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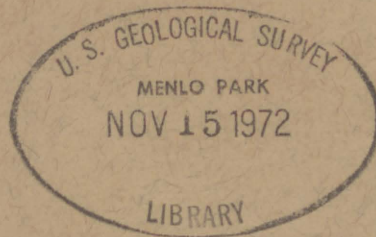
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TECTONICS OF THE INDONESIAN REGION

by

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## TECTONICS OF THE INDONESIAN REGION

by

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Since early 1970, I have been making a tectonic analysis of the Indonesian region as part of a program of assistance, supported in part by the Agency for International Development, U. S. Department of State, for the Government of Indonesia and the Economic Commission for Asia and the Far East. The work has included the study of most of the published primary geologic and geophysical literature on the region, the integration of data given generously by many petroleum companies, and the study of marine seismic-reflection profiles, particularly the voluminous records obtained by the Lamont-Doherty Geological Observatory and kindly made available to me by Maurice Ewing. A preliminary version of the in-progress tectonic map was released recently for limited distribution (Hamilton, 1972). The present note summarizes some of the conclusions reached in the course of the study. The descriptive basis for this summary is contained in more than a thousand published papers; in this note, I have cited only a few papers that develop conclusions particularly important for plate tectonics.

The exceedingly active present seismicity, volcanism, and tectonism of the Indonesian region are products of motions between lithospheric plates. Throughout most of Cenozoic time, the Australian-Indian Ocean plate has been moving northward relative to the Asian plate, and the

Pacific plate has been moving relatively west-northwestward (e.g., Heirtzler et al, 1968). The Indonesian-Melanesian region represents a broad "soft" boundary zone by which the obliquely convergent motion of the three megaplates has been accommodated. The behaviour of the region has been characterized by constantly changing arrays of platelets, subduction zones, transform faults, migrating arcs, and oroclines.

The continuous, curving Andaman-Sumatra-Java-Timor-outer Banda-Seram subduction system now bounds the Indonesian region against the Indian Ocean-Australian plate. The Benioff zone of mantle earthquakes dipping under Indonesia from the trench has gentle dips at shallow depths but steepens downward in most sectors (fig. 1). Volcanoes form a magmatic arc lying mostly above that part of the Benioff zone which is 100 to 200 km deep. There is a continuous outer-arc ridge between magmatic arc and trench. This ridge is wholly submarine in the Java sector, where only thin pelagic sediments veneer the Late Cretaceous and early Tertiary oceanic plate being subducted, but it rises to produce many islands to both east and west where voluminous sediments are being subducted. These islands consist largely of subduction melanges probably formed mostly in Miocene time. The distance from ridge to trench represents the amount of post-middle Miocene accretion to the hanging wall of the subduction system as materials were scraped off against it from the underflowing oceanic plate. In the Sumatra-Nicobar-Andaman sector, the terrigenous clastic sediments of the east lobe of the Bengal abyssal fan are being subducted. Around the Banda arc sector, shelf sediments of Australia and New Guinea are being subducted. Thus,

