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TECTONIC MAP OF INDONESIA--A PROGRESS REPORT

by

Warren Hamilton
U. S. Geological Survey

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1. Tectonic map of Indonesia--a progress report, by Warren Hamilton. 29 p., 2 figs.

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TECTONIC MAP OF INDONESIA--A PROGRESS REPORT

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INTRODUCTION

Orogeny, volcanism, and seismicity are now intensely active in Indonesia. Many Dutch tectonists--Brouwer, Umbgrove, van Bemmelen, Smith Sibinga, Vening Meinesz, Westerveld, and others--recognized that this complex cluster of islands represents an early stage in the evolution of orogenic belts. Not until Indonesia is understood can we comprehend the Alps.

This report summarizes some aspects of work to date on the Tectonic Map of Indonesia. The preparation of this map is a joint project of the Geological Survey of Indonesia and the United States Geological Survey, sponsored by the Government of Indonesia and the United States Agency for International Development.

The Tectonic Map of Indonesia will be published at a scale of 1:5,000,000. Adjacent regions in other countries will be included to provide a broader context. The map limits presently envisaged are the parallels of 12° N. and 15° S., and the meridians of 91° and 148° E. Tectonic features will be shown in many colors and patterns. Bathymetry is being newly compiled, and will be shown with contours and shades of blue. Figure 1 shows the islands of Indonesia.

THE PLATE-TECTONIC MODEL

The explosion of data and concepts from marine geophysics during the late 1960's resulted in the placing of island arcs and continental drift into the context of newly-developed views concerning plate tectonics and ocean-floor spreading. The independent approaches of geomagnetism, paleomagnetism, seismology, tectonic analysis of bathymetry, and deep-ocean drilling have converged sharply upon a single explanation. According to this explanation, the earth's crust is fragmented into about a dozen large plates and many small ones, all of which are moving relative to all others. Mid-ocean ridges are present where plates are pulling apart; strike-slip faults occur where plates slide past one another; and inclined Benioff zones of mantle earthquakes mark the sliding of oceanic plates beneath either continental plates or other oceanic plates. The velocities of underflow along Benioff zones reach at least 10 cm/yr, or 100 km/10^6 yr. Important papers developing these concepts include Heirtzler and others (1968), Isacks and others (1968), Le Pichon (1968), McKenzie and Morgan (1969), and Morgan (1968). The impact of plate tectonics upon continental geology has been discussed by Coney (1970), Dewey and Bird (1970), Dickinson (in press), Ernst (1970), Hamilton (1969a,b; 1970), and others. Applications of plate tectonics to Indonesia in particular has been made by Fitch (1970) for seismology and by Hatherton and Dickinson (1969) for petrology of active volcanoes.

The systematic relationship of the active tectonic and magmatic features of Indonesia to the deep submarine trenches was early recognized by the Dutch geologists. We now visualize that these trenches mark the downturns of oceanic plates beneath other plates. Where that downturn occurs at the edge of a continental plate, as along Sumatra and Java, the following zones are obvious, listed in order inland from the trench:

1. The zone of subduction (underflow).
2. The magmatic zone.
3. The foreland basin.

These zones are characterized briefly below, and their relationship to the Benioff zone is shown schematically in figure 2.

1. The presently active subduction zone lies beneath the sea and can be studied only indirectly. Acoustic profiling across other trenches shows such zones to be marked at the surface by underthrusting and deformation of the trench-filling sediments. A characteristic of trenches seen in profiling is that the acoustically transparent pelagic oozes of the open ocean, which lie upon oceanic crust, continue beneath the terrigenous and volcanic sediments of the trench: the oceanic conveyor belt carries crust and pelagic sediments to the trench, where they are covered by trench sediments before they disappear beneath the continental slope. The study of fossil subduction zones in Cenozoic and late Mesozoic eugeosynclinal terranes in Indonesia and elsewhere shows that these zones can be recognized by geologic criteria. Subduction zones consist of tectonically chaotic deposits that typically include sections of oceanic upper mantle (alpine ultramafic

