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Tertiary stratigraphy and tectonic evolution of southern Sumatra

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Abstract: Physiographically southern Sumatra can be divided into four zones, from the west to east: Mentawai, Bengkulu, Bukit Barisan and Jambi-Palembang Zones trending northwest-southeast. These zones have been established as a result of subduction-related activities during Tertiary time.

The subduction regime that has occurred since the (middle) Paleogene, has been from the south-southwest and related activity has resulted in the different tectonic setting of each of the four zones.

The Mentawai Zone is a non-volcanic arc, occupied by an Oligocene-Miocene mélange complex and fine to coarse clastic accretionary prism sediments. The Bukit Barisan range is a continental margin volcanic arc which was formed by the subduction of the Indian-Australian Plate under the Eurasian Plate. The volcanic rocks of this range are characterised by andesitic to basaltic compositions typical of a calc-alkaline island arc setting.

Between the Mentawai Zone and Bukit Barisan Zone is the Bengkulu Zone which comprises turbiditic sequences of the fore-arc region. East of the Bukit Barisan Zone is the Jambi-Palembang Zone. This zone is characterised by transgressive and regressive sedimentary rocks deposited in back-arc basins. Both the Bengkulu and Jambi-Palembang Zones have hydrocarbon potential.

INTRODUCTION AND TECTONIC SETTING

Southern Sumatra, is south of the equator defined by latitudes 0°-6°S and longitude 97°-108°E, including some small islands to the west of the mainland namely Pagai, Sipora, Enggano, and Bangka and Belitung of the tin islands to the east (Fig. 1).

Sumatra lies along the southwest margin of Sundaland, the Southeast Asian continental extension of the Eurasian Plate, and forms part of the Sunda Arc (Fig. 2). Oceanic crust flooring the Indian Ocean and part of the Indian-Australian Plate is being obliquely subducted along the Sunda Trench off the west coast of Sumatra (Hamilton, 1979; Curray *et al.*, 1979). This zone of oblique convergence is marked by the Sunda-Arc Trench system which extends for more than 5,000 km from Burma, in the north, to Eastern Indonesia. Lower Tertiary to Recent subduction under Sumatra has given rise to the extensive magmatic arc of the Barisan Mountain Zone. Arc-related lithologies along the length of Sumatra, however, suggest that subduction has probably been taking place, albeit intermittently, under Sumatra since late Permian times, (Katili, 1969, 1973; Cameron *et al.*, 1980) although the present positions of the arc and trench most probably date only from the Miocene. Stress built-up as a result of the oblique subduction regime has been periodically released through dextral faulting parallel to the plate margin (Fitch, 1972) and is manifested in the Sumatra Fault System (SFS) which runs the length of the island and transects the Barisan magmatic arc. Relative to the magmatic arc, Sumatra can be subdivided into four tectonic provinces from W to E: the Accretionary (Mentawai) Zone, Fore Arc (Bengkulu) Zone, Magmatic Arc (Barisan) Zone and Back Arc (Jambi-Palembang) Zone (Fig. 3).

GEOLOGICAL OUTLINE

The oldest Tertiary rocks recorded in the southern Sumatra are the Lower Paleogene sedimentary rocks of the South Sumatra Basin of the Jambi Palembang Zone, and sporadic volcanic rocks exposed in the Barisan Zone (Fig. 4). During Eocene to early Oligocene times, extension in the back-arc region produced block faulting across northeast-southwest and northwest-southeast faults and the development of the South Sumatra Basin. The early history of the basin reflects dominantly transgressive sedimentation which continued until the late Middle Miocene, followed by regression during the remainder of Neogene, reflecting the rise of the Barisan Geanticline. The Bengkulu Basin of the fore-arc zone probably developed initially as a localised "pull apart" basin, in the late Oligocene (Hall, 1990).

Widespread, subduction-related, calc-alkaline, volcanism was established by the late Oligocene-

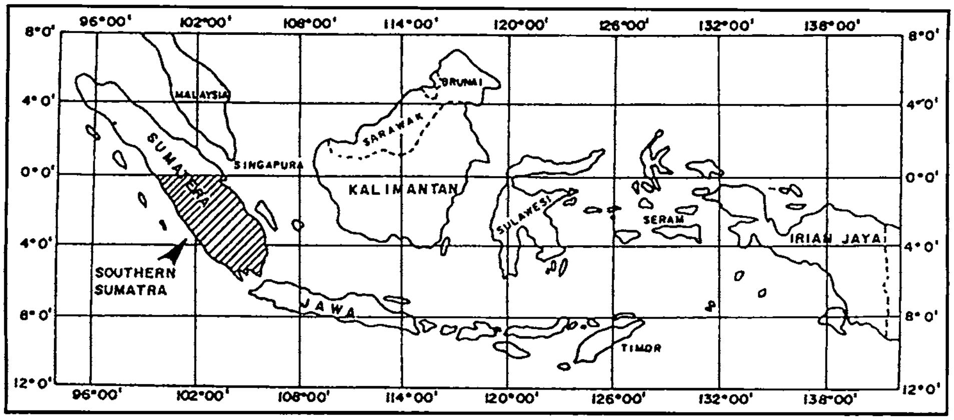

Figure 1. Location map of southern Sumatra.

