STRUCTURAL HISTORY OF THE EAST INDIES

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BY

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PREFACE

THE PRESENT VOLUME contains the text of a series of lectures which were delivered to an audience of students of geography, geology and geophysics in the University of Cambridge, in May 1946.

In order to augment the usefulness of the book a few additions have been made to the original text, which for the rest appears as the word was spoken.

Apart from the subject treated in this volume two lectures were delivered on the structure and physiography of the Netherlands. Parts of them have been worked up in a preliminary article which has been published in the *Proceedings of the Royal Netherlands Academy of Sciences* (vol. XL, 1947) under the title 'Origin of the Dutch Coast'.

Some subjects, more especially those of the Synthesis (see Chapter VI), were treated in part of Chapter VII, 'Island Arcs', of the second edition of *The Pulse of the Earth*, published by Martinus Nijhoff, The Hague, early in 1947. I wish to extend my thanks to Mr W. Nijhoff for permission to use some parts, including Figs. 65, 66 and 68, in the present book. If no source is mentioned, the illustrations are either published for the first time or are taken from recent papers by the present author.

I wish to thank my many friends and colleagues of the University of Cambridge for their great hospitality and kindness. I greatly appreciated the discussions on several problems of geology which I had with Dr E. C. Bullard, Professor Harold Jeffreys, Professor W. B. R. King, Sir Gerald Lenox-Conyngham, Dr N. E. Odell and Mr J. A. Steers.

I extend cordial feelings of gratitude to my friend Steers, to whom I owe the arrangement of the lectures and who kindly undertook the troublesome task of making linguistic corrections in the manuscript. It is to him that I dedicate this book.

J. H. F. U

Delft, July 1948

To

JAMES ALFRED STEERS

PRESIDENT OF ST CATHARINE'S COLLEGE

IN RECOLLECTION OF
OUR SIMILAR EXPERIENCES ON CORAL ISLANDS
WHICH FORMED THE STARTING POINT
OF OUR FRIENDSHIP
TWO DECADES
AGO

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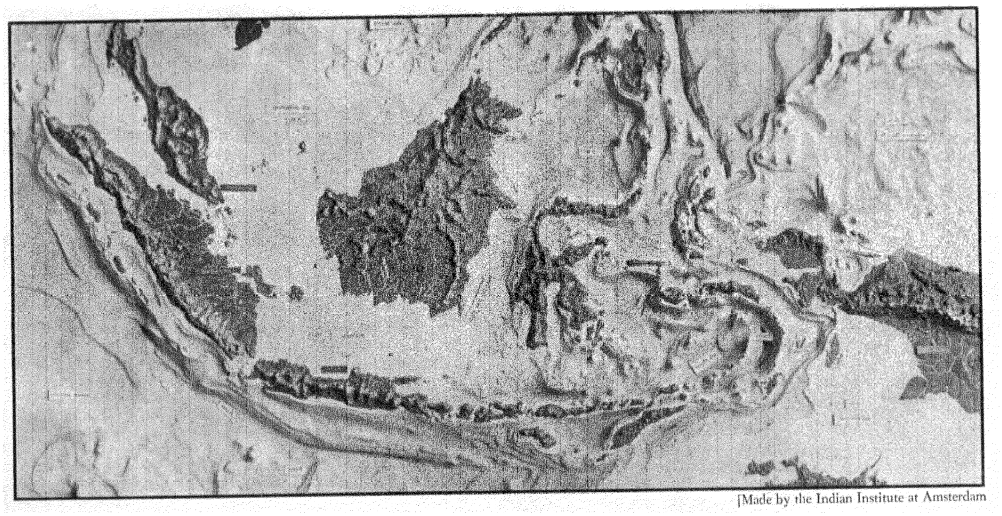


[Made by the Indian Institute at Amsterdam

Plate I. *Relief-block of the East Indies.*

CHAPTER I

THE SHALLOW SEAS

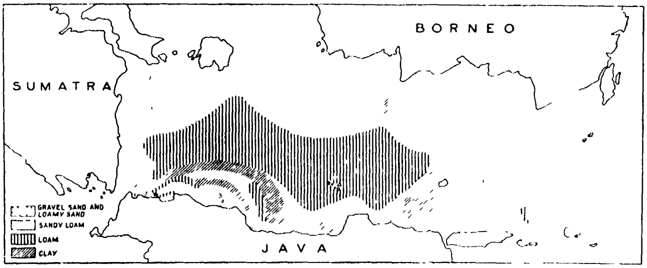
Perhaps no region in the world is more inviting for a geologist than the remarkable festoon of islands that swing around the equator in the East Indies. The first question that arouses one's curiosity is how and when this pattern of islands came into being.

A single glance at the map (Plate I) shows that a shallow shelf-sea unites the Greater Sunda Islands Borneo, Java and Sumatra with Malaya, including some smaller groups of islands in the Java Sea and south China Sea. It is called the Sunda shelf. Another shelf is found in the eastern part uniting New Guinea and the Aru Islands with Australia. In between the two shelf-areas are: (1) Celebes, with its remarkable four-armed appearance, (2) a whirl-shaped series of islands continuing from Timor towards Buru—the southern Moluccas, (3) a parallel row from Bali eastwards—the Lesser Sunda Islands. Between the two arcs is Sumba Island. And, finally, there are several islands north of Boeroe and Ceram, viz. the Banggai and the Sulu Islands and, north of New Guinea's 'Bird's Head', Halmahera and other islands called the northern Moluccas. West of Sumatra is a narrow festoon which is continued by a submarine ridge nearly as far as Sumba. The inner row of elongated islands is crowned by a chain of lofty volcanoes, running over the highest part of western Sumatra towards the Lesser Sunda Islands. A double row of volcanoes appears in the northern Moluccas, one in north Celebes and farther north in the Sangi Islands, another in western Halmahera and some smaller adjacent islands. It is a challenging question how this remarkable distribution of islands and volcanoes came into being.

One's curiosity is drawn to still another feature of great interest. The submarine relief shows a series of elongated troughs and a number of deep basins. What was the origin of these depressions in the earth's crust, and how was their development connected with the evolution of the archipelago?

Many more remarkable features come to light when one proceeds to investigate the structural geology of the region and the geophysical data that are known at present.

It is the aim of my lectures to answer, as well as possible, these and other tantalizing questions. In the comparatively short time of these lectures I cannot possibly tell you more than what, in my opinion, are the most generally interesting results obtained so far. Enumeration of details and a discussion of the various theories and conflicting opinions will not be attempted.



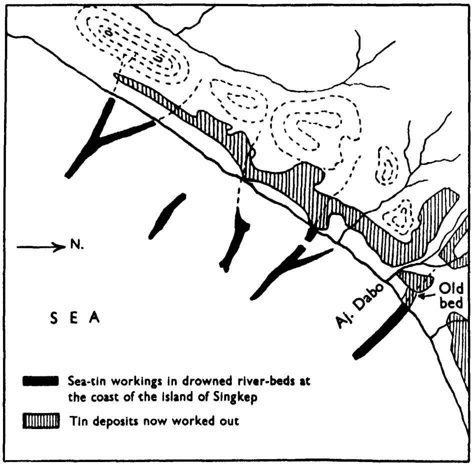
[After E. C. J. Mohr and J. Th. White

Fig. 1. *Bottom deposits of the Java Sea.*

The seas will be our first topic. Then follow the islands. Geophysical results form the next subject. Finally, an endeavour will be made to unite the present state of our knowledge into a harmonious synthesis. But I shall also point to some serious gaps in our knowledge and draw your attention to those areas that seem especially promising for future research.

THE SUNDA SHELF

The distribution of the bottom deposits in the Java Sea shows a few remarkable facts (Fig. 1). Some of the sediments which are rich in coarse clastic products from the land, such as gravel, quartzose sand and sandy loam, are found in areas which cannot possibly have originated under oceanographic conditions prevailing at present. The distribution of bottom sediments would be quite comprehensible if the Sunda shelf was formed under subaerial conditions of weathering and river transport and became drowned afterwards. Now this is what actually has happened: the present Sunda shelf was drowned, either as a result of the post-glacial rise of sea-level or as a consequence of a real downward movement of the bottom, or a combination of both phenomena. That the sea-level was much lower in the subrecent geological past is revealed by several other convincing facts. A few may be mentioned.



[After G. A. F. Molengraaff

Fig. 2. *Submarine continuation of rivers and secondary tin-ore deposits of Singkep Island.*

The bathymetric charts even allow the reconstruction of drowned rivers in the south China Sea (the north Sunda rivers), and in the Java Sea (the east Sunda rivers, Fig. 3).

The tin ores of Singkep Island are found as secondary deposits in rivers and along the shore. Similar deposits, however, were traced and worked below sea-level in the drowned parts of the rivers (Fig. 2).

The former existence of the system of north Sunda rivers which debouched in the China Sea near the present isobath of 100 metres explains the great number of similar species of freshwater fish fauna of the Kapuas river in western Borneo and the rivers of eastern Sumatra. On the other hand, such a strong resemblance may not be expected between the fauna of the rivers of southern Borneo and northern Java, inasmuch as the rivers of Borneo and those of Java debouched separately into the Makassar Straits (Fig. 3). A temporary connection may have existed between the two which must have been situated close to their debouchment; it must have come into existence towards the end of the sinking of the sea-level, and must have been broken shortly afterwards with the rising of the sea-level. This forms an important contrast to the system of rivers of the south China Sea where the connection between the rivers of eastern Sumatra and western Borneo was situated much farther from the debouchment, and consequently came into existence much earlier and was broken off much later. Indeed, such a striking resemblance does not exist between the freshwater fishes of Borneo and Java (Fig. 3).

Between the basins of the north and east Sunda rivers there existed a divide from Sumatra, across Banka, Billiton, and the Karimata Islands, to Borneo. This divide must, by its height, have offered great possibilities of migration to a number of animals and plants for which the conditions of life were less favourable or insufficient in the extensive flat and low-lying area of the north and east Sunda rivers. Moreover, this land-bridge between Sumatra and Borneo must have remained in existence to the very last during the rising of the sea-level, whereas the lower areas must have been submerged much sooner and the river systems dismembered.

If we suppose that the movement of the sea-level was eustatic and occurred under the influence of the Pleistocene glacial periods, we must take into consideration the recurrences of these happenings in conformity with the four glacial and three inter-glacial and the post-glacial periods. In that case, it is improbable that the level of the sea returned again and again to its pre-Pleistocene level, or sank to its lowest level.

In a more distant past the area of the Java Sea undoubtedly had a strong relief and delivered denudation products towards the south. This was amply demonstrated by Rutten when he published his petrographic studies of Tertiary sediments of Java. The size of the clastic products in the Tertiary sediments of Java diminishes as one proceeds from north to south. Hence the area of denudation from which the sediments derived must have been in the north, that is, in the area of the present Java Sea. Now the sediments of northern Java containing an abundance of quartz and other clastic products have a thickness of at least 1500 m. Consequently, the land that undoubtedly occupied the region of the present Java Sea in Upper Tertiary times must have had considerable dimensions in a horizontal as well as in a vertical direction.

Molengraaff considered the series of reefs running parallel to the east coast of Borneo, along the edge of the shallow shelf, to be a barrier-reef—the Great Sunda barrier-reef, with a total length of about 500 km.—that gradually grew up from a Pleistocene fringing reef during the latest rising of sea-level (Fig. 4).

However, we might as well start from a real movement of the bottom instead of from eustatic movements, or we might think both phenomena combined, and come to an adequate explanation. The lands surrounding the Sunda shelf show numerous signs of Pleistocene and post-Pleistocene movements.

Geological sections across the folded Upper Tertiary

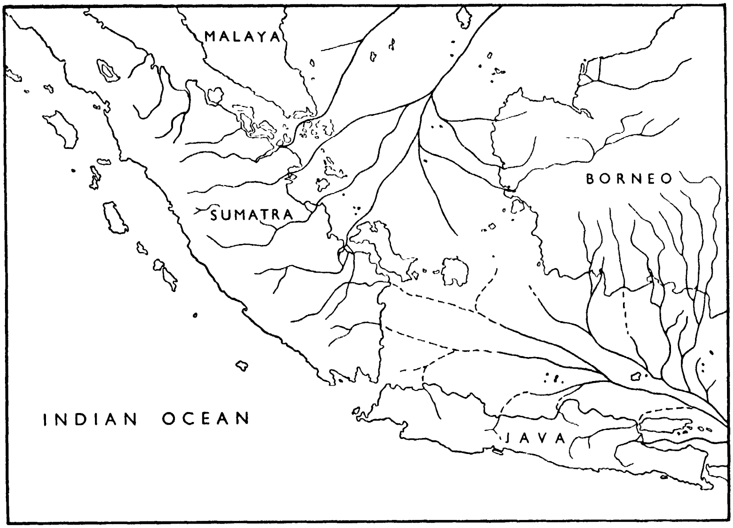
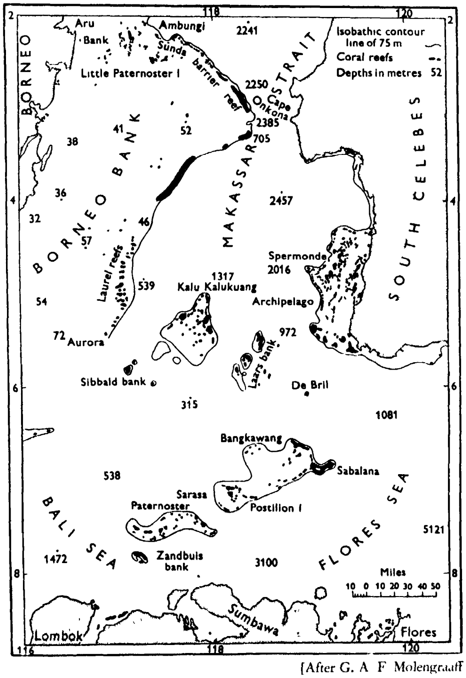


Fig. 3. *Drowned rivers in the south China Sea and Java Sea.*



[After G. A F Molengraaff

Fig. 4. *Barrier-reefs and atolls in Makassar Straits.*

strata, the outcrop of which is found between Surabaja and Semarang (north Java), show that an average of more than 2000 m. of Tertiary strata has been denuded. The peneplain that originated as a result of this process of denudation has been elevated almost vertically to a height of 100–200 m. In this the present valleys have cut their courses. In Atcheen (northern Sumatra) the amount of this elevation appears to be about 1000 m. Numerous other examples of Pleistocene and post-Pleistocene movements in the immediate surroundings could be given. It seems, therefore, highly questionable whether the Sunda shelf would have remained stable during the same time.

It has already been mentioned that clastic products from the area of the Java Sea were transported towards the south. Hence in Upper Tertiary times the Java Sea was land, whereas parts of Java were sea (cf. Fig. 55). In the Pleistocene the Tertiary deposits of northern Java were elevated above sea-level (after they had been folded and peneplained). It seems, therefore, highly probable that the bottom of the Java Sea underwent a subsiding movement approximately at the same time as the rising movement of the Javanese area took place. Other considerations support this point of view, as will be seen presently.

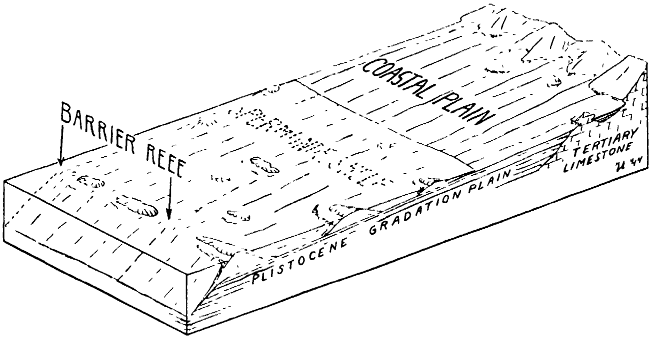


Fig. 5. *The Spermonde shelf with barrier-reef and coral cays.*

THE SPERMONDE SHELF

On the opposite side of Makassar Straits another barrier-reef occurs, the Spermonde barrier, bordering the Spermonde shelf of south Celebes. The Spermonde barrier-reef rises from the same depth as the Sunda barrier-reef. However, the Spermonde shelf rises gently from the barrier towards the coast and there it passes gradually into the coastal plain of Makassar, which obviously belongs to one and the same gradation plain (Fig. 5). The coastal plain of Makassar rises up to 30 m. above sea-level, where a whole series of remarkable sea coves and notches in the Miocene limestones mark the former extension of the sea (Plate II, B).

Similar corniced limestones and mushroom-shaped rocks are known from many places in the present seas of the archipelago (Plate II, A). They are the result of the solvent action of the sea and boring organisms on the limestone. This action seems to be limited between the tidal range of the sea.

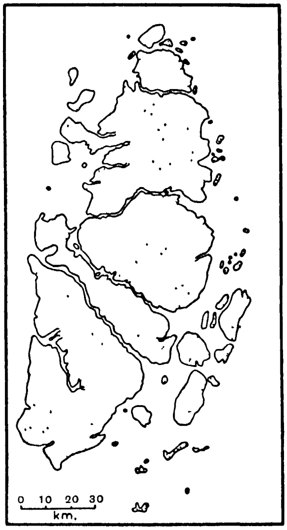
We have no data with which to fix the exact time of origin of the cornices in the Miocene limestone near Makassar. They may date from post-glacial, Pleistocene or even pre-glacial times. If the origin of the cornices dates from pre-glacial or from Thyrrénian times (that is, from a time when the earth was free or nearly free of land-ice caps and the sea-level was about 50 m. higher than at present), we have to account for a subsidence of the bottom of $50 - 30 = 20$ m. If, on the other hand, the sea coves date from a different Pleistocene epoch, we may imagine a rise of the land simultaneously with the rise of sea-level, or shortly after it. Whichever explanation may be the correct one, it remains a remarkable fact that the Spermonde barrier-reef rises from the same depth as the Sunda barrier-reef.

Now south Celebes was an area of marine sedimentation similar to north Java, in Upper Tertiary times. And again, similar troughs of sedimentation existed in east Borneo (cf. Fig. 57). In all these areas the Tertiary sediments underwent moderate folding towards the end of the Pliocene and subsequent elevation (cf. Figs. 58 and 59). Probably adjacent areas subsided simultaneously with the rising movement of the present land areas. Therefore it seems to me that, apart from the influence of changes of sea-level, a downward movement of the bottom ought to be taken into account for such areas as the Java Sea, the Spermonde shelf and the shelf along which the Great Sunda barrier-reef grew up in Pleistocene times.

In a synthesis of the structural history of the East Indies these movements have to be elucidated. For the moment we merely note the problem, and wait for an attempt at explanation later on.

THE SAHUL SHELF

During the low levels of the sea in the Pleistocene, important alterations must have occurred in other places as well. The bathymetric chart shows, for instance, that a connection between Sumatra and the islands west of Sumatra must be taken into account. In the same way the Arafura Sea must have been a land area connecting Australia with New Guinea. The available charts do not permit a reconstruction of contingent drowned rivers on this so-called Sahul shelf. The shallow and narrow straits of the Aru Islands are, however, generally supposed to be fragments of original river-beds (Fig. 6). It is still problematic why the Aru Islands and their 'rivers' are on such a comparatively high level. Another problem is why the Sahul shelf is not bordered by a barrier-reef in the same way as the Sunda shelf.



[After Ph H Kuenen

Fig. 6. *The Aru Islands on the Sahul shelf between New Guinea and Australia, showing parts of dismembered rivers.*

THE TOGIAN ISLANDS

Narrow river-like channels are also known between Batoe Daka, Togian and Talata Koh in the Togian Islands (Fig. 7). Probably these furrows had a similar origin. They, too, must be considered as remnants of former rivers. A remarkable fact about the channels in the Togian Islands is that on both sides of the island group is deep sea. It is more than probable that the group of the Togian Islands was not yet surrounded by a deep sea in a recent past, geologically speaking. The steep northern and western boundaries indicated by the barrier-reefs that run at right angles to each other show very clearly that the block of the Togian Islands is bounded by steep faults (Fig. 26). It may be reasonably supposed that at the same time as the elevating movement of the Togian block—which may be concluded from the raised reef limestones—adjacent blocks were submerged. This was the origin of the deep sea now surrounding the islands. Part of the existing rivers remained as the present furrows between the Togian Islands. The remaining parts of the former rivers are mere fragments without head or tail. The sea invaded these fragments, and locally corals grow on the roots of trees, or on stones and shells that lie scattered on a shallow muddy bottom.

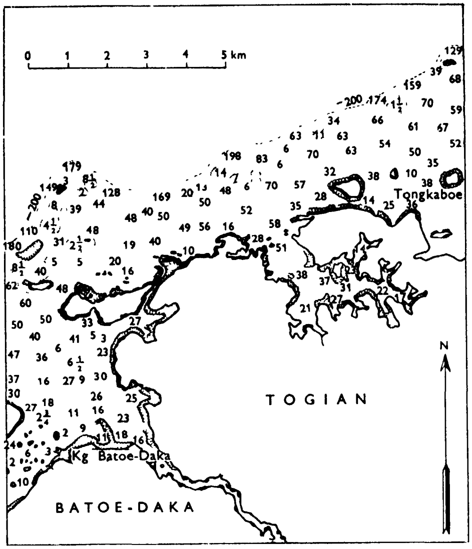


Fig. 7. *Part of the Togian Islands, showing part of a drowned river between Togian and Batoe Daka.*

THE SCOURING EFFECT OF SEA-CURRENTS

Of course, not all furrows on the shelves originated as drowned rivers.

Where monsoon currents pile up between narrow passages, it is very clear that a strong erosive action must take place along the bottom. Indeed, we see deep erosive channels wherever such narrow passages occur.

When the masses of water have once passed these straits, then the stronger erosive action ceases; the rather abrupt, 'blind' ends of such erosive channels are characteristic.

Fig. 8, a detailed map of the southern part of Banka Straits, shows a number of narrow mudbanks, which along their longer axes are arranged according to the currents. It will be noticed how these long stretched forms converge towards the Banka Straits. This same phenomenon occurs at the channels which are between these mudbanks; moreover, these turn out to be deeper as one approaches the narrows of the straits. The current through the Banka Straits thus turns out to have eroded a channel, which is broad and deep in the straits itself; as this strait widens outwards, the erosive working divides into a series of channels, which converge towards the strait, and between which less deep banks remain.

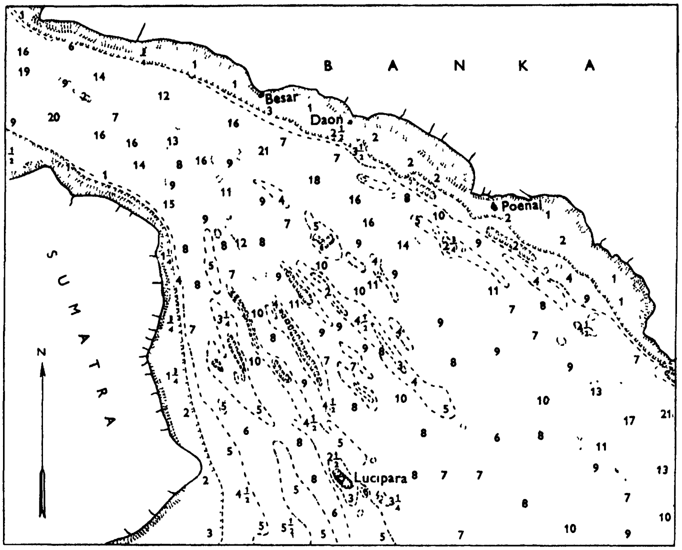


Fig. 8. *Bathymetric map of Banka Straits.*

We also observe this phenomenon in other straits, e.g. Sunda Straits with the Thousand Islands.

The reefs and islands of the group of the Thousand Islands all have a more or less drawn-out shape and several islands are situated behind one another in the direction of their longer axes. Plates II C and III A, and Figs. 9 and 11, elucidate this.

The whole grouping of the islands and channels gives the impression that it was caused by the erosive working of a current, which is directed towards the Sunda Straits.

Comparing the oceanographic data about the currents in the Java Sea with the morphology of the submarine topography, the situations of some of these currents turn out to coincide with deep channels.

Fig. 10 shows two hydrographic charts, one for the west monsoon, the other for the east monsoon.

There happens to be a current, which runs from the Banka Straits to the Sunda Straits; on the sea floor this is indicated by a channel. During the whole year a current flows along the north coast of Java, eight months westward (six months uninterrupted) and four months eastwards (two months uninterrupted), but this eastward current may be twice as fast as the westward current. These currents are indicated by the deep channels between the Thousand Islands and especially by the very deep channel between the Hoorn Islands and the Agemeten, where the current is probably strongest. In Sunda Straits this channel reaches its greatest depth, and there the rate of flow is stated to be 44 cm. per sec. On the other hand, in the open sea the rate of flow is 28 cm. and 17 cm. per sec. respectively for the west and east monsoons.

In the Sunda Straits, in the same way as in the case of the Banka Straits, a converging system of channels is formed, which in the direction of the open sea become more shallow, and between which only a system of banks remains, also converging towards the entrance of the straits. As regards the trend of the whole group of the Thousand Islands, shown on Figs. 9 and 11, one probably has to admit that originally there must have existed a ridge-shaped elevation of the bottom. There the later post-Pleistocene developed system of sea currents met most resistance, and it is there that a topography has been eroded as we see it nowadays. In the lower parts on both sides of this ridge there has also been erosive action, but only where the current is very strong, and where this current is cutting and deepening from Sunda Straits eastwards its course can to-day be clearly traced in the submarine topography.

