VAN BEMMELEN'S CONTRIBUTIONS TO THE GROWTH OF GEOTECTONICS AND THE PRESENT STATE OF EARTH-SCIENCE RESEARCH IN INDONESIA

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ABSTRACT

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The undation theory launched more than half a century ago in Indonesia by Van Bemmelen had a tremendous impact on the development of earth sciences. An attempt is made to trace Van Bemmelen's scientific activities prior to the birth of the undation theory. First envisaged as a fixistic concept, the theory was later developed into a mobilistic one which accommodates continental drift and sea-floor spreading hypothesis. However, instead of accepting the theory of extensive rigid plates it utilised a rheological approach in dealing with island arcs. A geotectonic evolution of Indonesia is presented in this paper. Recent marine geophysical findings which appear to contradict the results of prior geological investigations are also discussed. Problems and present status of geoscientific research in Indonesia are also discussed such as active collision processes, mechanism of ophiolite emplacement, geometry of subducted lithosphere etc.

INTRODUCTION

European scientists, among them Van Bemmelen, trained in the classical continental geology with the Alps as background recognized decades ago that the Indonesian island arcs represent a mountain belt *in statu nascendi.* They also realized that the archipelago possesses a dual character, namely as the place of intersection of two of the world's largest, youngest mountain systems and as an intra-continental zone between Australia and Asia. They were fascinated by the beautiful arcuate shape of the Sunda arc and wondered how the loop-shaped Banda arc and the K-shaped islands of Sulawesi and Halmahera had come into being. They discovered the largest negative gravity anomalies at sea about 45 years ago and established that the depth of earthquake hypocentres increases from the trenches towards the continent. They enthusiastically tried to unravel the secrets of one of the largest volcanic areas in the world, which harbours more than 120 volcanoes. They were startled to discover that, since 1800, volcanic calamities in Indonesia have occurred on average once in every three years, causing more than 140,000 casualties.

Van Bemmelen and his colleagues had already observed that an intimate relationship exists between these volcanoes and trenches and have constructed profiles to relate these features with the shallow, intermediate and deep earthquakes in Indonesia.

The impact of the geotectonic theories of VENING MEINESZ (1954), UMBGROVE (1949), KUENEN (1935), and VAN BEMMELEN (1949) can only be understood if one realizes that they were the pioneers who for the first time recognized the importance of integrating land and marine geology to understand the complex nature of Indonesian geology; an approach which several decades later became known as the new global tectonics.

In the next three chapters, the authors will discuss the impact of Van Bemmelen's idea on the development of earth sciences in Indonesia with special emphasis on volcanology and geotectonics. The geotectonic evolution of the Indonesian island arcs is interpreted according to the concept of plate tectonics, and further the present and future trends in earth science research in Indonesia will be dealt with.

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VAN BEMMELEN'S ROLE IN THE DEVELOPMENT OF VOLCANOLOGY IN INDONESIA

In 1920, a year after the disastrous eruption of Mt. Kelut, which claimed hundreds of lives, and a year before the First Pacific Science Congress, a section for Volcanological Research was established within the Bureau of Mines of the Netherlands East Indies. Its principal task was the search for, and recommendation of, means to restrict the extent of volcanological catastrophes as far as possible. Permanent volcanological observation posts were established in the vicinity of dangerous eruptive centres, and instructions were given to the local authorities and population to keep a watch on nearby volcanoes in order to be prepared for catastrophic eruptions.

Van Bemmelen enthusiastically participated in tackling some of the fundamental problems of Indonesian volcanology. Very interesting features of the Indonesian volcanoes are the calderas and volcanic-tectonic depressions. During the Fourth Pacific Science Congress, the Caldera problem – origin and mechanism of formation – was discussed in detail. Well known are Escher's 'scoring out – collapse' theory and Van Bemmelen's 'emptying out-breaking down' theory.

ESCHER (1929) was of the opinion that during the eruption a Perret gas phase occurs, causing the scouring out of a cylinder in the central part of the volcano. Consequently, the material of the inner walls of the cylinder starts sliding, gradually filling up a considerable part of the cylinder. Subsequent outflows of lava may then convert the funnel-shaped depression into a flat-bottomed caldera.

Contrary to Escher, who seeks the cause of eruption at a great depth, Van Bemmelen's formation of a caldera (VAN BEMMELEN, 1929) begins at a rather shallow depth. Here, also, a Perret gas phase occurs. The gases escaping from the magma disperse the lava into a very fine ash. During the gas eruption the base of the eruption descends towards the magma chamber and in this way a reverse cone-shaped depression is created with open space in the upper part of the magma chamber. Consequently, this chamber will collapse, and a caldera will be formed. The Krakatau caldera is used by Van Bemmelen as an example to describe his idea about caldera formation.

On account of the chemical character of the volcanic products of Krakatau, an important conclusion was made by VAN BEMMELEN (1949) concerning a possible future eruption. From the analysis it appears that the occurrence of a major eruption, accompanied by a collapse of the volcanic structure and tidal waves, is not probable unless the chemical composition of the eruption products changes from a basaltic to a dacitic-rhyolitic composition.

