Indonesian Landforms and Plate Tectonics

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Abstract

The horizontal configuration and vertical dimension of the landforms occurring in the tectonically unstable parts of Indonesia were resulted in the first place from plate tectonics. Most of them date from the Quaternary and endogenous forces are ongoing. Three major plates – the northward moving Indo-Australian Plate, the south-eastward moving SE-Asian Plate and the westward moving Pacific Plate - meet at a plate triple-junction situated in the south of New Guinea's Bird's Head. The narrow North-Moluccan plate is interposed between the Asia and Pacific. It tapers out northward in the Philippine Mobile Belt and is gradually disappearing. The greatest relief amplitudes occur near the plate boundaries: deep ocean trenches are associated with subduction zones and mountain ranges with collision belts. The landforms of the more stable areas of the plates date back to a more remote past and, where emerged, have a more subdued relief that is in the first place related to the resistance of the rocks to humid tropical weathering Rising mountain ranges and emerging island arcs are subjected to rapid humid-tropical river erosions and mass movements. The erosion products accumulate in adjacent sedimentary basins where their increasing weight causes sub-sidence by gravity and isostatic compensations. Living and raised coral reefs, volcanoes, and fault scarps are important geomorphic indicators of active plate tectonics. Compartmental faults may strongly affect island arcs stretching perpendicular to the plate movement. This is the case on Java. Transcurrent faults and related pull-apart basins are a leading factor where plates meet at an angle, such as on Sumatra. The most complicated situation exists near the triple-junction and in the Moluccas. Modern research methods, such as GPS measurements of plate movements and absolute dating of volcanic outbursts and raised coral reefs are important tools. The mega-landforms resulting from the collision of India with the Asian continent, around 50.0 my. ago, and the final collision of Australia with the Pacific, about 5.0 my. ago, also had an important impact on geomorphologic processes and the natural environment of SE-Asia through changes of the monsoonal wind system in the region and of the oceanic thermo-haline circulation in eastern Indonesia between the Pacific and the Indian ocean. In addition the landforms of the region were, of course, affected by the Quaternary global climatic fluctuations and sea level changes.

Keywords: mega landforms, morphostructures, plate tectonics, Indonesia

Sari

Konfigurasi horisontal dan dimensi vertikal bentang alam terjadi di wilayah-wilayah Indonesia, yang secara tektonik tidak stabil terutama sebagai akibat dari pergerakan lempeng tektonik. Sebagian besar bentang alam tersebut berumur Kuarter dan dipengaruhi oleh gaya-gaya endogen. Tiga lempeng utama yaitu Lempeng Indo-Australia yang bergerak ke utara, Lempeng Asia Tenggara yang bergerak ke tenggara, dan Lempeng Pasifik yang bergerak ke arah barat, bertemu pada satu simpang tiga (triple junction) yang terletak di selatan Kepala Burung, Papua. Lempeng Maluku Utara yang sempit menyisip antara Asia dan Pasifik, Lempeng ini miring ke utara pada sabuk Filipina yang mobil dan berangsur menghilang. Amplitudo relief yang terbesar terjadi dekat batas-batas lempeng: parit laut dalam yang berasosiasi dengan zona subduksi dan jajaran pegunungan dengan sabuk tumbukan. Bentang alam daerah-daerah yang lebih stabil terdapat pada lempeng yang berumur jauh lebih tua dan tempat pemunculannya mempunyai relief yang lebih mudah berubah. Hal ini berkaitan dengan resistensi batuan terhadap pelapukan tropis lembab. Jajaran pegunungan dan busur kepulauan yang

terbentuk, mengalami erosi yang cepat oleh sungai tropis lembab dan gerakan tanah. Produk erosi menumpuk di cekungan sedimen yang terdekat. Peningkatan penyebaran dan ketebalan sedimen tersebut menyebabkan terjadinya terban oleh gravitasi dan kompensasi isostatik. Terumbu karang yang hidup dan tumbuh, gunung berapi dan gawir sesar merupakan indikator geomorfik penting lempeng tektonik aktif. Bagian-bagian sesar mungkin sangat mempengaruhi busur kepulauan yang meregang tegak lurus terhadap pergerakan lempeng. Kasus ini terjadi di Pulau Jawa. Sesar mendatar dan cekungan-cekungan tarikan adalah faktor penciri adanya pertemuan lempeng yang menyudut satu sama lain, seperti halnya di Sumatra. Situasi paling rumit ditemukan di dekat persimpangan-tiga (triple junction) dan di Maluku. Metode penelitian modern, seperti pengukuran pergerakan lempeng dengan GPS dan pentarikhan absolut produk gunung api dan tumbuhnya terumbu karang merupakan cara yang penting. Mega-bentang alam akibat benturan India dengan Benua Asia, sekitar 50 jtl., dan akhir tumbukan Australia dengan Pasifik, sekitar 5 jtl., juga memiliki dampak penting pada proses geomorfologi dan lingkungan alam di Asia Tenggara melalui perubahan sistem angin musiman di wilayah dan sirkulasi termo-haline samudera di Indonesia timur antara Pasifik dan Samudra Hindia. Selain itu bentang alam wilayah ini, tentu saja, dipengaruhi oleh fluktuasi iklim global Kuarter dan perubahan permukaan air laut.