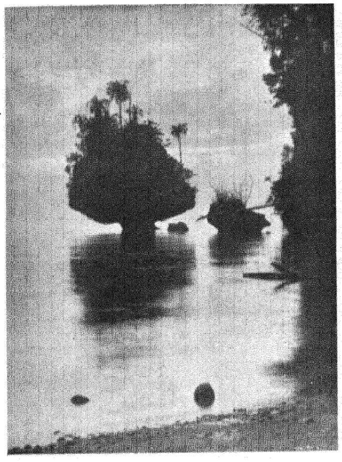
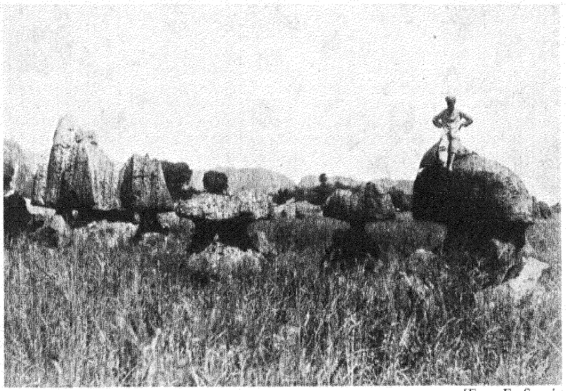
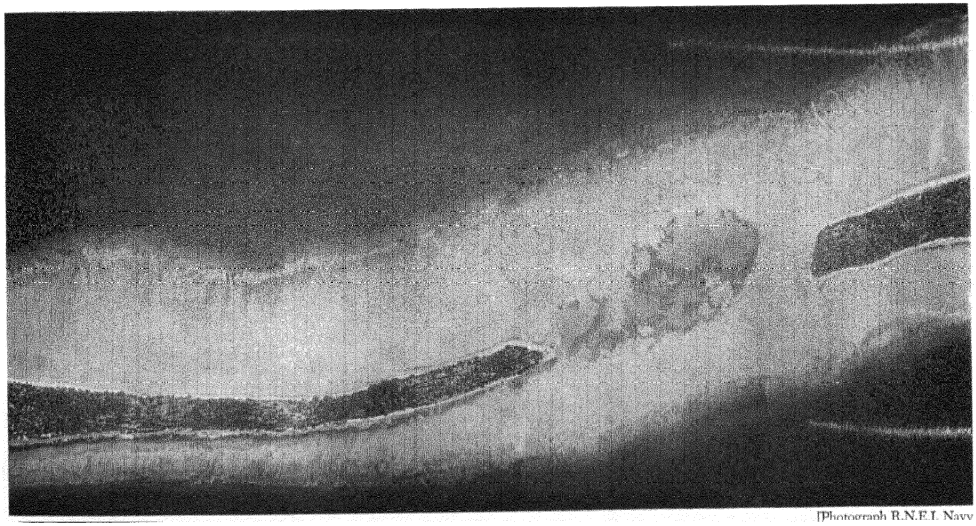


Plate II. A. *Mushroom-shaped erosion remnant along the northern coast of Togian, north Celebes.*



[From Fr. Sarasin

B. *Mushroom-shaped rocks in the plain of Makassar, south Celebes.*



[Photograph R.N.E.I. Navy

C. *Two of the Hoorn Islands, Java Sea, seen from a height of about* 1000 *m. Compare Fig.* 11.

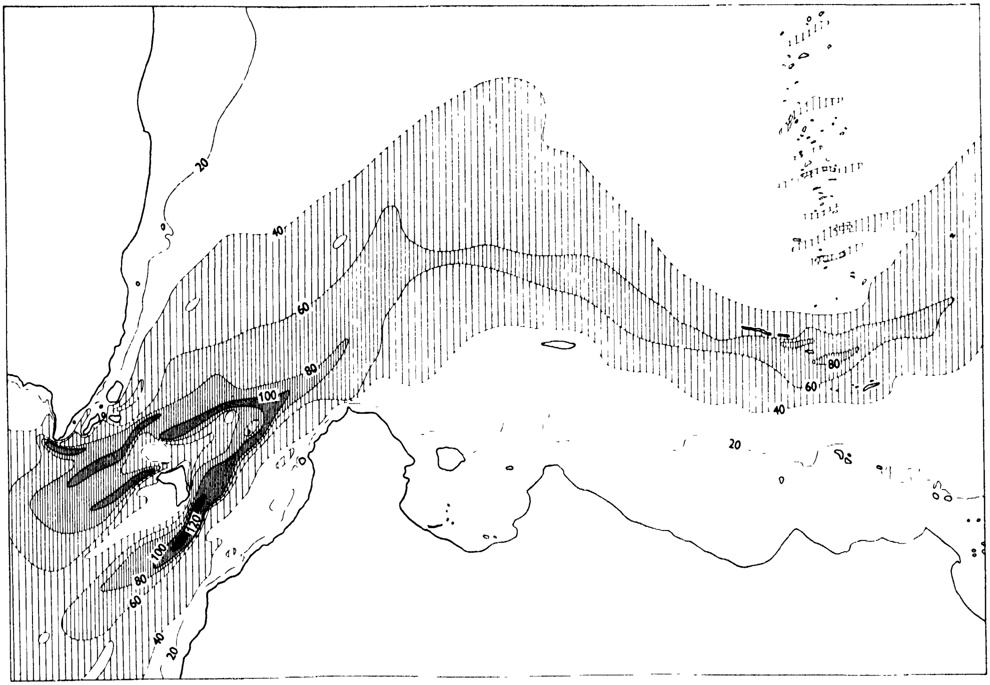


Fig. 9. *Bathymetric map of Sunda Straits and part of the Java Sea, with the group of Thousand Islands.*

ORIGIN OF SEA-STRAITS

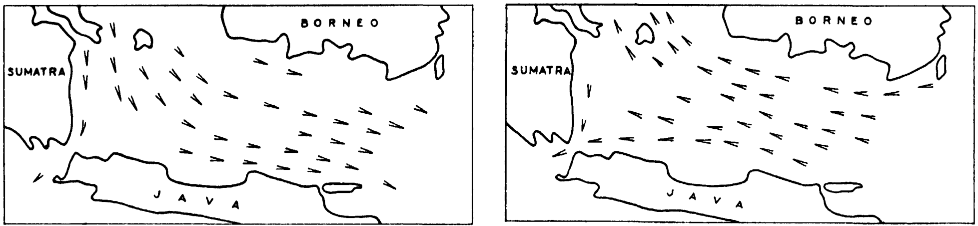
It is necessary to point out another characteristic in the relief of the bottom of the sea which also came into being in the near geological past. It is quite conceivable that during the rising of the sea-level, low parts of the land which had been encroached upon by stronger erosion on a lowered erosion base during a large part of the Pleistocene made a sea-connection between the Java Sea and the Indian Ocean possible. This possibility is quite independent of the speculative question whether or not the Sunda Straits correspond to the situation of a transverse fault.

Once a sea-strait is formed, the scouring effect of sea currents deepens the passage. It was found that the strong current passing over shallow ridges and through sea-straits prevents the deposition of sediments. Hard bottom was found by the Snellius Expedition in many places (Fig. 20). They occur in general on all the ridges between deep-sea basins, or between inland seas and the open ocean.

CORAL CAYS

Before terminating our short survey of the shelf-seas a few words must be devoted to some morphological features of the many patch reefs that are known from these areas. Obviously, the coral reefs in the Java Sea cannot date from a more remote past than the last rising movement of sea-level in post-glacial times. It may be that some of them grew up from remnants of older Pleistocene reefs. A boring which pierced Onrust Island, a coral cay in the bay of Batavia, revealed a thickness of 20 m. of reef products. Taking post-glacial time at 20,000 years, the corresponding growth-rate of the cay as a whole would be 1 mm. per year. Of course this rough estimate is only a minimum value. We know from the boring on Heron Island in the Great Barrier-reef area of Australia that 150 m. of reef products, i.e. about 7·5 mm. per year, accumulated on the subsiding sea-floor in approximately the same lapse of time.

The coral reefs in the Java Sea and the bay of Batavia are rooted in a muddy bottom. Numerous hard objects, rock fragments, shells and especially pieces of pumice stone lie scattered all over the floor of the sea and form a convenient foundation for the beginnings of a coral reef. And so coral reefs are actually found in every conceivable stage of development. Fig. 11 shows a great number of submarine reefs. Some are still small patches at various depths below the surface. Other patch reefs just reach the surface, to form



a FEBRUARY (WEST MONSOON) b AUGUST (EAST MONSOON) After H P Berlage

Fig. 10. *Direction of sea-currents in the Java Sea during the east and west monsoons.*

a small sandy island. The older cays are covered with a dense vegetation.

Conditions similar to those prevailing in the bay of Batavia and the Java Sea are known from the Spermonde shelf (south-west Celebes), Emmahaven (west Sumatra), and probably occur in a great number of other areas.

The influence of the wind is shown very strikingly in the distribution of the debris of a coral reef, which has been broken off and battered by the surf. We can distinguish the fine detritus—for the sake of convenience called coral sand, which is most easily carried away by wind and waves, and therefore is carried farthest—and the coarser fragments called coral shingle.

The finer erosion products are transported by waves bending round the reef and meeting at its leeward side. Where sedimentation of the material takes place on that side of the reef a sand cay may originate, which eventually gets covered with a dense vegetation. In the very early stages, when only the bare sand-plate just lifts itself above the water, the wind and, in a minor degree, the breakers force the sand into a crescent-shaped sand-bar, the horns of which follow the direction of the alternate monsoons. In the older islands, this movement becomes more and more impeded by the vegetation, until in the end a rounded, slightly oval-shaped island is formed with proportionately short horns of loose barren sand, which keep on changing their direction with the prevailing wind.

On the other hand, the coarser debris is heaped up on the windward side and may form shingle ramparts (Figs. 12 and 15) that are highest on the side where the wind exercises its greatest force most regularly.

The striking relation between prevailing wind-direction and morphology of a coral island is well known from the notable explorations by Steers on the low-wooded islands of the Great Barrier-reef of Australia and the coral cays of Jamaica. Very similar relations occur in the East Indies.

The reefs of the Indian archipelago are found within the monsoon zone. With regard to the influence of the monsoons, we distinguish the following possibilities, depending on the distribution of land and sea.

1. Both monsoons can blow without any obstruction or restraint and their strength is felt to its fullest extent.
2. The influence of one of the monsoons is screened off as the reefs occur on the lee of a large island with high mountains.
3. The influence of both monsoons is weakened because the reefs are shut in on either side from whence the monsoons blow.

A few examples may be mentioned.

In the Thousand Islands (Java Sea) strong winds from the north-north-west prevail during the west monsoon, and from the east during the east monsoon.

Owing to very strong wind velocity from the east, the sand islands are situated on the west flank of the reef. The shingle ramparts of the young islands emerge first on the east side; in the older islands it is on that side that these ramparts are highest and consist of the largest debris, and finally we find that on the east side the cay is wave-cut and that there is accumulation of sandy material on the west side (Fig. 12).

In other words, the east monsoon has more influence on the said Thousand Islands than the west monsoon (being preponderantly north). These statements are in accordance with the meteorological data.

The geological structure of the island cays on the Spermonde shelf clearly depends on a preponderant influence of the west monsoon, which blows unhampered on these islands across the Java Sea and Makassar Straits (Fig. 13). The force of the east monsoon, on the contrary, when blowing across the Flores Sea, is broken, at least in the lower layers of the atmosphere, by the high mountains of south Celebes. They form a shelter for the Spermonde archipelago against the force of the east monsoon. The much smaller influence of the east monsoon is shown by the alternating shape of the sand cays; its strength is not great enough to effect permanently the orientation of the coral reefs, the shingle ramparts or the sand islands.

With regard to the coral reefs in the bay of Batavia, their sheltered position weakens the strength of the winds a good deal. As we possess exact data, collected on the spot, about the frequency and the velocity of the wind, it has been

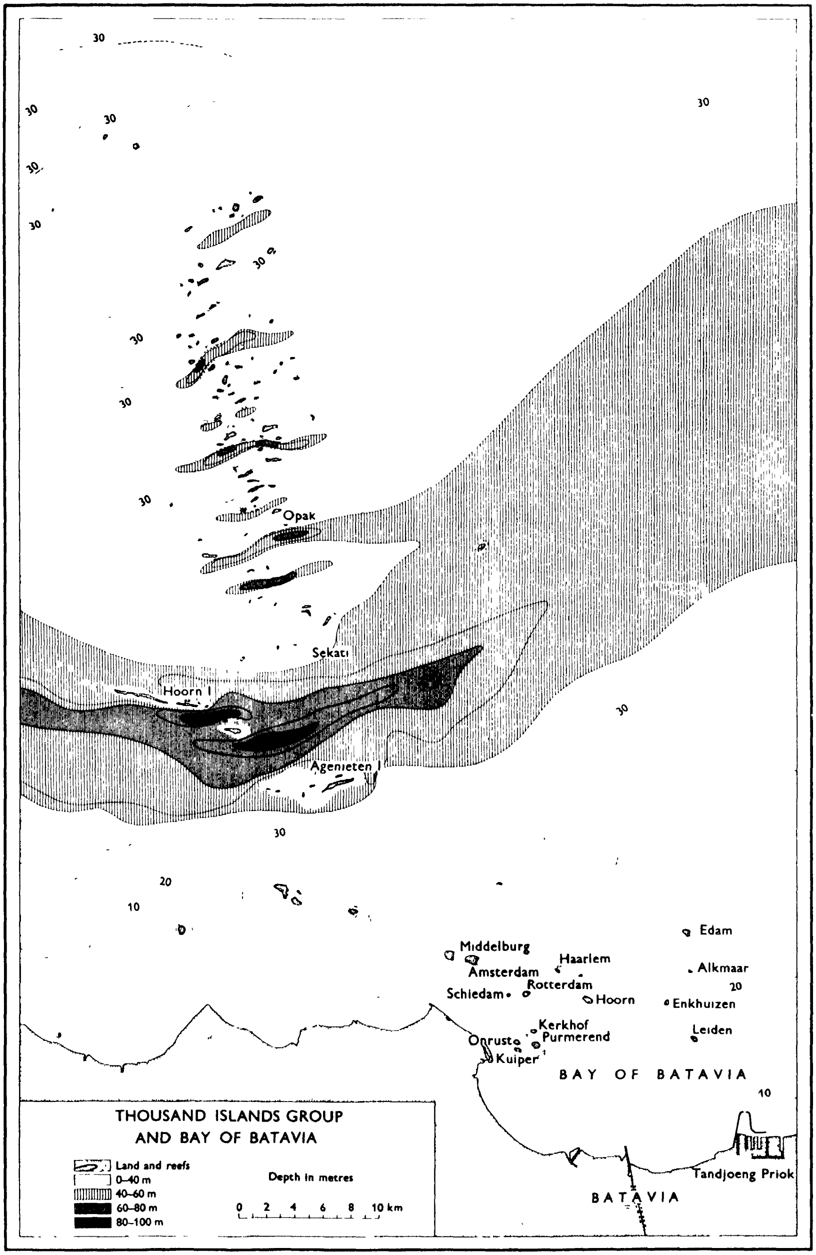


Fig. 11. *Bathymetric map of the surroundings of the Thousand Islands and the bay of Batavia.*

U S II

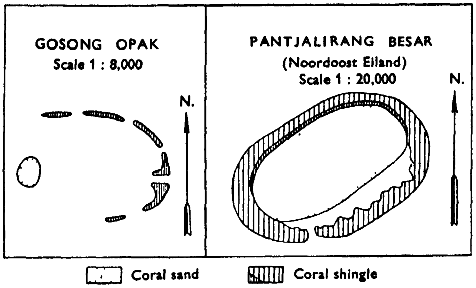


Fig. 12. *Opak and Pantjalirang Besar Islands, two coral cays in the Java Sea.*

possible to prove that their morphology is most intimately connected with the prevailing monsoons.

Data furnished by the Batavia Meteorological Observatory led to the following calculation: (*a*) the number of hours per annum which the wind blows from each of the eight principal directions; (*b*) its mean velocity in these directions.

The product of (*a*) and (*b*) gives a series of numbers, the equations of which have been shown on the accompanying picture of the compass, next to Leiden Island (Fig. 14, and compare Fig. 15).

This demonstrates very clearly that the influence of the monsoon winds and waves is just as might be expected from actual geological observations made around the islands.

According to the nature of the bottom (coral sand or shingle), the depth of the water, and the movement of the waves, several typical faunas have developed. An example of these various combinations of special kind of bottom and conditions for life, each with a corresponding fauna adapted to it, is shown by Figs. 14 and 15. The reefs of the Spermonde archipelago and Emmahaven (west Sumatra) show a similar distribution of facies types.

The question arises how a small sand cay can stand the battering influence of the waves without being demolished within a very short time. Consider a small volcanic island like Anak Krakatoa. In December 1927 volcanic action started from a submarine vent (Plate III, C) along the border of the caldera that was formed in the great cataclysm of the year 1883. Continued accumulation of ejectamenta caused the formation of a small island. A pause in the eruptions gave the influence of waves, currents, and submarine down-sliding free play. When an excursion of the Pacific Science Congress landed on Anak Krakatoa in May 1929, half of the island had disappeared into the sea (Plate III, D). In strong contrast the small coral cays may retain their shape and position for centuries and centuries. Two factors are of much importance in this connection.

In the first place the thriving reef forms a mighty bulwark against the breakers and causes the broken fragments to accumulate on the lee side. In the bay of Batavia a large quantity of huge coral colonies (principally Porites) is broken into pieces or is even blown up by native fishermen. Every year from 12,000 up to 25,000 cu.m. of coral material are conveyed to Batavia for the hardening of roads and the building of houses. Thus large parts of the reefs are being destroyed. The finer debris is heaped up by the breakers

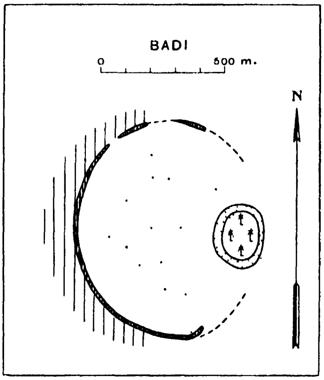


Fig. 13. *Badi Island, a coral cay in the Spermonde archipelago.*

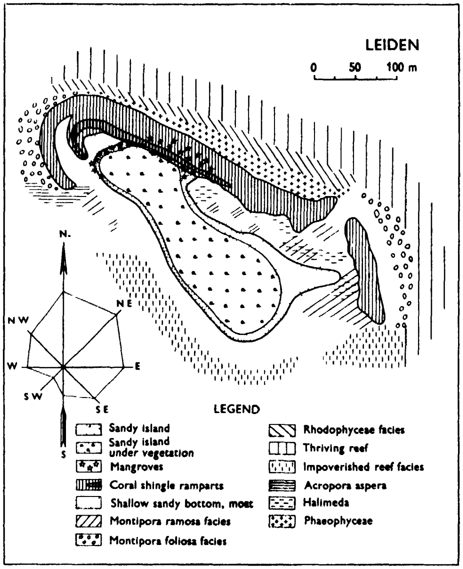
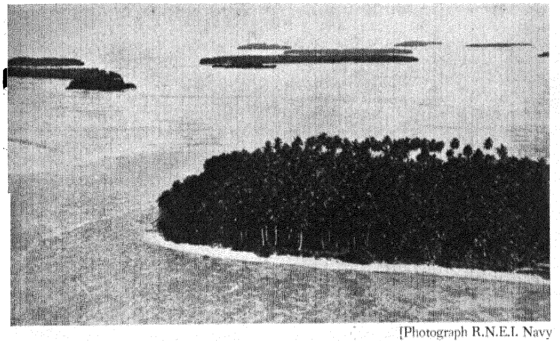


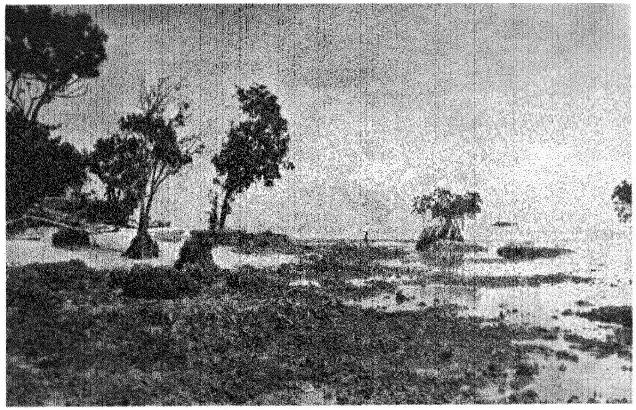
Fig. 14. *Leiden Island, a coral cay in the bay of Batavia.*

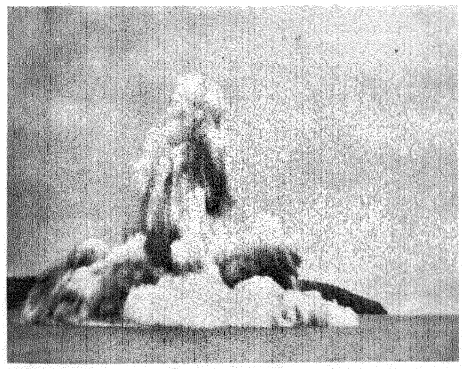


[Photograph R.N.E.I. Navy

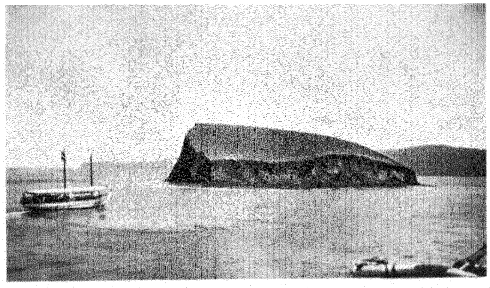
Plate III. A. *A group of coral cays in the central part of the Thousand Islands.*

B. *North-western part of Alkmaar Island, bay of Batavia, showing 'emerged' coral reef.*





C. *Submarine eruption of Anak Krakatoa Island, January* 1928.



D. *Remnant of Anak Krakatoa Island, May* 1929.

into new and fresh-looking shingle ramparts which are so characteristic in the bay of Batavia. The strength of the reef, however, is greatly weakened, and abrasion of the cay is furthered by the constant artificial destruction of large Porites colonies.

Probably a sub-recent lowering of sea-level is a second factor that favoured the maintenance of the cays. The occurrence of a small sub-recent negative shift of the coast-line has been observed almost everywhere, and as coral coasts are excellent geological tide-gauges, it is no wonder that they have been described from nearly all regions where coral reefs occur. Daly suggested that a recent worldwide sinking of ocean-level of about 5 m. has taken place. In the East Indies a large amount of evidence supports Daly's theory. Three successive slight negative movements have been recorded, viz. a level of 4–5 m., a second level of 1½–2 m. and a third level of ½–1 m. above the present level of the ocean. These recent elevations are best explained as the result of a series of stages in the withdrawal of the ocean. Plate III, B, shows three levels along the north-west coast of Alkmaar, in the bay of Batavia. It will be of great interest to know whether the same levels are of general occurrence also outside the area of the East Indies.

Many students of coral reefs have pointed out the important influence of the recent worldwide negative shift of the coast-line that favoured the formation of shingle ramparts and sand cays (see Fig. 15). Some authors are even convinced that without a negative shift of the strand-line no structure above the water can originate. Conversely, a positive shift of the coast-line is very unfavourable to the formation of shingle ramparts and coral islands. It is for this reason that no ramparts, not even a single sand cay, is found on the Togian reefs, which were formed on a subsiding foundation.

These few remarks conclude our short excursus on some of the many coral reefs that grow in great profusion in the East Indies. They suggest a great number of interesting questions; but they have to be left out of consideration. Only a few atolls will come up for discussion in Chapter II.

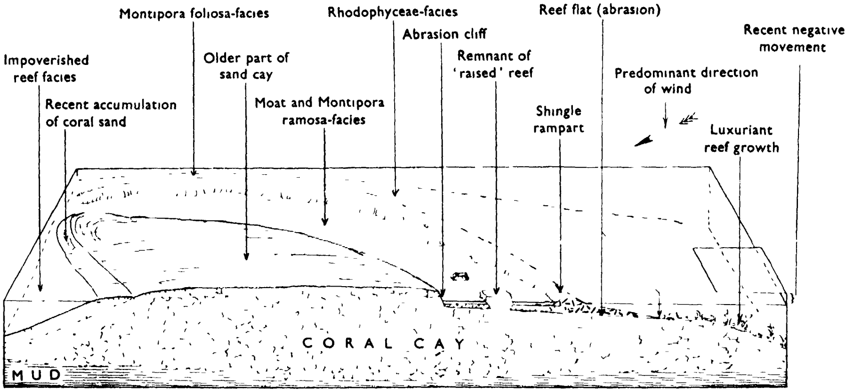


Fig. 15. *Schematic block-diagram of a coral cay in the bay of Batavia.*

TABLE I. GEOLOGY OF THE SEAS

Synopsis of subjects discussed in Chapters I and II

Submarine relief

(1) Drowned and dismembered rivers: Sunda shelf, Aru Islands, Togian Islands.

(2) Influence of eustatic movements:
  (*a*) Pleistocene: Sunda shelf and Sunda barrier-reef, ? Spermonde shelf and barrier-reef.
  (*b*) Sub-recent. morphology of coral cays

(3) Influence of bottom movements:
  (*a*) Submergence of shallow sea-floor, evidence from sediments of adjacent regions: Sunda shelf
  (*b*) Submergence of deep-sea areas.
    (i) Movements along steep faults. gulf of Tomini (Togian Islands).
    (ii) Movements along step-faults or flexures. most deep-sea troughs and basins.
    (iii) Evidence from coral reefs: Taka Garlarang and Tiger atoll, Tukang Besi Islands, Togian barrier-reef
  (*c*) Emergence of adjacent areas since Pleistocene.
    (i) Evidence from Tertiary strata: northern Java, eastern Borneo, northern and eastern Sumatra, Moluccas.
    (ii) Evidence from raised reef terraces Moluccas.

(4) Scouring effect of sea-currents since Pleistocene. Banka Straits, Sunda Straits, Thousand Islands

(5) Influence of wind. morphology of coral cays

(6) Relation of shape of deep-sea basins and troughs (as well as of their time of origin) to structural history of the archipelago as a whole.

Bottom deposits

(1) Influence of configuration of submarine relief on flow and oxygen-content of abyssal water: renewal of abyssal water of Moluccas from Pacific Ocean, along three entrances.

(2) Influence of oxygen-content of abyssal water on character of bottom deposits and rate of sedimentation: absence of red deep-sea clay and Radiolaria ooze, remarkable distribution of *Globigerina* ooze and blue mud.

(3) Influence of distribution of volcanoes.

(4) Influence of bottom configuration on high rate of sedimentation.

(5) Influence of low stands of sea-level on distribution and character of bottom deposits. Sunda shelf.

CHAPTER II

DEEP-SEA BASINS AND TROUGHS

Our knowledge of the submarine relief has been augmented considerably by the results of the deep-sea expedition on board H.M.S. *Willebrord Snellius* which explored the eastern part of the Netherlands East Indies in 1929 and 1930. The number of soundings, for instance, has been increased from 3500 to 35,000.

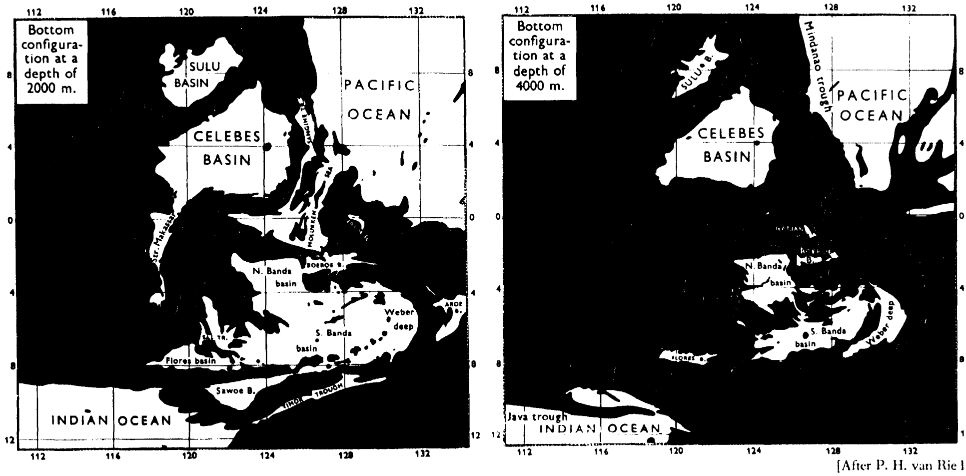
The configuration of the deep-sea basins and troughs is of fundamental importance for several oceanographic and geological questions. The flow and renewal of the abyssal water depends on the configuration of the submarine relief. In turn, the character and distribution of deep-sea deposits largely depend on the flow and oxygen-content of the bottom waters. Of course, a good understanding of the conditions under which the bottom sediments originate is of general interest to the geologist. The same holds good for observations on the rate of sedimentation.