VAN BEMMELEN (1935) also made an extensive study of volcanic-tectonic depressions. In Sumatra a large down-faulted area (Semangko rift zone, within and close to which many centres of eruption are situated) occurs on top of the Barisan geanticline. Van Bemmelen's field work here enabled him to make an interesting study of this subject. His theory on the origin of Lake Toba is well known. The petrographic provinces of the Indonesian volcanic rocks have also been studied by VAN BEMMELEN (1949), as have many other problems in relation to the structure of Java and Sumatra.

At present, beside carrying out visual, seismic and temperature observations and geothermal research, the Geological Survey of Indonesia is preparing volcanic hazard maps of the most dangerous volcanoes in the archipelago.

VAN BEMMELEN'S MAPPING ACTIVITIES IN INDONESIA

In 1957 KLOMPÉ compiled a new general geologic map of Indonesia, scale 1:2,000,000, which was presented to the ECAFE conference in Bangkok in 1957 to be used as a base for a general geologic map of Southeast Asia, scale 1:5,000,000. In the accompanying text Klompé also gives a general survey of the development of geological mapping activities in Indonesia.

Much compilation work was done by the Geological Survey for the publication of a general geologic map at 1:1,000,000, of which only twelve sheets were published. The most important field work carried out by the survey includes: the mapping of South Sumatra from 1927 to 1931 (scale 1:200,000), the mapping of Java during the period 1927-1941 (scale 1:100,000), and the reconnaissance of West Borneo in 1939 (scale 1:250,000). A considerable number of investigations were carried out in Southeast and Northeast Borneo, Southeast Celebes, Buton, Central and North Sumatra, the Riau archipelago, Bangka, Billiton, Karimata, Karimunjawa and in the Minahasa (North Celebes).

Before Van Bemmelen undertook actual geologic work, during the year 1928 his activity was related to the question on the affinity of agro-geologic and geologic mapping. During that period there was a question of whether pedological surveys should be conducted as a branch of a geological survey or stand independently. In later years it appeared that the Geological Survey did not undertake the job, which meant that the mapping was carried out separately.

Two quadrangle maps of Sumatra, sheet Baturaja and Kroei were published in 1932 and 1933 by Van Bemmelen namely:

(1) Toelichting bij blad 10 (Baturaja), Geol. Kaart Sumatra, 1:200,000. Dienst Mijnb. Ned. Indië, 1932
(2) Toelichting bij blad 6 (Kroei), Geol. Kaart Sumatra, 1:200,000. Dienst Mijnb. Ned. Indië, 1933

Three quadrangle maps of Java, sheets Bandung, Karangkobar and Semarang/Ungaran appeared in 1934, 1937 and 1941 as follows:

(1) Toelichting bij blad 36 (Bandung), Geol. Kaart Java, 1:100,000. Dienst Mijnb. Ned. Indië, 1934.
(2) Toelichting bij blad 66 (Karangkobar), Geol. Kaart Java, 1:100,000. Dienst Mijnb. Ned. Indië, 1937.