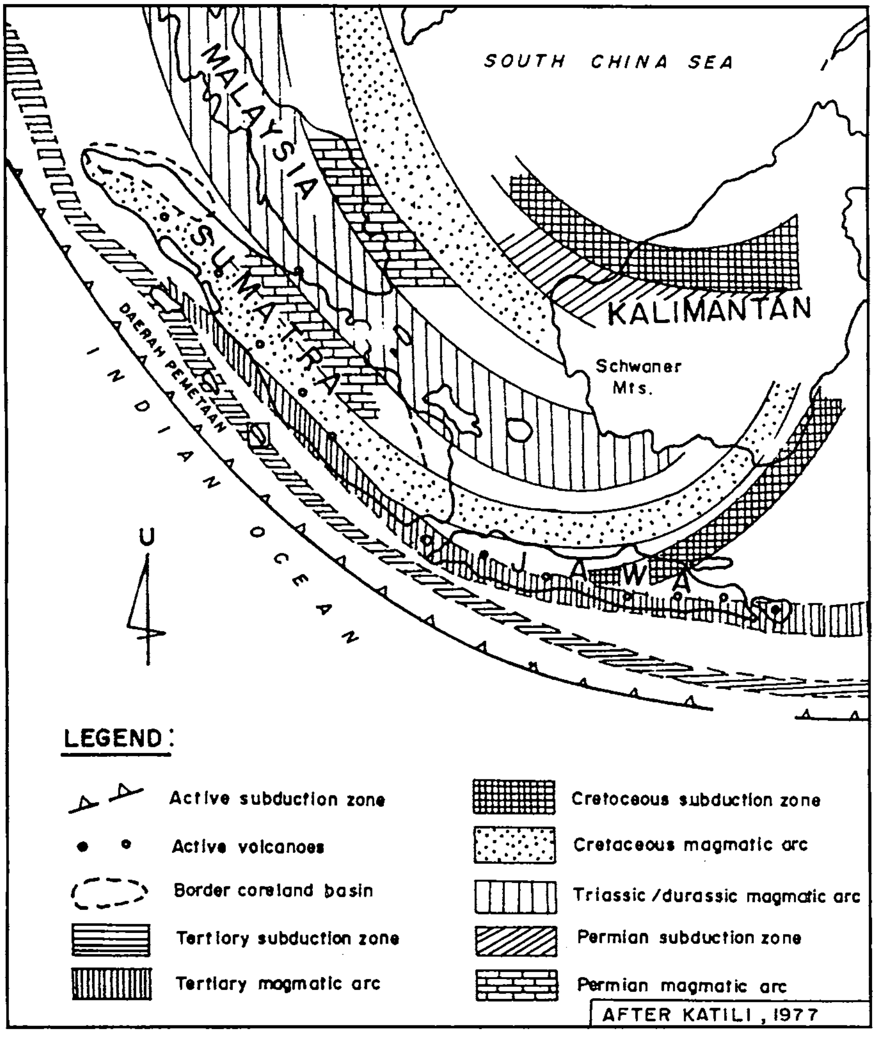

Figure 2. Subduction zones and magmatic arcs of West Indonesia.

early Miocene in the Barisan Zone. Magmatic activity increased during the Miocene extending through into the Pliocene (Fig. 5). In the Plio-Pleistocene it was followed by an important period of regional dextral faulting along northwest-southeast trending structures. Volcanic activity in the Barisan Zone during thè Quaternary resulted in tuffs, lavas and volcanic breccias of rhyolitic to basaltic composition.

The sequence of the Mentawai zone comprises a basal mélange unit overlain by interbedded sandstone and siltstone sequences. The general sequence is interpreted as an uplifted part of an outer or fore-arc ridge of the Sunda Arc subduction

