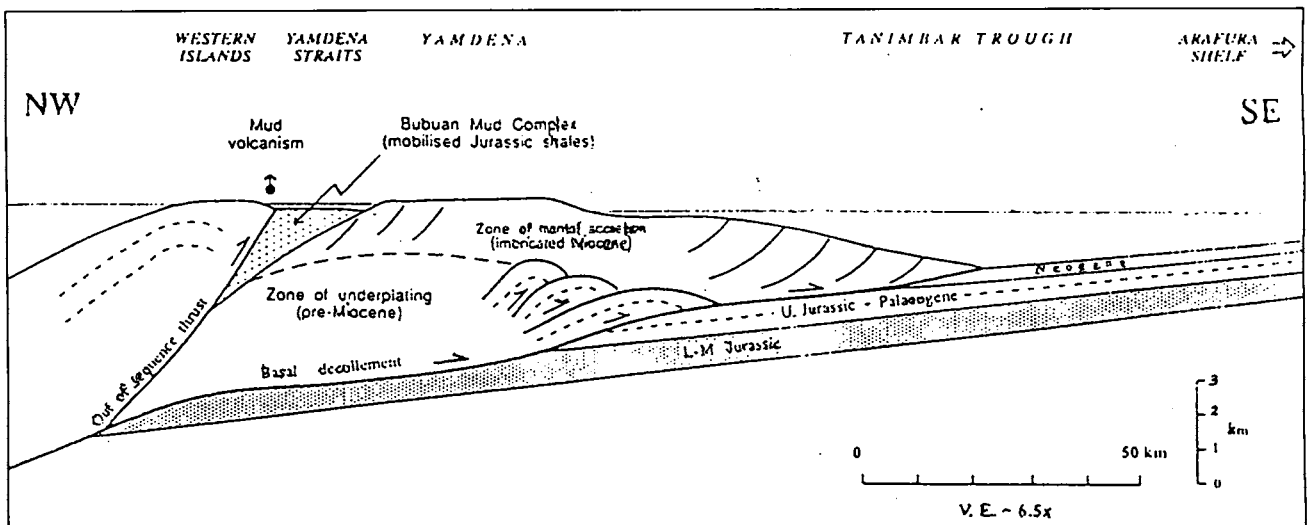
Figure 11. Schematic tectonic profile across Tanibar Trough showing the development of