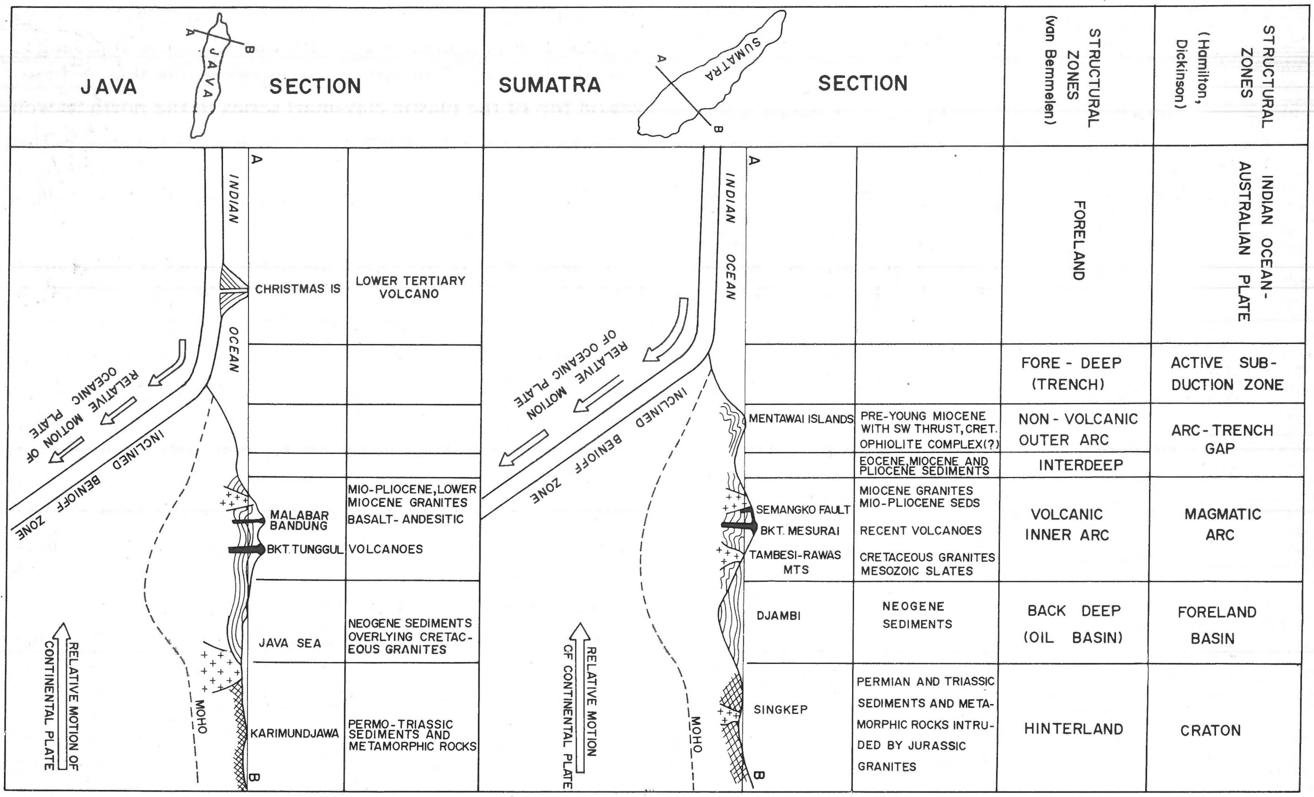

Fig. 1
Schematic sections across West Indonesia (Van Bemmelen, 1954) interpreted according to the plate tectonic model.

(3) Toelichting bij bladen 73 (Semarang) en 74 (Ungaran), Geol. Kaart Java, 1:100,000. Dienst Mijnb. Ned. Indië, 1941.

In Van Bemmelen's days only 5% of Indonesia had been mapped systematically on a large scale while at the present moment this has increased to 20%.

THE BIRTH OF THE UNDATION THEORY

During or subsequent to the publication of the geologic quadrangle maps of Baturaja and Kroei, Van Bemmelen advanced his undation theory to explain the development of a mountain system. The year of 1933 was a prolific one for Van Bemmelen in producing, putting forward and elaborating further his theory on undation. No doubt his fieldwork in Sumatra had inspired him to put forward his theory and it may be recorded that he applied this theory to Sumatra, to the western part of the Sunda arc and also to other mountain systems in the world.

The geological development of the Barisan range is a unique example of his contribution to the regional geology of Sumatra. The main geological events are summarized in table I (after VAN BEMMELEN, 1954).

On a larger scale VAN BEMMELEN (1949) further explained the zonal structure of Southeast Asia and delineated orogenic belts based on the distribution and the age of granites.

Mapping of sheet 36 (Bandung) could have inspired Van Bemmelen to develop the hypothesis of gravitational tectogenesis and further to the theory of volcano-tectonic collapses. The main idea is that at the summit of an active volcano during or subsequent to an eruption, a part of the volcanic cone collapses. This could happen if the rise of the magma upwards is negative or less than the materials erupted. A huge mass of a collapsed body may result in secondary folding at the foothills. This hypothesis has been applied to explain the structure of the Sunda Volcano Complex north of Bandung where the Tangkuban Perahu volcano is located, and the Merapi volcano in Central Java, and also to explain the tectonics of the Karangkobar area.

The ± 700 m height of the Tambakan ridge at Segalaherang which is in the northern foothills of the Sunda Volcano Complex north of Bandung, was folded as a result of the collapse of a 2000 m high mass of hills. The present height difference between the Sunda Volcano Complex and the Tambakan ridge is between 1000-1500 m at a distance of ± 15 km. Presumably the strength of the rocks can still stand further slumping and deformation. This event happened in historical time, about 2000 years ago, when the highland of Bandung was already occupied by people. It has reduced the elevation of the Sunda Volcano Complex to about 100 m and $7\frac{1}{2}$ km^3 rock materials were added to the foothill areas.

Another example of the gravity collapse of a volcano is

Table I
Summary of the geological development of the Barisan range, Sumatra

Phase	orogenesis	volcanism and plutonism
VI	3rd uplift during Plio-Pleistocene	regeneration of basalto-andesitic andesitic volcanism. Intrusion of granite-batholiths of the 3rd generation, creates big explosion of dacitic and rhyolitic pumice tuffs, such as Ranau and Toba.
V	Slow subsidence during Mio-Pliocene	Extrusive volcanism, primarily of basaltic and andesitic composition.
IV	2nd uplift during Middle Miocene	Big explosions of dacitic and rhyolitic pumice tuffs, mainly along the Semangko fault zone at the summit of fold, which is accompanied by intrusion of granite-batholiths of the 2nd generation.
III	Slow subsidence during Oligo-Miocene	Strong volcanic activity, mainly basaltic and andesitic, but sometimes also of dacitic composition, producing the 'Old Andesitic Formation'.
II	1st uplift during Late Cretaceous and Early Eocene	No extrusive volcanism. Intrusion of granitic batholiths of the 1st generation.
I	Geosynclinal subsidence mainly during late Mesozoic (geosynclinal foredeep of a mountain chain NE of the Barisan zone)	Intrusion of ophiolitic rocks in the geosynclinal sedimentary series, such as in the Garba and Gumai Mountains of South Sumatra.

shown by Van Bemmelen on the Merapi volcano in Central Java. Part of the volcanic cone that originally attained an altitude of ± 3300 m, collapsed westward towards the Progo valley. At a distance of 18-20 km from the top, the footlayers of the volcano were folded and reach an altitude of ± 452 m. The folding was due to a barrier represented by the Menoreh Mountain consisting of Miocene volcanic rocks. The collapse of the volcano was accompanied by a big eruption that probably happened in 1006AD, ruining the Buddhist and Hindu temples of Borobudur, Mendut, Prambanan, etc.