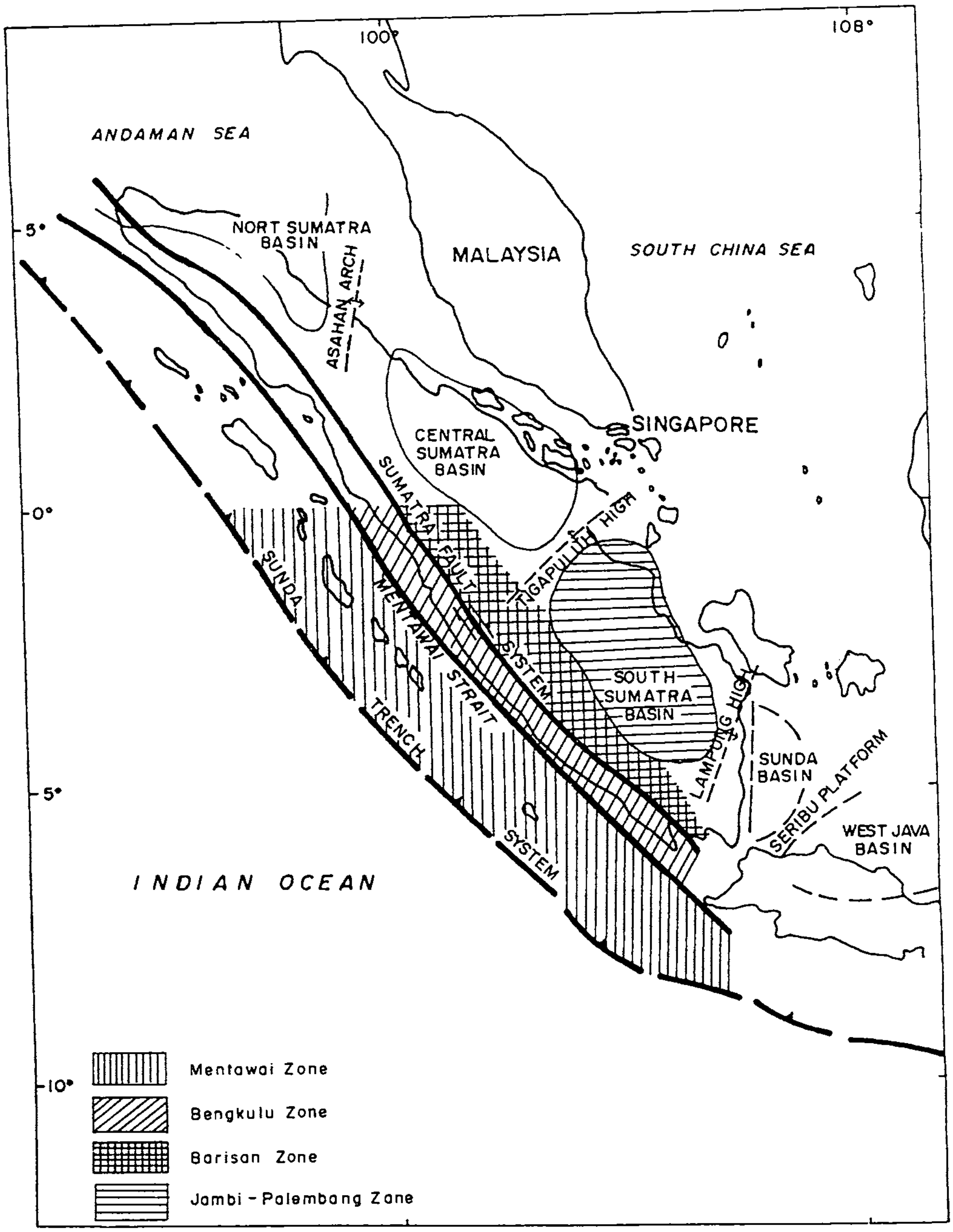

Figure 3. Tectonic provinces of southern Sumatra.

system that separates sediments of the accretionary wedge of the trench from those of the fore-arc basin.

Stratigraphy of the Mentawai Zone

The lowest stratigraphic unit of the Mentawai Zone found on Pagai island is a mélange complex of pre-Miocene age in which a wide variety of rocks, of different sizes and ages are found within a matrix of silt and clay which has a characteristic scaly structure. Some blocks show boudinage, with length direction approximately NW-SE. The proposed age of the mélange is based on the age of the youngest blocks present within it and the age of its sedimentary cover due to the fact that establishing the age of formation of the matrix is at best uncertain. The youngest block identified is a limestone that contains large foraminifera of late Eocene age, while the sedimentary cover is early Miocene. Therefore the age of mélange complex is Oligocene, in agreement with the age assigned to mélange units on islands of the fore-arc ridge off North Sumatra such as Nias and Simeule.

On Siberut island the youngest blocks present in the mélange are limestone of late Oligocene to early Miocene age. The sedimentary cover rocks are Pliocene, therefore the age of the mélange is most probably middle Miocene but may extend up to late Miocene. The apparently younger Mélange