thin-skinned tectonics (Charlton et al., 1991).
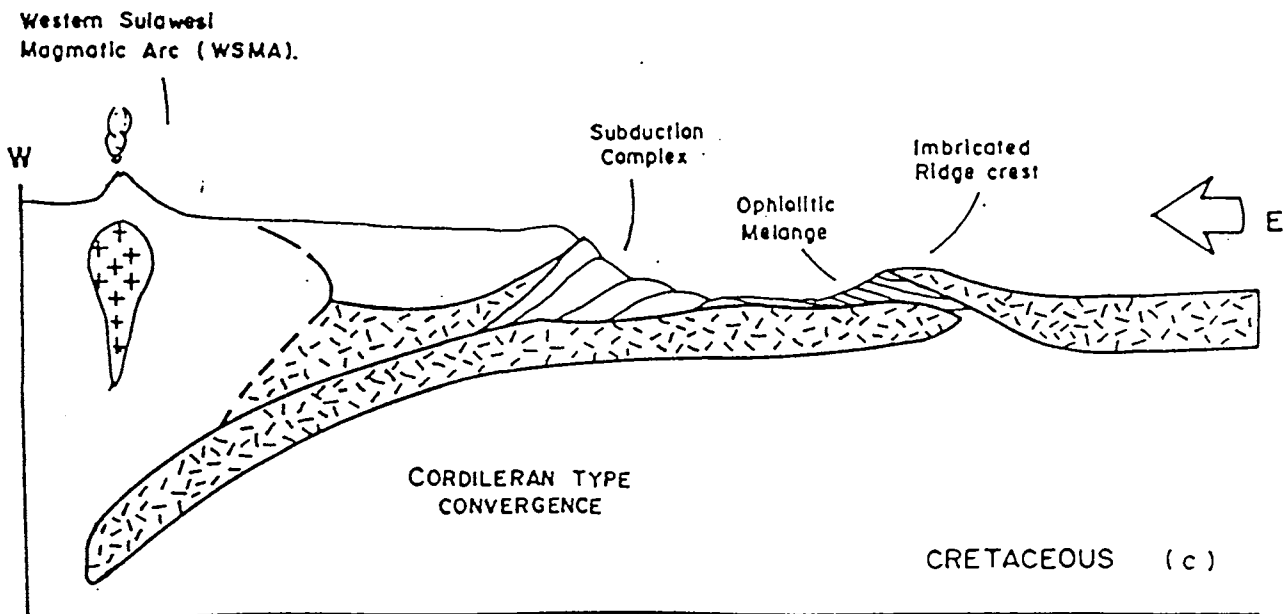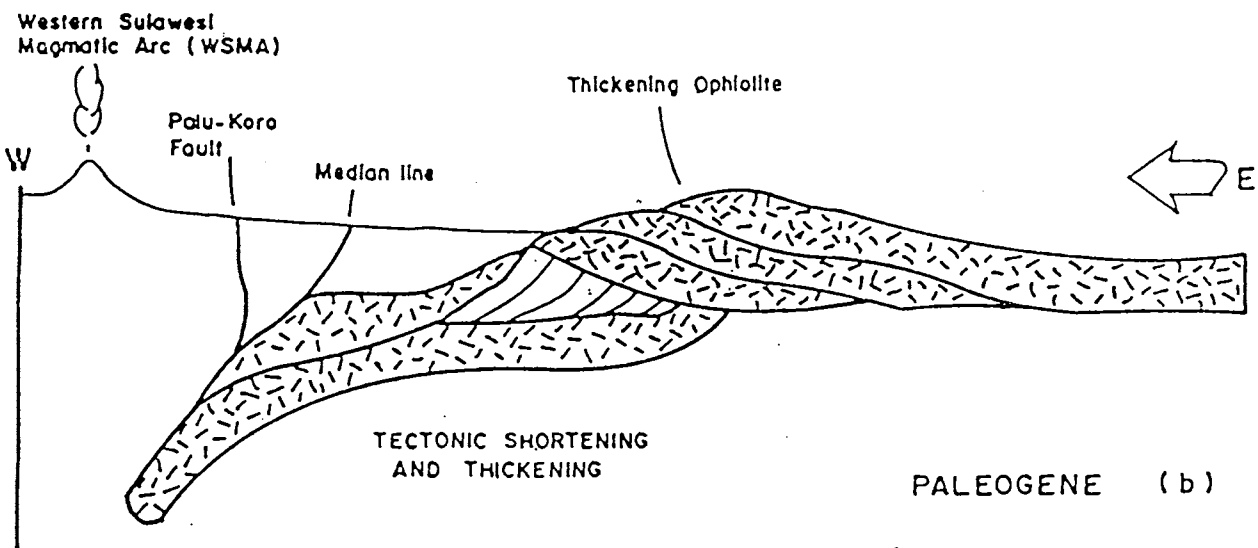