Kata kunci: *mega bentang alam, struktur morfo, tektonik lempeng, Indonesia*

INTRODUCTION

The landforms of Indonesia and adjacent areas are strongly related to Quaternary Plate tectonics. This applies especially to the volcanic- and non-volcanic island arcs of the archipelago (Hamilton, 1979; Hall and Blundell, 1996; Gupta, 2003). Their spatial distribution reveals the location of subduction- and collision zones caused by the lateral movement of a number of tectonic Plates. Most of these subduction- and collision zones are active and characterized by great sub-marine and sub-aerial relief amplitudes that have strongly increased during the Quaternary. Emerged island arcs and rising mountain ranges are subjected to intense humid-tropical weathering processes, river erosion and mass movements. The erosion products accumulate in adjacent sedimentary basins where their increasing weight causes subsidence by gravity and isostatic compensation. The relief amplitude of the Plates is much less and the landforms of their emerged parts around the Sunda- and Sahul/ Arafura shelves indicate an advanced stage of development related to geological events of a more remote past. The landforms in these parts of the country now reflect differences in resistance of the rocks to humid tropical weathering in the first place. Several geomorphic indicators exist for detecting zones of neo-tectonics in the lowlands. They include drainage anomalies, distributional patterns of swamps and other characteristics of alluvial plains, coastal configuration, etc.

The three most important plates affecting the Indonesian region are the SE-Asian Plate, the Indo-Australian Plate, and the Pacific Plate. They can be subdivided into a number of smaller Plates and meet at a triple junction situated south of New Guinea's Bird's Head. In addition, the narrow North Moluccan Plate is interposed in the north between the Sulawesi Sea Plate, an oceanic associate of the SE-Asian Plate, and the Philippine Sea Plate, a forerunner of the Pacific Plate. They both subduct under the North-Moluccan Plate (Kreemer *et al*., 2000). This plate tapers out northward in the Philippine Mobile Belt that extends up to Taiwan. (Figure 1) Active subduction zones form deep trenches with important negative gravity anomalies. The three main ones are the trough situated south of the Sunda Arc and curving up northward to the east of the Banda Arc, and the troughs occurring respectively to the east and west of the North Moluccan Plate / Philippine Mobile Belt.

Active volcanism is associated with belts of ongoing Plate subduction. The longest row is that connected with the subduction of the northward moving Indian Ocean Plate in Sumatra, Java, Nusa Tenggara and the SE-Moluccas. The volcanic activity of this row is extinct only on the islands of Alor and Wetar, where Timor, an outpost of the Australian continent, collides with it. Active volcanism also accompanies the subduction zones situated
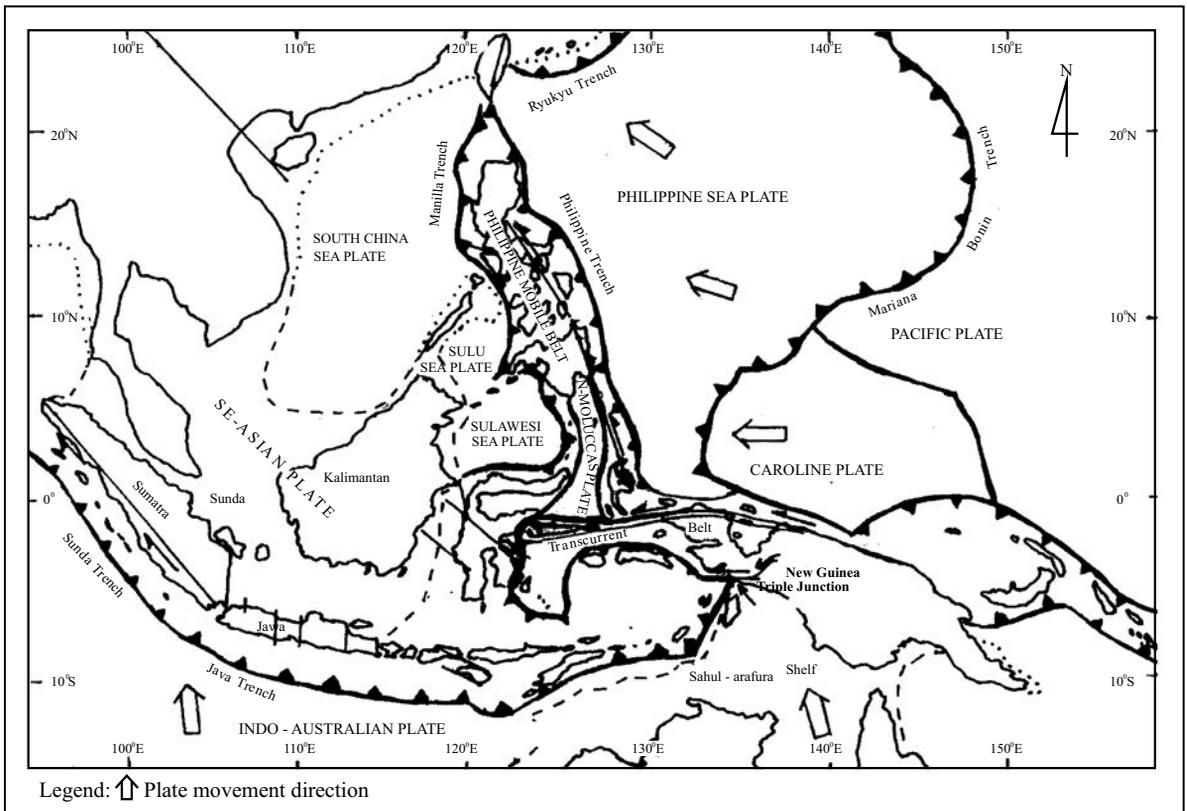
Figure 1. The plate-tectonic configuration of Indonesia and surroundings (Katili, 1980).

at both sides of the North Moluccan Plate, in the Minahasa and northern Halmahera respectively. These two volcanic arcs continue in the two parallel and closely spaced rows of active volcanoes in the Philippine Mobile Belt (Javelosa, 1994). Volcanism is extinct in western Sulawesi because the northward moving Australian Plate blocked Pacific subduction already in the Tertiary. Volcanism also fails in the collision zone of northern New Guinea where obduction prevails, and reappears only in the easternmost tip of the island and in the Solomon Archipelago where the westward moving Pacific Plate is subducting north-east of Australia.