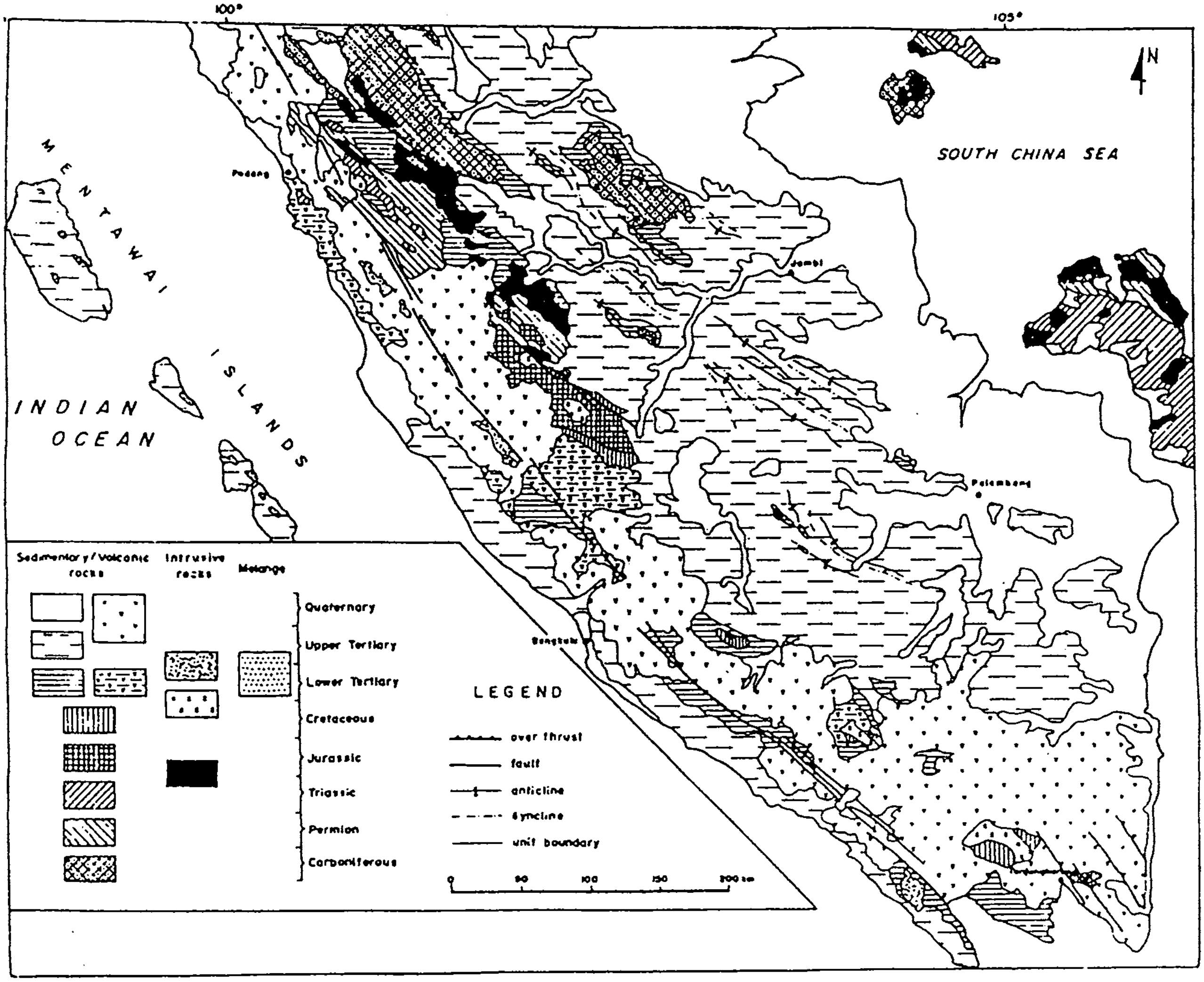

Figure 4. Simplified geological map of southern Sumatra.

Complex unit of Siberut island lies further west compared to that of the lithologically similar mélange unit of Pagai and Sipora islands (Fig. 4).

The sedimentary cover of the Mélange Complex rocks comprises turbidite "trench" sediments. The lower part of the unit particularly at the contact with the mélange is strongly folded, brecciated and faulted whereas the upper part is only weakly deformed. The sedimentary cover rocks occupy more than 70% of Mentawai islands (Fig. 5).

The Quaternary sediment is made up of coralline reef, polymict conglomerate, calcirudite and calcarenite, spread around the islands mainly in the south.

Stratigraphy of the Bengkulu Zone

The lowest exposed stratigraphic unit of the Bengkulu Zone comprises a marine, essentially turbiditic sequence, that was deposited during the main transgressive stage of the basin that extended up to the middle Miocene (Howles, 1986). The presence of strong tuffaceous component in the lowest sedimentary formation indicates coeval volcanic activity in the magmatic arc of the Barisan Zone at this time. Analyses of small foraminifera from black-grey shales from the Bengkulu area indicate an early to middle Miocene age. Further fossil evidence from elsewhere in the basin however, suggest an age range from late Oligocene to middle Miocene (Pardede and Gafoer, 1986). The upper part of the unit is taken to represent the culmination of the main transgressive stage in the Bengkulu Basin and can be broadly correlated with the Gumai Formation in the South Sumatra Basin.

This unit is unconformably overlain by late-middle Miocene to late Miocene epiclastic and volcaniclastic sediments that were deposited in a transitional shallow marine to fluviatile environment. The upper part of the Bengkulu Zone comprises Plio-Pleistocene fluviatile sedimentary and volcanic rocks which unconformably overlie the older sedimentary sequences.