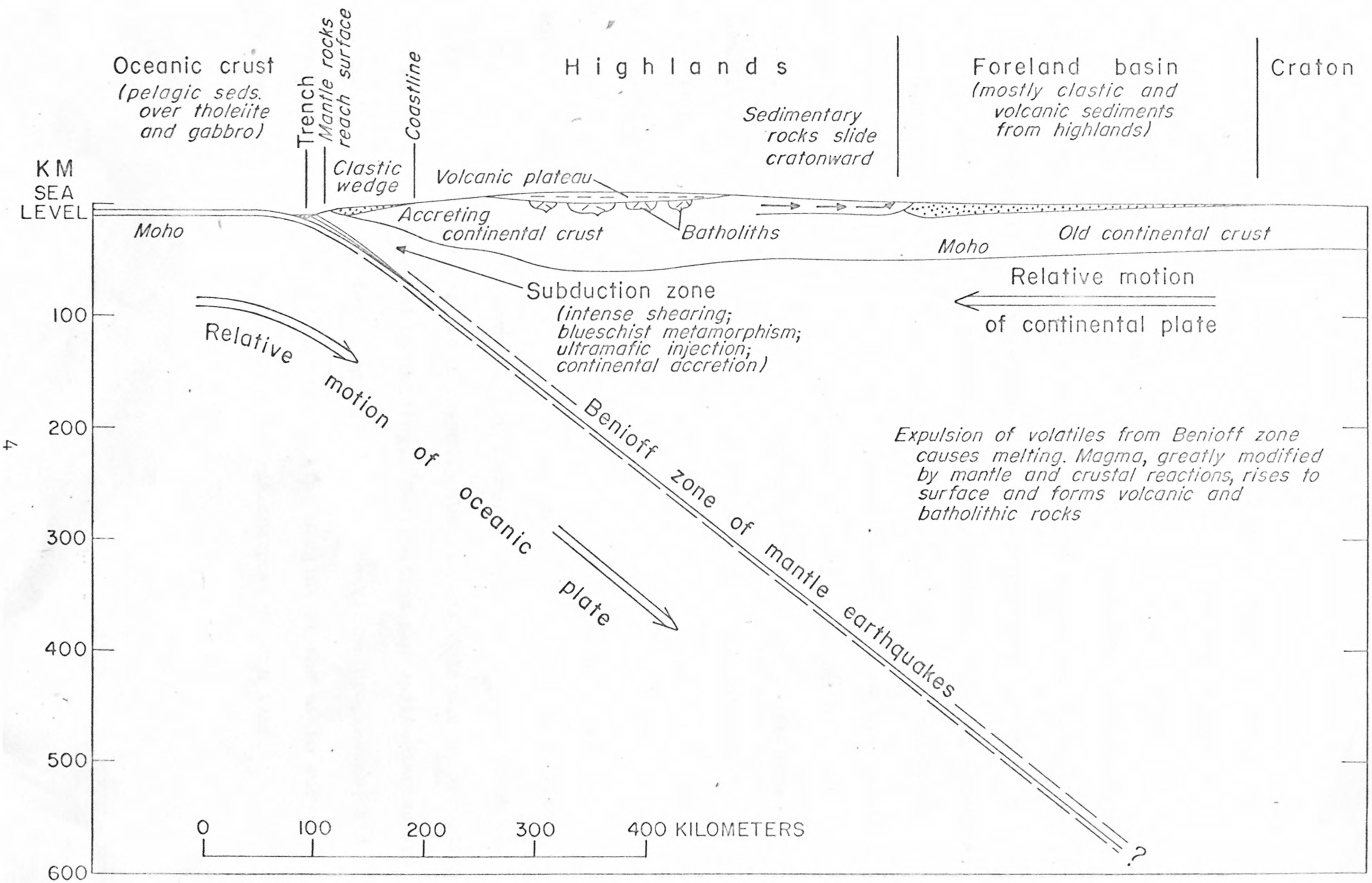


FIGURE 2. Schematic diagram of relation of zone of subduction, magmatic zone, and foreland basin to Benioff zone.

rocks), crust (serpentine, and gabbro and basalt dominantly of abyssal-tholeiite composition), and deep-ocean pelagic sediments (lithified calcareous, siliceous, and clayey oozes). Trench materials are represented by almost unfossiliferous clastic and volcanigenic sediments, although shallow-water deposits can be added by slumps and turbidites. Slices of metamorphic rocks include prehnite-pumpellyite, greenschist, and blueschist facies; the blueschists record tectonic churning to depths of perhaps 30 km. These diverse materials are shingled together in highly sheared complexes which may dip systematically landward near the fossil trench, but which are much contorted farther inland.