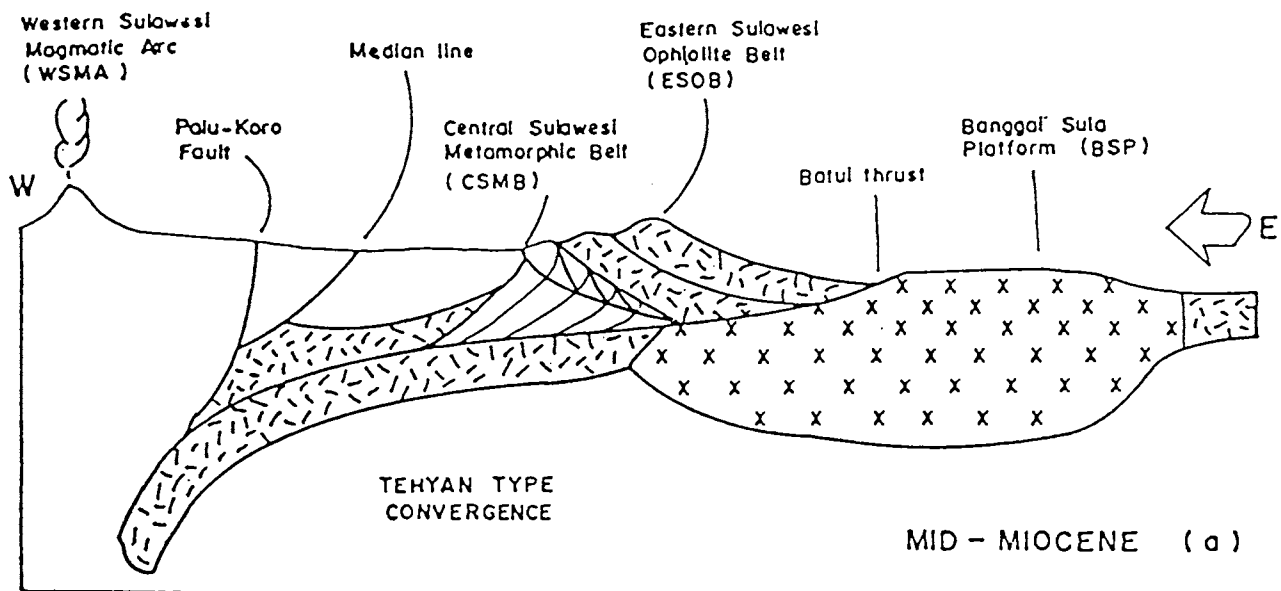
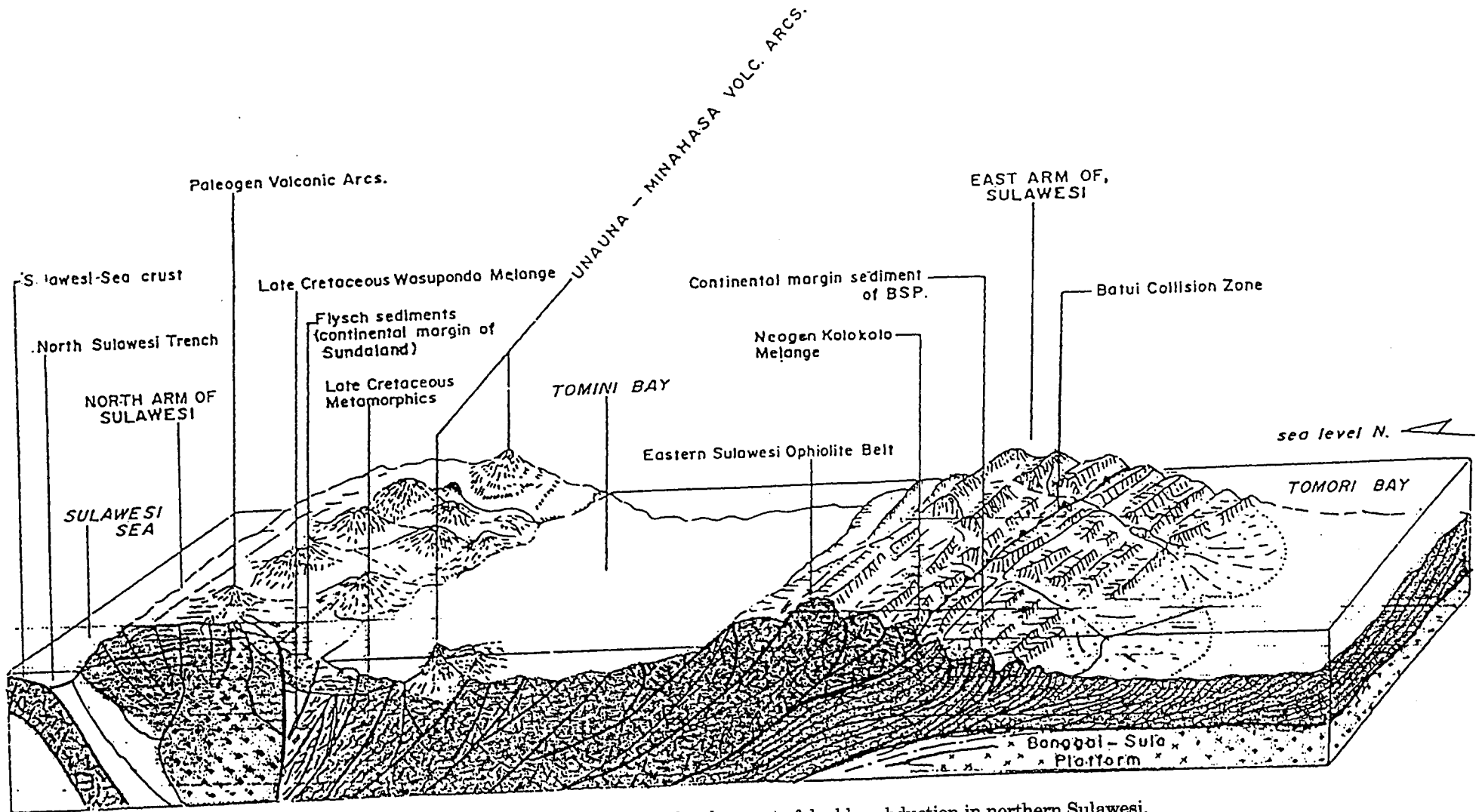**Figure 12.** Schematic tectonic profile of Sulawesi.

