Tectonics of the Indonesian Region*

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Abstract: The plate-tectonic evolution of a region can be deduced by following the assumptions that subduction zones are characterized by ophiolite, melange, wildflysch, and blueschist, that intermediate and silicic calc-alkaline igneous rocks form above Benioff zones, and that truncations of orogenic belts indicate rifting. Interrelatioships provide crosschecks, as do marine geophysical data.

Southeast Asia and "Sundaland" are an aggregate of small continental fragments. Late Paleozoic subduction westward beneath Malaya and Thailand (recorded by granites in eastern Malaya, and by melanges in western Laos and Cambodia) ended when Indochina collided with them. Early and Middle Triassic subduction was eastward, beneath the west side of the aggregate. Late Triassic and Jurassic subduction from the north ended in collision of the aggregate with China. Early Cretaceous subduction was again from the west. Late Cretaceous subduction was beneath the east side of the aggregate and followed continental rifting there. Cenozoic subduction, from the west once more, ended in the north when the aggregate collided with India, but subduction still continues in the south. Borneo similarly reflects changing subduction patterns.

The Philippines, Sulawesi, and Halmahera consist wholly of upper Mesozoic(?) and Cenozoic island-arc subduction and magmatic complexes and lack old continental foundations. The scrambled fragments of the Philippines came from several arc systems, including two extending to Borneo. Sulawesi and Halmahera record primarily subduction from the east and may be rifted and contorted fragments initially continuous with southeast Borneo and central Java.

In the early Tertiary, Australia and New Guinea, which then had a stable-shelf northern margin, moved northward until they collided with a southward-migrating island arc, behind which had formed the Caroline oceanic plate. Late Cenozoic tectonics in New Guinea have been dominated by southward subduction fo the Caroline oceanic plate beneath the Australian New Guinea continent, and by left-lateral strikeslip faulting. Such faulting tore the Sula Islands from northwest New Buinea and carried them to Sulawesi.

The islands of the outer Banda arc are formed of melanges of the shallow-water sediments of the New Guinea and Australian continental shelf, which is now disappearing beneath the active arc.

INTRODUCTION

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-north-westward (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 ACTIVE WESTERN AND SOUTHERN MARGINS

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 mélanges probably formed mostly in Miocene time. The distance from ridge to trench therefore 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, in both eastern and western sectors of the subduction system, voluminous sediments yield voluminous low-density mélanges, 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 which are generally 3–7 km thick along the basin axis.
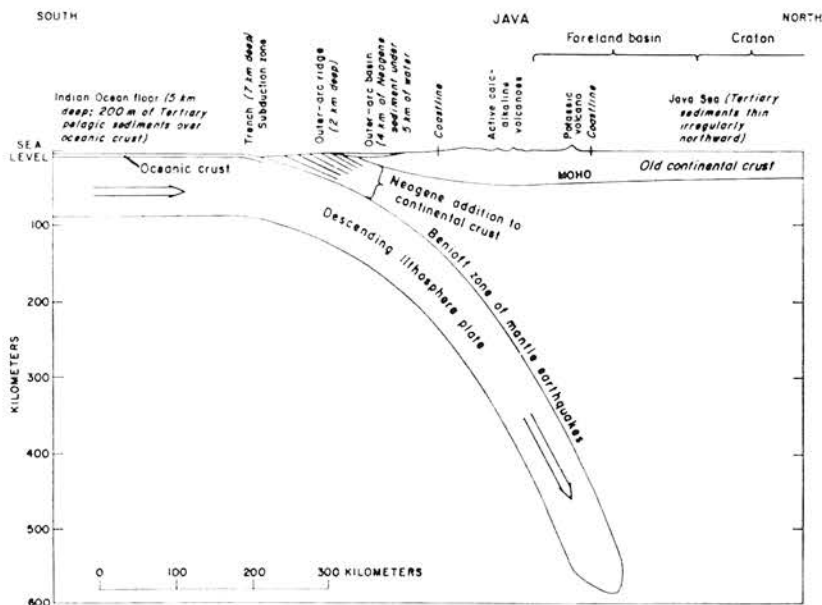
Fig. 1.   Generalized section through central Java, along the meridian of 111° East, showing the relationship of tectonic and magmatic zones to the Benioff seismic zone (which is located from data by Fitch, 1970).

The Holocene volcanic rocks erupted above the present Benioff zone show the usual correlation of ratios of potassium to silicon with depth to the 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 ACTIVE AND INACTIVE SUBDUCTION SYSTEMS

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-southeastward 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 one. 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 to the other. Geologic and seismic data suggest that along northeastern New Guinea, a subduction zone dipping moderately south under New Guinea is now overriding one 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 Palawan and nearby Borneo. The Yap trench is now almost inactive—Yap Island is formed mostly of Miocene mélange—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 on-shore geology. Many subduction zones are recorded by tectonic mélanges—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 mélanges. 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 mélanges 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 mélanges 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 NEW GUINEA REGION

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 mélange that includes such indicators of subduction as glaucophane schist. North of the mélange 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 andesites, basalts, diorites, 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 mélanges 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 mélange beneath south-topping ophiolites of the north-coast Cycloops Mountains.