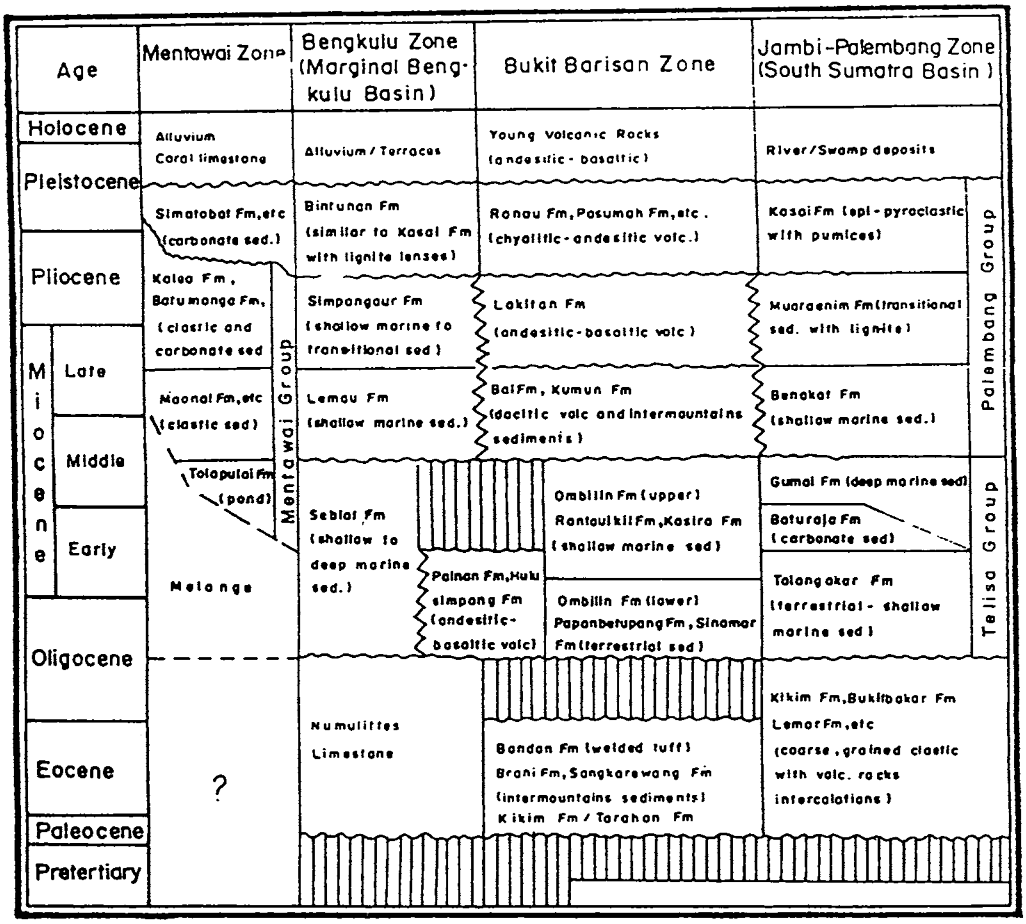

Figure 5. Tertiary stratigraphic unit of southern Sumatra.

Stratigraphy of the Barisan Zone

The exposed base of the Barisan Zone comprises calc-alkaline andesitic volcanics which are interpreted to have been formed by subduction close to an active continental margin. The intercalated nature of the contact between this volcanic formation and the lowest sedimentary rocks of the Bengkulu Zone, along the eastern edge of the Bengkulu Basin, establishes its age as late Oligocene to early Miocene. Younger volcanic rocks of the Barisan Zone are more diverse in composition ranging from basalt-andesite to dacite-rhyolite possibly reflecting a maturing of the subduction related volcanic arc with time.

These younger extrusive units are very widely distributed throughout the Barisan Zone and the relative age relations between local units are often difficult to establish. They all however characterically rest with pronounced unconformities on older volcanics.

Stratigraphy of the Jambi-Palembang Zone

The stratigraphic succession of this region is well established and comprises an older group of sediments deposited in non-marine paralic, to shallow and deep marine environments: the Telisa Group; and an upper sedimentary sequence deposited in shallow marine to transitional environment: the Palembang Group (Marks, 1957; De Coster, 1975). The complete sedimentary succession therefore reflects a change from a lower transgressive facies sequence (Telisa Group) to an upper regressive facies sequence (Palembang Group).

Throughout the early development of the Tertiary basins block faulting played an important role in controlling the topography of the pre-Tertiary basement and hence the distribution of the lower units (Pulunggono, 1986). The oldest sediments comprise detrital terrigenous clastic sediments derived from the erosion of local highs and horsts in the pre-Tertiary basement and from the eastern Barisan foothills. Sedimentation occurred in terrestial to transitional environments, initially in local depressions characterised by an admix of sedimentary and volcanic material in certain areas; followed by sedimentation in a lacustrine-brackish environment. There then followed by a major marine transgression and the upper part of the basin development is characterised by regressive sedimentation in the later stages of the Neogene.

The oldest known Tertiary sediments comprise detrital deposits of Paleocene to early Oligocene Lahat Formation unconformably overlain by the late Oligocene to early Miocene Talang Akar Formation which is characterised by fluviatile deltaic to shallow marine sedimentary depositions. A marine transgression initiated in the early Miocene, leads to the development of a lower Miocene coral reef limestone around local basement highs, which laterally, in the deeper parts of the basin, becomes more clayey and marly facies. During the maximum marine transgression in the middle Miocene the Gumai shales and equivalent units were deposited basin-wide. This was followed by the deposition of early sediments of the regressive cycle, such as the Air Benakat Formation, in the mid-late Miocene. By the late Miocene the depositional environment had become shallow marine and continued regression produced a continental environment by the lower Pliocene.

TECTONIC EVOLUTION

The active tectonic elements of mainland Sumatra all trend northwest-southeast parallel to the present day trench; accretionary zone, fore-arc zone and magmatic arc zone. The only proven subduction mélange in Southern Sumatra, identified as belonging to this northwest trending system, is that of the accretionary (Mentawai) zone and is of Oligocene to middle Miocene age.

The Barisan Zone is a geanticline comprising mainly volcanic rocks of the active magmatic arc. The belt is about 100 km wide with altitudes up to 3,000 metres (Mt. Raya, Mt. Kebongsong etc.). This northwest-southeast trending structural and topographic feature is a Tertiary phenomenon. Volcanism may have been initiated as early as the late Paleocene and was widespread by the late Oligocene-early Miocene. The age of the oldest dated calc-alkalic volcanic rocks, from the Kikim Formation, is 60 Ma and volcanic material is recorded as detritus in the sedimentary rocks of Oligo-Miocene Seblat Formation in the Bengkulu Zone and the Eocene-early Oligocene Lahat Formation of the Jambi-Palembang Zone. Thus the pattern of the development of subduction related magmatic arcs and sedimentary basins has existed at least since Eocene times in the Barisan Zone (Fig. 6).

The Tertiary tectonic evolution of Southern Sumatra can be broadly divided into four periods based on the presence of four major subduction related tectono-magmatic events that occurred during Tertiary times: Paleocene-early Oligocene, late-Oligocene-early Miocene, middle Miocene-early Pliocene and Pliocene-Pleistocene (Fig. 7).

Paleocene-Eocene to early Oligocene stage

This period is marked by the continuing rapid convergence of India on Eurasia and the very much slower, initially eastward and subsequent northwestward movement of Australia (Kallagher, 1990).