Obviously the configuration of the basins and troughs is intimately related to the tectonics of the archipelago as a whole. As a matter of fact a morphological analysis of the deep-sea areas is an indispensable link in a synthesis on the structural geology of the East Indies. The same cannot be said on such subjects as renewal of the abyssal water. Strictly speaking, a discussion of the bottom deposits and a topic like the rate of sedimentation might be left out of consideration. But the results obtained by the Snellius Expedition are of so much general interest that I cannot refrain from mentioning a few of these results by way of introduction.

THE RENEWAL OF THE ABYSSAL WATERS

Many basins and troughs appear to be separated from each other and from the adjacent oceans by submarine ridges. A clear image of the submarine connection between the islands and the isolated configuration of the abyssal part of the deeper basins is shown by Fig. 16. In the lefthand figure the areas below 2000 m. and in the righthand figure the areas below 4000 m. are left blank. The properties of the abyssal waters in the basins depend on the properties of the water outside at a depth corresponding to the depth of the deepest entrance.

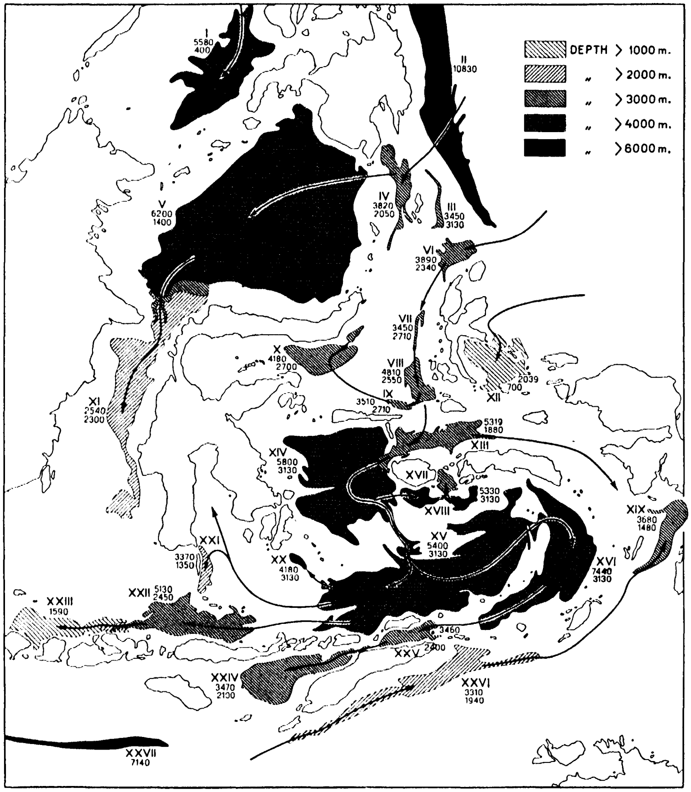
The Roman figures of Fig. 17 refer to the number of the basins in the accompanying Table II. Below these figures the greatest depth of the basin and the depth of its deepest entrance are mentioned. The arrows connect the deepest entrances of the successive basins and troughs. These arrows show the direction of flow of the bottom water.



[After P. H. van Riel

Fig. 16. *Bottom configuration of the Moluccas as shown by the isobaths of* 2000 *and* 4000 *m.*

It will be noticed that the bottom water arrives in the East Indies along four passages. The part played by the Indian Ocean is comparatively small. It is limited to a renewal of the bottom water of the Timor trough (XXVI) and probably also of the Aru basin (XIX). The Sulu basin (I) receives its water from the China Sea. No bottom water flows from the Sulu basin to the Celebes basin (V). The latter receives its supplies from the Pacific Ocean. The entrance is between the Talaud Islands and the Philippines. It flows via the Sangihe trough (IV) and the Celebes basin towards the Makassar basin (XI).



[After P. H. van Riel

Fig. 17. *Flow of the bottom water.*

The Roman figures refer to the number of the basins in Table II. Below these figures the greatest depth of the basin and the depth of its deepest entrance are mentioned.

Across another entrance, between Halmahera and Waigeo, Pacific water enters the Halmahera basin (XII). The major part of the East Indian bottom waters arrives across the Snellius ridge, between Halmahera and the Talaud Islands. It flows via the Morotai basin (VI), passes the Ternate trough (VII) and the Batjan basin (VIII), and these fill the many basins and troughs of the Moluccas along the routes shown by the arrows of Fig. 17. It takes a long time for the abyssal waters to flow from the Pacific to such very remote parts as the Flores basin (XXIII) and the Sawu basin (XXIV) near the Indian Ocean. During the long journey much of the oxygen of the water is used by deep-sea animals. In the Sawu basin a minimum of oxygen of 1·57 c.c./l. was observed, against 3·06 c.c./l. in the Morotai basin.

It is generally known that the abyssal waters of the ocean are renewed by a deep flow of oxygenated waters from polar regions. The ridges separating the East Indian basins from the ocean prevent the entrance of these deep waters. It has been mentioned already that the properties of the bottom water of the basins depend mainly on the properties of the water outside at a depth corresponding to the depth of the deepest entrance. This is illustrated by the schematic diagram of Fig. 18. The waters of the China Sea enter the Sulu basin (I) across a ridge which rises from the bottom up to 400 m. below sea-level. The oxygen-content of the water in the Sulu basin is correspondingly low, viz. 0·47 c.c./l. The entrance of the adjacent Celebes basin (V) is across the ridge that separates it from the Sangihe trough (IV). The depth of the entrance is 1400 m. The corresponding oxygen-content is 1·25 c.c./l., which is much higher than in the Sulu basin, but much lower than in the Sangihe trough (2·73 c.c./l.), for the entrance of the latter trough is across the ridge which rises up to a depth of no more than 2050 m. between the Philippines and the Talaud Islands.

The greater part of the abyssal waters of the Moluccas is renewed by a flow that crosses the still much deeper entrance over the Snellius ridge between Halmahera and the Talaud Islands. The entrance is at a depth of 2340 m. Therefore, the bottom water in the Molucca Sea is comparatively rich in oxygen as shown by the accompanying Table II and by Fig. 19, which shows the distribution of the oxygen-content at depths exceeding 100 m. (after Van Riel). It will be seen presently that these oceanographic results are of great importance for an understanding of the distribution of the bottom deposits.

TABLE II. BASINS AND TROUGHS IN THE EASTERN PART OF THE INDIAN ARCHIPELAGO

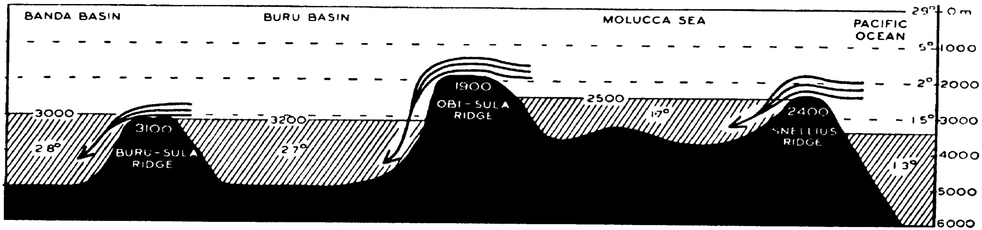
(*After Van Riel*)

No. on Fig. 17	Area	Sill depth (m.)	Greatest depth (m.)	Oxygen amount (c.c./l.)	
				Bottom water within basin	Outside basin at sill depth
Pacific Ocean					
VI	Morotai basin*	2340	3890	3·06	2·93
VII	Ternate trough	2710	3450	3·03	3·01
VIII	Batjan basin	2550	4810	2·69	3·03
X	Gorontalo basin	2700	4180	2·88	2·82
XIII	Buru basin	1880	5319	2·52	2·54
XIV	Northern Banda basin	3130	5800	2·50	2·56
XV	Southern Banda basin		5400	2·45	
XVI	Weber deep		7440	2·40	
XVIII	Ambalau basin		5330	2·40	
XVII	Manipa basin	3100	4360	2·42	2·49
XXV	Wetar trough	2600	3460	2·38	2·36
XXIV	Sawu trough	2100	3470	1·57	2·36
XXII	Flores trough	2450	5130	2·28†	2·38
IV	Sangihe trough*	2050	3820	2·73	2·61
V	Celebes basin	1400	6220	1·25	2·33
XII	Halmahera basin*	700	2039	2·92	2·86
Indian Ocean					
XXVI	Timor trough‡	1940	3310	2·93	3·26
XIX	Aru trough	1480	3680	2·16	—
China Sea					
I	Sulu basin§	400	5580	0·47	—

* Direct connection with the Pacific Ocean.
† In the extreme eastern part of the basin.
‡ Direct connection with the Indian Ocean.
§ Direct connection with the China Sea.

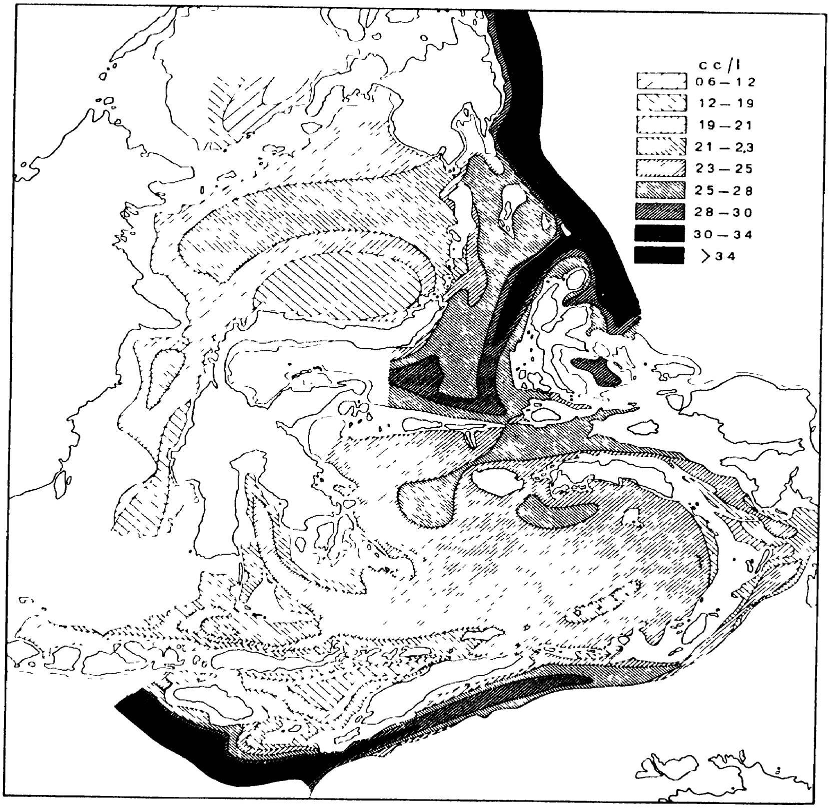
BOTTOM DEPOSITS

When Murray and Renard examined the bottom samples of the Challenger Expedition they gave a classification of deep-sea sediments based on the mineralogical and chemical character of the deposits. It appeared to them, for instance, that the content of $CaCO_3$ decreased with the depth of the ocean. Characteristic abyssal sediments of their classification are Radiolaria ooze, diatom ooze and red deep-sea clay. Only the latter was found in the area investigated by the Snellius Expedition. It is shown by Fig. 20 in the Pacific, i.e. outside the area of the archipelago, at a depth of between 4000 and 6000 m. Now compare the sediments in the Weber



[After Ph. H Kuenen

Fig. 18. *Diagram to illustrate the renewal of abyssal water in the basins of the Moluccas.*

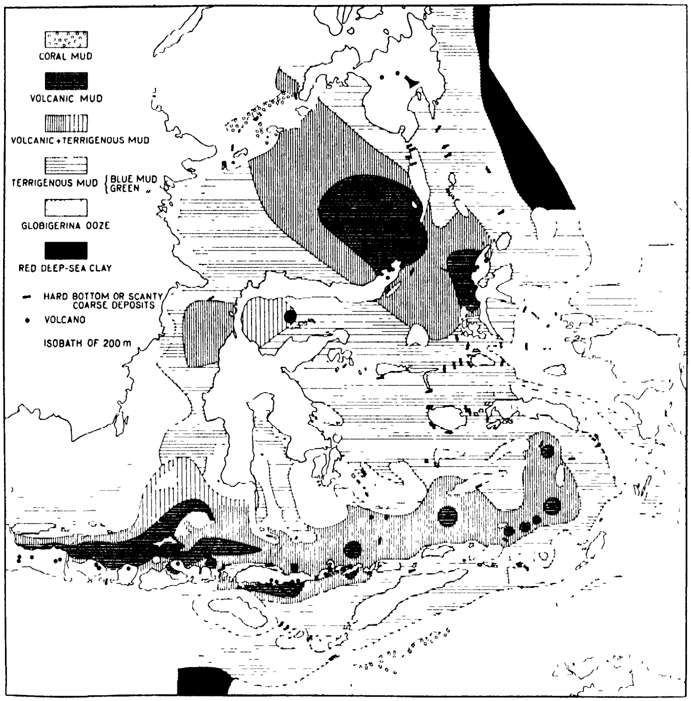


[After P H van Riel

Fig. 19. *Oxygen content of the deep-sea basins of the Moluccas.*

deep: blue mud was found down to a depth of more than 7000 m. And the same terrigenous deposits were recorded from the deep northern Banda Sea basin.

Red clay derives for the greater part from the disintegration of terrigenous material. It is an accumulation of minutely divided particles, held in suspension in sea-water and distributed to great distances by an ocean current and deposited at an extremely slow rate. The red colour is due to the oxidation of clay particles in the abyssal waters of the ocean, and the oxygen is supplied by a flow of cold oxygenated waters from polar regions. The penetration of these waters into the East Indian waters is hampered by the presence of the submarine ridges or 'sills' which separate the East Indies from the Pacific and Indian Oceans. The influx of water comes from medium depth or still higher levels. This explains the absence of red clay even in such an extremely deep trough as the Weber deep.



[After S. A. Neeb, simplified

Fig. 20. *Bottom deposits in the eastern part of the East Indies.*

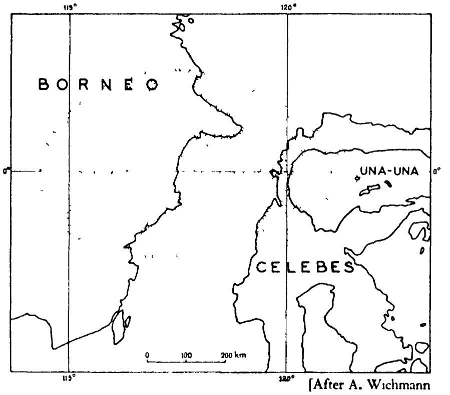
Decalcification of bottom sediments is another phenomenon that largely depends on the oxygen-content of the sea-water.

Take an example. *Globigerina* ooze occurs in the open ocean usually between 500 and 2000 m. The name is used to indicate a sediment with a calcium-carbonate content of more than 30 per cent and consisting for the greatest part of pelagic Foraminifera. In the area of Mindanao, the Sangi and Talaud Islands, it was found on submarine ridges to a depth of 2000 m. In the Sulu basin, however, it occurs from 4000 m. down to the bottom at about 4500 m. And this is also in strong contrast to the sediments in the adjacent Celebes basin. So we see that, under special circumstances, a comparatively high $CaCO_3$ content may occur at great depth. For it depends mainly on three factors: temperature, CO_2, and O_2 content of the sea-water. The decalcification of sediments depends less upon the depth than upon the action of cold oxygenated currents, inasmuch as the latter facilitate the formation of carbonic acid and this in turn causes the solution of calcium carbonate. In the Sulu basin, the temperature was found to be lowest at a depth of 1200 m. From 1200 m. down to the bottom, at 4500 m., it remained the same, about 10° (Table II). It follows from this state-ment that no deep connection can exist between the Sulu and Celebes basins. A high submarine ridge (400 m. below sea-level) forms a connection with the Chinese Sea. This allows only a slow flow of water which is poor in oxygen.

Hence geologists when studying sediments from older formations ought to be careful in their conclusion about the depth at which the deposits were formed. For the East Indian basins and troughs clearly show us that the depth at which a sediment is deposited is not a factor of primary importance to its percentage of calcium carbonate.

The lime-content of a marine sediment depends on still another factor, namely the rate of sedimentation of terrigenous material. Now in the East Indies terrigenous material is supplied to the basins from nearly all sides. Moreover, the basins have comparatively steep walls. And as soon as the angle of the deposits exceeds a few degrees a process of down-sliding causes great quantities of rich $CaCO_3$ sediment to slip down into the abyssal depth. It is for this reason that the map shows a distribution of terrigenous deposits over vast areas. (The term terrigenous deposits (Plate IV, A) includes both blue mud—and this sort of deposit forms the bulk of it—and green mud.) Deposits derived from still active volcanoes have been mapped with a special notation.

This helps us in understanding the distribution of Globigerine ooze (Plate IV, B), which at first sight seems rather capricious. It was found widely distributed along the south and east sides of the outer Banda arc, e.g. in the Arafura Sea, on the Sahul shelf near Sumba, Savu and Rotti Islands, around the 'Bird's Head' of New Guinea and south-east of Celebes. We may ask why it is conspicuously absent in the Gulf of Bone (between the southern arms of Celebes). The answer is that the samples show an abundance of terrigenous matter causing the calcium-carbonate content to remain below 30 per cent.



[After A. Wichmann

Fig. 21. *Distribution of ash from the eruption of Una-Una volcano* 1898.

If we ask why no *Globigerina* ooze was found in the northern Banda Sea basin, the answer is different. A comparison with Fig. 19 shows that the water has a comparatively high oxygen content. The partial solution of calcareous particles in the oxygenated deeper water is the main cause of the low calcium-carbonate content of the deposits of the northern Banda Sea.

As mentioned before, sediments in which material from still active volcanoes predominates have been mapped with a special notation. The volcanic material is largely volcanic ash distributed by the wind, with additions of some material washed off from submarine volcanoes or volcanoes bordered by the sea. The distribution of the volcanic mud depends mainly on the actual distribution of volcanic districts in the archipelago. One area of volcanic mud is seen in the surroundings of the Lesser Sunda Islands, from Java to Gunung Api of Banda, a second in the area of the volcanoes of Halmahera, northern Celebes and the Sangi Islands. A third area was found westward of the Una-Una volcano (in the gulf of Tomini, north Celebes). This volcano had its last eruption in 1898. Wichmann carefully assembled all data on the distribution of the ash of that eruption on the islands of the East Indies. He found a westward distribution under influence of the then prevailing east monsoon (Fig. 21). A comparison with Fig. 20 shows a remarkable congruence with the data based on the bottom samples of the Snellius Expedition. As a matter of fact some of the volcanic muds could be classified according to the special petrographic character of the ashes of the volcanoes from which the material originated.

RATE OF SEDIMENTATION

The last major eruptions of the Tambora volcano on Sumbawa Island took place in the year 1815. The characteristic mineralogical composition of its ash was recognized from a certain level up to the surface of the core of seven samples.

From four samples in the Flores Sea, taken by the large 4 m. long bottom sampler, the thickness of the part of the sample in which the ash occurs, in addition to the terrigenous or blue mud, could be measured. It was found that the mean rate of sedimentation of blue mud in the Flores Sea was about 7·5 cm. per 100 years, which is about fifty times the average sedimentation rate of blue mud in the tropical Atlantic Ocean, which was found to vary from 0·09 to 0·33 cm. per 100 years. The same order of magnitude was calculated from one sample in which the ash of the eruption of the Una-Una volcano of 1898 was recognized, viz. 6 cm. per 100 years. This rate of sedimentation would result in a layer of about 13 m. of post-glacial sediments, not regarding the sedimentation of volcanic matter and lime.

On the other hand, the rate of sedimentation of *Globigerina* ooze was found to be about 0·1 cm. per 100 years for a sample from the Flores Sea, and 0·24 cm. per 100 years for

[From G. A. Neeb

Plate IV. A. *Terrigenous mud* (× 16). *Java Sea, station* 25.

[From G. A. Neeb

B. Globigerina *ooze containing volcanic material and clay* (× 8). *North of Sumba, station* 148.

the Una-Una ash sample. These figures are scarcely higher than those found for the rate of sedimentation of *Globigerina* ooze in the Atlantic, which was found to be 0·05 to 0·2 cm. per 100 years.

It is well known that the long samples taken in the Atlantic and the Bartlett deep show two or more layers which are related to post-glacial and glacial stages. Nothing of the sort has been found in the East Indies. No variation of foraminiferal content which might be attributed to climatic changes is to be seen. This might be explained either by assuming that the post-glacial sediments are too thick to be pierced by the long bottom sampler of the Snellius Expedition, or that the 4 m. Pleistocene deposits are indistinguishable from the Holocene sediments because the Pleistocene climate was not appreciably different from present conditions in this tropical area.

From the data mentioned so far it may safely be assumed that the Pleistocene deposits are deeply buried below terrigenous and volcanic matter, at least several metres below the present level of the bottom.

A further characteristic of most of the samples—even those of 2 m. length—is that they are unstratified. Even the minor inconformities which Barrell called diastems, are entirely absent from the deep-sea deposits of the East Indies. The alternating rhythm of the monsoons, resulting in a marked seasonal variation in the amount of terrigenous material transported to the sea, is not reflected in the bottom sediments. Suppose a rate of sedimentation of 10 cm. per 1000 years. This would cause deposition on the sea-floor of 0·1 mm. each year, an amount easily discernible under the microscope when examining thin sections of undisturbed bottom samples. However, not the slightest indication of such a stratification could be observed. Kuenen's explanation of their total absence is that the particles which are sinking down have a diameter of the same order of magnitude. 'Only when the grains are themselves considerably smaller than half the yearly deposit could the stratification show up. However, these small particles of clay, volcanic ash, etc. sink so slowly, that they take months or even many years to sink to the floor of a deep basin. Currents, turbulencies and convections will bring about perfect mixing on the way to the bottom.' The general conclusion is that 'an annual rhythm in the deposits of the East Indies is neither to be demonstrated nor to be expected'.

It is a very remarkable fact that the ash of the Tambora eruption of the year 1815 has not yet entirely sunk to the bottom. A clear solution of this oceanographic problem is not yet given.

The high rate of sedimentation in the basins, which may be assumed at 5 cm. per century if compaction of the sediments is taken into account, would result in a complete filling up of the basins in some 10 million years. It is tacitly assumed in this rough calculation that the surrounding islands could supply the sediments by being continually elevated and that the floor of the basins would remain stable. Indeed, most islands show signs of recent elevation, but there are reasons for believing that the floor of the basins and troughs is subsiding. We will turn to these phenomena presently, and eventually the same question will come up for discussion in later sections.

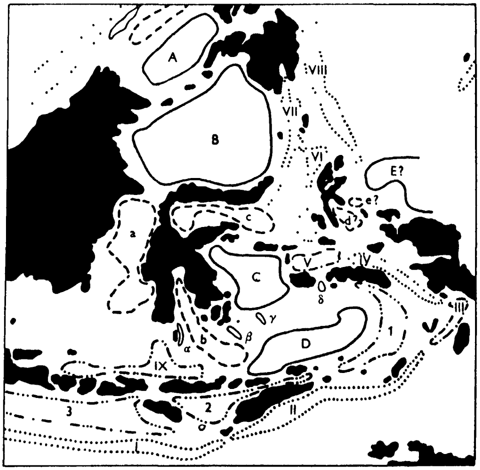
MORPHOLOGICAL ANALYSIS

From a morphological point of view the deep-sea basins and troughs fall into two main types.

One type has a roundish or slightly elongated ground-plan. Its U-shaped cross-section is caused by a flat and nearly horizontal bottom with comparatively steep sides. Examples are the Sulu, Celebes, and Banda Sea basins. Compare Fig. 22, A–D, which gives a synopsis of Kuenen's morphological analysis of the bathymetric results obtained by the Snellius Expedition.

The second type is represented by the troughs marked I–VIII in Fig. 22. They have a strongly elongated and mostly curved ground-plan and a V-shaped cross-section. They can be followed from west of Sumatra and south of Java along the outer Banda arc towards the Philippines.

Kuenen distinguishes two more groups, one of which is morphologically allied to the first type, but the shape is more elongated. The cross-sections are generally of the V-shaped type, but the basins have tapering ends. Examples are: (*a*) the Makassar, (*b*) the Bone, and (*c*) the Tomini basins.



[After Ph. H Kuenen

Fig. 22. *Morphological analysis of the bottom relief.*

I–IX, marginal deeps, 1–3, troughs of the intramontane type, A–D, nuclear basins, *a–c*, discordant basins. I, Java trough, II–VII, Timor-Ceram and Molucca troughs; VIII, Mindanao trough, IX, trough of the Flores Sea. 1, Weber deep; 2, Sawu trough, 3, Java-Mentawei trough. A, Sulu basin, B, Celebes basin, C and D, Banda basins. *a*, Makassar Straits, *b*, Gulf of Bone, *c*, Gulf of Tomini

On the other hand, (1) the Weber deep, (2) the Sawu trough, and (3) the Java trough are more like those of the second type, but their bottoms are more flat and horizontal.

Hence the extremes are very different, but there are transitional types. It is, for instance, difficult to place the Flores trough (IX), the Aru trough (III) and the Buru trough (V) in one of these four groups on purely morphological grounds inasmuch as they combine characteristics of more than one group. (The small basins α, β, γ, δ and ε are left out of consideration, as well as E.)

TIME OF ORIGIN

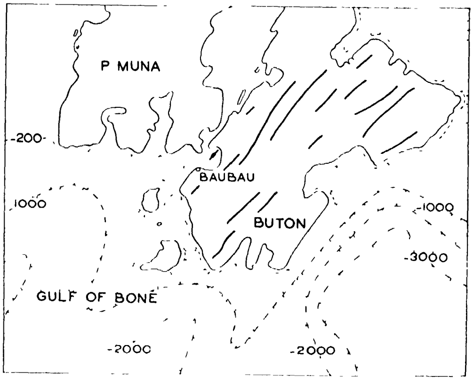
It is obvious that the site and shape of the elongated troughs I–VIII and 1–3 must be connected in some way with the origin of the island arcs along which they occur. And it seems apparent that the two other groups of basins, too, are adapted to the trends of the islands and submarine ridges that enclose them.