Sheet 66 (Karangkobar) could be considered as a type locality of a gravity-tectonic model with free gliding of mountain flanks. Two small volcanoes Pawinihan and Telagalele are displaced from their original position and move towards the Serayu valley with a speed of 25 to 40 cm per year. This movement has been proven by triangulation measurement. The base of these volcanoes consists of Neogene marls and clays that at the end of Tertiary had been uplifted and now form the northern Serayu mountains. During uplift, magma was intruded and extruded, thus building a number of volcanoes which are known as the Jembangan volcano complex. This volcano complex is unstable and moves on top of the plastic clay-marl series to the north as well as to the south. The Neogene clay-marls participated in this movement and have overlain younger volcanic materials, resulting in the formation of overthrust sheets. The overlap can reach up to 10 km.

In short, Van Bemmelen's undation theory is based upon his field experience in several parts of Indonesia, particularly in Sumatra and Java, where the relation between the magmatic and structural features of the process of mountain building can best be studied. It was influenced by Haarmann's theory and Baily Willi's conception of asthenoliths. Haarmann's ideas have been expanded by Van Bemmelen by taking into consideration the time and space factors. The oscillatory movements were then interpreted as wave-like earth movements, which he calls undations. The undation theory seeks the origin of the primary tectogenesis in the earth's crust itself, in differentiation to the salsima, producing a lighter sialic, and a heavier simatic magma. The sialic magma (lumps of magma or asthenoliths) ascends and causes uplifts in the earth's crust. Secondary tectogenesis will only take place if, due to gravity, the layers in the uplifted areas start sliding into the adjacent depressions, during which movements folding and overthrusting take place. In his tectonic scheme Van Bemmelen illustrates the Neogene structures of the Indonesian archipelago by distinguishing (1) stable areas without transgressive Neogene; (2) semi-stable regions with transgressive Neogene not affected by the Neogene undation cycle; (3) orogenes and orogenic centres or undation centres; and (4) where an undation cycle is thought to have originated. Nine undation centres have been illustrated in his map, four belonging to the Alpine orogenic system, four to the East Asiatic and one to the Circum Australia orogenic system.

Such a far-reaching hypothesis met, of course, with considerable opposition (VAN TUYN & WESTERVELD, 1931; CORNELIUS, 1949). In 1949 VAN BEMMELEN's voluminous book 'The geology of Indonesia' was published, giving us a complete picture of the investigations and results of geological activities in Indonesia since 1927. A synthesis of the geologic structure of Indonesia, based upon his undation theory, is treated extensively in this book. In the U.S.A. the undation theory is well known since VAN BEMMELEN published his book 'Mountain building' in 1954 with an introduction by Moore. In this book Van Bemmelen illustrates the evolution of Sundaland, western Indonesia, as caused by lateral undulating displacements in the earth's crust. This theory is also well known in the U.S.S.R. due to the translation of 'Geology of Indonesia' into the Russian language.

In a series of articles, VAN BEMMELEN (1965-a, 1965-b) ascribed continental drift to the lateral movements and spreading of the crust caused by upward and downward movements of the outer sphere of the crust. Such extensive deformations of the geoid measuring thousands of kilometres, known as mid-ocean ridges or rises, are called 'mega undations' by Van Bemmelen. Characteristic geotectonic features such as dextral transcurrent faults will be formed at the starboard and sinistral ones at the part of the crustal shield which moves under gravity away from the crust of the mega undations.

In a recent article, VAN BEMMELEN (1978) gave an outline of the present status of the undation theory. This geodynamic model accepts the continental drift and sea-floor spreading hypothesis but differs from plate tectonics in its mechanical concept and its geochemical and geothermal views. It supports a more rheological approach of structural evolution in which rigid plates represent only a surface skin effect. Based on this a comparison is made between the island groups of Southeast Asia and Australia on the one hand and those in the Pacific, East of Australia, on the other.

GEOTECTONIC EVOLUTION OF INDONESIA

The zonal structure of the Sunda arc was explained by VAN BEMMELEN (1949) as the result of a wave-like movement of undations, originating from a number of undation centres. This zonation was re-interpreted in the late sixties in the light of plate tectonics as a migration of subduction zones, related to an oceanic spreading centre (KATILI, 1970). The zonal but irregular pattern of the corresponding island arc was explained by the difference in dips of the Benioff-zones. The Indonesian plate-tectonic model was further refined, utilising data from cruises obtained by Mobil Oil during their regional investigations of offshore basins of Indonesia (KATILI, 1975-a).

The following account is an attempt to construct the geotectonic evolutions of Indonesia based on data from modern marine geology and geophysics.

Permian

In Permian time a subduction zone, dipping in the direction of the Asian continent, must have existed in or west of Sumatra. Andesitic volcanism and granitic emplacement in Sumatra accompanicd this subduction proccss.