Faults and shear zones are common in the tectogene parts of Indonesia. Compartmental faults, without major lateral displacements, are dominant features where Plates meet at a right angle, such as in Java. Transcurrent faults occur where Plates meet at an oblique angle and clearly affect the landform configuration there. The three major ones are the right-lateral Semangko fault zone in Sumatra, the left-lateral Sorong - Koor fault zone stretching from the north coast of New Guinea to the Moluccas, and the left-lateral Philippine fault zone that can be traced from northern Luzon up to Halmahera. The Semangko zone is the scene of a number of pull-apart basins with related volcanic phenomena. The Sorong - Koor fault strongly affects the Mamberamo delta, the drainage pattern in the Bird's Head and the configuration of the islands farther to the west. It is the northern edge of the transcurrent belt of northern New Guinea that is bounded to the south by the also left-lateral, Tarera – Aiduna transcurrent fault stretching E-W from the triple junction along the south flank of New Guinea's Central Range. The Indonesian sector of the Philippine fault stretches probably between Halmahera and Morotai, but the N-S oriented fault in northern Halmahera and the Kau Bay – marked by a faultscarp and strato-volcanoes – is probably a related phenomenon. Transcurrent faults are also a dominant element in the geomorphology of Sulawesi.

Structural Landforms around the SE-Asian Plate in SW- Indonesia

The SE-Asian Plate stretches from Burma and Thailand in the northwest to the Makassar Strait in the southeast. The northern limit of the Plate is formed by the NW-SE oriented transcurrent Red River fault in Vietnam. Its southern limit is marked by the also NW-SE stretching transcurrent Wang Chao (May Ping) and Three Pagodas faults. In Indonesia the Plate includes the Sunda Shelf, Kalimantan and a narrow strip in Nusa Tenggara up to the triple junction. Recent GPS data (Michel *et al.*, 2001) indicate that it moves eastward at a rate of 12 +/- 3 mm/yr with respect to Eurasia and due south with respect to India and Australia.

The northward moving Indian Ocean Plate subducts in Indonesia under the SE-Asian Plate between the northern tip of Sumatra and Sumba, an outpost of the Australian continent. The subduction has only a minor vertical dimension in western Nusa Tenggara. The non-volcanic arc there is completely sub-marine and the substratum of the Quaternary volcanoes only at places emerges above sea level in the volcanic arc. The vertical dimension increases farther west, where the subducting Indian Ocean faces the main body of the SE-Asian Plate. This is already noticeable in Java but reaches its peak in the Sumatra sector where large parts of the non-volcanic arc emerge above sea level and extensive Tertiary and Pre-Tertiary outcrops occur in the volcanic arc, even at altitudes of more than 3000 m, especially in the north.

The subduction in the western Nusa Tenggara- and Java sectors is perpendicular to the SE-Asian Plate and transcurrency thus is absent. However, N-S oriented compartmental faults can be traced in emerged areas and play a leading part in the geomorphology of Java. The row of (strato) volcanoes is there bounded to the south by an ocean-ward tilted limestone Plateau (with some intercalated volcanic beds) with conical karst topography , and to the north by ridges of folded Old-Pleistocene beds where remains of ancient humans (Pithecanthropus erectus) have been found. However, both the southern Plateau zone and the northern fold zone are disrupted by several deep-seated N-S faults that have caused the collapse of parts of the Plateau zone and discontinuities of the folded zone. The great differences in landform patterns between East- Cen-tral- and West Java clearly relate to compartmental faulting. They also played an important part in the development of the Bay of Jakarta (Verstappen, 2000). The southward shift of volcanic activity during the Quaternary, evident from the Ungaran - Merapi and Welirang - Arjuna volcanic complexes, points to a gradual steepening of the underlying subduction plane, that at present is about 60°. Prior to the up-arching of the volcanic arc a low ridge in the Java sea formed the continental divide line.

In the Sumatra sector the subduction is oblique with respect to the NW-SE orientation of this island which is due to the shape of the SE-Asian Plate. A long, right-lateral transcurrent fault, the Semangko fault resulted and is a major geomorphic feature of this island (Sieh and Natawidjaja, 2000). Only a part of the crustal stress thus is released by subduction. The angle of subduction is only about 30° and volcanism is less active than on Java. Some important volcanic events, characterized by massive tuff- and ignimbrite deposits are, however, associated with the transcurrent faulting. The one located in the Lake Ranau tectonic depression has a K-Ar age of 0.55 +/- 0.15 Ma.(Bellier *et al.*, 1999). For the much larger one situated in the Lake Toba graben the much younger age of 70 Ka is mentioned, but this age refers to the youngest of a series of eruptions, the ignimbritic products of which are found in the gorge of the Asahan river that already drained the Toba graben before the eruptions started (Verstappen, 2000). It is not clear why these eruptions took place in that particular part of the mountain range.

Sunda Strait is situated exactly where the orientation of the Sunda volcanic arc changes and transcurrency starts. It is funnel-shaped, opening westwards to the Indian Ocean and has been the site of at least twelve major plinian eruptions in the last 1.000 Ka. The oldest and largest ones of these center in the widest part of the strait, near the Ujung Kulon peninsula. Fission track dating of the related Lampung tuffs give that same age; the Banten - Malintang tuffs are K-Ar dated 100,000 – 300,000/400,000 yrs. The most plausible explanation for the site and geomorphic development of Sunda Strait and of the violent volcanic activity is, in the author's view, its formation as a pull-apart basin where subduction perpendicular to the coast in the Java sector gives way to oblique subduction and transcurrency farther to the northwest.