The Paleocene-Eocene to early Oligocene subduction is recorded by sporadic occurrences of arc related andesitic volcanics such as the Bandan, Kikim and Tarahan Formations of the Barisan Zone, and sedimentation in the Ombilin and South Sumatra Basins. However, compared to both the earlier upper Cretaceous magmatic arc and the dominantly Neogene Arc of western Sumatra, this Paleogene volcanism is minor and the lack of an extensive active volcanic arc at this time is puzzling. A possible explanation on the basis of the spatial distribution of seafloor magnetic anomalies, is that during the period from the late Cretaceous to the middle Eocene, Southeast Asia from western Sumatra to at least eastern Java was in contact with the slow, northwest moving, Australian Plate, with a velocity of only a couple of cm/yr, rather than the fast, northward moving, Indian Plate with a velocity of about 15 cm/yr. The contact between the Australian and Indian Oceanic plates at this time was a major transform fault. Following the early Eocene collision between India and Eurasia and the subsequent reorganisation of plate motions, the Australia and India Plates essentially became a single plate and the combined India-Australia Plate moved north-northeastwards giving rise to the oroclinal bending of Sumatra and S.E. Asia as a result of indentation of India into Eurasia (Hutchison, 1992). The decrease in convergence rates as a consequence of the India-Eurasia collision during the Eocene created extension in the back-arc zone of Sumatra and the basin systems were initiated. The present day Sumatra fore-arc basin developed at a passive margin, behind a local marginal basin and oceanic island arc, during this general period (Hall, 1990; Daly *et al.*, 1991).

In the latest Eocene to early Oligocene an increase in the subduction rate at Sumatra from approximately 3 cm/yr to 5-6 cm/yr resulted in a change in the tectonic regime, the fore-arc was placed under compression that resulted in the closure of the above marginal basin, inversion throughout much of the fore-arc and back-arc basins and initiation of uplift in the Barisan Mountains with local intermontane volcanic activity. A major Oligocene unconformity underlies most of the Sumatran shelf (Karig *et al.*, 1979). In the Mentawai Zone the increased subduction resulted in thrust faults in trench area, emplacement of gabbros on Simeulue, and initiation of the accretion of the

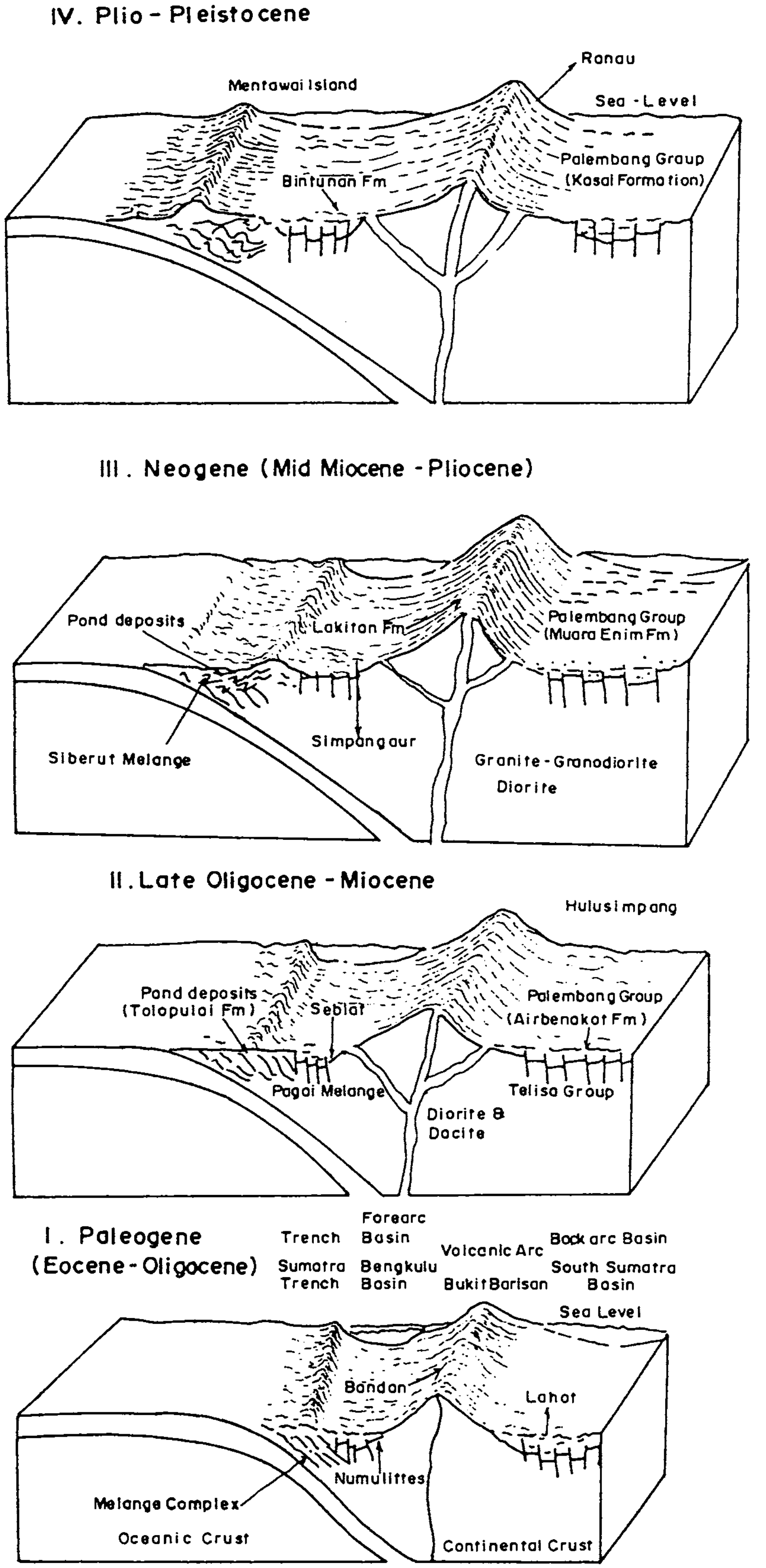

Figure 6. The development of Tertiary subduction in southern Sumatra.