(2). The igneous belt of the active Indonesian arc of Sumatra and Java is marked by intermediate and silicic calc-alkaline volcanism. The compositions of the rocks become systematically more potassic inland. Granitic batholiths presumably are now forming beneath the volcanic belt.

(3). The foreland basin is filled by clastic and volcanigenic sediments, derived primarily from the volcanic highlands and deposited in continental or shallow-marine environments. The basin fill thins toward the continental platform beyond. The fill is deformed by thrusting from the highland side and by folding. Deformation and sedimentation are concurrent: folds and faults grow as the sedimentation progresses, and control the details of sedimentation. The margins of the basin and of the severe deformation within it progress cratonward with time.

Where the subduction is of one oceanic plate beneath another, as is the case now around the Banda Sea, an island arc is present. The island-arc subduction zone is similar to that of the continental margin, except that nonvolcanic clastic sediments are of minor abundance. The volcanic arc consists of calc-alkaline rocks similar in composition to those of the continental-margin system, but bulk compositions are markedly more mafic--high-alumina basalt, andesite, and dacite, instead of andesite, dacite, and rhyodacite--than are those of continental-margin rocks. The foreland basin of the continental-margin system is not present behind the island arcs, and it is not yet possible to characterize the deep-ocean terranes behind the arcs.

Indonesia consists largely of terranes similar to these which can now be seen in the process of formation. The tectonic map is being prepared upon the presumption that such fossil terranes record processes analogous to those now acting.

The geophysical data upon which the concept of plate tectonics is based indicate that, relative to Asia, the Indian Ocean and Australia have moved something like 3,000 km northward, whereas the Pacific Ocean floor has moved a similar distance westward, within Cenozoic time alone. The active and past tectonic patterns of Indonesia record some of the shifting, swirling zones along which this enormous motion has been absorbed by subduction and other processes.

MAP PREPARATION

The tectonic map is based primarily upon the identification of tectonic belts of these types in terranes of all ages. As most of the geologic literature on Indonesia and neighboring regions represents only very sketchy reconnaissance, the problems are many. It has been necessary to review the primary literature to obtain as much as possible of the needed petrologic and structural details, and to permit analysis of evidence for age and other parameters. It has also been necessary to compile a new geologic map from primary sources. Secondary sources, including the Geologic Map of Indonesia by Klompé and Sigit (1965) and the compendium by van Bemmelen (1949), are very valuable, but are too generalized and too far removed from the original descriptions to be used directly for the identification of tectonic belts in most regions. Primary and secondary sources alike abound in assumptions that once were widely accepted but that now appear to be unsound.

The plate-tectonic model requires that parallel belts develop together, and that each belt should have systematic cross-strike variations, so there are many internal checks upon the interpretations as they are developed. Conversely, the interrelationships between and across belts provide valuable clues for the resolution of ambiguities.

Plate-tectonic concepts indicate that classical theories of orogeny are largely in error. There is no "geosynclinal cycle;" rather, a stable continental margin will sooner or later become an orogenic margin, either by the formation of a new subduction zone at the margin, or by the collision of the continent with a subduction zone in front of an island arc (Coney, 1970; Dickinson, in press). Orogeny is not periodic; plate boundaries are forever changing, and subduction shifts from one site to another, but global motion continues. There is no "eugeosyncline" in the sense of a filled downwarp; rather, there is a continental-margin zone of accretion of oceanic materials from the oceanic conveyor belt, enlarged by arc volcanism (Hamilton, 1969a, 1970). Batholiths are the plutonic phase of arc volcanism and are causes, not products, of crustal metamorphism (Dickinson, in press; Hamilton, 1969b).

King (1969b) recently summarized all prior systems of tectonic maps. Some systems, notably including those by Soviet tectonists (Eurasia: Yanshin, 1966; USSR: Spizharskiy, 1966), are wholly built around assumptions regarding the inevitably progressive nature of magmatism, sedimentation, and orogeny, and cannot be readily adapted to a map compiled on the basis of plate-tectonic concepts. Other systems, including those of the North American (King, 1969a) and Canadian (Stockwell, 1969) tectonic maps, although also in part wedded to assumptions regarding orogenic cycles, place much emphasis on the recognition of paleotectonic environments for units, and hence are basically compatible with a plate-tectonic approach.