Landforms of SE-Indonesia related to the Collision with Australia

The northward movement of the Australian continental Plate has resulted in its intrusion in the eastern part of the Sunda - Banda island arcs. The obduction generated by this collision has resulted in strong uplift of Sumba and particularly of Timor, to the north of which subduction and active volcanism came to an end. U-Th and luminescence dating of *raised coral reefs by* Pirazolli *et al.* (1991) show that the reef terraces along the north coast of Sumba, date from Interglacial high sea levels, and have risen up to 450 m above sea level at a rate of 0,5 – 0,65 mm/yr. Two datings of Level IV (275 m) are 584,000 $\pm$ 80,000 yrs. and 603,000 $\pm$ 90,000 yrs. The highest level (VI) is 1.0 my. old. Obduction is even stronger farther to the east where Timor – geologically quite distinct from Sumba - rises up to 1700 m and raised, undated, coral reefs have been reported from 1600 m above sea level. The volcanic arc is also affected by obduction in this sector. Dating of a reef cap at 600 m a.s.l. on nearby Alor by Hantoro *et al.* (1994) indicate an uplift of 1.0 -1.2 mm/yr. The rise in this sector thus was twice as fast as on Sumba. It is evident that large parts of eastern Nusa Tenggara have emerged above sea level during the Quaternary. Assuming that the uplift from oceanic depths was at a constant rate, the collision must have started about 5.0 my. ago. These concords with the second collision phase mentioned by Hall (2002).

The islands are subject to strong erosion as a result of the fast uplift, except where raised coral reefs or other limestone outcrops protect the underlying soft rocks. The reef terraces of Sumba are restricted to the north coast because the soft Neogene marls underlying them, and outcropping in the non-reef parts of the island, slumped down southward in the Indian Ocean during the uplift. These slumps even affected low reef terraces and thus must have occurred in the young-Quaternary. They may well have caused (a) major tsunami(s) affecting not only nearby areas but also the eastcoast of Africa.

The western margin of the Australian Plate, east of the Banda Sea, stretches SSW-NNE and both obduction and lateral displacement exist. The NW-ward tilted reef cap of the island of Jamdena is a result of this tectonic configuration. The Kai islands, situated farther to the north, reflect a particularly interesting situation. Nuhucut (Kai major) is a narrow, 800 m high mountain ridge in the east stretching parallel to the Australian continental margin, while Tual and the other low islands of Kai minor follow the curved trend of the Banda arcs and are covered by a, slightly undulating, reef cap (Verstappen, 2000).

The strongest obduction occurs in the Central Range of New Guinea where the Australian continental Plate collided about 5.0 my. ago with northern New Guinea and the Caroline Plate, situated off the north coast of the island. Large parts of this mountain range emerged above sea level before the advent of the Quaternary and a middle-mountain relief predating the ultimate Quaternary uplift still persists. These parts were the scene of extensive glaciation about 14,000 yrs BP, after they had reached alpine heights. No signs of earlier glaciations exist, probably because of the young age of the uplift. In the Himalayas such areas of pre-alpine landforms have since long disappeared because the collision of India with the Asian continent is much older (50.0 my.). Neogene limestone beds, that emerged during the collision, protect the underlying rocks from erosion in the central and southern parts of the Central Range. Their solution has led to a variety of karst forms. Dry river valleys, relic forms dating from shortly after the emergence of the limestones, and deep caves and underground river captures, formed after the uplift, are common features. The lower course of a dry valley in the Digul river basin is at present 500 m higher than its upper course which indicates that, at least in that part of the island, the axis of the final uplift was situated south of the mountain crest.

Landforms of NE-Indonesia related to the westward moving Pacific Plate

The plate triple junction situated south of the Bird's Head of New Guinea, is an important feature in the complex plate tectonic situation of eastern Indonesia (Figure 2). It is clearly reflected in the geomorphic configuration of the Aru Basin. This 3,680 m deep basin is narrow in the south and widens northward, thus forming a narrow triangle bounded in the west by the curved Banda Arcs and in the east by the straight SSW-NNE stretching western edge of the Australian Continent. The most striking element is, however, its east-west stretching northern limit, that coincides with the Tarera - Aiduna fault where
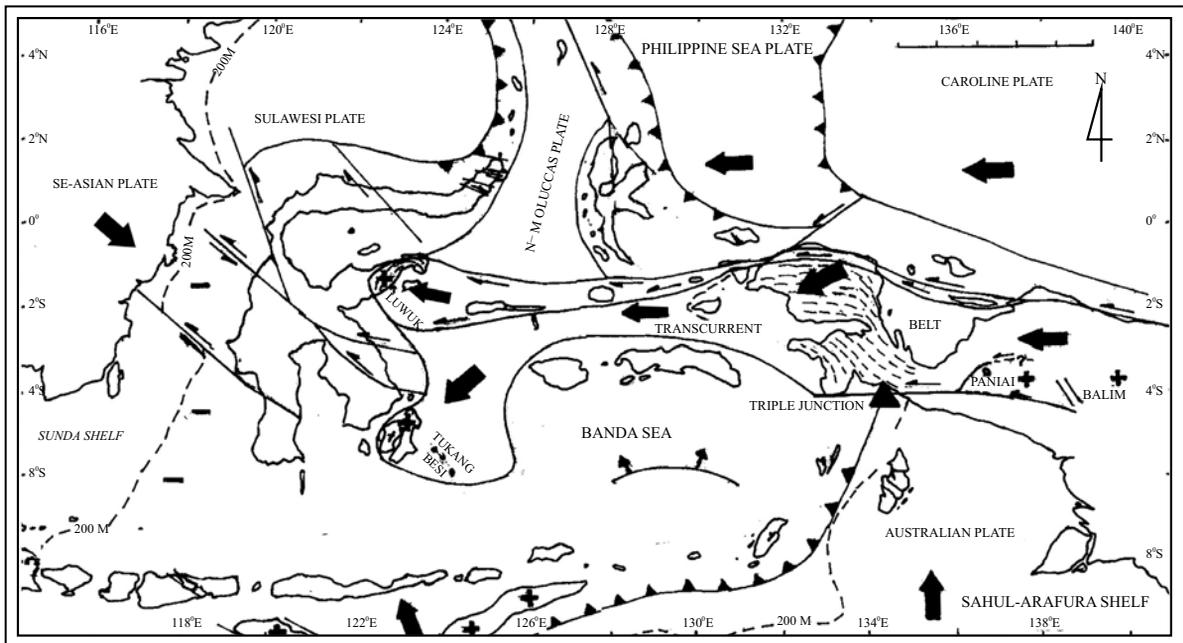
Figure 2. Plate-triple junction and transcurrent belt in East Indonesia (Katili, 1980).