basal mélange complexes presently exposed on Nias, Simeulue, Sipora and Pagai islands. The coarse clastic material present in these mélange units is interpreted to have its source, partly, in this elevated area of Sumatra and the transport of clastics across the fore-arc region indicative of a subdued trench slope break (Karig *et al.*, 1979).

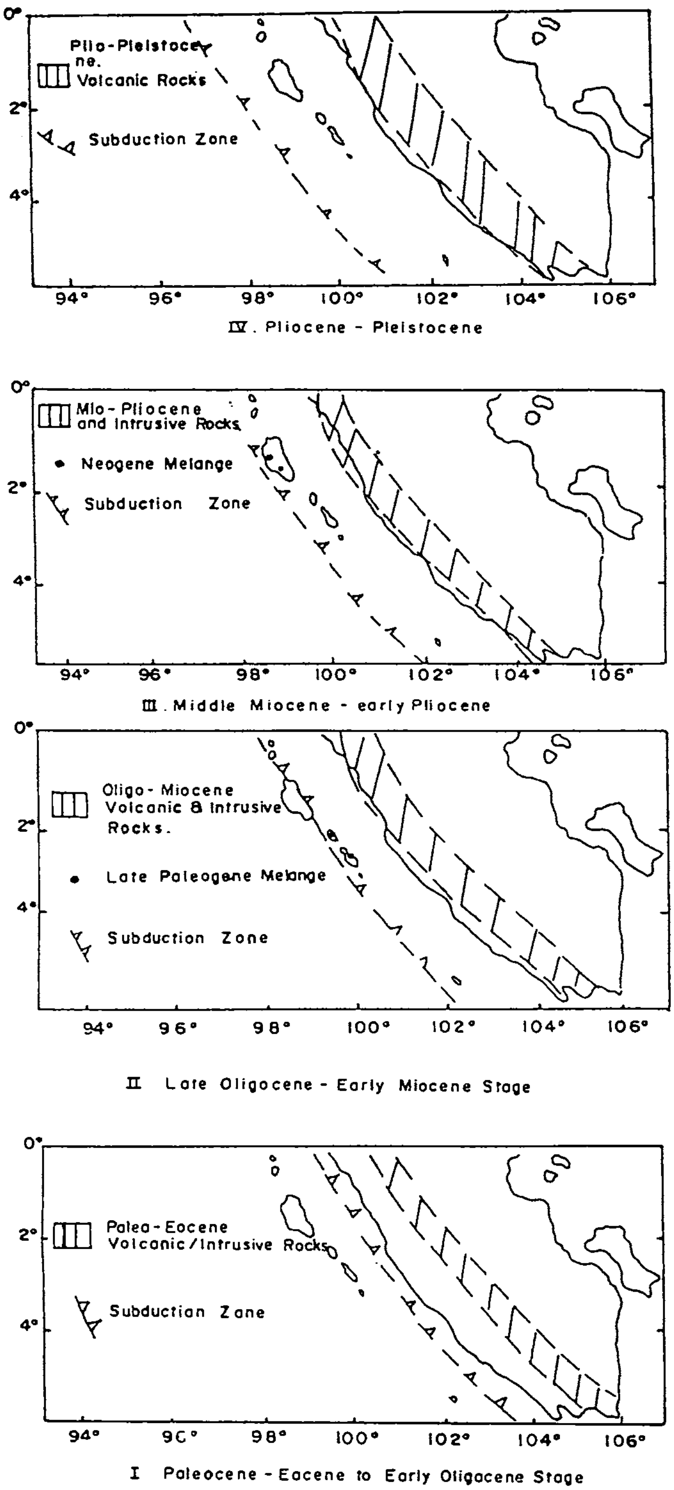

Figure 7. The Tertiary tectonic evolution of southern Sumatra.

Late Oligocene-early Miocene stage

By the late Oligocene the convergence rate of the Indian-Australian Plate had stabilised at approximately 5-6 cm/yr and the Sunda subduction system was active off Sumatra. The position of the Oligocene-Miocene trench was probably near to that of central Nias (Karig *et al.*, 1979). A major period of calc-alkaline volcanic activity was initiated throughout the Barisan Zone as evidenced by the extensive Hulusimpang and Painan Formations, the "Old Andesites" (Van Bemmelen, 1949), of late Oligocene to early Miocene age. Sedimentation in the (Bengkulu) fore-arc basin and the (South Sumatra) back-arc basins was under marine conditions as evidenced by the Seblat and Talang Akar Formations. Progressive deepening of the basins occurred from the latest Oligocene and resulted in a marine transgression across the slowly subsiding Sumatra shelf, that reached a maximum in the middle Miocene.