The Caroline Sea floor presumably opened behind this southward-migrating island arc. 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.

BORNEO AND THE PHILIPPINES

The broad "eugeosynclinal" crescent of the "Northwest Borneo geosyncline" is interpreted to be a mélange 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 mélange; 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 monoformational mélange. Lying unconformably upon this mélange(?) 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 mélange basement.

Three Tertiary arc systems trend northeastward from northern Borneo into the southwestern Philippine Islands. The mélanges 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 mélanges 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 the 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 mélange 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 mélanges, calc-alkaline volcanic rocks of Benioff-zone source, and volcanigenic sediments, arrayed in patterns of baffling complexity. The mélanges locally include rocks as old as Permian, but no data known to me require that any of the mélanges 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.

RELATIONSHIP TO ASIA

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 mélange 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 mélanges 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 mélanges is displayed by the late Mesozoic and early and middle Tertiary complexes, which become younger westward. The youngest Burmese mélanges, those of the Arakan coast, trend southward into the outer-arc ridge of the Andaman-Nicobar-Sumatra subduction system.

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NOTE ADDED IN PROOF

Remarkable oil-company deep-penetration seismic reflection profiles, including those of the landward slope of the Java trench presented and discussed by R.H. Beck

(Australian Petrol. Explor. Assoc. Jour., 1972, v. 12, pt. 2, p. 7–28), demonstrate that the formation of subduction melange involves much more than the simple shearing of material between oceanic and continental or island-arc plate. Where voulminous mélange is present, the top of the subducting plate is marked by oceanic basement, or by strongly reflecting sediments atop the plate, dipping very gently from the trench to a position approximately beneath the outer-arc ridge. An oceanward-thinning wedge, its top being the continental slope, of deformed, low-velocity sediments lies above this gently dipping plate. The wedge consists of mélange, as shown by its exposures on outer-arc-ridge islands such as Nias and Timor. The profiles show that the wedge is imbricted internally along shear planes dipping typically at moderate angles away from the trench. Shearing within the wedge is at a sharp angle to that in the zone of uncoupling between the wedge and the top of the subducting plate. Apparently the wedge spreads gravitationally seaward, its internal deformation accomplished primarily by imbrication and secondarily by downslope slumping and other processes, as the subducting plate slides beneath it and drags its base landward. The mélange wedge is a sort of standing wave, spreading forward at the same speed as it is being dragged back. The main source of sediment in many mélange wedges probably is the outer-arc-basin, which lies at the back of the wedge, rather than the deep ocean floor in front of the wedge.

The process of continuous imbrication provides a mechanism to raise metamorphic rocks formed deep in the system, and also slabs sliced from the subducting plate, to the surface of the wedge, and to thoroughly mix rocks of diverse ages and environments of formation. Extreme shearing of gentle dip occurs at the base of the wedge at the same time that shearing of steeper dip is distributed broadly throughout much of the rest of the wedge. A given mass of rock could be cycled repeatedly from base to top of the wedge. Sediments deposited on top of the wedge will gradually become imbricated into it, the degree of deformation and disruption tending to increase with age of the sediment.

Where such a mélange wedge is present, the gentle inclination of the subducting plate, and hence the trench itself, appears to be produced by down bowing by the weight of the wedge. Approximately beneath the outer-arc ridge, as shown by earthquake locations, the subducting plate steepens markedly and planes down into the mantle. This inflection to a steeper dip marks the fundamental plate boundary. Where, as in open-ocean island arcs, sediments are in short supply and little mélange is formed, no wedge is present, and the trench sides are much steeper and expose directly the fundamental, steep downturn of the subducting plate, and the front of the overriding plate. Bedrock configuration beneath the outer-arc ridges of mélanges-wedge systems may resemble that exposed in the open-ocean trenches.

The interpretation of the Sangir arc-Molucca Sea-Halmahera region presented in the preceding text is shown to be erroneous by newly available reflection profiling and by earthquake-location data. Althought the Mindanao trench contines southward as a major bathymetric feature to central Halmahera, no apparent Benioff zone of mantle earthquakes dips westward from it south of Mindanao: subduction may have ceased along this structure south of the Philippines. The earthquakes in the latitudinal sector between Mindanao and Halmahera roughly define two Benioff zones, one dipping moderately west to great depths beneath the Sulawesi Sea, the other dipping more gently east to lesser depths beneath Halmahera. The volcanoes of the Sangir island arc belong to the west-dipping system, and the active Halmahera volcanoes belong to the west-dipping system, and the active Halmahera volcanoes belong to the east-dipping

system, to judge by their heights above the seismic zones. The two seismic zones inter-
sect at a depth of perhaps 50 km beneath the western Molucca Sea, near the east side
of the Sangir arc. Reflection profiling indicates that the subduction reaching the surface
dips eastward, hence belongs to the Halmahera system, which thus has overridden the
west-dipping Sangir system. The northern Sangir arc has a subduction-type trench
along its west side, so the active trace of eastward-dipping Halmahera-system sub-
duction may have there jumped to the west side of the Sangir ridge.

The interpretation presented in this paper regarding the relationship of Palawan
to Borneo is also now seen to be in error.