The new concepts nevertheless require a new method of tectonic map depiction. The problem is to convey simultaneously the characteristics, the environment of initial formation, and the subsequent history of each major lithologic and structural unit. Various schemes of illustration incorporating dull and bright colors and overprinted patterns in both black and contrasted colors are being devised and tested. The relationships within Indonesia are so complex that a satisfactory depiction is not easily achieved. The geographic patterns of subduction and related phenomena have changed complexly with time, shifting from one part of a belt, but not from another part, to a new site: belts are only in part correlative when followed along strike. Old belts have been deformed and fragmented, and fragments have been swept against unrelated terranes as intervening ocean floor disappeared down subduction zones.

The units depicted are objective ones. Although the interpretative framework is that of plate tectonics, the units themselves are defined on the basis of concrete compositional, structural, and paleoenvironmental criteria that can be applied wherever geologic data are available. A major goal is to preserve this objectivity in the final tectonic map--to illustrate rocks as well as interpretations, and to show surface geologic contacts rather than hypothetical zone boundaries.

Fold axes or trends, faults identified as to type, structure contours on basement rocks, type of metamorphism, active volcanoes, and contours of depth to active Benioff seismic zones, are among the features to be shown on the map.

Petroleum exploration is underway in the continental shelf of the Indonesian region by various concessionaire oil companies. Extensive deep-penetration acoustic profiling has been done, and many exploratory wells have been drilled offshore. It is hoped that generalized data from these operations can be incorporated in the tectonic map.

SAMPLE INTERPRETATIONS

The evolution of each of the islands of Indonesia has been interpreted, in terms of the plate-tectonic model, from published data. The following short essays on the tectonics of New Guinea, Sulawesi, and Java illustrate the approach and criteria used, and provide representative conclusions that follow from the interpretations.

New Guinea

The geology of Indonesian New Guinea (Irian Barat) is known primarily through the petroleum-exploration studies summarized by Visser and Hermes (1962). Modern work in small parts of the territory includes that by Dow (1968), and Valk (1962). Early work was summarized by Zwierzycki (1928, 1932).

The main mass of west New Guinea--that from the neck near the 135th meridian east to the border of Australian territory at 141°--consists of east-trending tectonic belts, characterized here from south to north:

Foreland basin. The southern lowlands, site of active sedimentation, receive continental and shallow-marine clastic sediments from the north. Depth to basement of the Australian platform deepens northward, from sea level across northern Australia to 2 or 3 km at the south coast of west New Guinea and 6 km or so at the edge of the imbricate belt.

Imbricate belt. Southward-directed imbricate thrust faults and associated folds, which expose progressively older strata in north-dipping slices northward in the southern slopes of the Central Highlands. The latest Miocene to late Pleistocene clastic sediments of the foothills comprise the deformed margin of the foreland-basin facies. Early Tertiary and early and middle Miocene sediments are in carbonate-shelf facies; Jurassic, Cretaceous, and earliest Tertiary are in clastic-shelf facies, derived from the south; and the poorly known Silurian to Permian (and possibly Triassic) rocks are in mixed carbonate and clastic platform or shelf facies. Until late Miocene time, there was open water to the north of the belt.

Medial plateaus of the Central Highlands. Jurassic through middle Miocene shelf sediments, mostly gently dipping but broken by faults whose character is not yet adequately defined.

Metamorphic belt of the northern slope of the Central Highlands. Mostly greenschist and phyllite, but includes glaucophane schist (Verhofstad, 1966). Dips are steep in either direction.

Ultramafic and mafic belt of the northern edge of the Central Highlands. Serpentine, peridotite, and gabbro; basalt is at least locally present within the main belt, and forms extensive masses along its north edge.

Quaternary basin of the Meervlakte, receiving clastic sediments from both sides.

Northern Divide Ranges. The southern half exposes mostly gently folded Pliocene bathyal clastic sediments and Pleistocene continental and shallow-marine clastics, whereas the northern half exposes similar strata tightly interfolded and faulted with middle Tertiary volcanics and deep- and shallow-water sediments. Uplifts expose ultramafic, mafic, and metamorphic basement rocks, overlain by abyssal pelagic carbonate and silicic sediments representing various ages from Late Cretaceous to early Miocene.

North coast basin is receiving sediments now, and Pleistocene strata are exposed primarily in anticlines.

Cyclops Mountains basement rocks project through Quaternary strata at the east end of the north coast, and expose these belts in northward succession: volcanic and sedimentary rocks; gabbro; peridotite; and metamorphic rocks, including glaucophane schist.