the western edge of the Australian continental Plate abruptly ends. GPS-measurements (Pubellier *et al*., 1999) have revealed that this fault is a left-lateral transcurrent fault, along which the northern part of New Guinea moves westward at a rate of about 1 cm/yr. Because no offset continuation of the western edge of the Australian continent can be traced north of the Tarera – Aiduna fault it appears that the Australian Plate never reached much farther north. The North Panai Fault, looping around the western end of the Central Range, probably marks the northern limit of its obduction. The Tarera - Aiduna Fault can be traced at the south foot of the range also farther east. It is uncertain, however, whether the entire northern part of the island has been equally affected by the transcurrency. The NW-SE stretching Great Valley of the Balim River, best accounted for as a pull-apart basin, merits attention in this context.

The transcurrent fault along the north coast of New Guinea is an important geomorphic element of the island (Puntodewo *et al*., 1994). It affects the Mamberamo delta (Figure 3) where it causes an E-W stretching zone of swamps – with mud volcanoes to the south of it. The small lacustrine delta in the swamp zone and the strong meandering of the Mamberamo River downstream of it are also noteworthy. The fault splits in the Cenderawasi Bay in

two closely spaced transcurrent faults passing north and south of the island of Yapen. They are known as the Sorong- and Koor Faults in the Bird's Head and can also be traced farther west along the north- and south coast of the Sula Islands respectively, up to the short eastern peninsula of Sulawesi. To the north of the fault zone the Caroline Plate and the Philippine Sea Plate - westward moving forerunners of the Pacific Plate - occur off the coast of New Guinea. River offsets in the northern Bird's Head (Figure 4) and other landform characteristics indicate that both transcurrent faults are left-lateral. It is thus evident that the oceanic Plates in the Pacific move faster westward along the Sorong – Koor Fault than northern New Guinea with respect to the triple-junction. It appears that the Australian Plate hampers the westward movement of the Pacific Plate and that northern New Guinea is dragged along westward by the Pacific Plate. The subduction of the Philippine Sea Plate under the North Moluccan Plate east of Halmahera and under the Philippine Mobile Belt farther north, marks the end of the westward movement in the Pacific realm north of the transcurrent faults. To the south, however, this movement continues unhampered up to the island arcs of Sulawesi, and the northernmost of these two transcurrent faults thus becomes right-lateral.
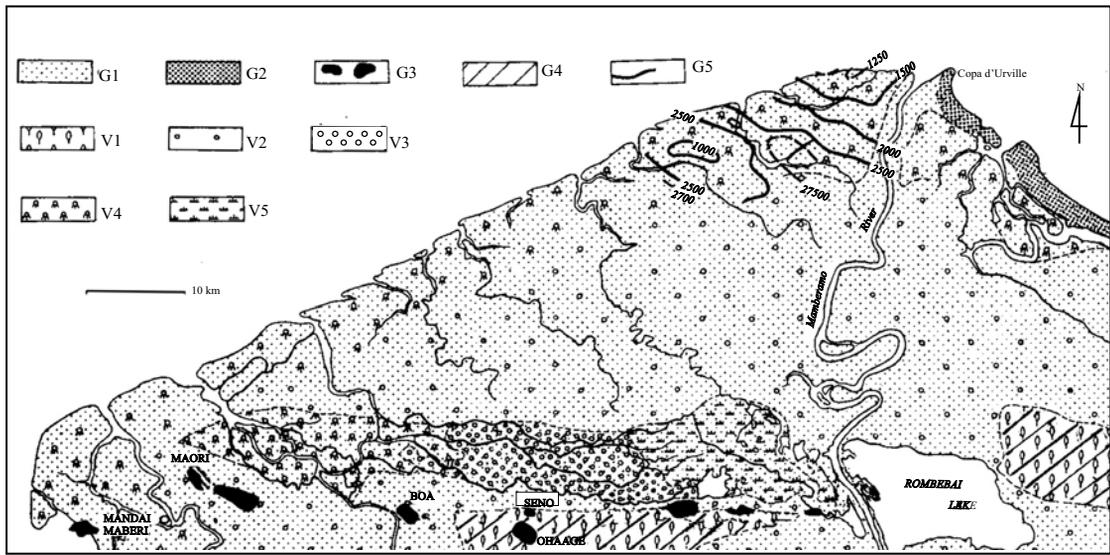
Figure 3. Mamberamo Delta, affected by sinistral transcurrent faulting. G1: alluvium, G2: beach ridges, G3: mud volcanoes, G4: hills unspecified, G5: depth of crystalline basement, V1: hill forest, V2: swamp forest, V3: low swamp vegetation, V4: mangrove, and V5: grass/rush marsh.
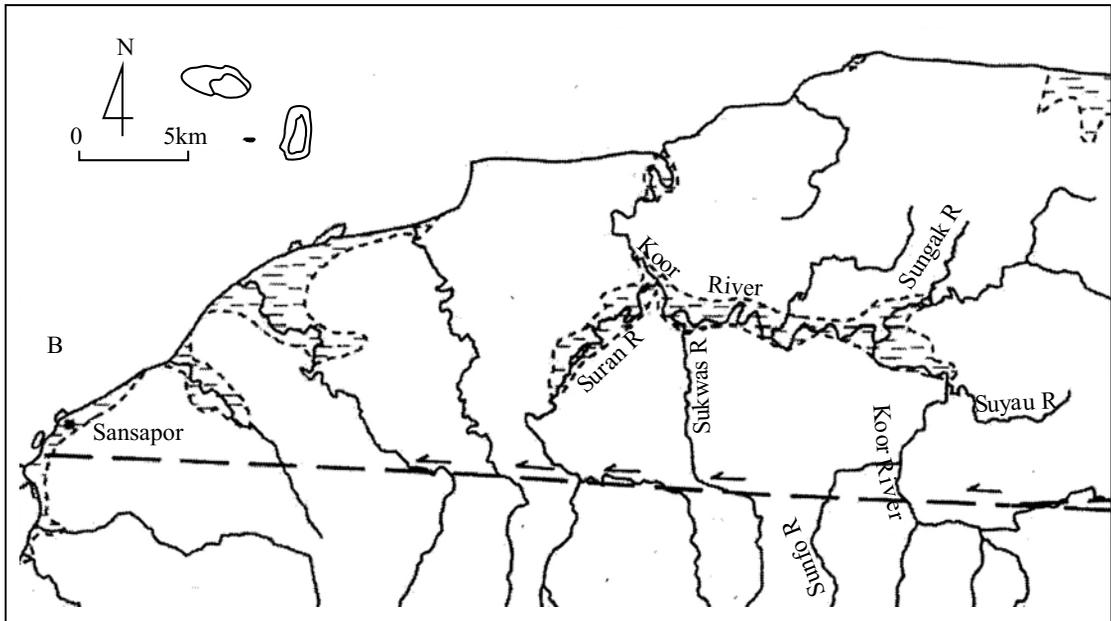