Andesitic, basaltic and granitic rocks, ecountered in the eastern part of West Malaysia and West Borneo indicate that at the same time a minor subduction zone dipping towards the southwest may have existed at the northeastern margin of the continent.

Triassic

During the Late Triassic Sumatra, western Malaysia and western Thailand can be considered as a single sialic platelet that was welded to the remainder of Indochina along the Billiton (?) Bentang – Chiang Mai suture during Late Triassic (CAMERON, 1977).

Triassic-Jurassic

In Triassic-Jurassic time the subduction zone at the southwestern continental margin shifted towards the Indian Ocean. The Benioff-zone was then probably shallower than the Permian subduction zone suggested by the well-developed broad volcano-plutonic arc of the Malayan Peninsula and the Indonesian tin islands. Another minor subduction zone with opposing dip developed at the same time, presumably along the Lupar line in Serawak (HUTCHISON, 1973), indicating a migration of the northeastern subduction zone towards the South China Sea. The corresponding volcanic arc consists of the Serian Volcanic rocks and the Triassic volcanics encountered in drill holes in the Sunda Shelf.

Cretaceous

In Cretaceous time both the southwestern and the northeastern subduction zones became larger as they moved towards the Indian Ocean and the South China Sea, respectively. Towards the end of the Cretaceous a rift system of the Gondwana continent developed into a major spreading axis, separating India and Australia from the Gondwana block.

Tertiary

During Tertiary time the development of the arc-trench system in Indonesia reached its highest point. The new spreading centre in the Indian Ocean generated an arc-trench system that stretched from the northwestern tip of Sumatra via Java, the Lesser Sunda Islands, Timor, Tanimbar, Kai, Ceram to Buru and Buton. The arc at that time comprised approximately a 6000 km long Tertiary subduction zone dipping at a relatively steep angle towards the continent.

Intensive volcanism was associated with this renewed subduction and its products are now well exposed along the west coast of Sumatra, the south coast of Java and the Lesser Sunda Islands.

Granitic rocks found in Sumatra, Java, Flores, Alor and Ambon also belong to this Tertiary volcano-plutonic arc.

Oligocene

In Oligocene time andesitic volcanism started again in Sumatra and lasted until early Miocene. EGUCHI (1978) has suggested that the mid-oceanic ridge that migrated northward along the east-side of the Ninety East ridge collided with the western end of the 'Old Sunda trench' in the Middle to Late Miocene (10-20 Ma BP). The ridge then jumped to the back-arc region, and opened the Andaman-Sea.

During the mid-Miocene time the initiation of the right-lateral strike-slip movement along the Sumatran fault system is thought to have started (PAGE, 1978).

Emplacement of the serpentized ultramafic rock in northern Sumatra occurred at about the same time.