As a matter of fact Kuenen argued that the East Indian basins, entirely surrounded as they are by sial, originated recently, geologically speaking, as depressed continental areas. The basins are not surrounded by fault planes, their margins are either stepped faults or weak flexures.

These conclusions agree well with deductions of a geological nature.

If a thick sequence of clastic sediments of non-volcanic origin be found on an island which is surrounded by deep sea, one is forced to the conclusion that a land area occupied the site of the present deep sea at the time when the sediments were deposited. For at the time when the sediments formed there must have been a land area from which the denudation products were transported to the area of sedimentation. Such a land area must have existed on one side at least. Consequently, one cannot escape the conclusion that the basins and troughs of the East Indies originated in a not very distant past. Of course the same reasoning is applicable to other islands, such as Fiji and New Caledonia. In general, the same conclusion holds good for the whole extensive area that is called Melanesia, or the foundered part of Australasia as Bryan called it. Now clastic sediments dating from Tertiary times do occur on most of the islands of the Moluccas.

With the aid of detailed investigations in the field the direction of transport may be fixed. The importance of sedi-



[After W. Hetzel

Fig. 23. *Upper Tertiary anticlines in Buton Island, south Celebes.*

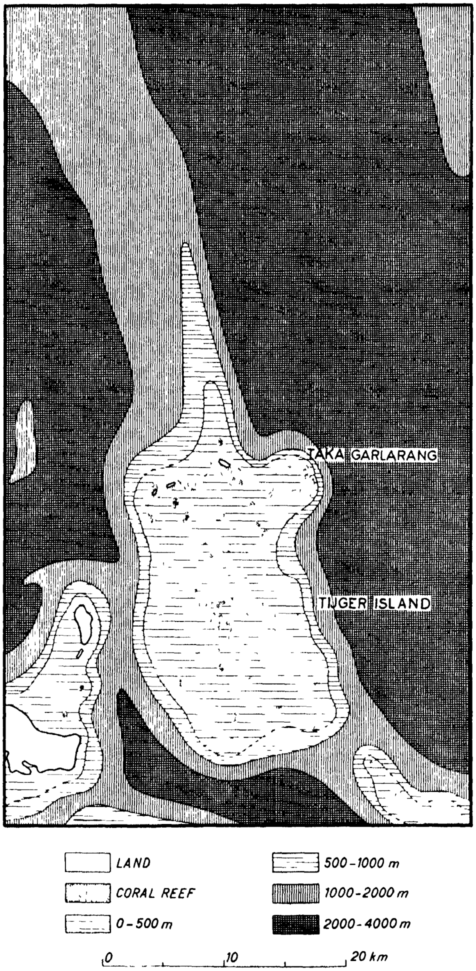
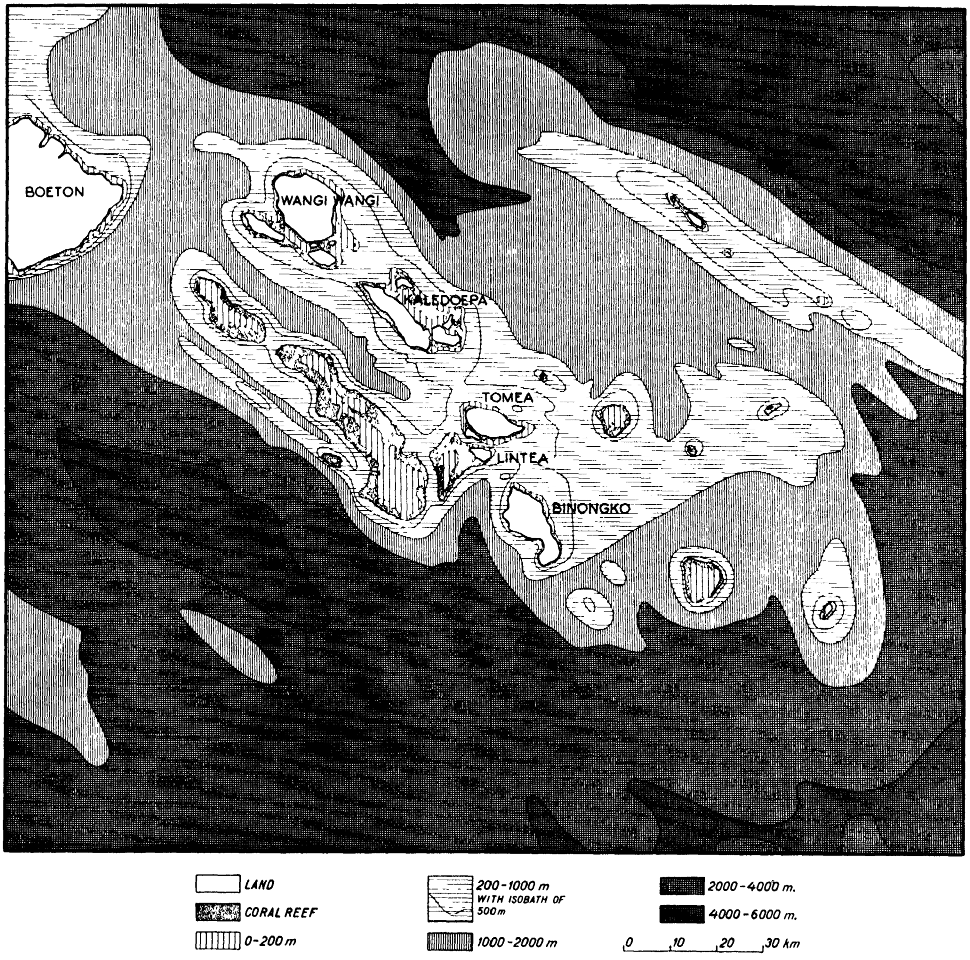


Fig. 24. *Tijger atoll and the atoll Taka Garlarang, Flores Sea.*

ment-petrographic data for such problems was amply demonstrated above when the history of the Java Sea was treated (p. 2).

Other examples of former areas of denudation in the Moluccas will be mentioned later when the paleogeography of the East Indies is discussed.

Data of a different kind support the conclusion about the comparatively recent origin of the deep-sea basins. In several places the trend of folded Miocene strata is intersected at an angle by the present coast-line which at the same time is the boundary of a deep-sea trough or basin. Hence the basins must have originated or they must have been rejuvenated at least after the Miocene folding. Molengraaff pointed this out, for example, for Timor, where the Amanuban mountain chain is intersected at an angle of 12° by the coast. The Upper Tertiary strata of Buton (south Celebes) have been folded with a trend that intersects at right angles the neighbouring Bone basin (Fig. 23). Along the western coast of Celebes, too, the Tertiary folded chains are intersected by the coast of the Makassar basin.



[Redrawn after Ph. H. Kuenen

Fig. 25. *The Tukang Besi Islands, south-eastern Celebes.*

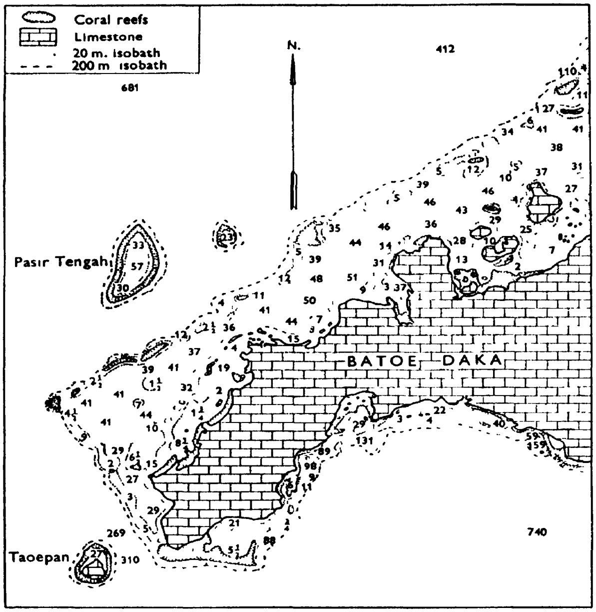


Fig. 26. *Barrier-reefs and atolls of the Togian Islands, Gulf of Tomini, north Celebes.*

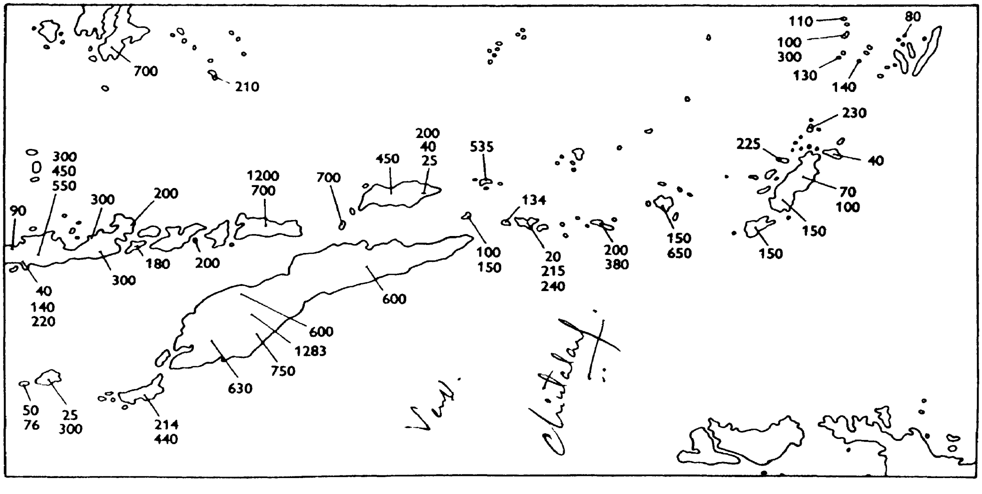
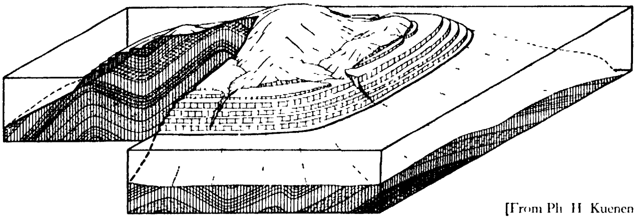
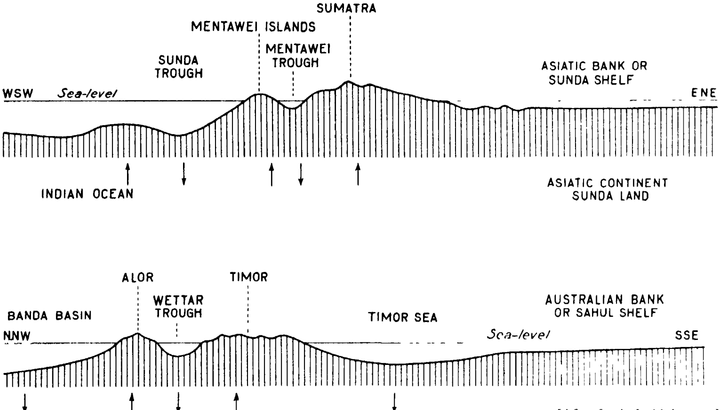


Fig. 27. *Elevated coral limestones and river-terraces in the southern Moluccas.*



[From Ph. H. Kuenen

Fig. 28. *Kissar, a terraced island in the southern Moluccas.*



[After G. A. F. Molengraaff

Fig. 29. *Post-Tertiary bottom movements in the East Indies.*

Subsidence of the bottom in the order of some thousands of metres is also deduced from some atolls and barrier-reefs. The steepness of the submarine slopes is one of the most characteristic features in East Indian atolls; sometimes the declivities even approach the vertical down to a depth of several hundred metres. They must consist of solid coral reef structures and they were formed by up-growth on a subsiding bottom. Moreover, most of the atolls have grown on deeply submerged submarine ridges from which they rise abruptly and steeply to the surface.

Kuenen has contributed considerably to a solution of many problems on the origin of atolls by his careful examination of the deeper slopes outside these reef structures and of the general morphology of the surrounding sea bottom. The echo-soundings of the Snellius Expedition and the fair sheets of the hydrographic survey of the East Indies give convincing evidence. To mention one example (Fig. 24): Taka Garlarang atoll rises up abruptly from a depth of over 2000 m. and is built on the side of a deeply submerged ridge running from south Celebes to the south. The Tijger atoll rises from the same ridge 'like a chimney-pot standing on a roof, but it is much broader than the crown of the ridge and has evidently built outwards on its own screes'.

The most interesting atolls are situated in the Tukang Besi group, south-east Celebes. The atolls and islands of this group show a linear arrangement, which is related to the tectonic structure of the basement. A row of atolls on the south-west side is followed by a row of elevated islands, which is followed by another series of atolls and a last row of islands with elevated reef terraces (Fig. 25): Lintea consists of an atoll on the west side, bordered by an elevated island on the east side. In the middle of the north-east coast of Kaledupa, Tertiary strata occur; they have also been found on Wangi-Wangi, Kaledupa and Tomea.

Echo soundings prove the great steepness of the submarine slopes of the atolls down to 500 and 600 m. resting on an undulating submarine plateau of 900 m. depth. The features can only be explained by the up-growth of coral reefs, as neither a talus of loose material nor a submarine volcanic slope ever shows such extreme inclines. Kuenen has given special attention to this point. These features are, however, very simply explained by a gradual sinking of the bottom on which the atolls grew up. Probably towards the close of Tertiary times reefs grew round the highest points of the anticlines of a slightly undulating plateau, which gradually sank several hundreds of metres. By block-faulting movements roughly parallel to the original anticlines and synclines some reefs were intermittently raised above sea-level while on the sinking blocks a series of reefs grew up as atolls. One of these atolls was slightly tilted (Lintea). The western atolls are oblong shaped according to the original anticlinal ridge on which they started growing. The eastern atolls are round, however, and scattered arbitrarily on a submarine plateau which is now submerged about 1000–2000 m.

So in this region subsidence of the bottom has amounted to 1000 m. at least since the formation of the reefs. For Tijger atoll and Taka Garlarang this amount may be estimated at 2000 m., i.e. about 0·2 cm. per year.

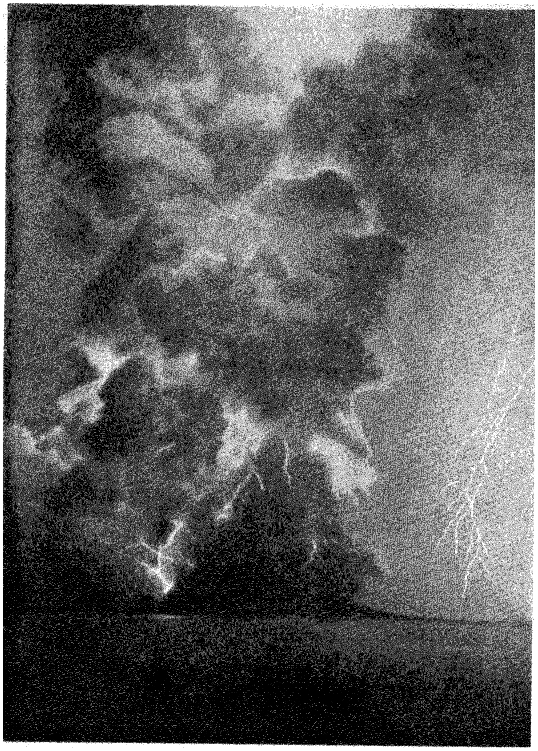
Deep borings on one or more of the atolls might provide us with data from which the age of the downward movement could be fixed. At least it appears from the Tertiary strata on some of the Tukang Besi Islands that the beginning of the movement dates from Pleistocene times or at the most from the uppermost Tertiary.

The remarkable barrier-reefs of the Togian Islands in the gulf of Tomini, north Celebes, have already been mentioned. These barrier-reefs, running at right angles to each other (Fig. 26), apparently grew up along the border of a block that is bounded by steep faults. It was argued (p. 5) that these faults and the adjacent deep-sea areas originated in a comparatively recent past, which certainly was not longer ago than Upper Tertiary or Pleistocene.

On the other hand, several islands in the Moluccas show signs of elevation since Upper Tertiary times. It is especially the elevated reef limestones that give a good impression of the amount and of the intermittent character of these movements. In Fig. 27 some figures have been brought together for part of the southern Moluccas and Fig. 28 shows one of the many examples of terraced islands of the Moluccas. According to Molengraaff the elevation of the series of islands, and the origin of the deep-sea basins situated along and in between them, must have occurred simultaneously, geologically speaking. His opinion is shown by the schematic section, Fig. 29. Of course the question arises of what caused these movements. For the moment, however, we must leave the interesting problem of the origin of island arcs and deep-sea relief. The question will be taken up in Chapter VI after some other groups of data have been considered.

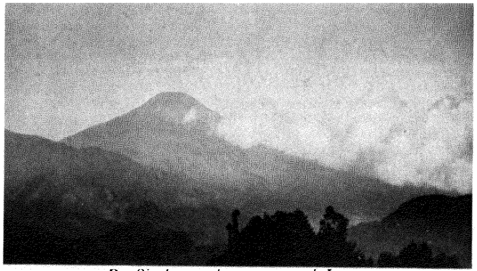
PROBLEMATIC QUESTIONS

Apart from the general problem of the origin of the deep-sea areas, there arise the following questions: Why have the basins and troughs these peculiar shapes? Why is the series of troughs between the double row of islands interrupted by Sumba Island? And further, why are the two large shelf areas (Sunda land and Australia with the Sahul shelf) separated by such an intricate pattern of deep-sea troughs, basins and chains of islands? And why is the island-arc a double festoon: why not a single arc, or, say, half a dozen strips of islands and submarine ridges? These are some of the principal questions that will have to be answered in any synthesis on the structural history of the East Indies, in addition to the unanswered questions of the first chapter. The list of problems will, however, grow much longer when other subjects come up for discussion, such as the volcanoes, for example, which will form the topic of the next lecture (Chapter III).

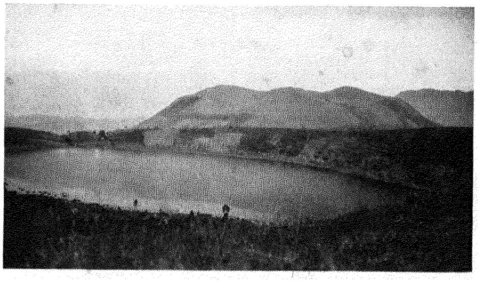


[From *Bull. Volcan. Survey*, no. 63, 1933

Plate V. A. *Birth of Anak Krakatoa, no.* 3, 1 *May* 1933.



B. *Sindoro volcano, central Java.*



C. *Explosion crater in the volcanic Dieng Mountains of central Java.*

CHAPTER III

VOLCANOES

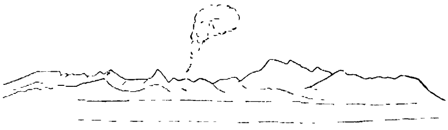
Many islands of the East Indies are crowded with volcanoes. They provide fertile soil and consequently they are the source of prosperity, but at the same time they are awe-inspiring by their devastating eruptions. It is, therefore, not surprising that the attention paid to them dates from long ago and has grown increasingly with the progress of geological science during the last hundred years. Many volcanic districts have been described in huge memoirs, some of them illustrated with a wealth of photographs and diagrams. Other monographs are devoted to the eruption of one special volcano. The notorious eruption of Krakatoa in the year 1883 was even described twice, once in a big volume by Verbeek, while another book on the same cataclysm was published by the Royal Society a few years later. From the year 1928 a monthly Bulletin was published by the Volcanological Survey of the Netherlands East Indies. Some authors investigated all available records in order to trace in as much detail as possible the volcanic eruptions in the past. On the other hand, members of the Volcanological Survey are continually on the look-out for means of enabling them to predict the approach of a future eruption. Plans were worked out to evacuate the population in time from the most dangerous sectors to safer places. Tunnels and a large siphon were built to lower the crater-lake of the Kelut volcano artificially. Experiments were carried out to investigate the usefulness of solfataric gases. Some workers studied the mineralogical and chemical properties of ashes and lavas. Others were absorbed in problems concerning the geographic distribution, the deeper structure and the structural history of the volcanic districts. Once more I must seriously restrict myself. What I am going to give you is no more than a very short synopsis of some of the multitude of subjects of entrancing interest to the volcanologist and geologist.

DIFFERENT TYPES OF VOLCANOES

In his *Physical Geology* Arthur Holmes distinguishes six types of volcanic forms (see Table III). The different types depend mainly on the quantities and character of the lavas and pyroclasts erupted. Two types, viz. wide lava plateaux and gently sloping shield volcanoes, are conspicuously absent in the East Indies. These types originate when highly fluid basaltic lavas come to the surface either from long-continued fissures or from central vents. The lavas of the East Indian volcanoes are, however, predominantly more acid and belong to two different magma-clans which in turn are conspicuously absent among the shield volcanoes of Hawaii and Samoa. Of course you will ask 'Why?' Let us note it as a first problematic point, and try to find a solution farther on.

The lavas that are richer in silica are therefore more viscous and of a more explosive character. On the possible combinations of these two depend the type of eruption and the type of volcanic structure that will originate: explosive, effusive or mixed. In the East Indies they are represented by craters of a mere explosive nature, cinder cones and domes or tholoids, but usually more than one type appears in one and the same volcanic complex during its long though intermittent activity. Frequently explosive and effusive activities alternate. Hence the commonest type is the composite or strato-volcano. Let me give you a few examples.

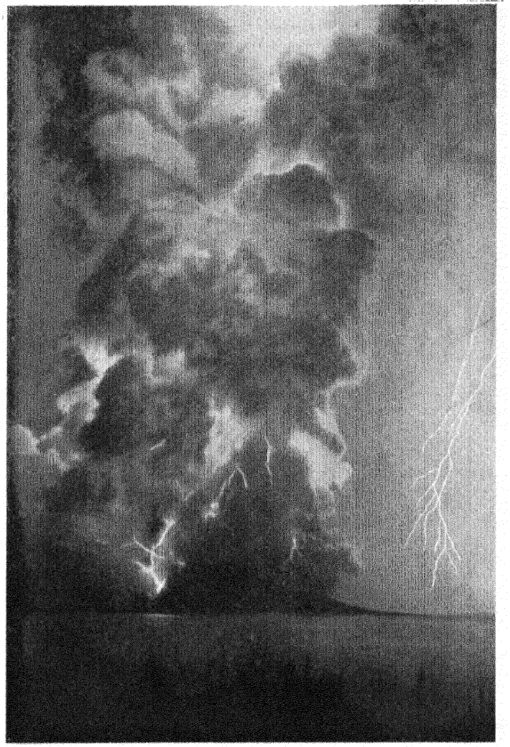
The outline of the strato-volcano may vary from a high lofty cone, such as the Sindoro (Plate V, B), to the rather low and irregular aspect of Una-Una (Fig. 30).



[After a sketch by G. A. F. Molengraaff

Fig. 30. *Una-Una volcano, September* 1901.

The first-named type may be of a rather simple structure, although on investigation it often appears to be much more complex. The other extreme is invariably due to a long history in which building up and destruction played their part alternately. Often a new generation of volcanoes grows up in the large caldera that originated when a huge volcanic body was largely destroyed. In the year 1928 Anak Krakatoa, which means the 'Child of Krakatoa', was born as a cinder cone along the margin of the submarine caldera that was formed by the enormous cataclysm of that volcano in 1883 (Plate III, C). You know that it succumbed to the attack of the waves (Plate III, D). A short time afterwards, however, a new child was born during a phase of even more violent eruptions and eventually Anak Krakatoa nos. 3 and 4 originated (Plate V, A). A further developed stage is a large strato-volcano such as Gunung Api of Banda or the central volcano in the huge Batur caldera in Bali Island (Fig. 31), and several such eruption cones (Bromo, Batok, Widodaren) originated in the Tengger caldera, East Java (Fig. 32).



[From *Bull. Volcan. Survey*, no. 63, 1933

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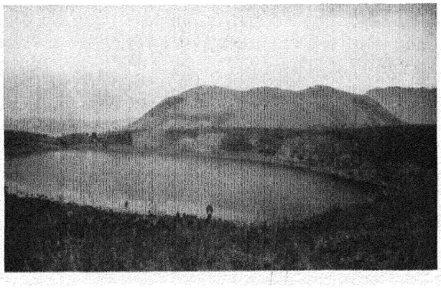

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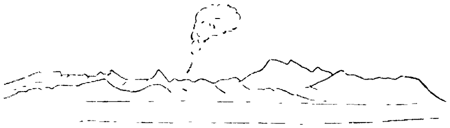

[After a sketch by G. A. F. Molengraaff]

Fig. 30. *Una-Una volcano, September* 1901.

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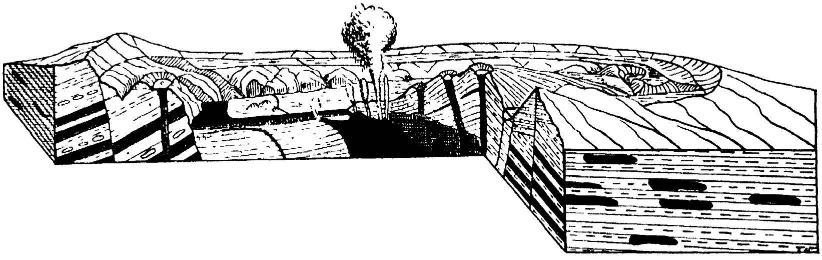


[From Ch E. Stehn

Fig. 31. *Block-diagram of the Batur caldera, Bali.*

Craters that owe their origin to one or more large gas explosions are known from several volcanic districts. The surroundings of the Dieng plateau in Central Java show many striking examples (Fig. 33 and Plate V, C), and the Lamongan volcano is surrounded by a great number of explosion craters, which possibly originated from one or more laccolithic intrusions.

Lava domes or tholoids occur with a great number of volcanoes. An active tholoid is known from Lobetobi Perampuan in Flores Island, the Gunung Api of Sangean Island, the Toduka of Halmahera, the Galungun of Java and, in a fossil state, in the craters of the Sumbing in Java and the Sibajak of Sumatra. A similar dome rose in the Ruang crater (north Celebes) in the year 1909 and was destroyed by an explosive eruption five years later. Two lava plugs protrude on the top of the Javanese Merapi like oil-paint from a tube. At times when the viscous or nearly solid lava of a dome is thrust up from below, great quantities of lava-blocks crumble off from the dome and slide down along the flanks of the volcano.

Highly heated gas escapes from the lava and this, together with the finer lava particles which are separated from each other by a cushion of compressed gas, rushes down along the slope of the volcano as an awe-inspiring *nuée ardente* (Plate VI, A, B). In his last monograph on Mount Pelée, the famous volcano of Martinique in the French West Indies, Perret was able to point out that in the *nuées ardentes* of the last eruption of that volcano the lava was self-explosive. 'The gas-charged substance,' he wrote, 'when the critical point is reached, suffers a sudden vesicular expansion throughout its entire mass, an explosive process so distributed that it may merely lift the material soundlessly, without marked violence, from its pocket and down upon a slope, where it descends gravitationally as a hot avalanche.'