Figure 13. Block diagram showing the development of double subduction in northern Sulawesi.

margin and the fragments diverged and drifted westwards. Tectonic divergence seems to have been followed by transcurrent displacement of the continental fragments westwards and formation of the platforms (micro-continents) in the Banda region of eastern Indonesia (Fig. 14).

Considering a rate of horizontal movement of less than 10 cm/year, the continental slabs may have drifted westwards all the way during Triassic-Early Tertiary until they collided with the subduction complex and/or island arcs in Middle-Miocene in Eastern Sulawesi and other places in the Banda region. The transcurrent movement along the Sorong-Sula Fault and Tarera-Aiduna-Sula Fault and the other faults might be temporarily have been much slower or ceased during the history of their displacement.

The Sumba Platform is quite distinctive from neighbouring Volcanic Arcs and oceanic crust of the Indian Ocean and is much younger than the other micro-continents in the Banda Sea regions. Simandjuntak (1992c, in press) discussed the origin of the Sumba Platform, and geologically correlates it with Southeast Kalimantan and South Arm of Sulawesi especially during the Cretaceous to Paleogene times. He further suggested that the

origin of the Sumba Platform, kinematically, may be due to one of the following alternatives:

1. A continental fragment detached from the SE margin of the Sunda Shield and rifted away to the south by transcurrent displacement, prior to the development of the Nusatenggara Volcanic Arcs in Neogene times.
2. A continental slab detached from the SE margin of the Sunda Shield and left at the relatively nearby its present position during and/or subsequent after the anti-clockwise rotational movement of Kalimantan, prior to the development of the Nusatenggara Volcanic Arcs in Neogene times.
3. A continental slice drifted away to the south by transcurrent displacement subsequent after "rifting" of the SE margin of the Sunda Shield in the Makasar Strait, prior to the development of the Nusatenggara Volcanic Arcs.

The transcurrent fault appears to have become a zone of discontinuity between the western and eastern parts of Indonesia called the Sumba Fracture by Audley-Charles (1975).

The fault appears to extend northwards through the South Arm of Sulawesi to Makasar Strait and East Kalimantan.