The following history is interpreted from the characteristics of these belts:

(1). From Silurian through middle Miocene time, southern New Guinea was part of a stable platform. At least the upper Mesozoic and Tertiary sediments represent the northern edge of the stable continental shelf of Australia.

(2). Beginning in the late Miocene, these shelf sediments have been uplifted and thrust southward. A foreland basin has developed concurrently to the south of the highlands and is still being overridden by the growing thrust faults. The thrusting does not involve the basement, and may represent gravitational spreading of the highland region by mechanisms such as those deduced by Price and Mountjoy (1970).

(3). The north slope of the Central highlands consists of, in order northward, schists including blueschist, ultramafic and gabbroic rocks, and basalt. This is the succession anticipated for a north-dipping subduction zone, wherein the schists record the zone itself, and the ultramafic and mafic rocks are the oceanic mantle and crust of the hanging wall.

It is inferred that the oceanic plate which lay north of the continental shelf vanished down a north-dipping subduction zone beneath an island arc until, in late Miocene time, the continental slope and outer shelf collided with the arc and were crumpled against it. (A similar interpretation has been made for the eastern end of the island by Davies, 1968.)

(4). The Cyclops Mountains expose a similar succession but in the opposite direction. A south-dipping subduction zone is inferred to have operated there, perhaps after the collision involving the island arc to the south.

(5). The basement uplifts of the Northern Divide Ranges are of Late Cretaceous and early Tertiary oceanic crust and mantle and of subduction-zone materials. Available data do not permit detailed interpretations. Tectonic thickening has given these oceanic materials, plus the thick overlying rocks, a continental crustal thickness.

(6). The middle Tertiary to early Pleistocene sedimentary and volcanic rocks of the Northern Divide Ranges represent many environments, including abyssal pelagic sediments, island-arc volcanic rocks and volcanigenic sediments, and clastic sediments derived from new highlands along the accreting continental margin.

(7). Active subduction along northern New Guinea stopped within Pleistocene time, but compressive deformation in the newly continental mass is continuing.

The belts of the foreland basin and Central Highlands swing northwestward into Vogelkop (far northwestern New Guinea), where they are truncated obliquely on a regional scale against the left-lateral, active, west-trending Sorong strike-slip fault. The fault is marked by a broad zone of sheared rocks and juxtaposed slivers of diverse rock types, and has a displacement of more--possibly much more--than 350 km according to Visser and Hermes (1962). Carey (1958) and Krause (1965) argued for the presence of huge left-lateral strike-slip faults along northern New Guinea, both onshore and offshore. These structures have recently been put in the context of plate tectonics; they are transform faults, along which the relatively westward motion of the Pacific Ocean plate is stepped from the Tonga-Kermadec subduction zone to the subduction zones of the Marianas and the Philippines.

Sulawesi

The island of Sulawesi (Celebes) consists of two arcs, mostly convex toward the west, joined in the middle by land but separated at both ends by deep water. The western arc consists largely of volcanic, granitic, and metamorphic rocks of the types that form above Benioff zones, whereas the eastern arc exposes subduction complexes. The northeast end of the western arc is marked by active volcanoes in a chain that continues northward to Mindanao as the Sangir island arc; an active Benioff zone dips westward beneath these volcanoes. The geology of the rest of Sulawesi is interpreted as recording subduction zones active during late Mesozoic and Tertiary time.

Information on the geology of the western arc has been given by Brouwer (1934, 1947), Egeler (1947), 't Hoen and Ziegler (1917), Koperberg (1929), von Steiger (1915), and others. Volcanic rocks and intercalated sediments are of various Late Cretaceous and Tertiary ages. Deep-water pelagic Cretaceous sediments may have formed early in the submarine volcanic history of the arc. Tertiary sediments are mostly of shallow-water and continental origin. Exposed granitic rocks cut strata at least as young as Eocene. Recognizable volcanic landforms indicate that volcanism became extinct in parts of the western arc only within very late Cenozoic time. Two active strike-slip faults are inferred by Katili (1970) to cross obliquely through the western arc.

The east arc of Sulawesi may be a composite of two major subduction complexes. The western one dipped eastward, the eastern one, westward.

The western of these two subduction complexes contains a broad western belt characterized by widespread glaucophane schists (de Roever, 1947, 1956; Willems, 1937). These rocks are interspersed with little-metamorphosed sediments, mostly pelagic, which are of Mesozoic age where dated, and with mafic and ultramafic igneous rocks; the complex is a tectonic mélange, much sheared and brecciated (Bothé, 1927; Brouwer, 1947; Dieckmann and Julius, 1925). East of this terrane is a belt dominated by peridotite and serpentine. The glaucophanitic mélange is inferred to have formed in a subduction zone which dipped eastward beneath the hanging wall of the great mass of ultramafic rocks.