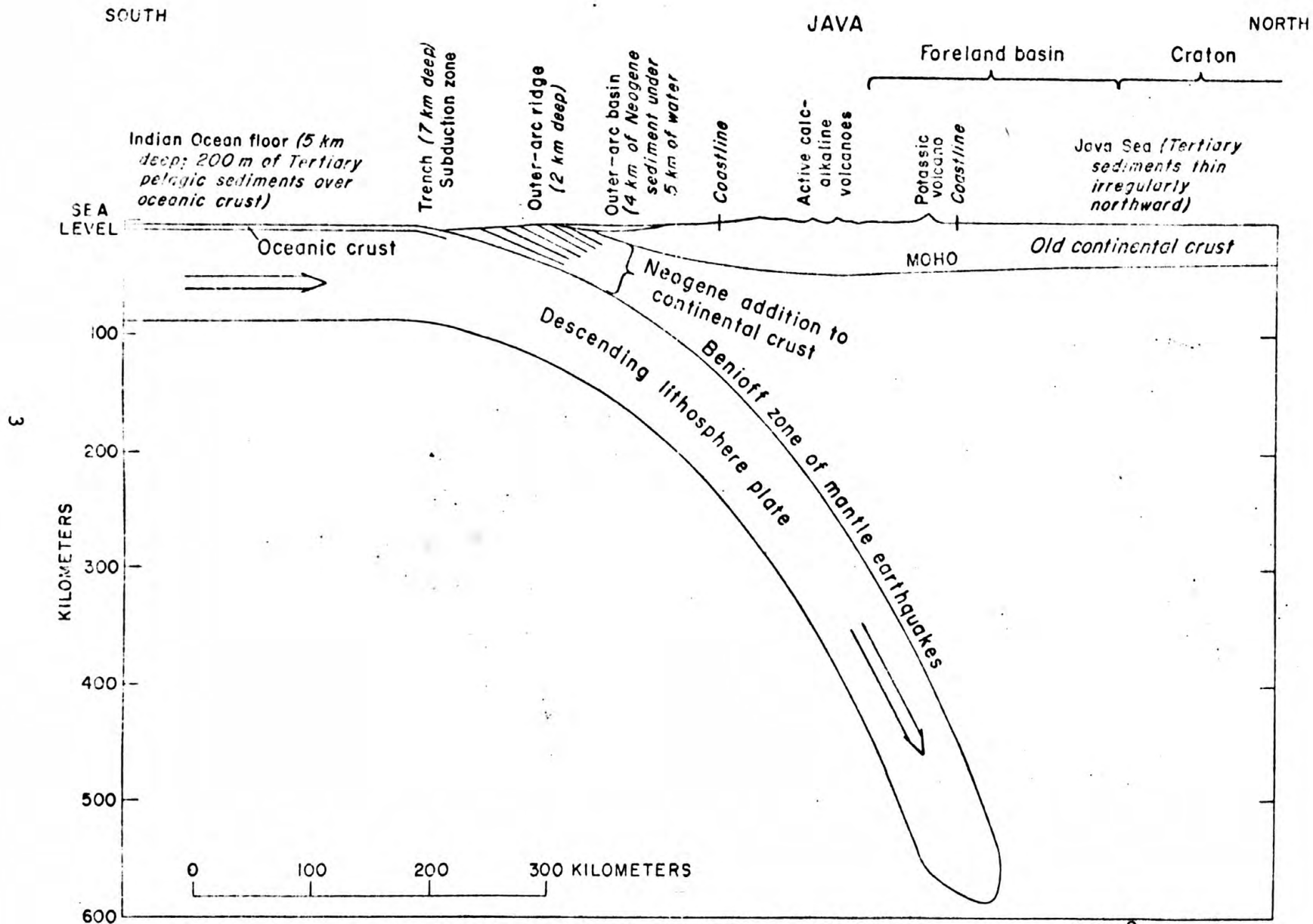


Figure 1.--Generalized section through central Java, along the meridian of  $111^{\circ}$  E., showing the relationship of tectonic and magmatic zones to the Benioff seismic zone (which is located from data by Fitch, 1970).

in both eastern and western sectors of the subduction system, voluminous sediments yield voluminous low-density melanges, which buoy up the ridge. Behind the ridge is a broad submarine basin, mostly about 2 km deeper than the outer-arc ridge and filled with Neogene sediments that are generally 3-7 km thick along the basin axis.

The Holocene volcanic rocks erupted above the present Benioff zone show the usual correlation of ratios of potassium to silicon with depth to seismic zone (Hatherton and Dickinson, 1969). Bulk compositions of the volcanic rocks, however, are controlled by the type of crust through which the magmas rise from the Benioff zone. The rocks are mostly silicic and intermediate in Sumatra, where the magmas rise through old continental crust; intermediate in Java, where the crust is continental but relatively thin, mafic, and young; and intermediate and mafic around the rest of the arc, which is closely flanked on both sides by oceanic crust. There is no apparent correlation between the thickness of sediments being subducted and the intensity of magmatism above the Benioff zone. Very thick abyssal clastic sediments go into the north Sumatra-Nicobar-Andaman sector of the subduction system, where volcanism is of minor volume, whereas only thin pelagic sediments enter the Java sector, where volcanism is intense.

Other subduction systems are now active farther north in the Indonesian region. The Mindanao trench extends south to an abrupt end off northeastern Halmahera, likely at a left-lateral transform fault trending east-southeast toward New Guinea. A short trench trends southward along the west side of central Halmahera. Another trench lies along the east side

of northeasternmost Sulawesi and the Sangir island arc that trends from there to south-central Mindanao. This Sangir subduction system is imbricate in the north with respect to the Mindanao--northeast Halmahera Benioff zone, and convergent in the south with respect to the west Halmahera Benioff zone. Another trench lies along the north side of the north arm of Sulawesi; this trench ends at the west against the very active left-lateral north-northwest-trending Palu fault, and at the east at an orocline that is rolling up the north arm as subduction flips from one side or the other. Geologic and seismic data suggest that along northeastern New Guinea, a subduction zone dipping moderately south under New Guinea is now overriding a subduction zone dipping steeply north under the Schouten-New Britain arc. The Mariana arc is migrating Pacificward even as it consumes Pacific crust, opening new ocean in the Philippine Sea in its wake (Karig, 1971). Most of these active subduction systems have Benioff zones that dip relatively steeply, and the landward slopes of the trenches are marked by platforms bearing thin, perched sedimentary basins rather than by the broad and strongly developed outer-arc ridge-and-basin pairs of the Andaman-Sumatra-Timor system. The trench along the north side of Sulawesi, however, is paralleled on the south by a well-developed outer-arc basin, although this basin is narrower than is the Andaman-Sumatra-Timor one.