DOUBLE ARC COLLISION
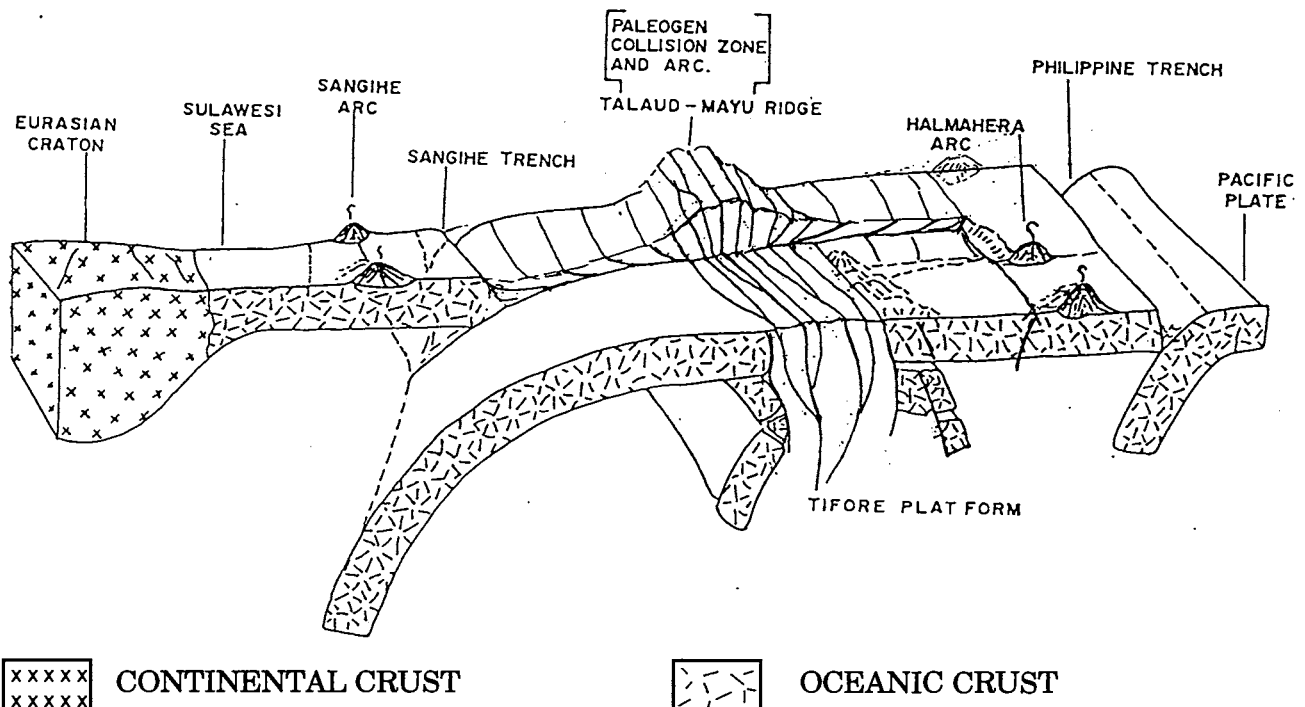

CONTINENTAL CRUST   OCEANIC CRUST

Figure 14. Block diagram showing the development of double parallel sided subduction zones in North Maluku Basin.

DISCUSSION AND INTERPRETATION

On the basis of geological and geophysical data described above, it is obvious that Neogene tectonic convergence in Indonesia has given rise to the formation of the archipelago with its complicated geology, structures and tectonics. The end-products of the Neogene convergence is the development of very significant mountain building episode of fold and thrust belts in most of the regions.

In the following section, the discussion is focused on the development of this Neogene Orogenesis in the Indonesian region, which kinematically can be divided into 4 types: 1) Sunda Orogeny, 2) Banda Orogeny, 3) Melanesian Orogeny and 4) Talaud Orogeny.

Sunda Orogeny

Tectonic convergence in western Indonesia, which is dominated by Cordilleran type collision, appears to have reoccurred since Permian through Mesozoic to present times and subduction zones migrated oceanwards with time (Katili, 1970).

The subduction and volcanism in Sumatera, Jawa and Nusatenggara seem to have temporarily ceased or died out in the Neogene. In this situation, in order to accommodate the compressive stress due to the northward-moving Indo-Australian Plate and maintaining an equilibrium isostatics nature of the active margin, the driving force ought to be released in the form of back-arc thrusting along northern Jawa and Nusatenggara.

In Sumatera, however the situation is different due to the oblique nature of the convergence, and the Barisan Fault System was (re)activated with dextral transpressional movement.

The present geological mapping and geophysical survey of western Indonesia by the Geological Research and Development Center (GRDC) partly in collaboration with the British Geological Survey (BGS), geological research by Lemigas, Pertamina and private oil companies and also Indonesian students reveals actual and comprehensive data confirming the occurrence of the back-arc thrust in Jawa, which is herein called the Baribis-Kendeng Thrust (Fig. 7). This thrust trends E-W parallel with the long axis of Jawa and appears to be terminated at the southern end of the Barisan Fault System in the Sunda Strait to the west. To the east it continues off-shore to the north of Bali to the Flores Thrust and terminates in the southern extension of the Palu-Koro Fault, off-shore, to the North of Sumba Island (Fig. 8). Seismicity and the presence of earthquake hypocenters indicate that the thrusts might being reactivated in most segments.

The Mio-Pliocene back-arc sequences in northern Jawa were cut and deformed by the Baribis-Kendeng Thrust, hence the Sunda Orogeny was developed in very late Neogene times.

To date no evidence for Neogene back-arc thrusting in Sumatera has been recognised. The Neogene orogeny in this island seems to be confined to dextral transpressional wrenching faulting on the Barisan Fault System (BFS), due to the oblique convergence in this region. The occurrence of earthquake hypocenters strongly suggest that at least some segments of the BFS are being reactivated (Fig. 2; Fitch 1970; Katili, 1971; Kertapati et al., 1992). In the recent earthquakes some of the ponds of sulphuric hot water springs along the BFS, in North and Central Sumatera, were lifted up and ceased, suggesting a transpressional dextral movement of the fault.