Gunung Kunir is an example of a lava dome that originated outside a crater or volcano, but it is situated in the volcanic Dieng district of central Java. Eight lava domes protrude along the slopes of the Penanggunan (Plate VI, C). Only seldom has a lava flow originated from a dome. In the Sibajak this phenomenon seems to have taken place.

In some craters, the bottoms of which are filled up with lake sediments, the activity of a projecting lava dome is demonstrated only by the up-doming of the bottom deposits. It appears as an island in the crater lake of the Kelut (Plate VI, D), and a similar knoll, though much larger, is to be seen in the crater of Una-Una.

The presence of a crater lake in an active volcano is of course a much-feared phenomenon. The Kelut suddenly threw some 40 million cu.m. of water on its flanks when the eruption of 1919 started. The water rushing down the slopes of the volcano, mixed with loose detritus and larger blocks, devastated large areas.

The erosive power of such a mud-flow or *lahar* is seen in the broad and steep-walled valleys, as illustrated by Plate VI, E, which shows a *lahar*-valley formed by the 1898 eruption of the Una-Una volcano.

VOLCANO-TECTONIC STRUCTURES

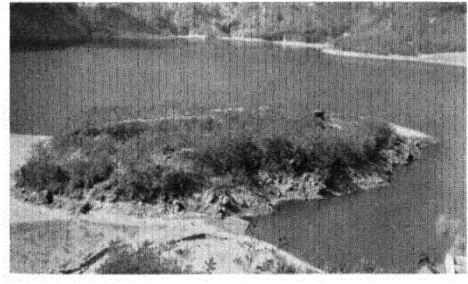
Another phenomenon that must be mentioned is the rather frequent occurrence of a barranco, a large valley of tectonic origin in a volcanic body. The valley of Sapikerep in the Tengger Mountains is a well-known example (Plate VII, A, and Fig. 32). And probably the crater of the Papandajan owes its horse-shoe shape to the collapse of part of its walls along pre-existing fracture planes. A similar phenomenon probably took place in the Galunggun (west Java) and the Sibajak (Sumatra). The larger tectonic valleys presumably owe their origin to the collapse of the roof of the magma chamber deep below. Two of these remarkable elongated depressions may be seen in the submarine relief of the Krakatoa caldera which originated with the great eruption of the volcano in the year 1883 (Fig. 34). The caldera of Krakatoa is the only caldera whose formation was witnessed in historical times and studied immediately afterwards. The amount of fragments from the destroyed former volcanoes that are now spread over its remnants (Long Island, Verlaten Island and Rakata) is so small that most of the missing material representing the titanic outburst undoubtedly must have foundered into the underlying magma chamber.

[From Ch. E. Stehn

Plate VI. A *and* B. 'Nuée ardente' *descending from the top of Merapi volcano, central Java, December* 1934.

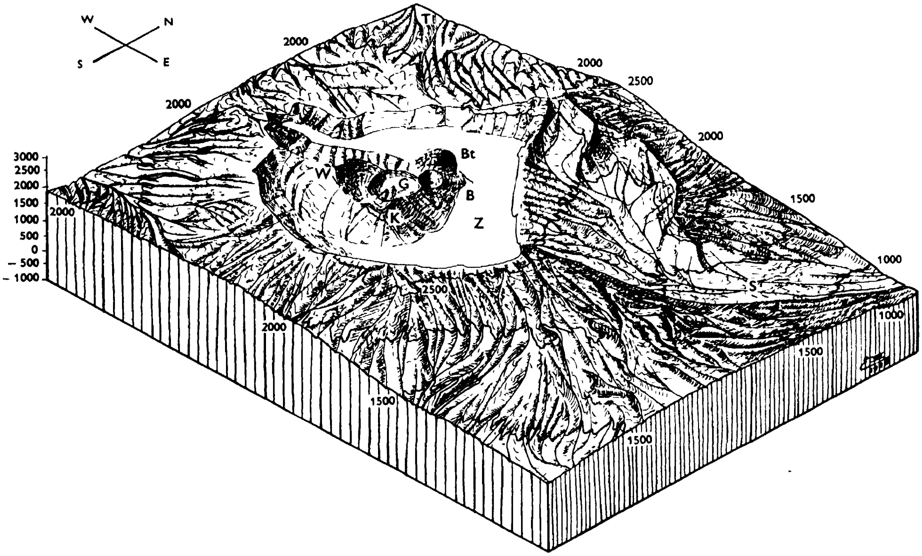
[Photograph R.N.E.I. Air Forces

C. *Lava plugs on the flanks of Penanggunang volcano, eastern Java.*



D. *Mound of crater-lake deposits caused by the up-doming action of a lava-plug, Kelut volcano, east Java.*

E. *Mud-flow valley of Una-Una volcano, northern Celebes.*



[From B. G. Escher

Fig. 32. *Block-diagram of the Tengger caldera, east Java.*
To the right the volcanic-tectonic valley of Sapikerep. Compare Plate VII, A

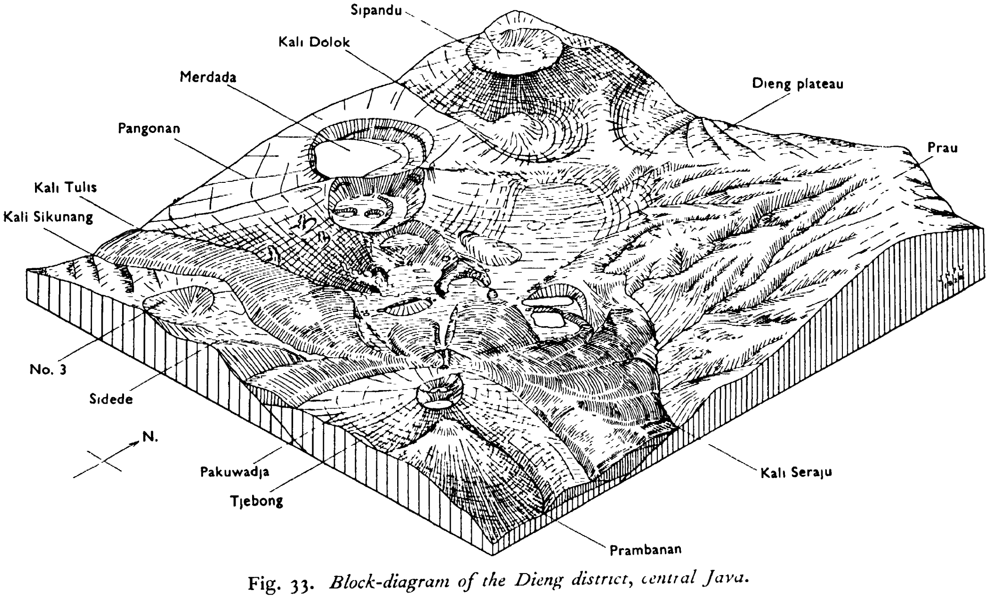
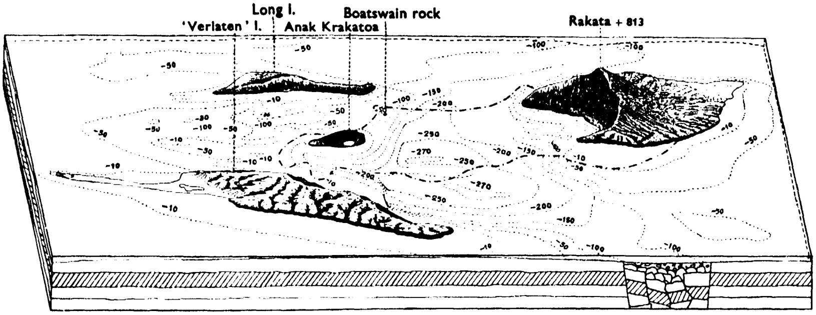


Fig. 33. *Block-diagram of the Dieng district, central Java.*



[From M. Neumann van Padang

Fig. 34. *Submarine caldera and volcano-tectonic valleys of Krakatoa.*

The tectonic valleys show that in some of the volcanic structures volcanic and tectonic activity go hand in hand. According to Van Bemmelen one of the largest volcano-tectonic depressions is Lake Toba in northern Sumatra (Fig. 36). This giant cauldron, which is 87 km. long and 31 km. broad, originated in the course of a violent eruption in Pleistocene times. Samosir is considered as the collapsed roof of a granite batholith, the gas-laden magma of which caused the catastrophe when it nearly reached the surface (Fig. 35).

Another diagram by the same author represents the south-western part of Sumatra and exhibits some longitudinal faults including the Semangka rift-valley and some volcano-tectonic depressions such as Lakes Ranau and Suoh (Fig. 37). In the latter region a tectonic earthquake was recorded along one of the major faults of the rift-valley on 25 June 1933. Thirteen hours afterwards the hot springs of Suoh showed a general increase in steam activity. Fourteen days later a strong phreatic steam explosion took place (Plate VII, B), giving origin to two large explosion craters, one about 2 × 1½ km., the smaller one 1 × ¾ km. Fumarolic activity was observed over a length of 5 km. and an average breadth of 1½ km. and escaping from more than a hundred vents. The explosion was probably caused by the development of large quantities of steam from the ground water which, penetrating along the fault zone, reached the surface of a not yet cooled batholith.

RELATION BETWEEN VOLCANISM, PLUTONISM AND TECTONICS

The faults and rifts of Sumatra are phenomena occurring along the axis of the geanticlinal ridge of the so-called Barisan. The main trend of the strip of volcanoes and volcano-tectonic depressions is along the same geanticlinal zone (Fig. 38). Both the tectonic phenomena and the distribution of the volcanoes are narrowly correlated with the geanticlinal zone. Not all the volcanoes are arranged along longitudinal faults. Moreover, the connection between volcanoes and tectonic structure is comparatively seldom revealed at the surface. But often a well-marked linear arrangement of craters or volcanic bodies suggests that they are fed from deep-seated fissures. Fig. 39 shows the arrangement of eruptive centra according to two directions, one longitudinal, the other at about 45° to the geanticlinal axis.

From Sumatra the strip of volcanoes can be followed over Java and the Lesser Sunda Islands. Another strip runs over northern Celebes and the Sangi Islands. Opposite are the volcanoes of Halmahera and adjacent islands (Fig. 40).

The striking example of Suoh clearly demonstrated the presence of a not yet cooled batholith comparatively near the surface. A number of large intrusions of granite originated in Upper Tertiary times. Large bodies of igneous rocks of the acid or calc-alkali type characterize the geanticlinal belts and are connected with certain epochs of tectonic movement. In order to make clear this remarkable correlation I must draw your attention to a few details concerning the petrographic provinces of igneous rocks in the East Indies.

In strong contrast with the uniformity of the basalts of the Pacific, the East Indies reveal a diversity of rock types belonging to two magmatic clans. Mostly the petrographic and petrochemical character of the rocks is of the calc-alkali or so-called Pacific suite. Igneous rocks of the potash or so-called Mediterranean type are also frequently met with. Their distribution in the East Indies may be seen in Fig. 41, while Fig. 40 shows the distribution of active volcanoes in the same region. The igneous rocks of the calc-alkali type characterizing the geanticlinal belts of the volcanic inner arc are connected with certain orogenetic cycles. But they did not originate by differentiation of a primary or juvenile tholeitic magma. Probably migmatization of pre-existing crustal rocks by ascending emanations from greater depths was a fundamental process. Also, hybridization or contami-

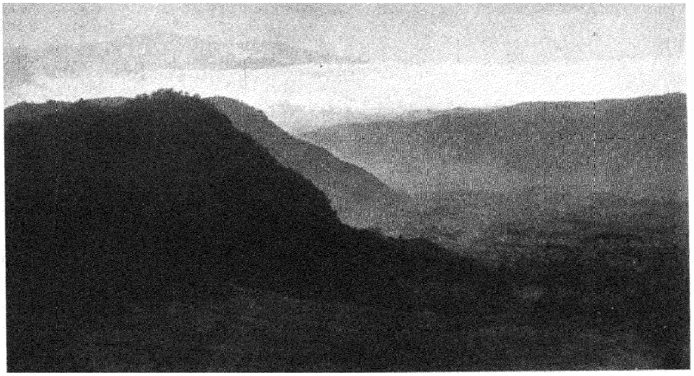
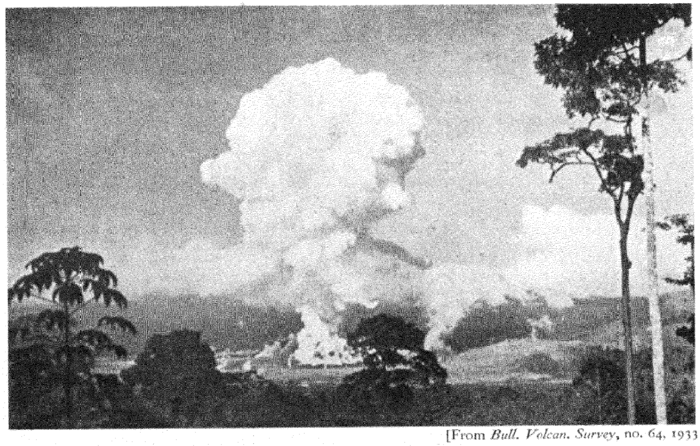
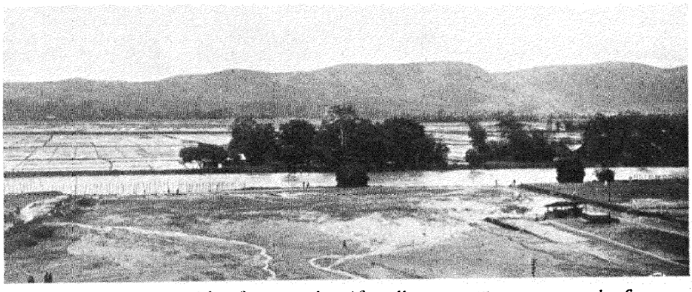


Plate VII. A. *The volcano-tectonic valley of Sapikerep in the Tengger Mountains, eastern Java. Compare Fig.* 32.

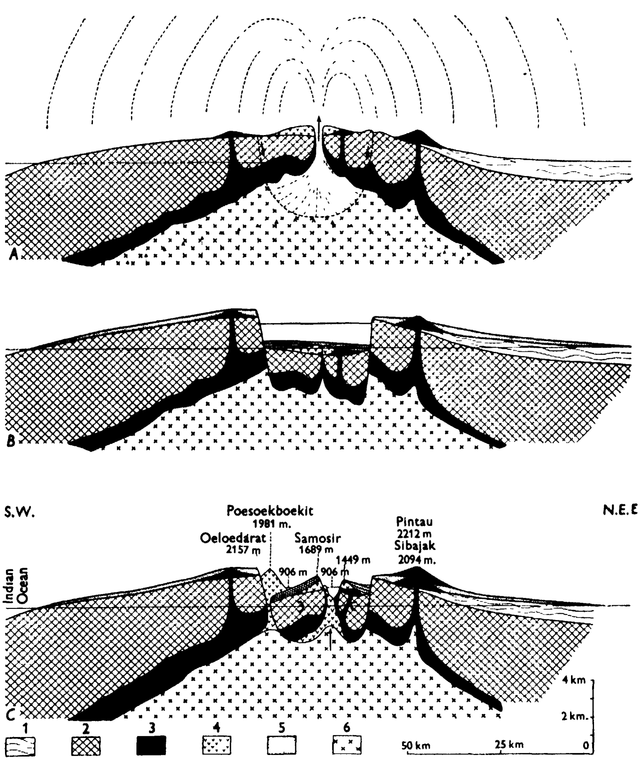


[From *Bull. Volcan. Survey*, no. 64, 1933

B. *Steam explosions in the Suoh depression, southern Sumatra,* 17 *July* 1933.



C. *Eastern side of Semangka rift-valley near Tarutung, south of Lake Toba, Sumatra.*



[From R W van Bemmelen

Fig. 35. *Origin of Lake Toba, a volcano-tectonic depression.*

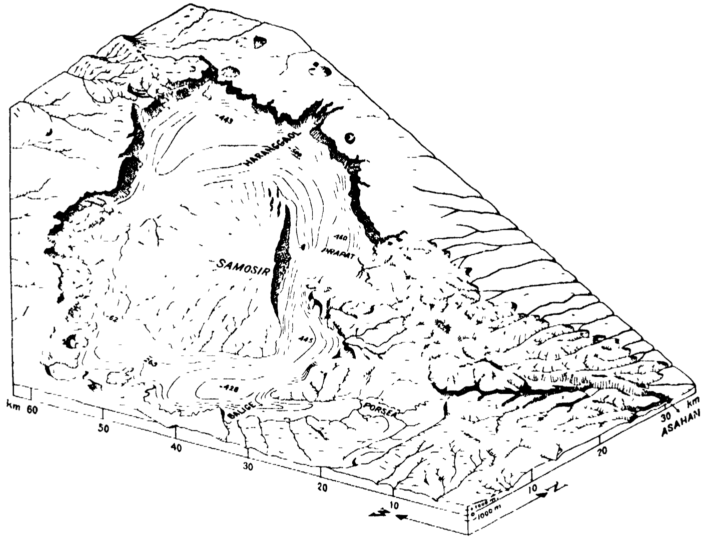
nation of the ascending magma by assimilation and migmatization of sialic crustal rocks played an important part. If the plutonic rocks were entirely the product of juvenile origin and normal gravitational differentiation, they would be more basic in the deeper parts. Instead of such a sequence the rocks appear to be more acid towards the depth of the batholith (Fig. 42). And this supports the view that the granitization was effected by migrating materials emanating from a rising migmatite front, thereby causing a progressive metamorphism of the existing crustal layers.

The alkaline rocks of the potash provinces are considered by Van Bemmelen as 'pathological' products, the origin of which is doubtful. Their formation may be the result of assimilation of comparatively large quantities of limestone and subsequent loss of soda in the hydrothermal phase. But according to other, more recent views, the alkaline rocks may be due to a more intensive action of magmatic emanations. At any rate this seems probable for rocks from Uganda described by Holmes.

EPOCHS OF INCREASED ACTIVITY

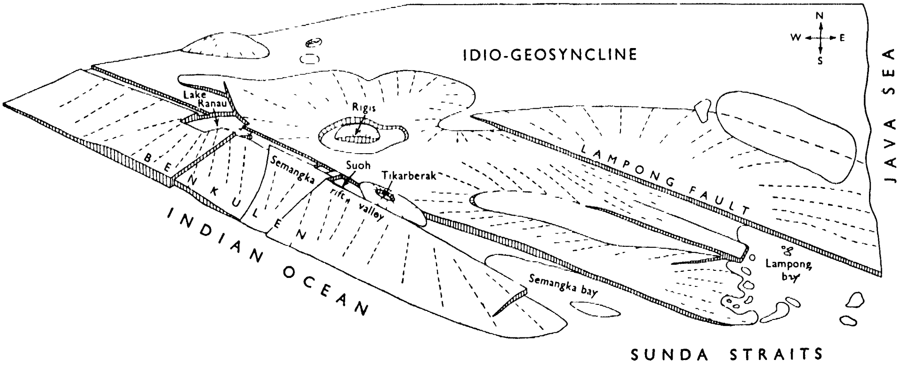
It will be seen presently that the upward migration of magmatic emanations from the depths was especially active during epochs of increasing compression in the earth's crust. During these epochs the geanticlinal areas tended to rise and apparently this process stimulated and activated the underlying earth material.

Batholithic intrusions, mainly granodiorites and granites of Upper Neogene age, are known to occur on certain islands of the inner arc, viz. Sumatra, Java, Flores, Lirang and Wetar; and obviously the present volcanic action might be genetically related to such bodies. We owe to Van Bemmelen a clear insight into their mutual relations. It is worth while quoting a passage which summarizes the historical succession of igneous activity in the inner arc. Before doing so it should be mentioned that previous to the Upper Miocene, a series of calc-alkaline volcanoes called the Lower and Mid-Miocene 'old andesite formation' had accumulated in Sumatra.



[From R. W. van Bemmelen

Fig. 36. *Block-diagram of Lake Toba.*



[After R. W. van Bemmelen

Fig. 37. *Structural features of south Sumatra.*

During the younger Miocene [Van Bemmelen writes] an orogenic phase occurred. The geanticlinal zone was lifted above sea-level and at the same time it was block faulted and intruded by acid magma. These intrusions nowadays are exposed as batholiths, stocks and bosses of coarse-medium grained granite and granodiorite with contemporaneous offshoots and dikes of dacitic and liparitic appearance. The whole old-andesite formation has been more or less altered by hydrothermal processes (such as propylitization) and locally gold-silver ores originated.

Thereafter, the geanticline sank down again and in some places this system of old-andesite formation with acid intrusions has been covered unconformably with younger neogene (Pliocene) marine sediments.

After this orogenic phase during the younger Miocene, with its concomitant acid intrusions and explosive paroxysms, in some places, the basic-intermediary volcanism temporarily came to rest, at other places however it seems to have continued uninterrupted. But soon it gathered again enough force to cause the

[After L. Rutten

Fig. 38. *The geanticline of Sumatra and the distribution of volcanoes.*
Stippled area higher than 1000 m Volcanoes are indicated by black triangles

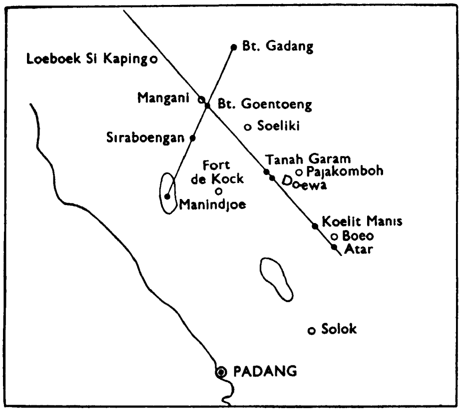
general, formidable volcanic activity of the geanticlinal zone during the Plio-Pleistocene.

These numerous, younger strato-volcanoes of basic-intermediary, calc-alkaline composition and plio-pleistocene age form an unconformable capping of the geanticlinal zone. This so-called younger andesitic series has not been altered (or only locally) by hydrothermal processes.

In southern Sumatra this period of younger andesitic eruptions was followed by a second uplift of the geanticlinal zone, which was accompanied by a second suite of acid (dacitic-liparitic) eruptions. These eruptions occurred chiefly along the remarkable rift-graben on the top of the geanticlinal, the so-called Semangko-graben....

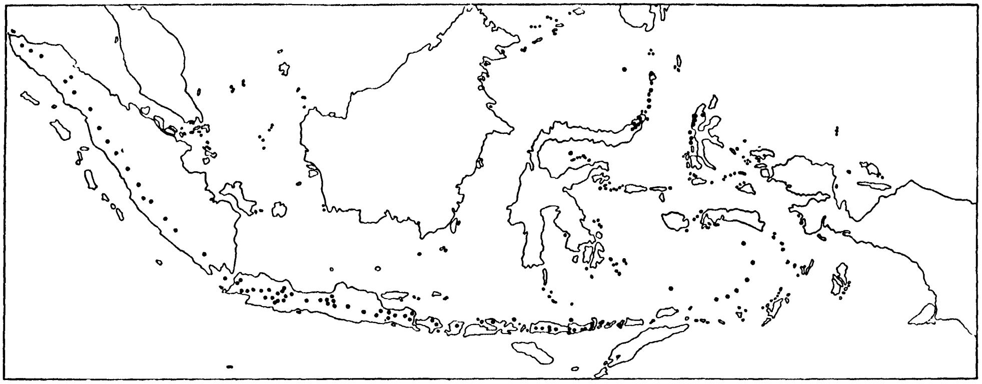
It appears from this short review that since the Upper Miocene the geanticlinal ridge of western Sumatra has been subjected more than once to a rising movement. During these epochs the arching geanticline became faulted and fractured. In its present state Sumatra shows longitudinal faults and a central rift-valley. Volcanism was very active along these faults and in many places its activity has continued along the tectonic fractures up to the present day.

The comparatively recent origin of the longitudinal



[After J Adam

Fig. 39. *Linear arrangement of volcanoes, near Padang, Sumatra.*



[After Ch. E. Stehn

Fig. 40 *Distribution of active volcanoes in the East Indian Archipelago.*

Semangka rift-zone in Sumatra is clearly demonstrated by its youthful appearance as the high escarpments bordering a broad and flat-bottomed valley. Near the spot, illustrated by Plate VII, C, solfataras escape along the eastern fault.

It is of importance to consider a different area of volcanic activity. Fig. 43 represents the historical succession of events in the Karangkobar region of central Java. Apart from the rising migmatite front, accompanied by an increasing migmatization of the crust, the figure clearly demonstrates the principal epochs of tectonic activity. The region is situated at the northern side of the geanticlinal belt of southern Java, where the latter is bounded by a geosynclinal trough. Volcanism started in Upper Miocene times with the formation of the submarine (geosynclinal) volcano Penjatan.

Its vents, cutting through the Miocene Merawoe shales (Fig. 43, A), are now exposed by erosion. They are composed of gabbro-dioritic rocks. Pliocene volcanism produced the volcanic products of the Ligoeng series (Fig. 43, B) which is of andesitic composition. Finally, Fig. 43, C shows the formation of the Pleistocene and more recent volcanoes. In the same region, but farther to the north in the geosynclinal trough, there occur a few intrusions which belong to the alkali or Mediterranean series of igneous rocks.

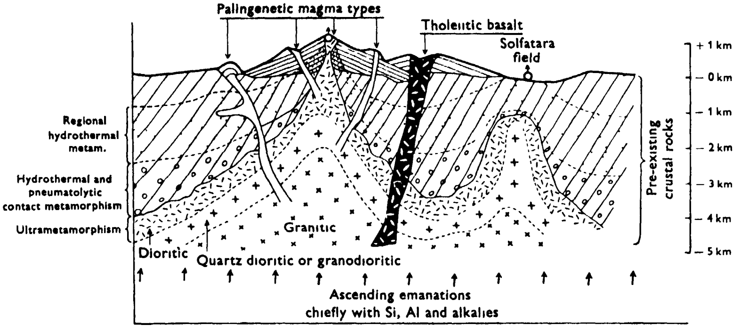
Finally, it should be noted that several epochs of tectonic activity are represented in the schematic Fig. 43. After subsidence of the bottom during the Miocene, a warping movement took place in the Upper Miocene. Then, after continued subsidence of the trough and folding of the Pliocene series, the region was subjected to a rising movement in the Pleistocene.

A theoretical synthesis of the formation of the East Indian island arcs ought to account for these various expressions of plutonism, volcanism and tectonics.