Figure 4. River offsets along the sinistral transcurrent Koor Fault, "bird's head".

The transcurrent Tarera - Aiduna Fault contin- ues westward south of the Bombarai Peninsula, from where onward the Banda Arcs are interposed between the northward moving Australian Plate to the south and the westward moving belt situated to the north. This has led to an acquired sinuosity of the structural trends in the southern part of the "Bird's Head", already observed by Hermes (Visser and Hermes, 1962). GPS data (Stevens *et al*., 2002) have shown that the Bird's Head at present moves rapidly (75-80 mm/yr) SW-wards with respect to Australia. It thus converges with the Banda Arcs

and joins the westward moving narrow transcurrent belt of the Sula Spur.

Geomorphic evidence for the westward movement of he Sula Islands and their collision with eastern Sulawesi includes the truncated southern limit of the North-Moluccas Plate, the relief in the Batui thrust zone situated east of the ophiolites in the eastern peninsula of Sulawesi (Silver *et al.*, 1983), and the location of the raised coral reefs at the Lamala Bay near Luwuk (Figure 5), facing the westernmost side of the Sula Islands (Sumosusastro *et al.*, 1989). This reef cap is younger (highest level, 410 m: 229,000 $\pm$ 55,000 - 35,000 yrs) than those of Sumba and Alor. This suggests that the collision near Luwuk and the westward dragging of northern New Guinea postdates the Quaternary collision of Australia with eastern Indonesia. The epicentre of the Luwuk earthquake of May 5, 2000, situated just offshore in the Lamala Bay, proves that tectonism is ongoing.

The geomorphology of the coral reefs of the Tukang Besi Islands, situated farther south in the transcurrent belt, is particularly interesting in the context of plate tectonics (Figure 6). Rows of raised reefs alternating with rows of atolls indicate differential vertical movements in this archipelago during the Quaternary (Umbgrove, 1949). The NW-SE alignment of these reefs reflects a Quaternary neotectonic

trend deviating from Tertiary trends. The reef building is in fact only a minor element in comparison to the relief amplitude of the underlying submarine ridges (2000 – 4000 m). In the author's view, it is a geomorphic indicator of the Banggai - Tolo thrust zone, the southern continuation of the Batui thrust zone mentioned from the east arm of Sulawesi by Silver (1983). It appears that the transcurrent belt is spreading west of the Banda Sea. The westward-tilted reef cap of the island of Muna (Verstappen, 2000) is a related feature indicating subduction. The southern limit of the transcurrent belt is, in the author's view, a shear zone converging with the volcanic arc of Nusa Tenggara, as suggested by a row of submarine volcanoes and the earthquake (with tsunami) that affected the north coast of Flores in 1993.