The significance of the Sunda Orogeny is now marked by the following tectonic features, most of them can be readily observed in the outcrops and in remote sensing imagery.

a. Uplifting of folded and partly faulted rocks of the Southern Mountain Ranges in Jawa and also in Nusatenggara to over 3,500 m above sea level and the intensely folded and faulted rocks of the Barisan Mountain Ranges in Sumatera to nearly 4,000 m above sea level, testifying the rapid rising of the regions (or Mountain building).

b. A tightly folded even partly isoclinally folded Miocene back-arc sediments along northern Jawa and Nusatenggara and uplifting of deformed Paleogene fore-arc sequences and the underlying imbricated complex of Cretaceous subduction zones in and along southern Jawa. Similar structural and tectonic features also developed in Sumatera.

c. The development of flower structures on and along the Barisan Fault System in Sumatera. This structure seems to have been magnified by the repeatedly reactivation of the Barisan Fault System in both transpressional and transtensional dextral strike-slip movement prior to the Neogene Sunda Orogeny.

d. Deepening of the back-arc basin in the Jawa Sea, Bali Sea and Flores Sea as indicated by the subsiding of the Karimun Jawa High in Jawa Sea. The high appears to have been at once emerged above sea level and become the source of quartz sandstones of the Paleogene and Neogene clastics of back-arc sequences in northern Jawa, Madura and Sapudi Islands.

Banda Orogeny

The collision of the micro-continents of the Banggai-Sula, Tukangbesi-Buton and Mekongga Platforms against the Eastern Sulawesi Ophiolite Belt (ESOB) occurred in the Middle Miocene. The
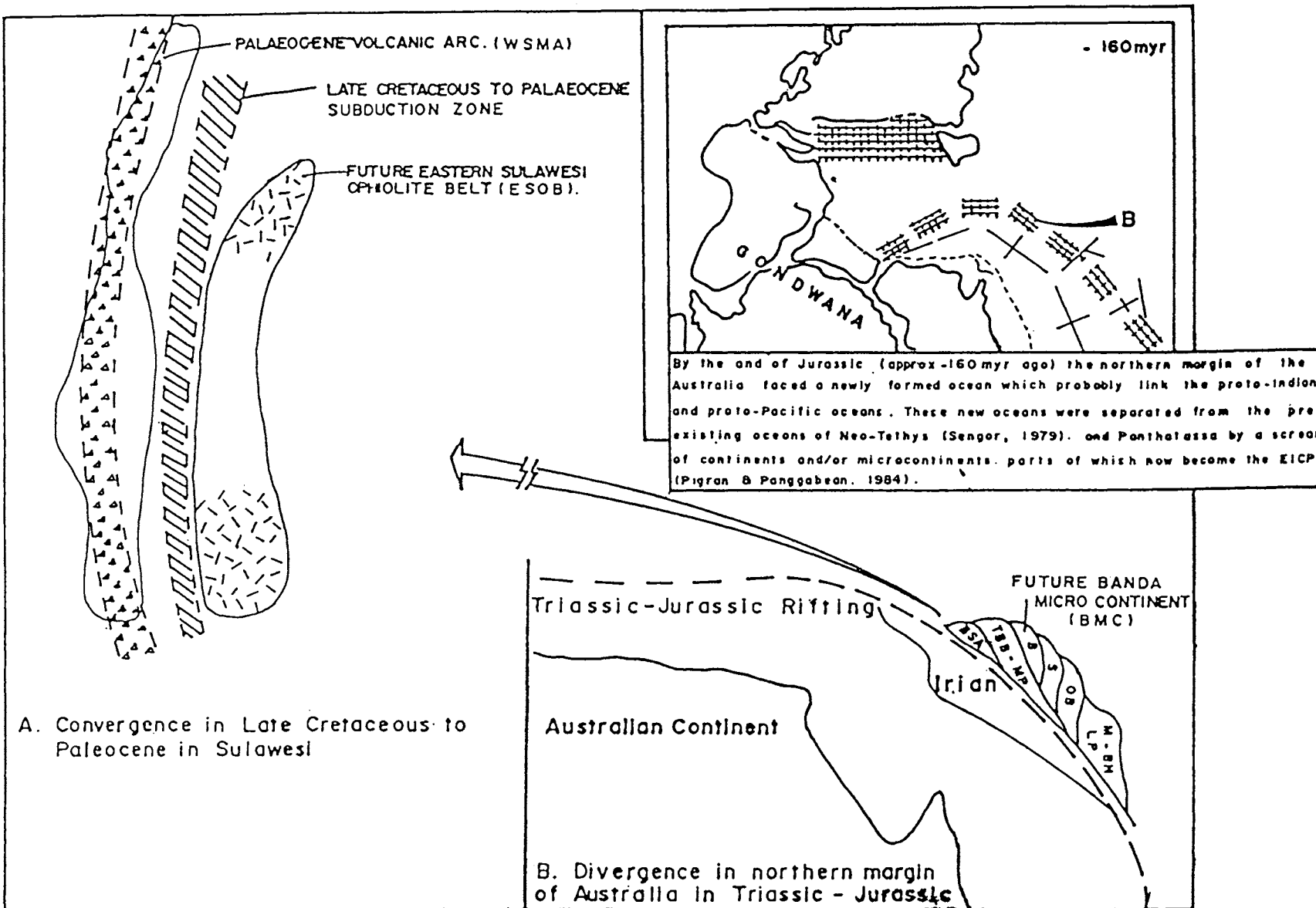
- 160 myr