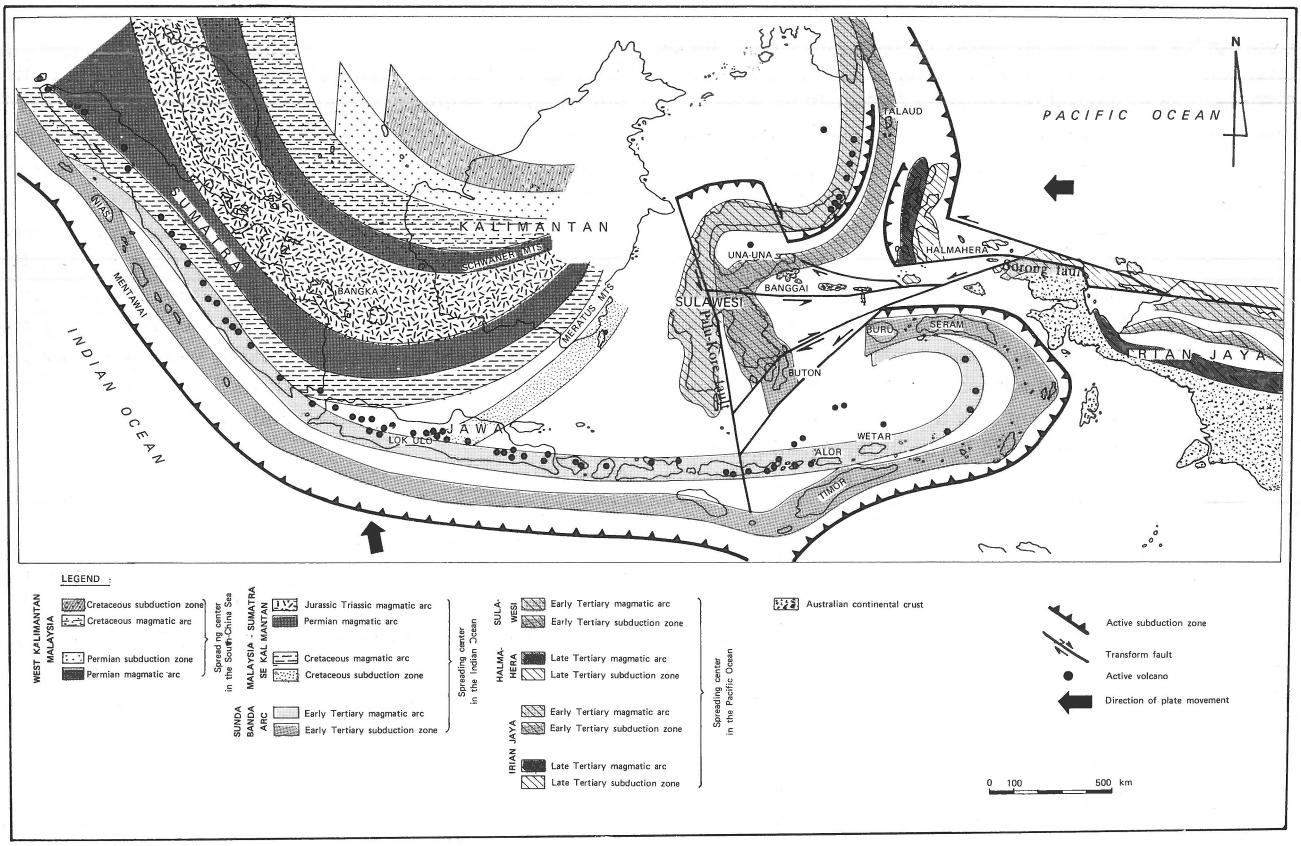

Fig. 2
Tectonic scheme of the Indonesian Archipelago.

Miocene

In Miocene time or perhaps even earlier a new pattern of subduction in the form of a north-south trending east-facing island arc began to form 600 km east of Borneo originating from a spreading centre situated in the Pacific Ocean. This emergence of the Sulawesi-Philippine island-arc system coincided with the change in movement of the Pacific Plate which since Eocene-Oligocene time was directed west-northwestward (BEN-AVRAHAM & UYEDA, 1973).

Middle-Upper Miocene

In the Middle to Upper Miocene time this north-south trending Sulawesi-Mindanau subduction zone migrated farther eastward and created the eastward-facing Halmahera island arc. This arc could not be developed further south as its growth was hampered by the northward-advancing Australian continent with New Guinea attached to its northern border.

Subduction ceased, presumably at the end of the Miocene, and the Indonesian non-volcanic outer arc, Mentawai-Nias, Timor, Tanimbar, Kei, Buru, Ceram and Buton was uplifted (or emerged).

Plio-Pleistocene

In Plio-Pleistocene time the subduction zone west of Sumatra and south of Java shifted oceanward to the present Sumatra-Java trench. Late Cenozoic to recent volcanism, however, migrated in opposite directions as the dip of the Benioff-zone is much shallower than the previous one.

CARDWELL & ISACKS (1978) suggest that Irian Jaya is being subducted beneath the Banda Sea. They maintained that subduction is not continuous around the arc and that the north-eastward directed subduction in the Aru trough is separated from the southward subduction below Ceram by a transform fault in the neighbourhood of the Banda Islands.

The most dramatic event in the geologic history of Indonesia took place in Pliocene time (KATILI, 1975-a) when the northward-advancing Australian continent coupled with the counter-clockwise rotation of New Guinea and accompanied by the spearheading westward thrust of the Sorong fault system, caused the westward bending of the east-west trending Banda arc.

Collision took place, this time between the western arc of Sulawesi and eastern Kalimantan, obducting ophiolites in the Meratus Mountains and slightly deforming the sediments in the eastern Kalimantan oil basins (KATILI, 1978).