Structural Landforms in Sulawesi and around Makassar Strait

Sulawesi is bounded in the west by the collapse zone of Makassar Strait and in the east by the Batui – Banggai – Tolo thrust zone. The island arcs of Sulawesi date back to the time that Australia was situated farther south and the area east of Sulawesi was the westernmost part of the Pacific realm where active subduction and related volcanic activity occurred. The area has been detached from the Pacific
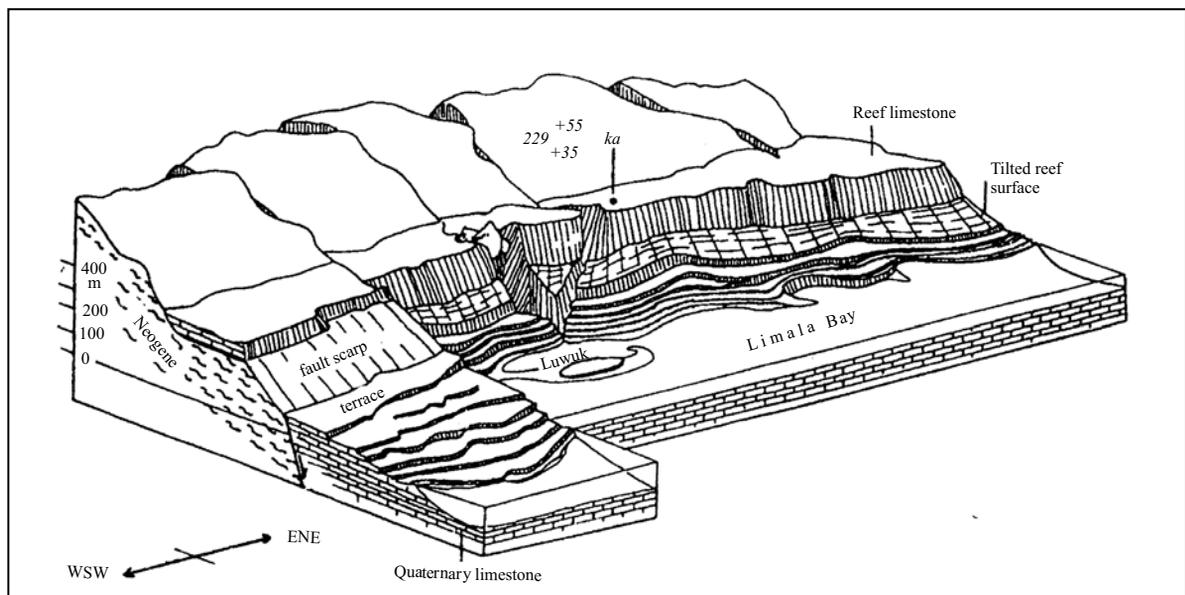

Figure 5. Block diagram of the raised reefs near Luwuk, East Sulawesi (Sumosusatro *et al.*, 1999).
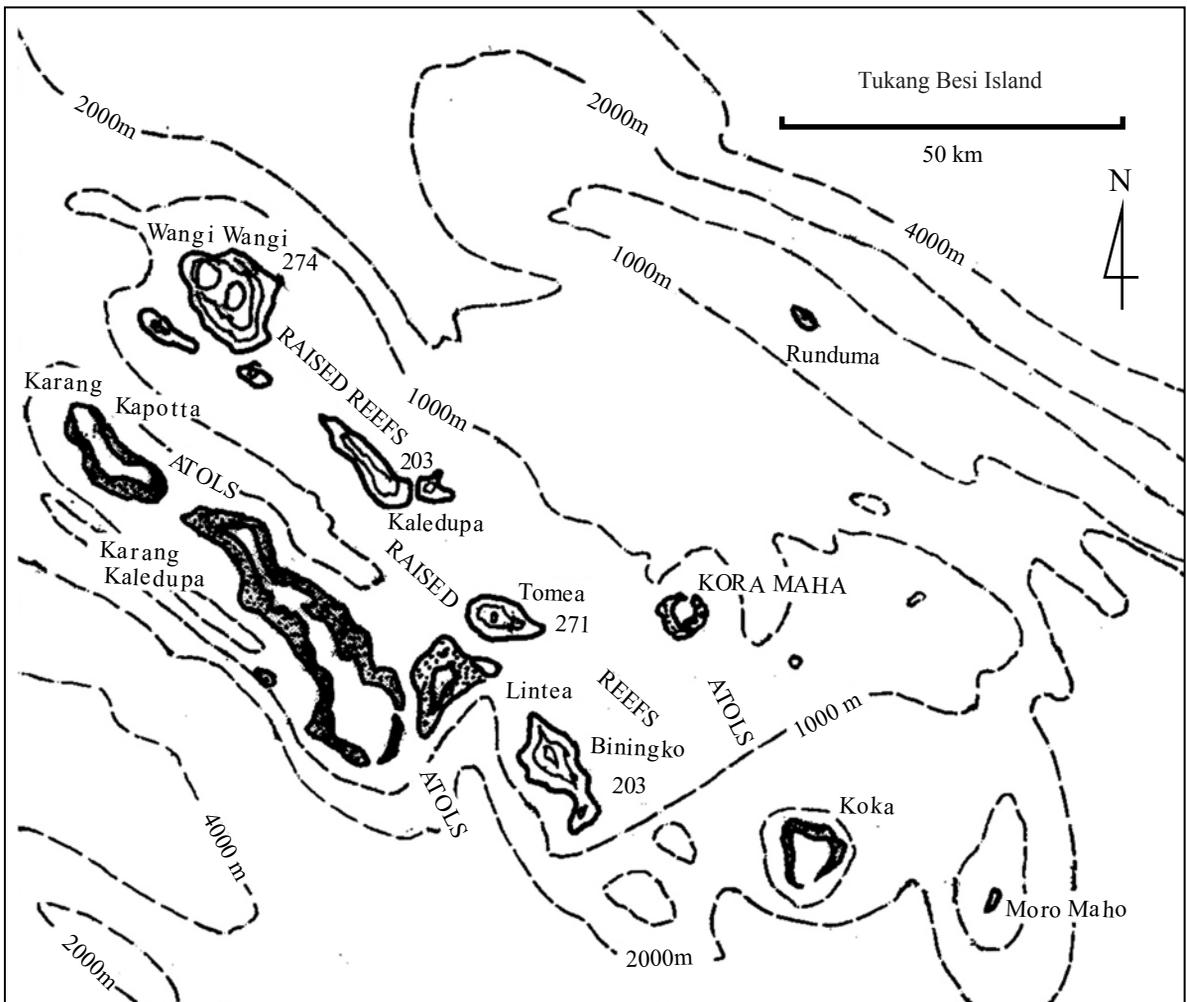
Figure 6. Reef caps, atolls, and submarine relief of the Tukang Besi.

influence in the Neogene by the northward moving Australian Plate whereafter also volcanic activity came to an end. Makassar Strait separates Sulawesi from the SE-Asian Plate and testifies the collapse that occurred west of this island when subduction in the east came to an end with the elimination of Pacific influences. Sea floor spreading may have occurred (Katili, 1980) but is difficult to substantiate on the basis of the geomorphologic configuration of Makassar Strait.