PALAEOCENE VOLCANIC ARC. (WSMA)

LATE CRETACEOUS TO PALAEOCENE
SUBDUCTION ZONE

FUTURE EASTERN SULAWESI
OPHIOLITE BELT (ESOB).

By the end of Jurassic (approx -160 myr ago) the northern margin of the
Australia faced a newly formed ocean which probably link the proto-Indian
and proto-Pacific oceans. These new oceans were separated from the pre-
existing oceans of Neo-Tethys (Sengor, 1979). and Panthalassa by a screen
of continents and/or microcontinents. parts of which now become the EICP.
(Pigran & Panggabean. 1984).

FUTURE BANDA
MICRO CONTINENT
(BMC)

Triassic-Jurassic Rifting

Irian

Australian Continent

A. Convergence in Late Cretaceous to
Paleocene in Sulawesi

B. Divergence in northern margin
of Australia in Triassic - Jurassic

Figure 15. Tectonic divergence of the northern margin of Australia followed by tectonic convergence in Sulawesi regions.

age of this convergence is indicated by the presence of Middle Miocene foraminifera in the matrix of mélanges developed during this collision and a Mio-Pliocene age of the post-orogenic clastics (molasse) sediments (Smith, 1983; Simandjuntak, 1980, 1986a). The collision is typical of Tethyan type convergence, where the micro continents underplated the subduction complex and/or the island arcs (Simandjuntak, 1986c, 1991). In Timor the collision seems to be earlier, considered as Paleogene by Audley-Charles et al. (1972). It was then followed by collision in Tanimbar-Kai and Seram Island in Neogene times (Fig. 10).

During late stage and/or subsequent after this convergence the ophiolite belt in eastern Sulawesi (ESOB) was imbricated giving rise to the shortening and thickened nature of the overriding ophiolite belt. While the continental margin sequences on the underplating platforms were imbricated and some may be in the form of duplexed stacks due to forward migration of the thrust (Fig. 11).

Micro-seismicity, occurrence of earthquake hypocenters and the development of several terraces of Quaternary coralreefs in most of the islands, suggest that at least partly the thrusts might be reactivated at present times (McCaffrey et al., 1983; Simandjuntak, 1986a, c; Vita-Vinzi and Hidayat, 1992).

The significant of the Banda Orogeny is evidenced by the development of the following structural and tectonics features, most of which are readily recognized in the field and on remote sensing imageries.

a. Uplifting of mountain ranges to over 3,000 m above sea level in Sulawesi and the surrounding islands, testifying the rapid rising of the regions.

b. Deformed, folded and thrusted of the over-riding ophiolite belt and the island arcs together with the overlying molasse sediments.

c. Termination of deposition of non-marine molasse sediments due to the uplifting of the block fault-originated basins within the collision complex.

d. During late stage, or subsequent to the orogeny volcanic arc seems to be shifted, such as Unauna and Minahasa Sangihe arcs in the northern part of Sulawesi Island.

Melanesian Orogeny

Recent geological mapping of northern Irian Jaya conducted by the GRDC in collaboration with BMR of Australia (Dow and Sukamto, 1986) reveals data, which suggest that the northern margin of Australia may had been collided with Pacific Plate in Tertiary times, prior to the development of thin-skinned tectonics in central Irian Jaya. Subduction of such, much thicker, continental margins beneath

the oceanic crust and/or subduction complexes and/or island arcs means the sedimentary pile on the continental margin would be thrust over the continental basement.

Similarly, the Tertiary tectonic development of Timor Island was described by Audley-Charles (1975), Barber and Carter (1977), in Kai-Tanimbar Island (Charlton et al., 1992), in Seram (Audley-Charles et al., 1981) and typifies the Tethyan collision described by Simandjuntak (1986a) above. However, the occurrence of an extensive metamorphic complex in the region implies that the thrusting might be initiated by thick-skinned tectonics if the metamorphics are part of the basement complex. Considering the metamorphic rocks originated as a sedimentary cover, then the thrusting orogeny in Timor is, kinematically, similar to that in the Central Irian Jaya Fold and Thrust Belt.