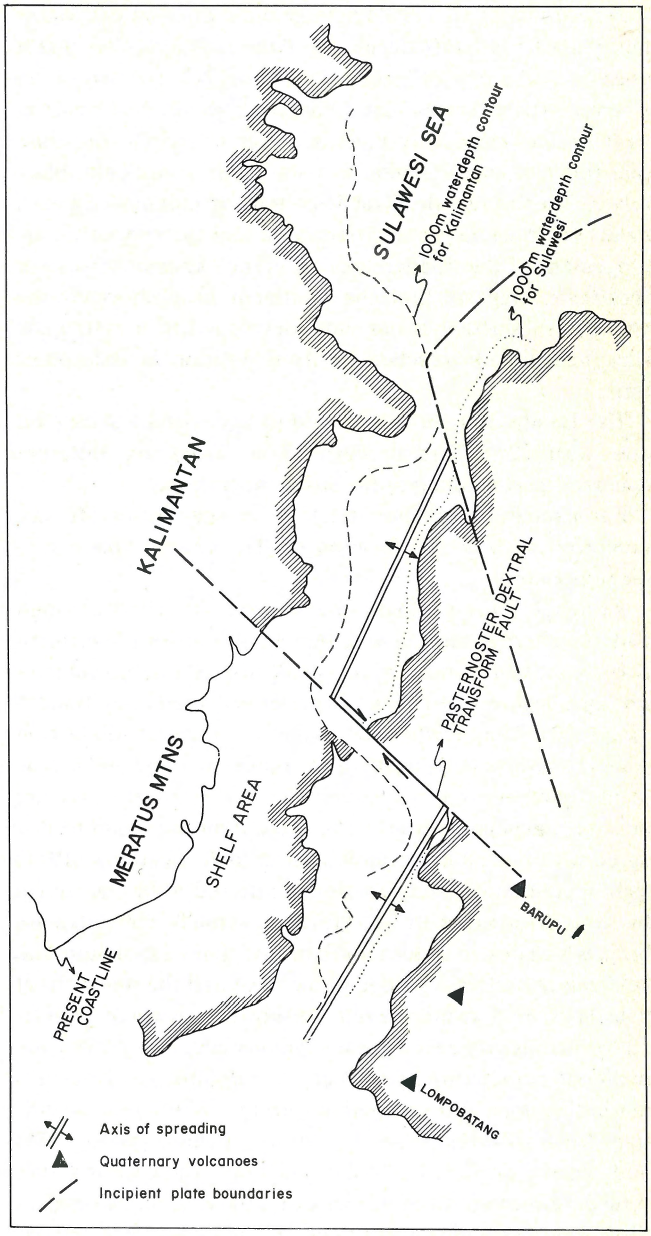

Fig. 3
Opening of the Strait of Makassar by sea-floor spreading along the east-west trending dextral Paternoster transform fault. Development of Late Quaternary volcanoes in the southern arm of Sulawesi.

Opening of the Makassar Strait took place in Quaternary time or earlier along the Paternoster and Palu-Koro transform faults (Fig. 3).

The youngest subduction zones that formed northwest of Sulawesi, east of northern Sulawesi and west of Halmahera could be held responsible respectively for the formations of the active Una-Una volcano in the gulf of Gorontalo, the volcanoes in the Minahasa-Sangihe region and for the generation of the active volcanoes west of Halmahera. Collision between the active Minahassa-Sangihe and Halmahera arcs is supposed to occur at the present time.

TRENDS IN EARTH-SCIENCES RESEARCH IN INDONESIA

The four series of Hamilton's tectonic map of Indonesia scale 1: 5,000,000 prepared on behalf of the Ministry of Mines and Energy of the Government of Indonesia and the US-AID in collaboration with the Geological Survey of Indonesia, have recently been completed.

A very extensive East-Asia International Decade of Ocean Exploration (IDOE) Programme also called Studies of East Asia Tectonics and Resources (SEATAR) was introduced through CCOP/ESCAP in 1973.

It was decided to concentrate the investigations along a number of so-called transects, sections of the earth's crust where the processes operating in the earth's interior manifest themselves in a number of geological and geophysical features; six transects were defined in the region of East and Southeast Asia.

In those five years, the SEATAR programme made impressive progress. In 1976-1977 alone, 10 research vessels operated in East and Southeast Asia, directly or indirectly carrying out surveys for the programme.

A CCOP/SEATAR workshop commemorating the 5th anniversary of SEATAR was convened in Bandung in October 1978. A review of research work which had been carried out on the transerts, had been thoroughly prepared by Barber and Jongsma. Some of the results are included in this paper. New recommendations for research in the transect areas were prepared.

The Lamont Doherty Geological Observatory presented a geophysical atlas of the East and Southeast Asian seas, comprising tectonic, sediment isopachs, crustal structure, gravity and magnetic anomalies, heat flow, thermal conductivity and thermal gradient maps.

With two transects located in Indonesia, the country benefited greatly from the SEATAR programme. This was well demonstrated during the Workshop on the Sumatra Transect held at Parapat, Sumatra, early in 1978.

As many as 18 organisations from 10 different countries took part in the work on this transect and a combined and well-integrated land and sea survey was carried out by the National Institute of Geology and Mining, the Indonesian Institute of Sciences (LIPI), Scripps Institution of Oceanography and Cornell University.

In Sumatra, a mapping team from the Geological Survey of Indonesia and the Institute of Geological Sciences, London, drew up geological and geochemical anomaly maps. Accounts of the sedimentary deposits in the back-arc basins were also published by oil companies.

One of the most important problems pertaining to western Indonesia is the position of South East Asia in the framework of plate tectonics.

MCELHINNY ET AL. (1974) have pointed out that the Malay Peninsula lay at 15°N during the Palaeozoic era, and that it once formed a part of Eurasia. WILSON (1972) pointed out in a recent article that the late Cenozoic high-alkaline basalt in western Indonesia may mark a volcanic hotspot, implying that this part of the region is a stationary continental plate relative to the mantle of at least tens of millions of years. KATILI (1975-a) has already indicated that the concentric arrangement of the Phanerozoic arc-trench system of western Indonesia suggests that the continent around which the younger subduction zones have developed in a systematic way, had already reached its fixed position in Palaeozoic time.

The Banda transect can be said to have been a successful one with 12 different organisations from six different countries participating in the work programme.

Fundamental problems relating to the Banda-arc are numerous such as the location of the present Timor subduction zone.

Although most geologists interpreted the Timor Trough and its eastern extension as a subduction zone or underthrust zone, AUDLEY-CHARLES ET AL. (1972) argued that no subduction has occurred between Australia and the Outer Banda-arc islands. They further stated that the trace of subduction zone has always been north of the outer-arc ridge and is now in the outer-arc basin between the non-volcanic outer arc and the volcanic inner arc. The present authors tend to disagree with this latter opinion, and FITCH & HAMILTON (1974) rightly pointed out that the trough inferred to be the trench by AUDLEY-CHARLES ET AL. (1972) is actually the outer-arc basin which lies, as it does south of Java and west of Sumatra, between the outer arc ridge of melange and the inner arc of volcanoes. This geometric relationship already was established by Vening Meinesz after his famous undersea gravity expeditions more than 45 years ago and reinforced by Kuenen's marine geological investigation during the Snellius expedition. Modern investigations by oil companies, (BECK, 1972) and seismic profiles by Mobil and Gulf, show clearly that little deformed strata continuous with those of the Australian Shelf dip gently northward beneath Timor and that the Timor slope represents a thrust front.