[After H. W. V. Willems

Fig. 41. *Distribution of rock clans in the East Indies.*

Vertical shading, Pacific clan, horizontal shading Mediterranean clan



[From R W van Bemmelen

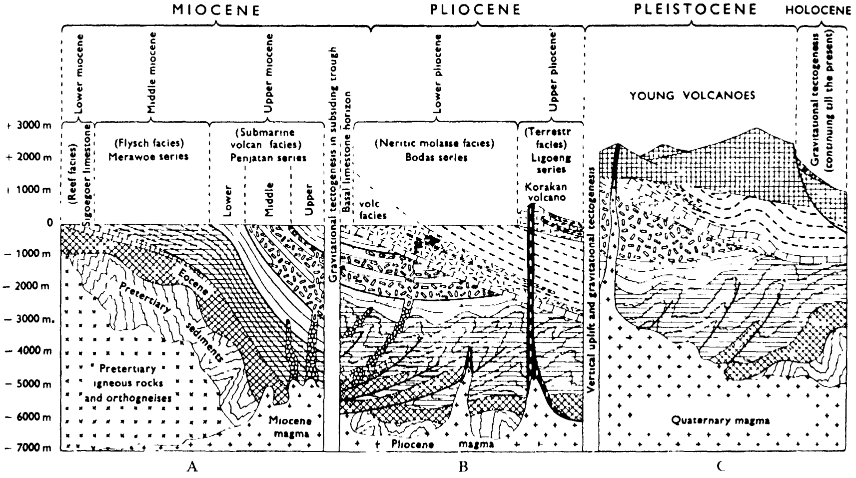
Fig. 42. *Schematic representation of the rising migmatite front in the inner arc of the East Indies.*

PROBLEMATIC QUESTIONS

At the end of our short survey of volcanic and plutonic phenomena a list of open questions for which answers are eagerly wanted, will be made.

It has to be made clear why, in the double festoon, the volcanic arc is the inner one, i.e. why it is on the concave or inner side and not on the convex or outer side of the non-volcanic arc. We want to know why there were two phases of elevation and rejuvenated magmatic phenomena in the region of the East Indian inner arc since Miocene times. The situation of the Mediterranean rocks on the concave side of the inner arc is a further problematic point. It has to be explained, moreover, why active volcanoes are lacking on the islands of the outer arc. Why, then, is active volcanism absent on the inner row north of Timor Island? A further problematic point is the presence of volcanic rocks of Upper Tertiary age on Buru, Timor and Sumba. Finally, the occurrence of serpentines and other ultra-basic rocks on many islands has to be explained.

We will consider other sources of data, and then an attempt will be made to elucidate all these problematic features into a general synthesis.



[From R W van Bemmelen

Fig. 43. *Diagrammatic representation of epochs of plutonism and volcanism in the Karangkobar region, Java.*

TABLE III. SYNOPSIS OF THE VOLCANIC AND RELATED PHENOMENA DISCUSSED IN CHAPTER III

			Examples	Illustrations
Volcanic forms	(1) Explosive type:	Cinder cone	Anak Krakatoa (1928)	Plate III, C, D, and V, A
	(2)	Explosion crater	Dieng (Central Java)	Fig. 33, Plate V, C
	(3) Effusive type:	Lavadome (tholoid)	Galungun (1919, Java)	
			Merapi (1933), ***nuée ardente***	Plate VI, A and B
			Penanggunan (eastern Java)	Plate VI, C
			Kelut (1918, Java), mud-flows	Plate VI, D and E
	(4)	Lava plateaux	Absent in the East Indies	
	(5)	Shield volcanoes		
	(6) Mixed:	Composite- or strato-volcano	Sinabung (Sumatra)	
			Sindoro (Java)	Plate V, B
			Ruang (Sangi Islands)	
			Una-Una (Celebes)	Fig. 30
		Composite- or strato-volcano in caldera	Batur (Bali)	Fig. 31
			Tengger Mountains (Java)	Fig. 32
Volcano-tectonic structures	(1) Baranco		Valley of Sapikerep (Tengger Mountains, Java)	Fig. 32, Plate VII, A
			Krakatoa (1883), submarine valleys	Fig. 34
	(2) Caldera		Krakatoa (1883)	Fig. 34
	(3) Volcano-tectonic depression		Toba	Figs 35, 36, 38
	(4) Rift-valley		Semangka-graben and Suoh eruption (1933)	Fig 37, Plate VII, B, C
Relation between volcanism, plutonism and tectonics	(1) Geanticlinal up-doming and volcanic lineaments		Barisan (Sumatra)	Fig. 38
			Padang volcanoes	Fig 39
	(2) Tectonics and magmatic clans		Distribution of Pacific rock clan and Mediterranean rock clan	Fig. 41
	(3) Epochs of increased tectonic and magmatic activity	In geanticline	Upper Miocene and Pleistocene epochs in Sumatra	Fig 42
		In geosyncline	The same epochs along the margin of the geosynclinal trough of northern Java	Fig. 43

CHAPTER IV

STRUCTURAL ZONES

From the volcanoes we proceed to the other geological features of the islands. Again I will draw your attention only to a few results of general interest. Moreover, it is clear that I could not possibly communicate in a few hours something like a 'geology of the East Indies'. What we know about the geology of the Dutch island empire is the result of nearly a century of work by about 500 geologists and specialists like palaeontologists, stratigraphists, petrographists and geophysicists. One of our most distinguished geologists, the late Professor Rutten, of Utrecht, published an excellent book on the geology of the Netherlands East Indies in 1927. The fruit of about 50 lectures, it contains more than 800 pages and 243 illustrations.

To mention another example: four years later Vol. v of the *Leidsche Geologische Mededeelingen* devoted 630 pages to a synopsis of our knowledge of the palaeontology and stratigraphy of the East Indies, including a map showing 320 localities from which fossils were derived. And, finally, let me mention that Verbeek's and Wing Easton's Bibliography contains nearly 6000 references to the literature up to the year 1937.

Hence for evident reasons I must greatly restrict myself and, as we are engaged in deciphering the structural history of the archipelago, it is self-evident that my choice falls on a synopsis of the structural zones.

PALEOZOIC

Our knowledge of geological formations in the East Indies begins with a few localities of marine Devonian in Borneo and New Guinea (Fig. 44).

Several localities of Carboniferous and Permian strata are known from the western part of the archipelago. A series of strata, called the Danau formation, is of widespread occurrence in the region of the great lakes ('danau') of central Borneo. The series consists mainly of (1) basic effusiva and pyroclastics, (2) Radiolaria-bearing cherts and silicious slates, and (3) quartzites and sandstones. It appears that (1) and (2) belong to the Paleozoic, whereas (3) is of Upper Triassic age. The presence of Upper Paleozoic is proved by the occurrence of Fusulinidae in several places, whereas in east Borneo a Devonian locality seems to belong to the same series. Some authors have considered the Radiolaria-bearing rocks as typical deep-sea sediments, and they have constructed an ancient deep-sea trough through central Borneo. Similar rocks in Malaya, however, were regarded as shallow-water deposits and some 'radiolarites' in western Borneo led to the same conclusion. Neritic organisms and land plants have been found in these radiolaritic rocks. It may be that these are exceptional finds of local importance while, in general, the deep-sea genesis holds good for most of the

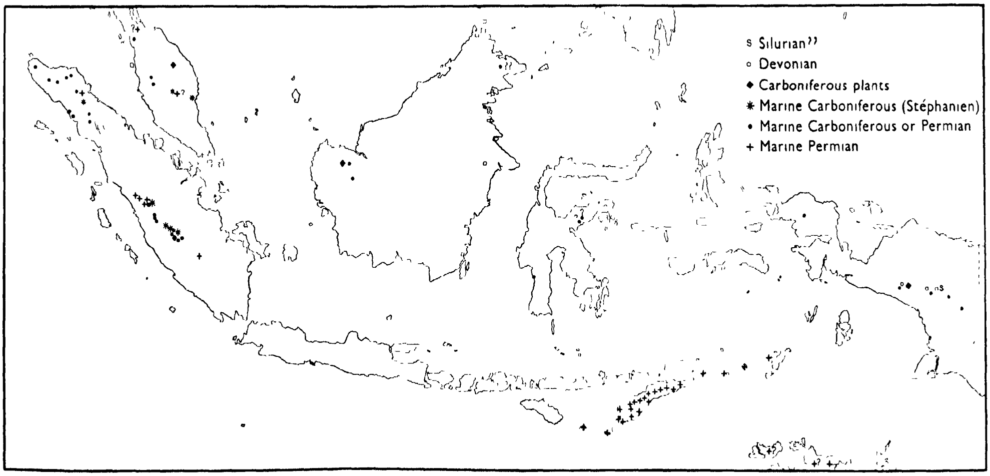


Fig. 44. *Distribution of Paleozoic formations.*

radiolarites of the Danau formation. The problem can only be solved by new data obtained by field observations and a detailed petrographic examination of these interesting sediments.

Apart from radiolarites of the Danau formation the marine fossils from the Paleozoic known at present come from neritic to littoral sediments. It is more than probable that islands or larger areas of land lay scattered about in the shallow seas. This is indicated not only by the presence of Carboniferous plants, but also by the occurrence of clastic products in the Paleozoic deposits. Weathering products of granitic rocks were found in Permian marine deposits of western Sumatra. Permian volcanic rocks are known in Sumatra, Borneo and Malaya as well as on Timor Island. It may be accepted as a fact that many volcanic islands existed, but it is impossible to indicate the distribution of land and sea during the Paleozoic.

During the Upper Carboniferous the land plants had differentiated into at least four more or less well-defined botanical provinces. One of these flora types, called the Atlantic-Chinese by Seward, extended eastwards as far as Korea and Sumatra. In the latter region it was found mingling with plants of the *Gigantopteris* flora, which is also known as the *Cathaysia* flora in China (and in Texas and Oklahoma). Another remarkable combination of fossil plants was found in New Guinea, viz. elements of the *Cathaysia* and *Glossopteris* flora. The finding of these plants on Sumatra and New Guinea has induced some authors to shuffle with these islands in a 'Wegenerian' manner which conflicts with fundamental facts of geology and geophysics.

The Paleozoic sequence in Sumatra and Borneo was folded during a Late Variscian epoch of compression. An indication of Caledonian folding in central Borneo has been announced in a recent thesis by J. C. H. Albrecht.

Permian strata in the southern Moluccas are famous for their abundance of well-preserved fossils. These deposits have a considerable thickness, as much as 5000 m. on the small island of Letti. It may be that the development of a geosyncline started in this area in Permian times, but the still too scanty data of the Paleozoic will be left out of further consideration.

MESOZOIC

At any rate the same group of islands of the southern Moluccas coincides with the southern part of a zone that has a geological history different from that of the surrounding areas during the Mesozoic. This Timor-east-Celebes zone is marked by the letter A on the accompanying diagram and map of Fig. 45. As it winds itself around the present area of the Banda Sea it will be called the *Banda geosyncline.*

Most of the sequence of strata from Permian to Upper Cretaceous is known from this zone, but they were not deposited in a trough which had an uninterrupted downward movement. Several epochs of compression may have been of influence during the Mesozoic evolution of the Banda geosyncline, causing several regressions, transgressions and breaks in the sequence. Much field work has still to be done before a clear picture of the history can be given. Moreover, it must be mentioned that neritic as well as bathyal and abyssal deposits of the same age have been met within this zone, showing the simultaneous existence of shallow sea and deep troughs. Plate VIII, A gives an illustration of fossil red deep-sea clay with manganese nodules in Timor Island, the Upper Cretaceous age of which was demonstrated by the occurrence of teeth of Reptiles (*Champsosaurus*, *Mosasaurus*, *Globidens*), teleostome fishes (Pycnodontidae, Enchodontidae) and elasmobranchs (*Ptychodus*, Lamnidae, Carcharidae). The shark's teeth are coated with manganese and the dentin is dissolved, as is characteristic in analogous finds of shark's teeth from recent deep-sea deposits. If these remarkable deposits are true deep-sea sediments comparable to red deep-sea clay, circumstances must have been very different from present conditions (of course, the same holds good regarding the Paleozoic radiolarites of Borneo if these are true deep-sea deposits). For we know already that the deep oxygenated bottom waters of the Pacific and Indian Oceans cannot penetrate into the present deep-sea troughs of the East Indies on account of the comparatively high ridges that separate them from the ocean. And, therefore, no Radiolaria ooze and no red deep-sea clay originate in the deep basins and troughs of the East Indies.

It follows from the occurrence of the different facies types that we are not dealing with a simple subsiding synclinorium. On the contrary, the geosyncline must have been of the complex type, which Schuchert called a polygeosyncline.

A further characteristic of this zone is the widespread occurrence of basic to ultrabasic effusive material. A Triassic age was claimed for part of them, though a younger age seems more probable for some places (e.g. post-Triassic on Ceram).

The geosyncline underwent strong compression towards the end of the Mesozoic, post-Senonian and pre-Eocene. It is the Laramide epoch of folding which manifested itself strongly in this region. It is possible to define the boundaries of the Banda geosyncline, though only in part and schematically, because we know something, although very little, about the surrounding areas, where the Mesozoic history was entirely different.

In all probability the regions indicated by B formed an extensive area of denudation during the Triassic, the denudation products being transported into the Banda geosyncline. (It may be noted in parenthesis that these and other deductions concerning the later history of the East Indies are incompatible with the line of thought about the origin of the East Indian archipelago given by Wegener and worked out by other authors.) Part of the Triassic land was flooded in Jurassic times, and possibly a Jurassic geosyncline originated in New Guinea. According to Glaessner it belonged to a circum-Australian geosyncline which had a connection with the Banda geosyncline. And a break in the sedimentation

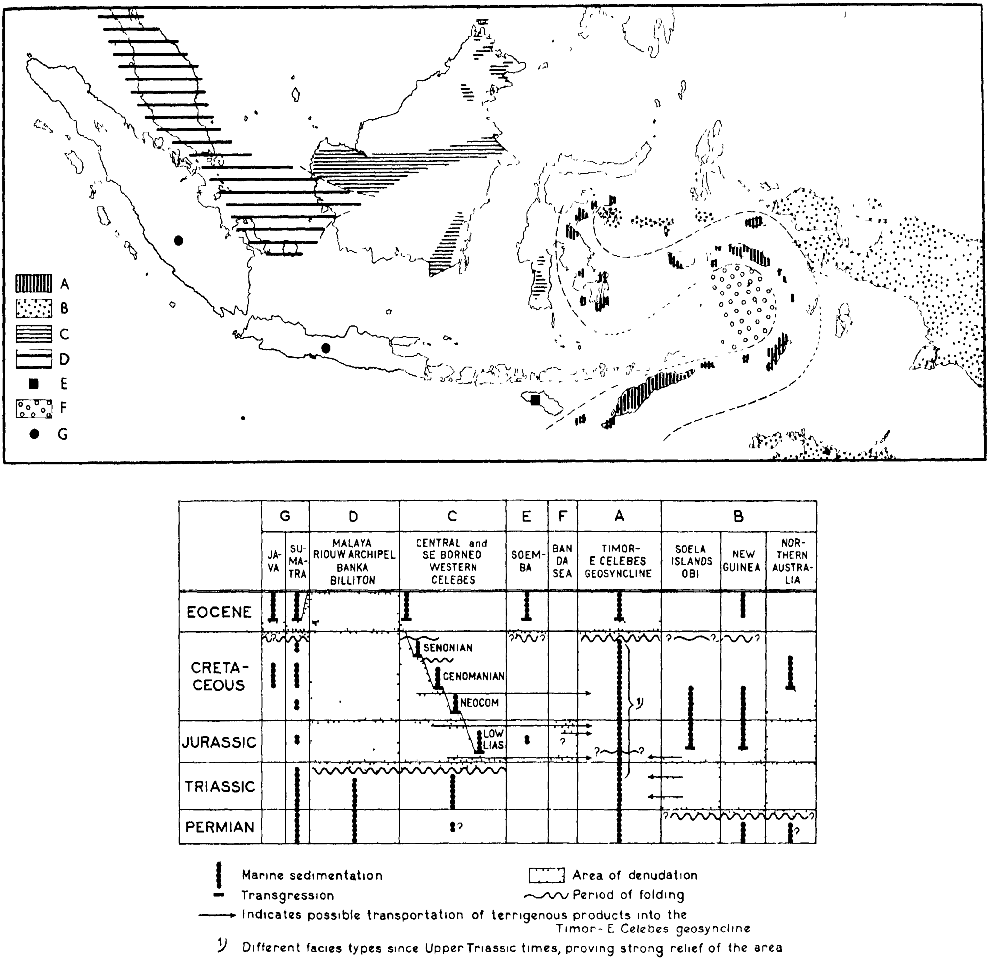


Fig. 45. *Structural zones of the Mesozoic.*

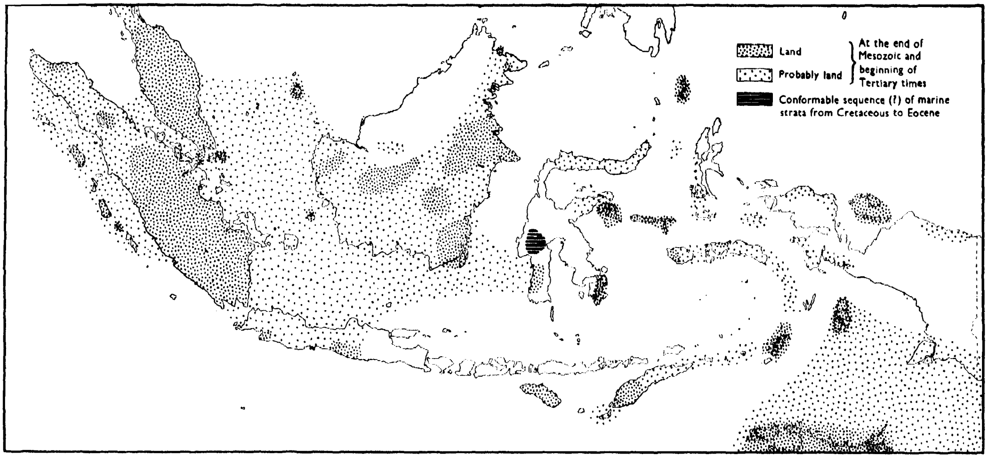
corresponding to the important Late Cimmerian or Nevadian epoch of folding was noticed in New Guinea. The history of the regions marked C, including western and central Borneo, is again different. It is here that we find the so-called Danau formation.

Its older part was folded during a Late Variscan epoch; the entire sequence was subsequently refolded during the Early Cimmerian phase of compression, i.e. towards the end of the Triassic.

Transgressive seas belonging to the Lower Lias, Lower Cretaceous, Cenomanian, and Senonian, invaded parts of the area. They are indicated on the diagram of Fig. 45 which also shows the post-Cenomanian folding and the moderate Laramide movement. With the necessary changes an analogous scheme may also be applied to south-eastern Borneo and southern Celebes.

Probably almost simultaneously with, or shortly after, the intensive Early Cimmerian folding of the Danau formation, numerous granite batholiths developed in south-western and central Borneo.

It seems that the many granite batholiths of the tin districts of Malaya, Billiton and Banka are post-Triassic too.



[After Bading

Fig. 46. *Paleogeographic map after the Laramide epoch of compression.*

Hence this region, roughly indicated by D, presumably had a history similar to that of region C in many respects, but it was probably not invaded by the Cenomanian transgression. It had been gradually lifted above sea-level after the Early Cimmerian folding at the end of the Triassic. The regions indicated by C and D formed an extensive area of denudation from which terrigenous material was transported into the Banda geosyncline in Jurassic and Cretaceous times.

Part of the Banda geosyncline—marked E—was bounded on the north-west by an area of which very little is known, namely Sumba. Eocene rests unconformably on folded pre-Tertiary, but the epoch of folding cannot be fixed more accurately than post-Jurassic and pre-Eocene. The clastic material in the Jurassic rocks of Sumba suggests an area of denudation which may have been situated either west or north-west of Sumba, or perhaps north. It cannot have come from the south-east because that area was below sea-level at that time.

Very little can be said concerning such an area as the deep Banda Sea, marked F on Fig. 45. Weber pointed out that the character of sediments (probably belonging to the Jurassic) on Ceram and the Tanimber Islands, indicates the existence of land in the area of the present Banda Sea. This demonstrates again most clearly the importance of sediment petrographic data for such problems. Another example was mentioned before when the history of the Java Sea was discussed (p. 2). An increase in our very elementary knowledge of the pre-Tertiary and Tertiary history of the Greater and Lesser Sunda Islands will be of the greatest importance in obtaining an insight into the Mesozoic history of large parts of the East Indies including the Banda Sea.

Sumatra and Java (G) are striking examples of the scarcity of data about the pre-Tertiary history of several islands. There is no certainty regarding many fundamental questions such as Mesozoic epochs of folding. Most authors think it probable that continual sedimentation took place in Sumatra during the Mesozoic, at any rate in a central part of the present island, and that a folding occurred towards the end of the Cretaceous, while another epoch of compression possibly occurred in the Lower Cretaceous of Djambi. The largest of three Javanese pre-Tertiary areas probably belonged to a zone of Upper Cretaceous folding. It seems that the folding towards the end of the Mesozoic was much more intensive on Sumatra and Java than it was on Borneo.

Fig. 46 shows that towards the end of the Mesozoic extensive land areas must have existed in the East Indies. A study of the Tertiary formations leads to the same conclusion. All Tertiary marine deposits originated in shallow transgressive seas. A typical shallow-water sediment from the Eocene of Java is shown by Plate VIII, B. The unconformity of the Tertiary on pre-Tertiary rocks, has for the greater part either been proved or strongly suggested by the occurrence of fragments of pre-Tertiary rocks in those marine Eocene sediments; from which it follows that those areas must have been land before that time. In Fig. 46 these data are supplemented by analogous deductions for areas where no marine Eocene occurs, but where one or more horizons of the Neogene rest unconformably on the pre-Tertiary. A conformable marine sequence from pre-Tertiary to Eocene could not be proved with any certainty anywhere in the archipelago; the possibility of such a conformable

[After H. G. Jonker

Plate VIII. A. *Cretaceous red deep-sea clay with manganese nodules, Timor.*

B. *Marine shallow-water deposits with numerous Foraminifera (Nummulites), Kali Guha, central Java.*

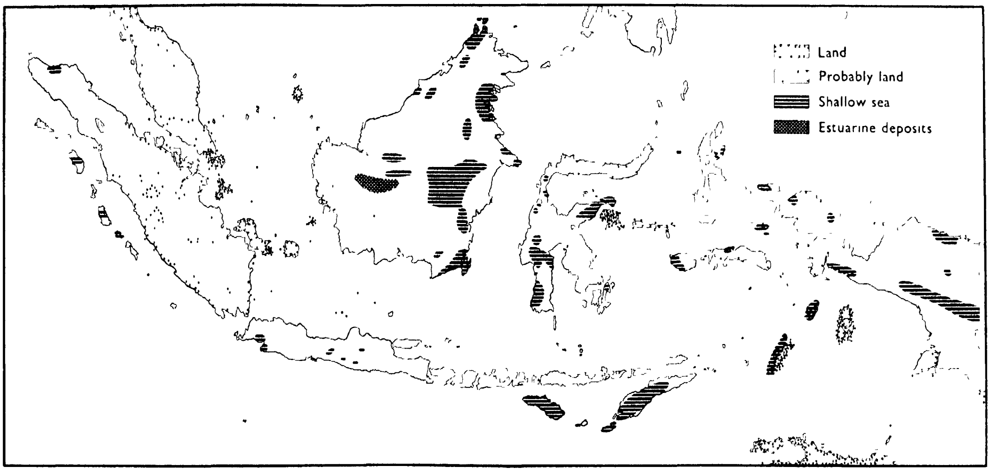


Fig. 47. *Paleogeographic map of the Eocene.*

sequence is left open for three places only (western Celebes, part of Ceram and Tanimber).

Another feature that fits entirely in the conception given above is the increasing extent of the several Tertiary transgressions. One of these is shown by Fig. 47, which gives a maximum of marine Eocene notations. Although I have intentionally avoided uniting the scattered occurrences of marine Eocene in an Eocene sea of hypothetical extent, it is evident, from the similarity of the marine faunas, that these areas must in one way or another have been connected. A glance at the map shows that it is only locally possible to determine the boundaries between land and sea at that time (e.g. central Borneo): but at the same time it is evident that the data tally with the conception of a transgressive sea separating land-areas in Australia and Asia. Fig. 48 shows the extent of a marine transgression in the Lower Miocene. The unconformable character of the Miocene strata is very striking in southern and central Sumatra. Notwithstanding the blank parts, one needs little imagination to perceive that the sea invaded the areas of Sumatra and the Nias-Mentawei Islands from the west and south-west. It has already been argued in the second lecture (Chapter II) that the present deep-sea basins and troughs did not yet exist at that time. The probable cause of their origin in more recent times will be discussed later on (Chapter VI).

CENOZOIC

A synopsis of stratigraphic sequences of the Tertiary, Fig. 49, clearly demonstrates the many gaps in our knowledge of the Paleogene history. Many more detailed investigations will have to be carried out before a clear insight is obtained into the evolution of the East Indies during the older part of Tertiary time.

The curved line drawn in Tertiary *e*4 of Fig. 49 has only two fixed points. For the other islands this line is intended to show only that movements occurred before Tertiary *e*5; but the exact time at which they took place cannot be given with any certainty in the present state of our knowledge, and it may have been very divergent for different islands.

However different the older history of several areas may have been, it is clear that during the Lower Neogene shallow seas were widespread and in many places had a transgressive character (Fig. 48).

In the Miocene, after the sedimentation of Tertiary *e* and part of Tertiary *f*, a period of the most intensive folding that occurred during the Neogene began. We may probably fix it in Tertiary *f*2.

Zone I

In Fig. 49 several areas where this folding has been met have been included, while Fig. 50 further illustrates this. The folding of the sediments must have been very intensive in several islands inasmuch as overthrust masses are known or supposed to exist. Fig. 56 shows a complex of strongly folded Mesozoic strata on Timor. In places Tertiary and pre-Tertiary formations are intensively kneaded together.

It will be noticed that this zone coincides with the Mesozoic Banda geosyncline (Fig. 45) which apparently was rejuvenated after the Laramide folding. The islands west of Sumatra had a similar geological history in Upper Tertiary times.