Inactive trenches, not now sites of subduction, are also plentiful in the region. A recently inactivated trench lies along the northwest side of the Sulu Islands, and a more ancient one lies along the northwest side of Palaway and nearby Borneo. The Yap trench is now almost

inactive--Yap Island is formed mostly of Miocene melange--and the Mariana festoon may be sliding southward past the Yap trench as it expands and migrates Pacificward. The Yap ridge bears a similar festoon relationship to the earlier Tertiary Palau ridge and trench. Yap and Palau systems continue northward, past the festoon junctions, as remnant arcs representing old positions of the Mariana system (Karig, 1971).

The positions and polarities of older subduction systems can be deduced from onshore geology. Many subduction zones are recorded by tectonic melanges--vast shear zones which typically contain such indicators as ophiolites (fragments of oceanic crust and mantle), abyssal sediments (carried on the conveyor-belt plates), and glaucophane schist and other high-pressure metamorphic rocks. Terrigenous clastic sediments, where available in quantity, are however the dominant component of some of these melanges. Magmatic arcs formed above ancient Benioff zones are now represented by andesitic and basaltic rocks where formed in island arcs, or by dacitic, rhyolitic, and granitic rocks where formed in continental plates.

The present subduction and magmatic-arc system trending eastward from Java has only recently reached its present position, probably by migrating away from Sulawesi. The Late Cretaceous and very early Tertiary ancestral subduction zones are exposed in several areas in the west half of Java, and can be traced northeastward across the Java Sea to southeastern Borneo. The subduction melanges of the southwest arm of Sulawesi likely formed as part of this same system, before the opening by rifting of Makassar Strait. Subsequent early and middle Tertiary subduction built the melanges of the east arms of Sulawesi. The magmatic rocks formed above the Benioff zone of this southeast-migrating subduction system lie in southern Sumatra(?), beneath the northwestern half of the Java Sea, in south-central Borneo(?), and in the southwest and north arms of Sulawesi.

The south half of New Guinea has been part of the Australian landmass since Precambrian time. The Tasman orogenic terrain--itself largely a product of subduction of oceanic material relatively westward beneath Australia during Paleozoic time (Solomon and Griffiths, 1972)--trends northward in the subsurface and in infrequent outcrops to medial New Guinea, where it was apparently truncated by continental rifting early in Mesozoic time. During the Jurassic, Cretaceous, and early Tertiary, southern New Guinea formed the continental shelf bounding Australia on the north; the continental margin was mostly stable, and open ocean lay to the north. About the middle of the Miocene, however, the shelf was compressed as imbricate thrust faults drove southward, and a foreland basin formed along the southern margin of the deformed terrain,



receiving sediments from the newly uplifted region. Calc-alkaline volcanic and granitic rocks were erupted through the old shelf materials later in the Neogene. The old New Guinea shelf sediments are now bounded on the north by highly contorted deep-water terrigenous sediments, and those in turn are bounded by a broad belt of melange that includes such indicators of subduction as glaucophane schist. North of the melange are great masses of north-topping ophiolite (Davies, 1971). Still farther north, projecting through voluminous upper Neogene fill, are Upper Cretaceous, Paleogene, and lower Miocene andesite, basalt, diorite, volcanigenic and subordinate carbonate sediments, and locally, their metamorphosed equivalents.

This geology is interpreted to indicate that, as Australia and New Guinea moved northward in early Tertiary time, their north margin was a stable continental shelf, beyond which lay ocean floor which was being subducted beneath a south-facing island arc. The arc migrated southward as the continental plate moved northward, and they collided in Miocene time. The great ophiolite masses are the hanging wall of the arc; the voluminous melanges south of the ophiolites formed mostly as the subduction zone consumed the continental rise-and-slope sediments of New Guinea; and the volcanic rocks of northern New Guinea represent the volcanic island arc itself. After the collision, which inaugurated the deformation of the old shelf, the site of subduction shifted, and subsequent subduction was southward beneath the continent as enlarged by the accretion of the island arc. The late Cenozoic calc-alkaline volcanic rocks of interior New Guinea

formed above this new subduction zone, a short sector of which is now exposed in the melange beneath south-topping ophiolites of the north-coast Cycloops Mountains.