Middle Miocene-early Pliocene stage

In the middle Miocene, the subduction zone had moved west and the trench was probably very close to its present day position. The Barisan Range was uplifted, possibly reflecting an increase in subduction rates and a consequent input of heat through magmatic activity. Available data quoted by Karig *et al.*, (1979) suggest that the subduction rate increased from about 5 to 6.5 cm/yr in the mid-late Miocene. Numerous I-type subduction related plutons were intruded into the Oligo-Miocene volcanics of the western Barisan Range with related precious metal mineralisation. Volcanic activity is evidenced by the basaltic-andesite to dacitic Bal and Latikan Formations of middle Miocene and late Miocene to early Pliocene ages respectively. Most of the magmatic activity is focused along major regional northwest-southeast faults of the Sumatra Fault System. Accretion of mélange material apparently took place on Siberut island about this time, (?)followed by deposition of the Tolopulai Formation and other units of the siliclastic cover sequence throughout the Mentawai Zone.

Sedimentation in both the Bengkulu and South Sumatra Basins, of the fore-arc and back-arc zones respectively, was taking place under regressive conditions by this time. The Lemau Formation (Bengkulu Basin) and Air Benakat Formation (South Sumatra Basin) although still marine were deposited in shallower water than preceding ones. By the latest Miocene the depositional environment had become shallow marine and continued regression produced a transitional environment in the early Pliocene.

During the late Miocene, approximately 11-10 Ma ago, pull-apart rifting in the Andaman Sea was generating oceanic crust and major strike-slip movements took place along the Sumatra Fault and related systems. Structural inversion began in the back-arc basins of Sumatra, and climaxed in the Pliocene causing local unconformities.

Pliocene-Pleistocene

The Plio-Pleistocene is marked by an increase in the convergence rate between the Indian-Australian and Eurasian plates to approximately 7 cm/yr, resulting in further uplift and erosion of the Barisan Mountains on Sumatra. Deposition in the South Sumatra Basin was under terrestial to brackish water conditions. Coarse clastic sediments were deposited in the fore-arc basin in fluviatile, deltaic and shallow marine systems which prograded away from the Barisan Mountains. This marks a significant change in the drainage pattern of Sumatra from predominantly eastwards prior to Pliocene times to westwards. Also at this time the Mentawai islands appeared above the sea surface.

During the late Pliocene and extending into the Pleistocene, a regional orogenic event produced upright folds about northwest-southeast axes: the Sumatra Trend (De Coster, 1975) in the back-arc basin. At approximately the same time, and related to the same stress system, major dextral movements occurred along the Sumatran Fault System in the magmatic arc of western Sumatra. Movements on this fault had been mainly vertical since pre-Tertiary times (Katili and Hehuwat, 1967); although Tjia (1977) estimated that the dextral movements also occurred before middle Miocene times.

Volcanic activity recommenced associated with renewed subduction along the Sumatra trench and major Quaternary volcanoes were established along the length of the Barisan Arc.

CONCLUSIONS

The Tertiary geologic evolution of south Sumatra is the direct result of plate tectonic processes. Changes in the convergence rate of the Indian-Australian Plate are suggested to be the single most important factor controlling the evolution of the area extending from the fore-arc ridge to the back-arc zone. Relatively slow convergence rates can be related to periods of extension and basin development, while rapid subduction is equated with compression, basin inversion and magmatic activity. Four tectonic provinces can be recognised from west to east, the non-volcanic fore-arc ridge of the Mentawai Zone, the fore-arc basin of the Bengkulu Zone, the magmatic arc of the Barisan Zone and the back-arc basin of the Jambi-Palembang Zone. The Tertiary tectonic evolution of these tectonic provinces can be broadly divided into four periods based on the presence of four major subduction related tectono-magmatic events that occurred during the Paleocene-early Oligocene, late-Oligocene-early Miocene, middle Miocene-early Pliocene and Pliocene-Pleistocene.

The basins and tectonic development in Mentawai island and Sumatra island are strongly affected by the movement of Indian Ocean Plate on Eurasian Plate. They were formed by compressional and tensional movements which result in uplifting and subsidence where sedimentation occurred during Tertiary time.

The relation between Mentawai island and the land of Sumatra, where geologically very contrasting, can be explained with plate tectonic concepts. The relationship happened since Oligocene where the convergence between the Indian Plate and the Eurasian Plate occurred in Mentawai.

The Mentawai Islands firstly appears to the sea surface in Plio-Pleistocene together with the development of the Great Sumatran Fault in the Magmatic Belt. The convergence belt of those plates moved westward at least since Oligocene while the magmatic belt did not move since Middle Miocene.

Late Oligocene Tertiary tectonics in Southern Sumatra occurred at the same time as the Oligocene-Miocene volcanic activity in the Barisan Mountain. The magmatism which is noted to be the primary cause of the uplift of the Barisan Mountains may also be the primary cause of subsidence and deformation of the basins in the region.

The early Middle Miocene is probably the beginning of compressive movements in the basinal areas, obviously related to renewed subduction of southwestern part of the island of Sumatra.

Two major structural lineaments can be recognised in this region: the NW-SE trending fault system, and the N-S trending fault system. The first one is the Sumatra Fault System. The second one appears to be generated by the lateral displacements along the NW-SE fault system, and shows an apparent dextral sense of motions along Sumatra. The patterns are represented throughout southern Sumatra, and they can be distinguished in several lineaments. They form laterally continuous structures limited to the Sumatra Fault System with short lineaments distributed on either side. The lineament show two distinct trends which are geographically separated. They trend between 300°N and 310°N but it changes abruptly around latitude 3°S to a trend of 320°N 330°N throughout area.

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