Dow et al. (1986) concluded that the Melanesian Orogeny is the end-product of the oblique tectonic convergence in Irian Jaya in the Late Tertiary. Subsequently after the ceasing of the Neogene southern-dipping subduction zone off-shore to the north of Irian Jaya-New Guinea (Smith, 1990), the northern margin sequences of the Australian Craton were thrusted southwards onto the foreland of the continent. It is called the **Asmat Thrust** trending E-W and bounded on the Southern Plains against the Central Irian Jaya Fold and Thrust Belt (Fig. 9).

The Asmat Thrust continues to Papua New Guinea in the east. To the west it merges with the Tarera-Aiduna Fault and terminates in the south extension of the Palu-Koro Fault further east (Tjia and Zakaria, 1974).

Considering the amounts of the northwards displacement of the Australian Craton since the Neogene, the Asmat Thrust might be in a straight line through the Kai Trough to Timor Trough in the west.

The significant physiographical, structural and tectonic features of the Melanesian Orogeny in eastern Indonesia can readily be recognised in the field and remote sensing imageries, including:

a. The uplifting of the Central Irian Jaya Mountain Ranges to nearly 6,000 m above sea level in a relatively short time indicating and testifying to the rapid uplift of the mountain building phase.

b. The development of the Central Irian Jaya Fold and Thrust Belt and its continuation to the east in Papua New Guinea is essentially due to the thin-skinned tectonics in northern margins of the Australian continent.

c. The ceasing of the foreland basin and/or inter-sag basin which is now uplifted and forms a flat lying low lands (peneplains) in southern Irian

Jaya.

d. The occurrence of Paleozoic metamorphic slabs possibly part of basement complex, may indicate that in Timor the development of the thrust sheets and klippe structures was instrumented by thick-skinned tectonics. Or alternatively, if the metamorphic rocks originated from sedimentary cover rocks, the thrusting orogeny in Timor is instrumented by thin-skinned tectonics similar to that in the Central Irian Jaya Fold and Thrust Belt described previously.

Talaud Orogeny

The Talaud-Tifore ridge in the center of North Maluku Basin is built up of imbricated mélange wedges, slices of ophiolites, Late Paleogene volcanics and the overlying Neogene clastics and carbonates. The mélanges are thrusted upon the Sangihe and Halmahera arcs in the west and east respectively. The mélanges are characterised by gravity lows and shallow seismicity, and may attain thickness of some 14 km (Cardwell and Isacks., 1978; McCaffrey et al., 1981; Sukamto et al., 1981; Hall et al., 1988).

The ridge seems to be formed as the southern extension of the Philippine Fault which is terminated in the North Sula-Balantak Fault further to the south (Simandjuntak, 1988).

The mélanges appear to be underlain by an inverted U-shaped fragment of oceanic crust (Silver and Moore, 1979; Hamilton, 1979; Moore et al., 1980). At present, however the convergence appears to be reactivated as a parallel-sided double arc with both Benioff zones dipping westwards. In the east the Pacific Plate is being subducted at the Philippine Trench giving rise to the Halmahera volcanic arc. In the west, the oceanic crust of the Maluku Sea subducted beneath the western parts of the Talaud-Tifore ridge initiating the development of the Sangihe volcanic arc. Seismicity suggests that the subduction may be continued to the Batui Thrust in the south giving rise the development of the Unauna-Minahasa arcs (McCaffrey et al. 1983; Simandjuntak, 1988).

The double convergences coupled with the dextral transpressional movement of the Philippine Fault resulted in the imbricated and even duplexed stacks of rocks in the form of flower structures on the Talaud-Tifore ridge (Fig. 13).

The significant features of the Talaud orogeny are evidenced and can be readily observed on the results of micro-seismics analysis and on the outcrops, including:

a. The uplifting of the Talaud-Tifore ridge giving rise to the emerging of some segments above sea level.

b. Formation of imbricated stacks of Cretaceous-

Paleogene rocks which is originated by the development of flower structures of the Talaud-Tifore ridge.

c. The shallowing of the North Maluku Basin due to the rising of the basement complex.

d. Shifting of the present active volcanic arc in the Minahasa-Sangihe Volcanic Belt.

ACKNOWLEDGEMENTS

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