What we are now able to study on the surface—that is to say, on the islands—are only parts of an originally connected whole. Are they the remnants of a Miocene folded

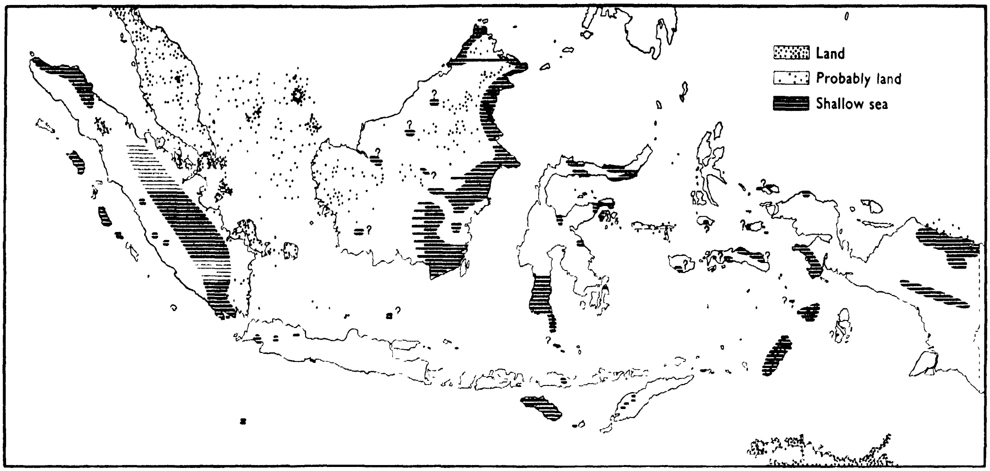


Fig. 48. *Paleogeographic map of the Miocene.* (*Tertiary e.*)

chain of mountains that wound itself through the area of the present archipelago but which was broken up by the formation of deep-sea troughs and basins, so that some parts are situated deep under sea-level now, while others were lifted high above it? The analysis of the submarine bottom relief already pointed in that direction. We will return to this question again later.

The 'spinal column' of New Guinea is another zone of intensively folded Tertiary strata (Plate IX, and Fig. 51). Possibly the principal epochs of folding are the same as those in the Banda geosyncline, but the data do not yet admit of a definite conclusion. The most recent folding might, for example, have taken place in a younger part of the Miocene. That is the meaning of the series of interrogation marks that have been inserted in Fig. 50. And supposing that it should be proved that this period of folding was indeed the same as that of the Banda geosyncline, should we conclude that these two folded mountain chains were connected? And where? These are questions to be solved by future field work.

The denudation of the areas which were folded during the Miocene generally appears to have proceeded so far in the Pliocene that the sea could invade them. It is precisely on certain islands of the Banda geosyncline that the sedimentation of the marine Pliocene appears to have been favoured by the formation of trough faults and 'graben', in which a thickness, in places, of some hundreds of metres of neritic sediments can be measured now. These trough faults and 'graben' are wellnigh parallel to the longitudinal axis of the present islands on Timor (Fig. 52), the Kei Islands (Fig. 53), the Tanimber Islands (Fig. 54), Ceram, and probably also Buru.

On Timor the Pliocene and Pleistocene deposits are not folded, or are only very moderately folded, with the exception of a steep distortion of the Upper Tertiary at the sides of the basins or 'graben'. They have been raised to a considerable height, however, during the Later Pleistocene; in central Timor, for example, to 1280 m. above sea-level.

Briefly we can summarize these movements as follows: after the Miocene folding followed a period of elevation combined with denudation and levelling of the landscape. Then, during the Pliocene, subsidence and formation of faults ('graben') occurred and finally, after an epoch of very moderate folding and denudation again, intermittent elevation above sea-level (as shown by coral-reef terraces at various altitudes) and faulting. In the course of the upheaval the troughs lagged behind and their contents were protected against erosion.

Finally, a negative character of this zone is the absence of volcanoes. Tertiary volcanic rocks have been met with in a few places, for instance, in the western part of Timor, the south coast of Buru, and the southern peninsula of western Ceram.

All these features ask for an explanation. But an attempt at synthesis must be postponed. First of all other structural zones have to be reviewed.

Zone II

It will be noticed, on Fig. 50 and 56, that the Miocene folding was much less intensive in other areas, as in the western part of Sumatra, southern Java, and on Sumba. During the Upper Neogene western Sumatra and southern Java formed part of a zone with a tendency to rise. Where in

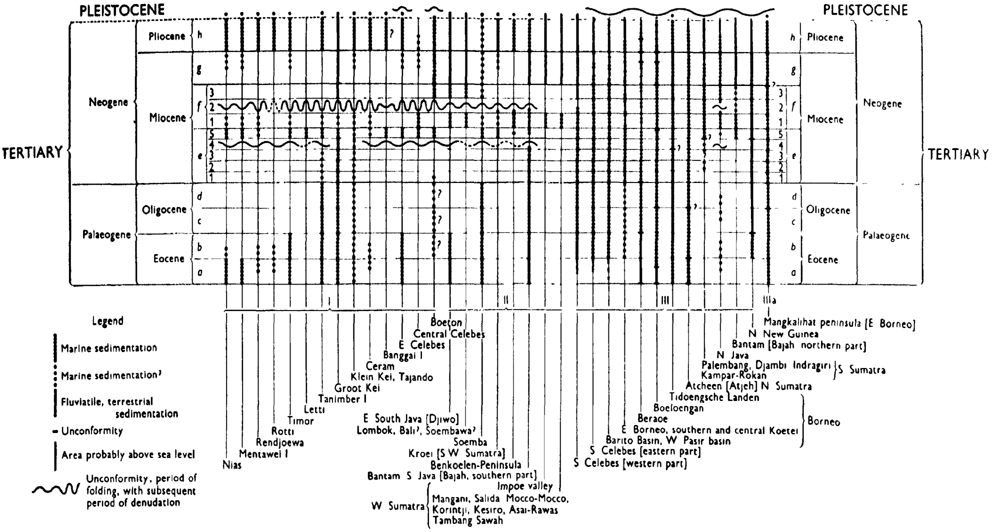


Fig. 49. *Synopsis of Tertiary stratigraphy.*

The numerals I–III correspond with those on Plate X.

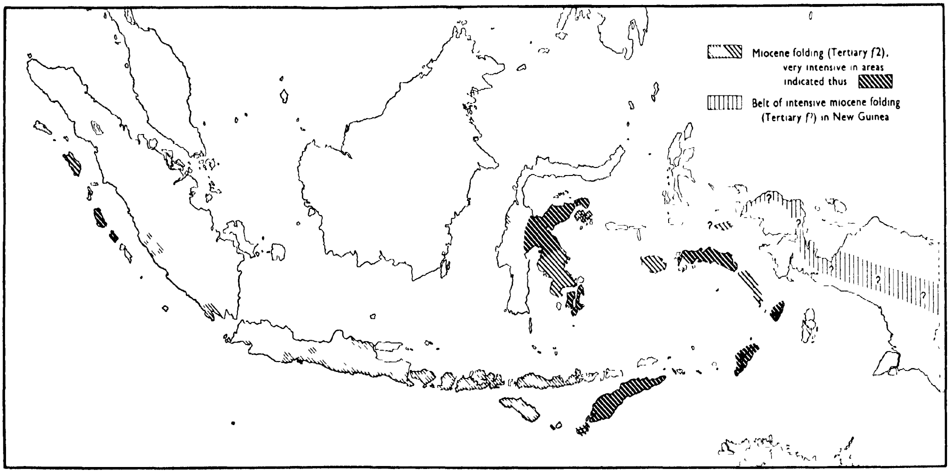
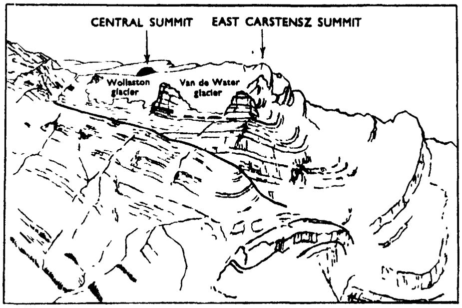


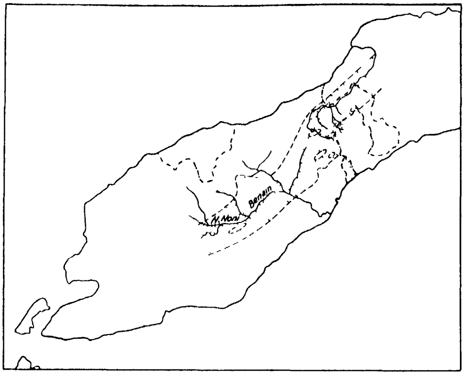
Fig. 50. *Areas of Miocene folding.*



[After J J Dozy

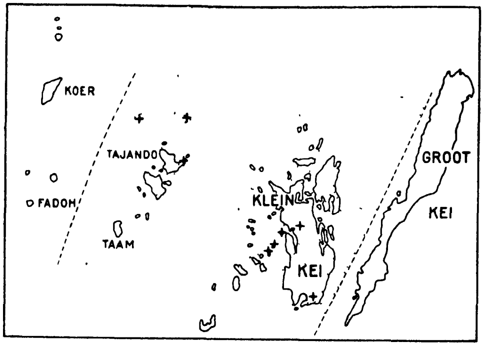
Fig. 51. *The Carstensz Mountains, central part of the strongly folded spinal column of New Guinea.*

The picture shows the outcrop of a thrust-fault in Tertiary limestones Compare Plate IX.



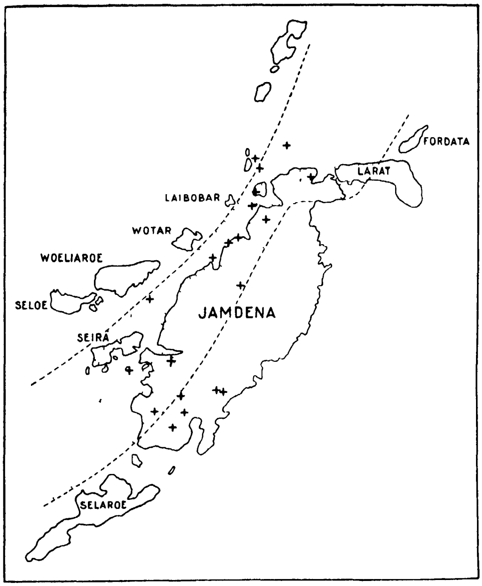
[After G A. F. Molengraaff

Fig. 52. *The Pliocene trough on Timor.*



[After Fr. Weber

Fig. 53. *The Pliocene trough in the Kei Islands.*



[After Fr. Weber

Fig. 54. *The Pliocene trough in the Tanimber Islands.*

this geanticlinal strip marine Pliocene was still deposited (Fig. 55), it was later elevated in a terrace gently sloping seaward. It is this zone that is characterized by the occurrence of a chain of active volcanoes. Their relatedness to the Miocene and more recent epochs of elevation of this zone was discussed in a previous lecture (Chapter III). Although Tertiary volcanics have been found widely spread over Sumba, recent volcanoes are conspicuously absent in this island. Why? What is the meaning of the remarkable site of Sumba, which belongs neither to the inner nor to the outer Banda arc? This is a further puzzle to be solved.

Zone III

Fig. 49 shows that other areas were folded mainly in more recent times, viz. towards the end of the Pliocene.

The expression 'towards the end of the Pliocene', is vague, but it cannot be improved so long as an exact correlation of the East Indian Neogene and Pleistocene deposits with their European equivalents meets with unsurmountable difficulties. Exact criteria failing, it is an open question where we should draw the division between Pliocene and Pleistocene.

We can say this much only: a series of Tertiary sediments, to which Pliocene sediments undoubtedly belong, was folded during a time that we shall have to call either Upper

[From A. H. Colijn

Plate IX. *Strongly folded Tertiary limestones of the spinal column of New Guinea. Carstensz-group in the Nassau Mountains. Compare Fig.* 51.

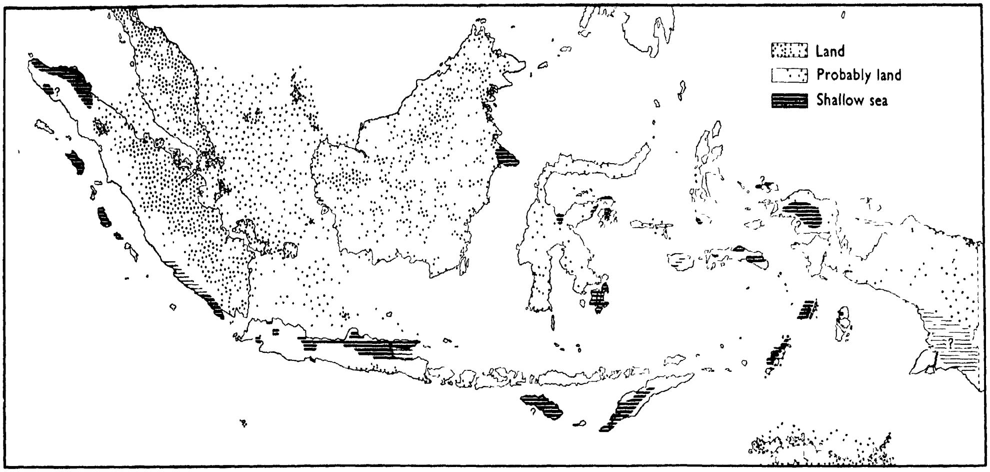


Fig. 55. *Paleogeography of the Pliocene.*

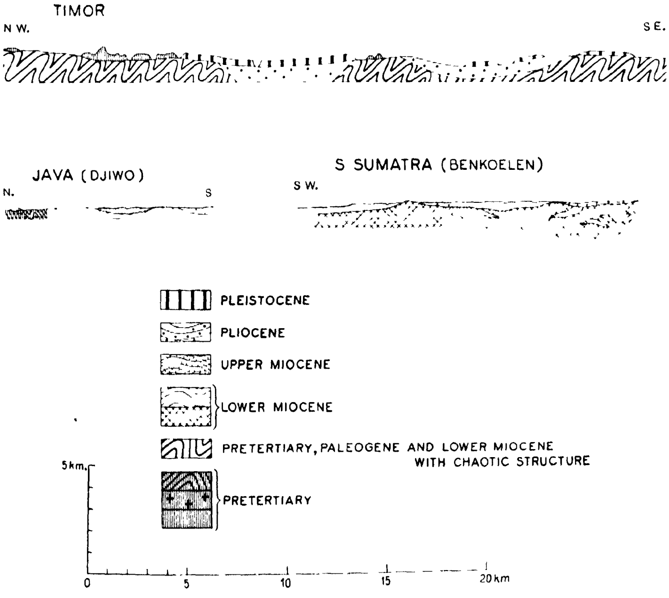


Fig. 56. *Schematic geological sections showing different types of folding in zones I and II.*

The schematic section through Timor is part of a profile by G A F. Molengraaff The sections through south Sumatra and south Java are after Westerveld and Bothé respectively

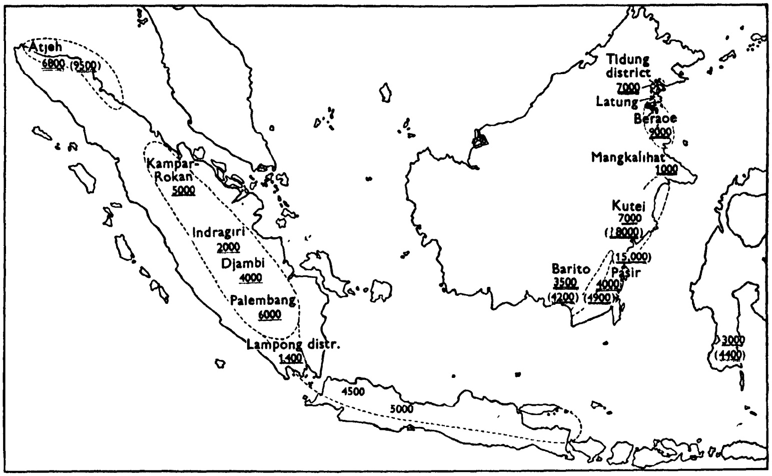


Fig. 57. *Idio-geosynclines in the western part of the East Indies.*

Pliocene or Lower Pleistocene. In Fig. 49 the stratigraphic sections folded 'towards the end of the Pliocene' have been grouped together in the series indicated by the numeral III, the dotting of the upper horizontal line indicating the uncertainty of the boundary between Pliocene and Pleistocene.

This refers to areas where the substratum sank gradually and thus gave rise to the accumulation of some enormously thick sediments. The subsidence of the bottom of these troughs of strong sinking and sedimentation began in the Eocene, or in some places in the Lower Miocene, Tertiary *e*.

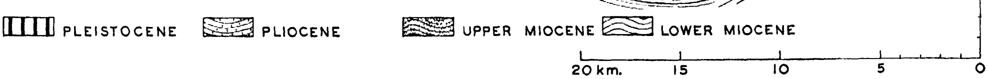
In Fig. 57 the situation of these geosynclines is represented. It is the combination of enormously thick sediments and a moderate folding that predestined them to be likely areas for oil research. Indeed, the most important oil fields are situated in these regions. The subsidence, filling up with sediments, and the ensuing period of folding of these geosynclines have been terminated, geologically speaking, comparatively recently.

In Fig. 57 a sketch-map of the most important of these troughs is given; the figures indicate the thickness of the Neogene sediments; the figures in brackets indicate the thickness of the whole Tertiary. Where the figures are underlined, the 'geosynclinal' subsidence began during the Miocene; where doubly underlined, during the Eocene; where they are not underlined, the time of the beginning of the subsidence is not known with sufficient certainty, though probably it began in the Miocene. The subsidence and sedimentation lasted in each case until the end of the Tertiary, after which followed a period of moderate folding (Figs. 58 and 59).

These figures clearly show that the intensity of sedimentation, and the amount of subsidence which can be deduced from it, have been much more marked in the Neogene than in the Paleogene.

These Tertiary sedimentation-troughs are filled principally with neritic and partly with hemipelagic deposits; limnic, lacustrine, and terrestrial deposits in some places also form an important part of the sediments. Abyssal deposits do not occur at all.

The strong subsidence and sedimentation begin everywhere in continental regions. Thus, for example, the geosynclinal series begins with fluviatile-terrestrial sedi-



[After Jetzler

Fig. 58. *Section through the idio-geosynclinal trough of East Borneo.*

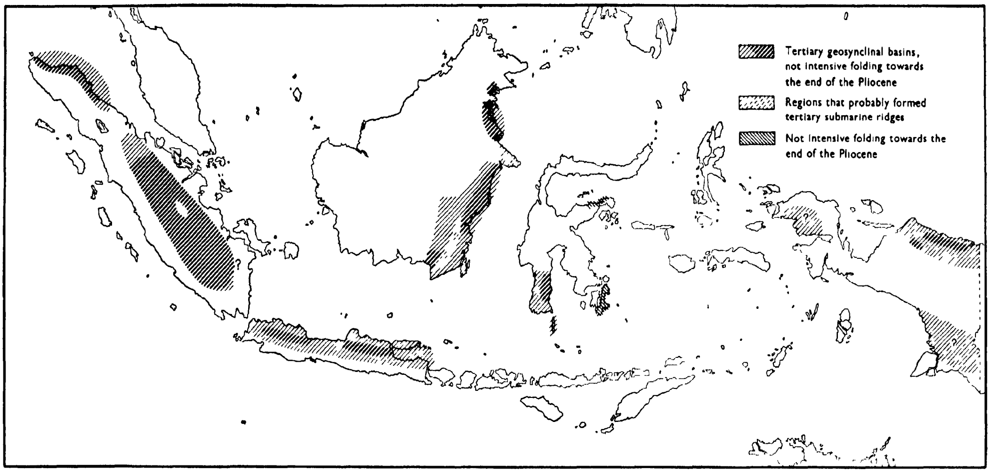


Fig. 59. *Areas of Plio-Pleistocene folding.*

mentation in the Barito basin (south-east Borneo) and the south of Celebes. In other places the lowest strata of the geosynclinal series consist of marine, that is, neritic sediments of a transgressive epicontinental sea.

These Tertiary geosynclines do not form continuous strips, but they form a series of troughs with a strong subsidence and sedimentation.

It is evident from the stratigraphic sections of the Tertiary as well as from the paleogeography before the origin of the troughs, that the accumulation of thick sediment layers became possible as a result of the subsidence.

Thus, for example, the lower layers of the geosyncline in Palembang, Djambi, and Indragiri are formed by the neritic (littoral) Neogene limestones (Tertiary *e* 5) of a shallow sea, which in its wider extent, however, was not limited to a strong subsidence, but covered unconformably a much more extensive area (Fig. 48). If the filling up with sediments keeps pace with the subsidence of the bottom, the facies remains the same; if the subsidence surpasses the rate of sedimentation, rocks originate which represent a deeper facies; in the reverse case a shallower facies occurs, perhaps ending in the areas becoming land.

Of course the folded areas were immediately affected by erosion. Rutten pointed out that an average of more than 2000 m. of folded Neogene strata must have been denuded in northern Java, between Surabaja and Semarang. The result was a peneplain which was situated just above sea-level. You will remember from the first lecture (Chapter 1) that this peneplain has been elevated almost vertically to a height of 100–200 m., and that the amount of this elevation appears to be about 1000 m. in Atcheen. In this the present rivers have cut their courses.

A synthesis of the structural history of the East Indies will have to account for all these different movements, the results of which are apparent either as folding of the idio-geosynclines, or as a subsequent uplift of their content.

SUMMARY

Summarizing, we may say that in the western part of the archipelago four zones are particularly clear during the Cenozoic history. Proceeding from the south-west to the north-east, we find (see Table IV):

(I) The islands west of Sumatra belonging to a non-volcanic strip, the most recent folding of which occurs in the Miocene. In the Moluccas an analogous strip coincides with the Mesozoic Banda geosyncline. The formation of 'graben' along the axis of the islands in Pliocene times and the subsequent elevation of their contents is a characteristic feature of the latter zone.

(II) The geanticlinal zone of western Sumatra, southern Java and the Lesser Sunda Islands bearing a conspicuous girdle of volcanoes.

In between zones I and II is Sumba Island. It is intermediate not only by its site but also by its geological history. For example, its Tertiary volcanics form a point of resemblance to zone II, but in its lack of recent volcanoes it resembles more closely zone I. A synthesis of the East Indies has to clear up its remarkable situation and geological characteristics, which might be called 'the problem of Sumba Island'.

(III) The series of idio-geosynclines, moderately folded towards the end of the Pliocene and then elevated.

(IV) The pre-Tertiary folded area of Malaya, Banka, Billiton, the Riouw archipelago, and part of Borneo including the area of the South China Sea and Java Sea and reaching perhaps as far as western Celebes. Variscian and Early Cimmerian folding may be mentioned as characterizing the structural history of this area, or of large parts of it. The greater part of this region was an area of denudation during most of Mesozoic times. Its Pleistocene history formed our starting-point in the first lecture (Chapter 1).

This may suffice as a synopsis of the intricate structural history of the East Indies: it will become much more clear, I hope, when the geophysical data have been considered.

TABLE IV. SYNOPSIS OF STRUCTURAL ZONES DISCUSSED IN CHAPTER IV (SIMPLIFIED). COMPARE FIGS. 49, 67 AND PLATE XV

	Zone I Timor-east Celebes zone; islands west of Sumatra (since Miocene)	Zone II Geanticline of west Sumatra and south Java	Zone III Idio-geosynclines	Zone IV Sunda land	Spinal column of New Guinea
Pleistocene	Emergence	Denudation	Emergence	Area of denudation	Denudation Emergence
	Coral limestones	Emergence, faulting, increased volcanism	Moderate folding		
Pliocene	Denudation Submergence Marine sedimentation in longitudinal 'graben'	Marine sedimentation (locally)	Sedimentation		
Miocene	Denudation Emergence	Marine sedimentation (locally)	Sedimentation		
	Strong folding	Moderate folding, emergence, increased plutonism and volcanism	Unconformity		? Strong folding
	Marine sedimentation				Geosyncline
Oligocene Eocene	Marine sedimentation ? Epoch of folding Marine sedimentation	Marine sedimentation (locally)			
	Laramide folding	? Laramide folding			Laramide folding
Mesozoic	Banda geosyncline			Several transgressions in Borneo Early Cimmerian folding	Geosyncline Jurassic transgression denudation
Paleozoic	? Banda geosyncline			Variscian folding ? Caledonian folding	? Variscian folding

CHAPTER V

GEOPHYSICS

Co-operation between geologists and geophysicists has overcome many difficulties in economic and industrial researches. If one tries to make clear the progress of pure scientific insight resulting from the combination of geological and geophysical investigations, perhaps no better example could be given than their association in the East Indies.

The geophysical investigations are threefold. They concern terrestrial magnetism, seismology and gravity researches. The first group will be left out of consideration at present. The magnetic data are still too scanty. It may be sufficient to say that the preliminary results, published by S. W. Visser, show some vague relations between magnetic anomalies and gravity anomalies.

SEISMIC RESULTS

In certain districts of the East Indies earthquakes are frequently felt. Most of the violent earthquakes belong to the normal class of tectonic earthquakes. Some foci are known to be associated with well-established fault-zones on the islands of the inner arc. It was mentioned in the discussion of the volcanism (p. 28) that the strong steam explosions of Suoh in southern Sumatra were initiated by an earthquake which undoubtedly had its focus along faults in the geanticline of the Barisan Mountains (Fig. 37).

Serious damage has been caused by several tectonic earthquakes which had their foci along faults in Sumatra and Java. A glance at Fig. 60, however, shows that most of the earthquake epicentres in the western part of the archipelago were located west of Sumatra and south of Java in the deep-sea troughs and on the intermediate submarine ridge. Owing to the intricate pattern of the Moluccas their distribution is less clear in the eastern part of the archipelago, but at any rate it will be noticed that most of the epicentres occurred in or near the deep-sea troughs.

The focal depth of the great majority of all tectonic earth-shocks does not surpass 35 km. In 1928, however, Wadati clearly pointed out that apart from the normal shocks other earthquakes with focal depth of several hundreds of kilometres undoubtedly occur in the surroundings of Japan. Taking the evidence from all parts of the world together, it may be said that at present earthquakes are known to originate at practically all levels ranging from the surface down to depths of approximately 700 km. Another seismic result of paramount importance to geological science is that the mechanism in the focus of deep earthquakes is in no essential respect different from tectonic earthquakes with foci comparatively near the surface. Deep-focus earthquakes are known from areas bounding the Pacific basin proper, and they are arranged continentward in zones of ever-increasing depth. They thus give the impression of originating along a deep-reaching shear-zone sloping inland from the Pacific border. The outcrop of this potential zone of shear is in or near a marginal deep-sea trough.

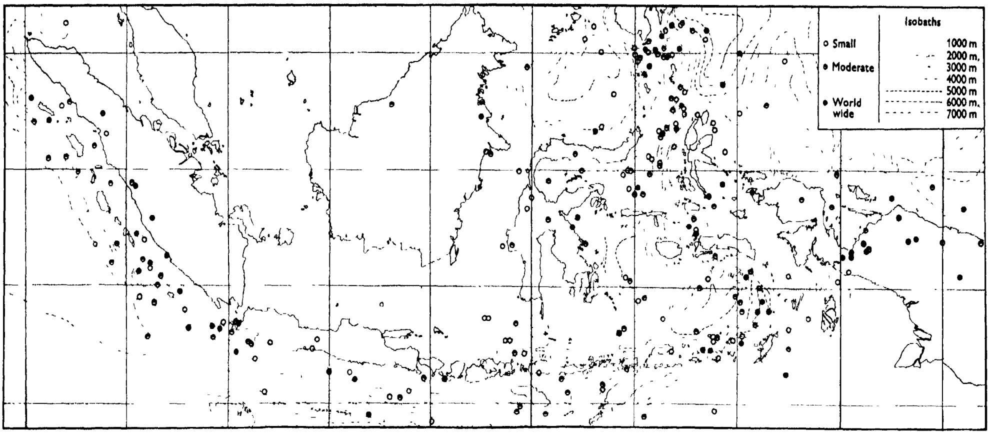
The distribution of epicentres of deep-focus earthquakes known from the East Indies is shown by Fig. 61. The rather complicated geographic distribution of deep foci is apparently due to the situation of the district along the south-eastern margin of the Asiatic continent and in the vicinity of Australia. However, the less complicated area between Borneo and the deep Java trough again shows the probable zone of foci along a plane sloping continentward. The angle of the seismic plane is nearly 50 to 55°. Its outcrop is in the belt of epicentres of normal tectonic earthquakes west of Sumatra and south of Java. Below the Java Sea the shear-zone appears to be at a depth of 600 km. below sea-level (Fig. 62).