Sulawesi and Makassar Strait (Figure 7) have been disrupted, in a later stage, by a number of NW-SE stretching transcurrent faults. The orientation of these faults deviates from the E-W trend that dominates farther to the east. This may relate to the SE-ward displacement (6 +/- 3 mm/yr) of

the SE-Asian Plate with relative to Eurasia and clockwise rotation of the East Sulawesi block as shown by recent GPS surveys (Bock *et al.*, 2003; Michel *et al.*, 2001; Replumaz *et al.*, 2004; Simons *et al.*, 1999). The left-lateral transcurrent fault stretching SE-wards from Balikpapan is a major structural element in the geomorphology of Strait Makassar and SW-Sulawesi. It is reflected in the off-set of the depth contours of Makassar Strait, in the wide shelf zone with living reefs off the southeast coast of Kalimantan and in the Tempe plain in SW Sulawesi. The landforms of SW Sulawesi are quite distinct, much lower and probably younger than those of farther north. The impression is gained that the area subsided and that parts of the older relief now form the basis of the Spermonde
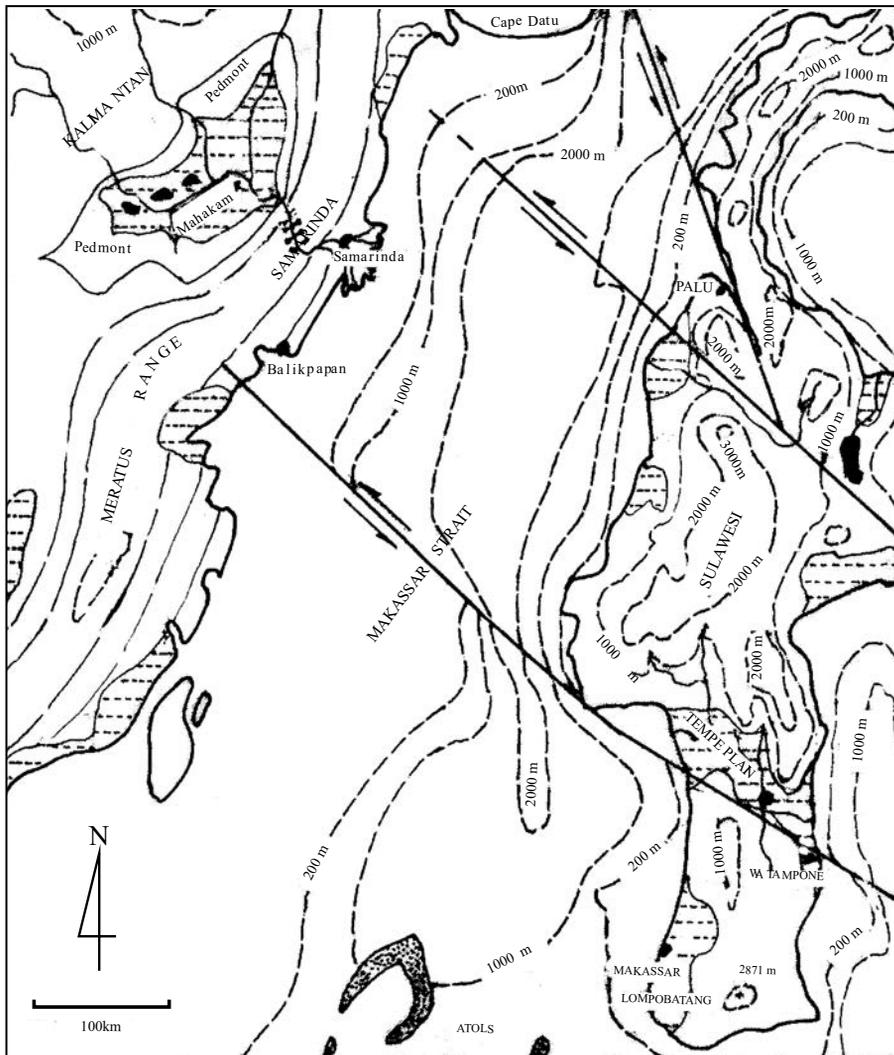
Figure 7. Makassar Strait and surroundings with transcurrent faults and related landforms (Katili, 1980).

archipelago west of Makassar and of the shelf zone SE of Watampone. The slender cone of the Lompobatang Volcano testifies Young Quaternary subduction. The raised coral reef near Luwuk in the east arm of Sulawesi demonstrates, however, that the geomorphology of Sulawesi is also affected by the impact of the westward moving transcurrent belt situated east of it.

Epilogue

The mega-landforms originating from plate tectonics have affected the climatic and oceanographic conditions in Indonesia and surrounding areas. The northward movement of the Austra-

lian Continent caused a zone of exceptionally high rainfall to the south of the Central Range of New Guinea and also forced the oceanic thermo-haline circulation (THC) to abandon the Weddell Sea as a passage from the Pacific- to the Indian Oceans. This is at present limited to a northeast - southwest route across the Moluccas, thus strengthening the "hot pool" occurring north of Indonesia when "El Niño" conditions prevail. The rise of the Himalayas and the Tibetan Plateau has strongly affected the monsoonal system of SE- and E-Asia since a much longer period. It is evident that plate tectonism has a profound effect not only on the geomorphology of Indonesia but also its natural environment in general.

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