The eastern of the two subduction zones is exposed mostly in the east arm--the north half of the eastern arc--of Sulawesi. Kündig (1956) presented a study of the geology of this zone which can easily be rephrased in subduction-geology terms. The tectonic units recognized by him can be carried along strike through the area studied by von Lóczy (1934), who had an unusually keen awareness of structural relationships. Going southeastward across strike from the large ultramafic mass that is inferred here to belong to the complex mentioned in the previous paragraph, the following zones are present:

1. A northwest-dipping mélange of intersheared serpentine, peridotite gabbro, basalt, and thin abyssal-pelagic sediments of Late Jurassic and and Early Cretaceous ages.

2. A similar but younger mélange, also dipping consistently northwestward, in which the abyssal-pelagic sediments are Eocene to lower Miocene. The southeast part of this zone contains shallow-water sediments of the same age; they are not involved in the imbrication according to Kündig, and their tectonic position is unclear.

3. A narrow basin filled by shallow-water clastic sediments of Pliocene age, which postdate the mélange and are only moderately folded.

4. Undated metamorphic rocks and pink biotite granite overlain by upper(?) Miocene and younger shallow-water limestone (Koolhoven, 1930; these rocks are present in the nearby Banggai Islands, not on Sulawesi itself).

The history of the eastern arc of Sulawesi is ambiguous, but the following is suggested. An eastward-dipping subduction zone existed in Mesozoic (Jurassic?) time. Deep water is now present east of Sulawesi where the accompanying volcanic-and-granitic belt might be expected, so this igneous belt if indeed once present has been removed tectonically. From Cretaceous until early Miocene time, a subduction zone dipped westward from the east margin of Sulawesi, and the island was widened eastward by accretion of oceanic materials in that zone. Magmatism in the western arc of the island accompanied this activity. In about middle Miocene time, the small continental fragment of the Banggai Islands, derived from an unknown site, was swept against the subduction zone. Subduction stepped to the outboard side of the Banggai Islands, and subduction zones younger than early Miocene are still hidden beneath the sea. Subduction continued along much of eastern Sulawesi until well into Pleistocene time, although subduction now is limited to the northern sector.

Java

Java exposes mostly late Cenozoic materials related to the present tectonic system. The very active volcanoes of the island show the northward increase in potassium-silicon ratios expected from their position over a northward-dipping Benioff zone (Brouwer, 1928; Hatherton and Dickinson, 1969). The active calc-alkaline volcanic belt is superimposed upon older volcanic rocks, intercalated with Miocene and younger sediments and intruded by granitic rocks, of similar composition; the tectonic system has not shifted greatly during late Cenozoic time.

The shallow-water and continental Neogene fill of the foreland basin of northern Java thins northward, and is deformed by northward-directed thrusts and overturned folds (~~Ringkasan~~ Koesoemadinata, 1963). The lower Neogene clastic sediments were derived in large part from crystalline sources to the north, whereas the upper Neogene is mostly volcaniclastic and derived from the south (Rutten, 1926). The stratigraphic level of the lower limit of abundant volcanic material becomes progressively younger northward (Rutten, 1926); progressive basining, the sedimentary axis migrating northward as folds developed in the south, seems indicated. Dips in anticlines become progressively more gentle with decreasing age of the sediments, but even late Quaternary materials are deformed (for example, see Duyfjes, 1938): folds have grown steadily during sedimentation, and there have not been distinct brief episodes of folding.

Pre-Eocene rocks, exposed beneath Eocene shallow-water sediments in a small area in central Java, have been described by Harloff (1929a,b, 1933), Loth and Zwierzycki (1926), and Tjia (1966). The south-dipping complex of old rocks appears to be a subduction mélange of Late Cretaceous or very early Tertiary age. Highly sheared rocks of widely diverse types are chaotically intercalated. These rocks include coarse glaucophane schist, greenschist, eclogite, phyllite, basalt, gabbro, peridotite, serpentine, marl and limestone containing Upper Cretaceous or early Tertiary Foraminifera, and undated slate, shale, graywacke, and red radiolarite.