The Caroline Sea floor presumably opened behind this southward-migrating island arch. Appropriately, the basaltic crust of the central part of that sea has been dated by JOIDES drilling as of early or middle Oligocene age. The boundary between the Caroline Sea plate and the older Pacific floor farther east may be the Mussau system of wholly submarine troughs and ridges, which, if so, represents an extinct island arc.

The various arc and collision belts of New Guinea trend westward to the Geelvink Bay region, where they swing northwestward to truncations against the left-lateral, west-trending Sorong fault system of northern New Guinea. Far to the west, the Sula Islands consist of rocks like those truncated in northwestern New Guinea, including Mesozoic shelf sediments, from continental sources, lying unconformably upon basement quartz monzonite and schist (which are dated as of middle Paleozoic age in northwestern New Guinea). The Sula Islands apparently stand on a sliver of continental crust, carried 1000 km westward during late Tertiary time by a strand of the Sorong as the oceanic plate to the north vanished into the eastern Sulawesi subduction system.

The broad "eugeosynclinal" crescent of the "Northwest Borneo geosyncline" is interpreted to be a melange of Eocene age, formed by subduction southeastward beneath Borneo of voluminous abyssal, terrigenous quartzose sediments of Asian source. The southern and eastern belt of the crescent contains abundant indicators of subduction, including ophiolite, glaucophane schist, and polymict melange; fossils are of late Late Cretaceous and Paleocene or early Eocene age. Most of the remainder of the crescent, however, is formed of abyssal Eocene sediments alone, although broad terrains of these sediments are sheared into monoformal melange. Lying unconformably upon this melange(?) in the northwest is an Oligocene and Neogene section which was deposited in gradually shoaling water, and which is interpreted as the fill of an outer-arc basin formed on a melange basement.

Three Tertiary arc systems trend northeastward from northern Borneo into the southwestern Philippine Islands. The melanges of all three systems contain abundant quartzose sandstones, which must have had sources in Borneo or Southeast Asia inasmuch as richly quartzose materials are otherwise lacking in the Philippines. The eastern Sulu arc, only recently inactivated, comes ashore in the northeast as the Zamboanga Peninsula of Mindanao, and in the southwest as eastern Sabah, both terrains consisting of Miocene melanges flanked on the southeast by appropriate andesites. The Palawan arc, also at least partly of Miocene age, spans from the north tip of Borneo to Mindoro. An arc midway between Sulu and Palawan systems is represented by a submarine ridge, which comes ashore in the northeast as western Panay Island. The

products of these three arcs and of the Eocene melange terrain of northwestern Borneo all come together in northern Borneo, where spatial relationships are not obvious from available reconnaissance mapping.

The Philippine Islands consist of subduction melanges, calc-alkaline volcanic rocks of Benioff-zone source, and volcanigenic sediments, arrayed in patterns of baffling complexity. The melanges locally include rocks as old as Permian, but no data known to me require that any of the melanges themselves, or any of the calc-alkaline volcanic rocks, have formed before Late Cretaceous or very early Tertiary time. The bulk of the southern Philippines appears to represent the products of the three northeast-trending arcs noted in the previous paragraph, of the Sangir arc system trending northward to southern Mindanao, and of the Mindanao trench system. Complications are provided by minor trench systems, possibly still active, along the southwest margins of Mindanao and Negros. The great Mindanao trench system ends northward east of the central Philippines, and the Manila trench continues northward on the opposite side of the island group. Between the north end of the Mindanao trench and the south end of the Manila trench, a broad, sigmoidal double orocline serves to transform lateral motion across the Philippines.

Southeast Asia, Sumatra, and westernmost Borneo were part of Asia by Cretaceous time, but their earlier history included Paleozoic and Triassic subduction and aggregation of continental fragments, and middle Mesozoic rifting. Indochina is bounded against the old platform of southern China by the Red River terrain, which records late Paleozoic and Triassic subduction beneath the Indochinese side until the two plates collided. The melange and magmatic-arc belts of this terrain trend southeastward to a truncation, presumably by rifting, against the South China Sea. A Cretaceous magmatic arc is overprinted, with northeastward trend, across the truncated end of the older system in southeastern Indochina. Another late Paleozoic or Triassic suture is indicated by polymict melanges exposed discontinuously from northern Thailand through southeastern Thailand to southwestern Cambodia. Ambiguous data suggest that this latter suture may also trend southward through medial Malaya to central Sumatra, where it is truncated obliquely against the Indian Ocean; in any case, west-central Sumatra was part of a stable continental platform in Permian and Triassic time. In Burma, westward growth of the continental mass by accretion of subduction melanges is displayed by the late Mesozoic and early and middle Tertiary complexes which become younger westward. The youngest Burmese melanges, those of the Arakan coast, trend southward into the outer-arc ridge of the Andaman-Nicobar-Sumatra subduction system.

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