Volcanism, plutonism and the pattern of mineralization in eastern Indonesia would be very difficult to understand if we adopted the geometric relationship of eastern Indonesia as proposed by AUDLEY-CHARLES ET AL. (1972).

Another problem relates to the structure of Timor. Hamilton (see FITCH & HAMILTON, 1974) forcefully argued that the island of Timor was separated structurally from the northwest shelf by a subduction zone located in the Timor trough.

He went on to interpret the structure of Timor as a chaotic imbricate melange formed on the hanging wall of the subduction zone by the northward movement of Australia. This interpretation is rejected by both the London (e.g. CARTER ET AL., 1976) and Flinders (CHAMALAUN & GRADY, 1978) groups on the grounds that distinct stratigraphic and structural units can be mapped over large areas of Timor, indicating that it is by no means a chaotic melange. They have also pointed out that the individual rock units, ranging from Permian to probably Palaeocene, are an extension of the same units seen in boreholes on the northwest Australian shelf, showing that the Timor Trough does not constitute a major structural discontinuity. The major break must therefore lie to the north of Timor.

The London group, following an earlier Dutch interpretation, see the structure as a series of overthrust units. This view has been challenged by the Flinders University group who advocate an autochthonous origin for the rocks in Timor and suggest that the crystalline massifs, metamorphic complexes and Permian crinoidal limestones and volcanics are not overthrust units but upfaulted blocks of underlying basement (GRADY & BERRY, 1977).

JEZEK & HUTCHISON (in press) argue that the apparent geographical eastwards continuity of the Sunda arc conceals a major geochemical discontinuity adjacent to the southern end of the Weber deep beneath Serua.

The results of geophysical investigation in the Banda Sea demonstrate that continental and oceanic crusts are juxtaposed across the south and west flank of the Weber deep. The Aru trough, although on trend with the northeastward extension of the Timor trough, is not a site of subduction but an extensional graben. Buru is not a typical island arc; instead it is considered to be a block of continental crust that has been rifted from the Sula Spur by opening at the North Buru Basin (BOWEN, 1978).

The geometry of the subducted lithosphere in Indonesia has been studied by CARDWELL & ISACKS (1978). They demonstrated that although the geometry of the subducted lithosphere trends of Sumatra and Java is a relatively simple one, the Benioff-zone is contorted at the eastern end where the trench and the active Banda arc volcanoes curve to the northeast.

The oppositely dipping seismic zones in northeastern Indonesia could be explained by a model in which the subducted plate has been deformed into an inverted U-shaped configuration.

Gravity investigations which were carried out by SILVER (1978-a) on the large ultramafic belt and associated melange in eastern Indonesia support the idea of slicing off slivers of oceanic crust and upper mantle in a subduction environment along faults parallel to the main subduction zone. Another interesting seismic study by SILVER (1978-b) regarding the Molucca Sea Collision Zone, demonstrates that the collision complex is at present being emplaced over the adjacent aprons along low angle thrust faults which dip opposite to the sense of subduction.

The joint Indonesian – U.S. workshop on the tectonic problems of Eastern Indonesia to be held in mid 1979 in Bandung, will certainly stimulate closer cooperation between land-based geologists and marine geophysicists to tackle jointly the intriguing scientific problems, particularly in a complex collision zone such as Indonesia.

EPILOGUE

Thanks to the excellent work of Van Bemmelen and other Dutch scientists the Indonesian island arc has become well-known in the scientific world as a testing area for earth science theories.

The region is also endowed with rich mineral resources and is a target area for mineral and hydrocarbon exploration and exploitation by foreign corporations. Indonesia is rapidly moving from its former position as one of the least explored to one of the most intensively investigated areas of the world. Since 1967 petroleum and mining companies have spent more than one billion US dollars in exploring on-shore and offshore areas.

Indonesia would be well suited as a clearing house and regional centre for earth-sciences information. The huge amount of data collected within the last decade needs to be systematically stored for distribution and retrieval and efforts are under way to make modern facilities available for this purpose.

The focusing of attention of so many renowned international scientific institutions on this classical area will lead to a better understanding of the earthprocesses and will also result in developing new approaches in the search for mineral deposits, both petroleum and metals.

Indonesian geologists feel that a follow-up to Van Bemmelen's 'Geology of Indonesia' has to be written, but they fully realise that a whole team of different specialists in earth sciences is needed to fulfill this gigantic task. Van Bemmelen's book is a constant reminder to continue the work he so courageously undertook in spite of the difficulties he and his family experienced during the second world war.

The leading role Indonesia is about to play in the development of earth sciences of East Asia, attests to Van Bemmelen's inspiring leadership in the development of earth sciences and to his tireless and dedicated effort to elucidate the geology and geophysics of the fascinating Indonesian island arcs where he was born seventy five years ago.

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