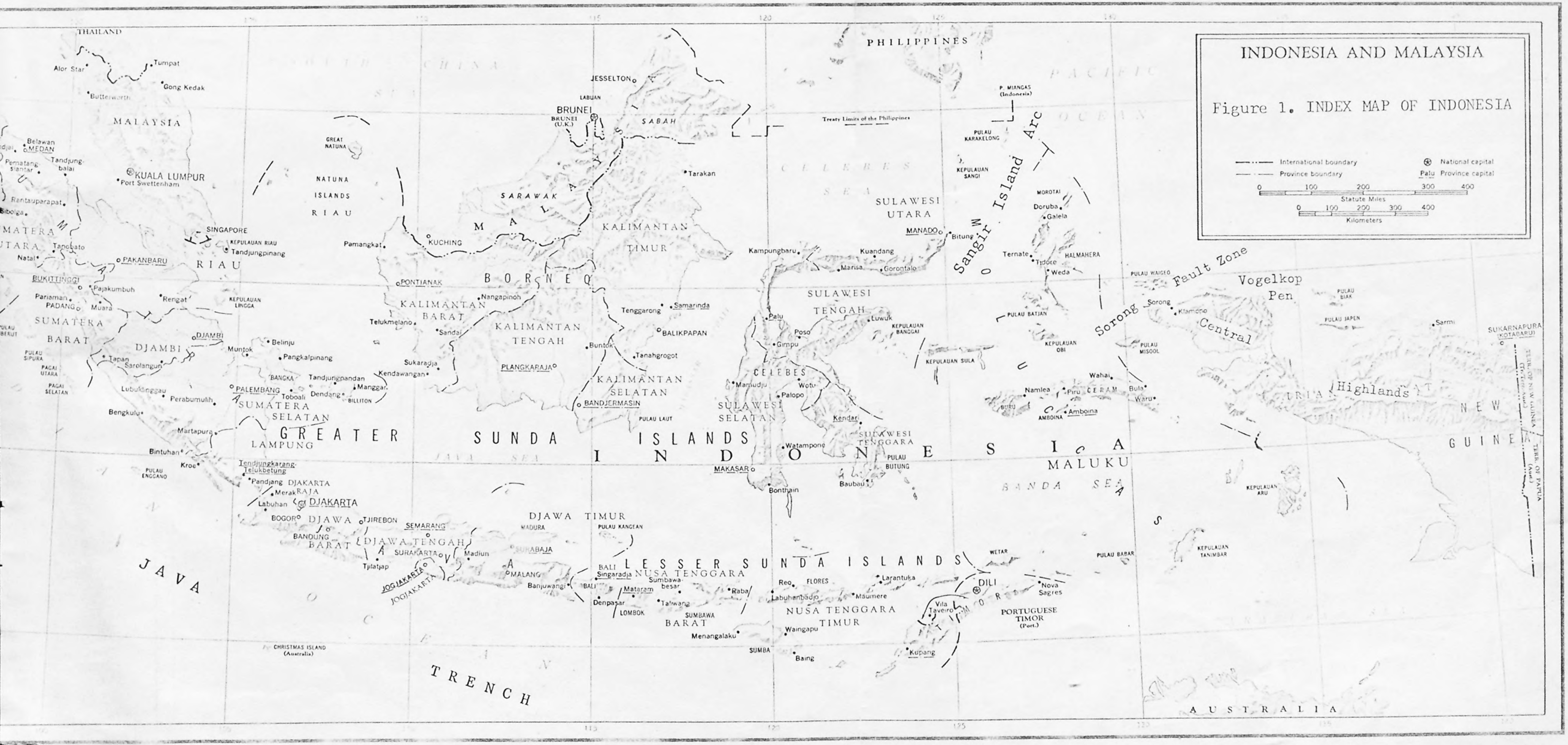
The presently active subduction zone lies low on the landward slope of the Java Trench, 200-250 km south of the Java coast. That slope rises to a submarine ridge, 50 km closer to Java and separated from it by a broad basin. The ridge forms islands along strike southwest of Sumatra, although not along Java itself. Van Bemmelen (1949, p. 162-177) summarized the otherwise unpublished geologic information on these islands from petroleum explorations. The islands consist of Miocene and younger bathyal to shallow-water clastic and carbonate sediments, lying unconformably upon highly deformed, oceanward-thrust complexes of clastic sediments, low-grade metamorphic rocks, and subordinate mafic and ultramafic igneous rocks. The old clastic rocks are almost nonfossiliferous but have locally yielded lower Tertiary (Oligocene?) arenaceous Foraminifera. The islands and the ridge from which they rise are inferred to consist of subduction complexes that were formed in early Tertiary time.

The inferred fossil and active subduction zones of Java and the submerged region south of it become younger southward: Late Cretaceous or very early Tertiary in southern Java, Oligocene(?) in the ridge 200 km farther south, modern in the trench another 50 km southward. This progression is interpreted to indicate accretion of the submerged continental margin by the scraping off against it of sedimentary and crustal materials from the underflowing oceanic plate. The accretion has proceeded at an average rate of something like 2 $km/10^6$ yr, whereas the rate of underflow of the oceanic plate has been at least 50 $km/10^6$ yr.

Middle and upper Eocene and Oligocene strata are known in small areas south of the midline of western and central Java. In several places subduction complexes, including the one noted previously, are exposed beneath these sediments. The lower Tertiary strata are variously clastic, carbonate, and tuffaceous, and are mostly of shallow-water origin (van Bemmelen, 1949, p. 103-106). The paleotectonic setting of the lower Tertiary rocks is not obvious from the data available, but an origin in a basin like that now present between Sumatra and Java and their offshore ridge would be consistent with other interpretations made here.

Remarks

Integration of such interpretations for all of the islands of Indonesia provides a picture of extremely complex evolution. Late Cretaceous to modern subduction zones appear to have been approximately parallel in and south of Sumatra and western Java, but the Late Cretaceous zone may swing from central Java to southeastern Borneo (Kalimantan) and the early and middle Tertiary one from eastern Java to Sulawesi (Celebes). Northwestern Borneo displays an early and middle Tertiary subduction zone, whereas the Asian side of the South China Sea does not; the South China basin has apparently been narrowed as Borneo has rotated counterclockwise toward Asia. The northwestern Borneo subduction zone continues northeastward as the Palawan ridge, which is truncated obliquely against the north-trending elements of the modern Philippine system, presumably indicating fragmentation of the older system. Halmahera stands above an active east-dipping Benioff zone, but an early Tertiary subduction zone dipped westward beneath the east part of the island.



INDONESIA AND MALAYSIA

Figure 1. INDEX MAP OF INDONESIA

The configuration of fossil subduction zones recognizable in the Late Cretaceous and Cenozoic of Indonesia becomes increasingly more complex and fragmented with increasing age. Continuous deformation by oroclinal folding, strike-slip faulting, and tensional opening of small ocean basins is inferred.

The broad pattern visible through this deformation is nevertheless relatively simple. Continuous northward motion of the Indian Ocean and Australian plates and westward motion of the Pacific plate have been accommodated in important part by subduction zones having sublatitudinal trends in the south and submeridional trends in the north. The detailed chaos of Indonesia can be viewed as due to ever-changing, swirling eddies in the contact region of the two great plate systems.

ECONOMIC SIGNIFICANCE

The plate-tectonic approach incorporates paleoenvironmental analysis and a search for continuity of tectonic belts of varying types and ages. Although the tectonic map project is not directly concerned with economic geology, it is hoped that the final map will call attention to favorable terranes in which to search for metals or petroleum.

Prospects for large fields of oil or gas are likely highest in the foreland basins and the carbonate shelves. The basins offer stratigraphic and structural traps in mostly clastic sediments, whereas the shelves may contain reef reservoirs. The exposed anticlines of the foreland basin of Sumatra have been extensively drilled, and many small, shallow oil and gas fields found. This foreland basin projects eastward onto the continental shelf north of Java, and small discoveries have been made in this basin both offshore and in northern Java and Madura. The plate-tectonic analysis summarized earlier suggests that the full basin does not continue eastward, parallel to Java, to the edge of the shelf, but rather that several thinly filled and obliquely superimposed basins may fan out across the shelf from north of western Java. South New Guinea and the adjacent shallow sea provides both foreland-basin and carbonate-shelf targets, the former being superimposed upon the latter.

Gold and silver are to be expected in small epithermal deposits in regions in which the altered roots of intermediate volcanoes are exposed--typically, in Miocene andesites. Tin is likely to be concentrated where deep tropical weathering has affected the upper parts of silicic and relatively alkaline granites. Concentrations of nickel, locally commercial, are likely to be found where laterites are formed on ultramafic rocks. These and other ore concentrations will tend to follow belts depicted on the tectonic map.

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