Possibly the site of the potential zone of shear, as well as the site of the arcs, corresponds to the boundaries of sial layers of different thickness.

So the Mariane and Bonin arcs developed near the boundary between the Pacific basin proper—which has no sial layer—and the thin sial layer which probably extends from the Marianas as far as the Philippines and the Riu-Kiu Islands. The latter developed on the transition of the thin sial layer to one of continental thickness, whereas the Kurile and Aleutian arcs came into being on the boundary between a crust of the continental type and the basaltic floor of the Pacific. It may be that the situation is similar in the East Indies between the Philippines and the Moluccas. But in the western part the shear-zone has its outcrop between a crust of continental thickness and the thinner sial layer of the Indian Ocean. The connection of the two parts intersects a crust of the continental type between the Moluccas and Australia. Possibly two shear-zones occur in the northern Moluccas, one dipping westwards, the other eastwards.

GRAVIMETRIC RESULTS

The seismic results in themselves have thus revealed some interesting features concerning the site of the island arcs. Moreover, the elongated deep-sea troughs seem in some way related to the outcrop of the potential zone of shear. Another phenomenon that appears to be closely related to the outcrop



[After S. W. Visser

Fig. 60. *Distribution of earthquake foci of the normal class.*

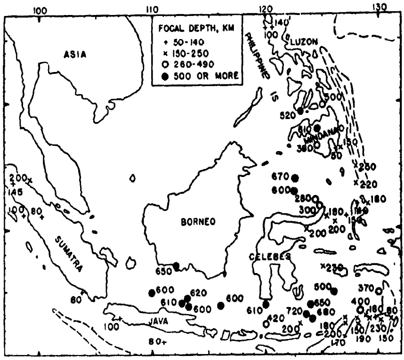
of the seismic plane is the remarkable belt of negative anomalies of isostasy discovered by Vening Meinesz in 1929 in the course of his gravity-expedition on board H.M.S. *K. XVIII*, a submarine of the Royal Netherlands Navy. The strip of negative anomalies (Plate X) implies that there is a corresponding deficiency of density in the earth's crust beneath. The only explanation covering all the observed facts is that the upper, i.e. lighter layers of the crust, must have formed a great downward fold or root of light material. The root pushed and displaced sideways the heavier material that originally built up these deeper parts of the crust and the underlying substratum. Obviously the crust broke and buckled downwards along a zone of weakness.

Another remarkable feature is the coincidence of the negative belt with the topography, as shown by the sections in Fig. 63.

The negative zone runs over the islands west of Sumatra and their continuation in the submarine ridge south of Java. Then it can be followed over the outer Banda arc towards Ceram and Buru via Timor, the Kei and Tanimber Islands, etc. Fig. 63 shows a morphologic and gravimetric profile south of Java.

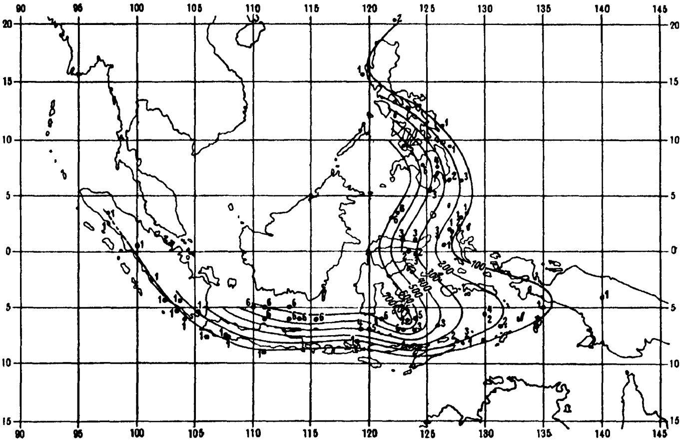
The meaning of this coincidence becomes clear when one notices the relation to the structural geology. An elongated strip of the earth's surface which subsides and is eventually compressed is very well known in geology as a geosyncline. Provided that the sinking strip is filled up with sediments, the latter will become folded, crumpled and squeezed out during an ensuing epoch of compression. When compression decreases the zone will try to re-establish isostatic equilibrium, and therefore it will rise. The crumpled contents of the trough become a mountain range or a submarine ridge. Obviously, this explains the coincidence between the zone of negative anomalies and the topographic features of that zone in the East Indies. A glance at Plate X clearly shows the zone of strong anomalies of isostasy to follow the zone of intensive folding in the Miocene. Other areas may be expected to show folding pertaining to the same epoch of increased compression, but of far less intensity; this was in fact found (Plate X). At the same time a geological determination of the age of the epoch of compression reveals the time of the last downward movement of the root.

You will remember that the same zone was subjected to earlier epochs of strong compression (Figs. 45 and 49) in the Lower Miocene, towards the end of the Mesozoic (Laramide) and perhaps still earlier epochs. Moreover, a com-



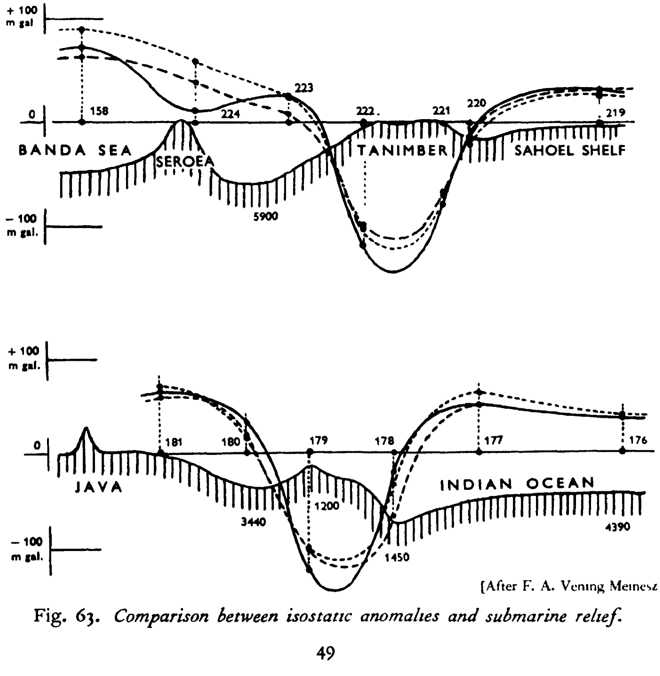
[After Gutenberg

Fig. 61. *Distribution of deep-focus earthquakes.*



[After H. P. Berlage

Fig. 62. *Distribution of deep-focus earthquakes.*



[After F. A. Vening Meinesz

Fig. 63. *Comparison between isostatic anomalies and submarine relief.*

parison with Fig. 45 shows that part of the zone of strong negative anomalies, viz. in the southern Moluccas and eastern Celebes, coincides with the Mesozoic Banda geosyncline. Hence it appears that at several epochs the crust was buckled downwards along the same zone of weakness. The first downward-buckling of the crust in this region may have happened in a very remote past. The first indication of the formation of the Banda geosyncline was found in the thick Permian deposits of the southern Moluccas (cf. p. 36). But when did the first downward-buckling take place? Hess pointed out that serpentinized peridotites are always present in the most intensely deformed part of the strip of strongly negative anomalies. They represent an ultramafic magma which was intruded in the course of the first great crustal downward-buckling. Probably a peridotitic substratum is present below the crust. Assuming this, a very deeply penetrating root would reach the peridotitic magma, while at the same time the latter would get an opportunity to invade the root. Hence a determination of the age of the oldest serpentines in the belt would fix the age of the first and greatest downward-buckling movement. Serpentines and other ultra-basic rocks (in some of the islands) probably date from Triassic times. In other places, however, a younger age was found. In Ceram, for example, they seem to be post-Upper Triassic.

It must be admitted, however, that the age of the peridotites cannot certainly be determined in many places. And it must be added that peridotites are of widespread occurrence on several islands outside the belt of negative anomalies. Following the first downward-buckling movement, a new epoch of increasing compression caused a rejuvenation, i.e. a further down-buckling of the root. And this process may have occurred repeatedly, at least three or four times, since the end of the Mesozoic.

Probably the potential zone of shear also originated in a very remote past and was rejuvenated time and again during the later history of the belt.

Obviously, the combination of geological and geophysical results clears up a great many questions that could not possibly be solved by one of these sciences alone. Some fundamental questions have now been answered. The moment has come, however, to try and answer the remaining questions, by uniting the results so far obtained into a synthesis, and by including the fields of strong positive anomalies of isostasy which have so far been left out of consideration.

CHAPTER VI

SYNTHESIS

In order to construct a synthesis of the geological history of the East Indies the following geophysical theory of Vening Meinesz should be recalled to memory. During an epoch of strong compression the earth's crust may react by the development of large waves of 200–400 km. diameter. Increasing compression will cause an increasing amplitude of the crustal waves until in one of them the strength of the crust is surpassed. Rupture sets in at the weakest place of a downward wave, and there the crust will form a downward-buckling root, the light rocks of the upper part of the crust penetrating into the heavier material beneath. It has already been noticed that the site of the root coincides with the outcrop of a deep-reaching potential zone of shear, as revealed by seismology, and that the shear-zone probably originated at the boundary between crustal parts of different composition.

ORIGIN OF THE DOUBLE ISLAND FESTOON

The schematic profile A of Fig. 64 shows the crustal buckling of zone I on Plate X. To the left two parallel waves are drawn, one upward, and one downward. Let us suppose that they are represented respectively by zone II (a geanticline with plutonism and volcanism) and zone III (an idio-geosyncline) of Plate X. In conjunction with this the seismic results (Figs. 60, 61 and 62), as well as the bathymetric map, Plate I, and Fig. 22, should be consulted repeatedly. Let us first confine our comparison between theory and facts to the western part of the archipelago, which lacks the complications of the Moluccas. It may be assumed, moreover, that profile A represents a Tertiary epoch of compression and rejuvenation. To make things simpler it is supposed that the crust consists of two layers, instead of three as is generally accepted, viz. an upper layer of light, acidic material (sialic rocks) and a lower layer of heavier, basic material (simatic rocks), underlain by a basic to ultra-basic substratum. The insertion of more than two layers would make the drawing more complicated, but would not affect the principle which has to be elucidated. The lower boundary of the crust is supposed to be the boundary between crystalline basic rocks and the basic material of the substratum. Hence it represents the fluidity boundary of the sima. It is assumed that the thickness of the crust depends upon the thickness of the sialic layer, the sial being considered to produce more radio-active heat than the basic rocks of the sima. So, when a root of sialic material is buckling downward, the fluidity boundary will migrate in an upward direction. The amount of this displacement is unknown. It is drawn in an entirely schematic manner in the profiles.

As soon as the compression in the crust decreases, the crust will try to re-establish isostatic equilibrium. The sialic root must have a strong tendency to rise. Simatic material will therefore flow towards the buckled belt, and, as a further consequence a furrow will form on either side of the folded zone I. This stage is represented by profile B.

One of these furrows will come into being between the volcanic belt and the root (I *a*), the other along its convex front (I *b*). The first corresponds to the deep-sea basins between Sumatra and the row of islands to the west of it. The second corresponds to the series of marginal deep-sea troughs running along their oceanic side.

Whether the intervening belt of folded strata (zone I) appears as a submarine ridge or as an island festoon depends on the quantity of strata squeezed out. The second possibility is represented by profile B. In that case a double island festoon has come into being; an inner volcanic arc and, parallel to it, an outer arc which in this stage will be a non-volcanic arc.

For the East Indies the theory is supported by what is known of their paleogeographic evolution in Tertiary times. The region of the archipelago was probably an extensive land-area at the end of the Mesozoic and the beginning of the Eocene (Fig. 46). The increasing extent of several Paleogene and Neogene transgressions is illustrated by Figs. 47 and 48.

A western land area, including large parts of Borneo, Malaya, the present Java Sea and South China Sea, and Sumatra is still to be recognized in the Eocene. A second large land area existed in the south-east, including northern Australia and the present Arafura Sea. Is it mere accident that the zone of buckling appears as islands exactly where it runs along the areas that for a long time resisted the invasion of marine transgressions? In the Miocene, at last, the sea invaded these old land nuclei over a larger extent, as shown by Fig. 48.

In all probability the downward folded root did not remain intact. It is reasonable to assume that the sialic matter of the root began to melt and spread. As a result the central part of zone I began to subside, forming a shallow depression, profile C. It is actually known as the central 'graben' or 'geosyncline' on Timor, containing a sequence of a few hundred metres of Pliocene sediments (Fig. 52). A similar feature is known from the Kei Islands (Fig. 53), Tanimber Islands (Fig. 54), Ceram, and probably also Buru. The ensuing epoch of compression at the end of the Pliocene —represented by profile D—caused a moderate folding of the contents of zone III. The shallow depression on zone I was only slightly affected at this stage, some tectonic phenomena at the margin of the shallow 'geosyncline' being the only phenomena that have been noticed. The plutonic and volcanic processes of zone II were more active.

The last stage represented by profile E shows the most recent period of decreasing compression. Again, zone I rises isostatically and the content of the central depression rises above sea-level—in places several hundred metres, and locally even more than a thousand metres. Zone III also rises isostatically, but to a slighter degree, and the plutonism and volcanism of the geanticlinal belt II decreases to its present, though still active, phase.

Again the root melts and spreads laterally in the substratum. A comparison of the gravimetric and bathymetric maps shows that the sialic root has spread, below the site of the Weber deep, for example, in the vicinity of the Kei Islands.

According to the considerations just mentioned, the topographic and bathymetric features of the East Indies would be of comparatively recent origin. They would all have come into being at least since the last epoch of strong compression in the Miocene. And this is what has been concluded from geological and morphological data. It would appear from theory, moreover, that the deep-sea furrows I*a* and I*b* were of a still more recent date than the depressions of zone III. In the same way the most recent elevation of zone I began at a later stage than the latest movement of uplift of zone II.

The upward movement of zone I is of a fundamentally different nature from that of the geanticlinal up-doming of zone II.

Fig. 27 shows the height of raised coral limestones and fluviatile terraces in the southern Moluccas. No data are available to fix their age exactly, nor would it be possible at the moment to discern such comparatively slight differences of age as are postulated by the theory. Mostly they are designated as 'Pleistocene' or 'Plio-Pleistocene'.

The different structural elements will now be considered in more detail, proceeding from the external side of the arc to its concave inner side.

DEEP-SEA FURROWS

One of the consequences of the foregoing theoretical deductions concerns what might be called the problem of Sumba Island.

Obviously the island does not belong to the volcanic inner arc. Neither in stratigraphy nor in structural history is it intimately related to the islands of the outer arc, such as Timor and Roti.

Now compare the submarine relief with the gravimetric results. A submarine ridge partly emerging above sea-level in the shape of islands such as Mentawei and Nias can be followed from off the coast of Sumatra to the neighbourhood of Sumba. The axis of the belt of negative anomalies coincides with the ridge, which on either side is accompanied by a deep-sea trough. Along the external side is the marginal deep, while another series of troughs lies along the inner side, among which is the Java deep. The belt of negative anomalies terminates south-west of Sumba, only to reappear once more south-east of Sumba, continuing north-eastward over Timor Island. And there the ridge is again accompanied on either side by deep troughs, viz. the Timor trough and the Sawu trough. The site of Sumba Island, as well as the submarine topography in its vicinity, thus seems to be intimately related to the interruption of the zone of negative anomalies. Of course the problem of Sumba might be put in two ways. One way would be to ask whether the presence of Sumba Island caused the zone of buckling to become interrupted to the south of the island, and a further point would be to examine the cause-and-effect relation. The other way might be formulated thus: if the zone of buckling were continuous, uniting the Timor ridge to the submarine ridge which is known to terminate south-west of Sumba, then Sumba Island would not exist, its site being occupied by a deep-sea trough.

In our opinion Sumba is the exceptional example of a sort of terrain that elsewhere subsided so as to form the bottom of one of the series of deep-sea furrows between the outer and inner arcs.

THE VOLCANIC INNER ARC

We started our inquiries by assuming the formation of crustal waves some 200–400 km. from crest to crest. The upward wave accompanying the zone of buckling on its continental side is more strongly developed than the corresponding wave on its convex side. It is always, moreover, a volcanic arc. We may put forward the following explanation of this state of affairs.

Subcrustal sima was pushed aside by the downward penetrating root (Fig. 64, A). The curved shape of the arc induced a centripetal crowding of the sima on the concave side of the arc, whereas it could expand more freely on the convex side of the arc. This caused the arching of the geanticlinal belt to be sustained and augmented by the accumulating sima. Hence it became an ever more pronounced belt of active plutonism and volcanism, according to the mechanism described on pp. 28 and 29. No such process happened to occur on the convex side of the buckled belt. And this may explain why a volcanic arc always develops at the concave side of the non-volcanic arc, never along its convex side. Theoretically volcanism might originate at the convex side as well, though to a far less pronounced degree. Perhaps Christmas Island is an example of an old volcano on an emergent outer geanticlinal.

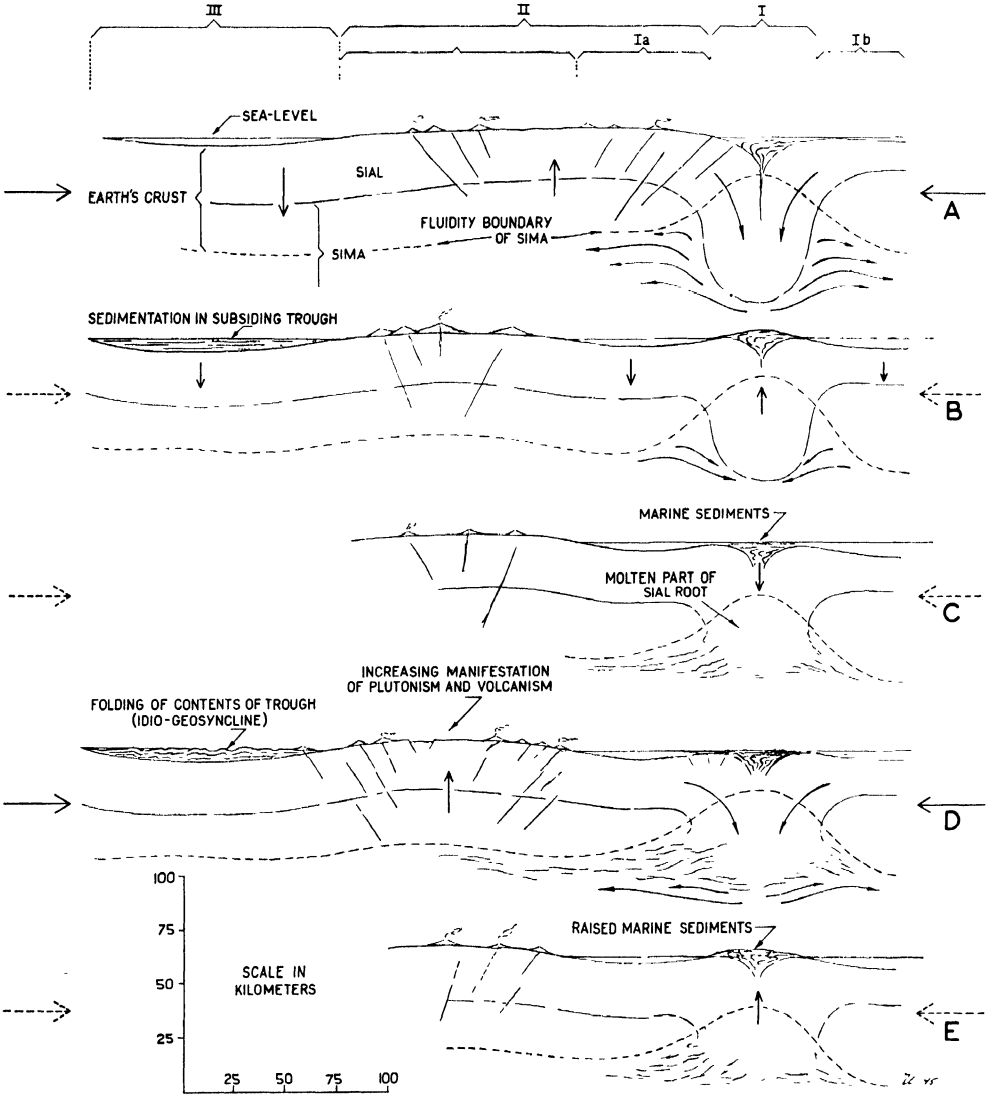


Fig. 64. *Schematic and tentative sections, showing the origin and development of the double island festoon of the East Indies.*

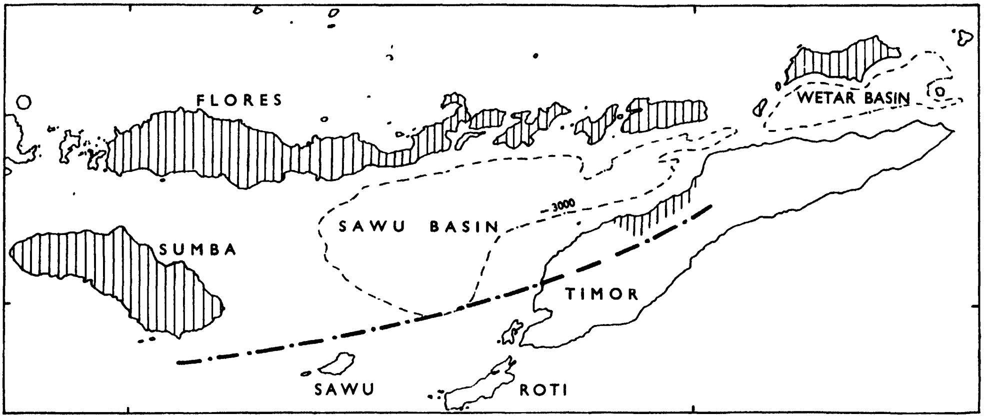


Fig. 65. *Distribution of Upper Tertiary volcanic rocks on Timor and Sumba.*

According to our theoretical deductions, plutonism and volcanism in the geanticlinal zone II would start during epochs of increasing compression. For arching of the zone induced relief of pressure at the underside of the crust and subsequent rising of a migmatite front as described on p. 29. Now the Miocene epoch of compression was followed by another at the end of the Pliocene, and accordingly two periods of increased volcanic activity might be expected in zone II, since the beginning of the Miocene. In fact these have been found by field observations (p. 31).

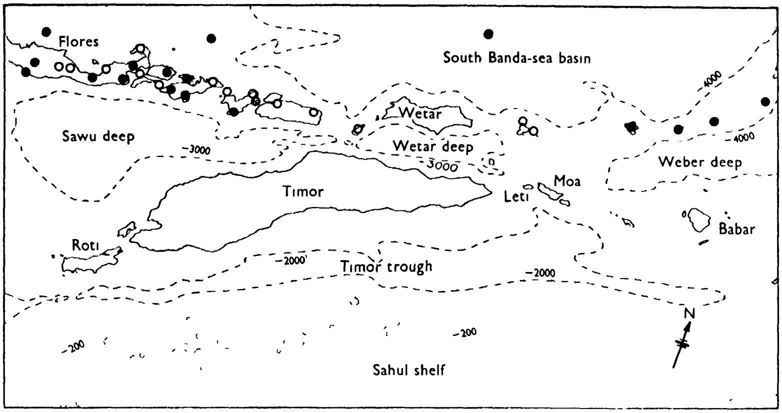
Quite different phenomena may be expected from the zone of buckling. For during an epoch of compression no geanticlinal arching or relief of pressure occurred. On the contrary, a root of mobile sialic matter penetrated downwards and the belt was strongly compressed. No manifestation of volcanism is to be expected under such circumstances. During the ensuing period of decreasing crustal compression, the melting and expanding sialic root might give rise to ascending batholiths. Obviously, however, the mechanism of their formation was fundamentally different from that operating in the geanticlinal belt II. Seldom do the batholiths penetrate to a high level, so as to become visible at the surface in the present stage of erosion of the arc.

Active volcanism is thus conspicuously absent in the outer arc of an island festoon. But volcanic rocks of Upper Tertiary age have been found on Timor, an island of the outer arc. One might suppose that these were derived from plutonism belonging to the buckled belt. Possibly, however, these volcanics originated in a different way. If we regard once more the schematic illustration, Fig. 64, it will be noticed that originally the buckled zone was bordered immediately by rising crustal waves. In stage B of Fig. 64, however, the geanticlinal belt was appreciably narrowed by the formation of the deep-sea trough, I*b*. Hence the volcanism of the remaining geanticlinal zone was also restricted. But one might expect to find volcanic rocks even as far as the present belt I. And one might add: (1) that these igneous rocks should date from Upper Tertiary times; (2) that their occurrence should be restricted to the concave part of zone I; (3) that they might possibly be of submarine origin; and (4) that they might be expected to occur on the bottom of trough I*b* as well. Now volcanic rocks and tuffs have indeed been found on Timor Island, and exactly where they might be expected to occur, viz. north of the central basin. Volcanic rocks of Upper Tertiary age have been found also on Sumba. But here they are widely distributed over the whole island. Once more this is in accordance with the view that Sumba must be considered as a crustal part which, unlike the areas east and west of it, has not subsided so as to form the bottom of a deep-sea trough (Fig. 65).

Tertiary volcanic rocks on Buru, Ceram and the islands on the concave side of that part of the arc show a similar distribution. Upper Tertiary volcanic rocks in Buru are known only from the south coast. In Ceram they are also known from the southern part of Huamoal, i.e. the western peninsula. They are widely spread over Amboina and other islands to the south of western Ceram, however, and the little island of Amblau south of Buru.

Finally, a feature of volcanological interest concerns the distribution of active and extinct volcanoes in the southern Moluccas, as shown by Fig. 66. On many occasions Brouwer pointed out that volcanic action is extinct in those islands of the inner arc that are situated nearest to Timor Island, which belongs to the outer arc. No active volcanoes are found on Alor and Wetar.

Proceeding from these islands towards the more western or eastern islands of the inner arc, the distance from the outer arc increases, and the number of still active volcanic vents



[After H. A. Brouwer

Fig. 66. *Distribution of active and extinct volcanoes in the southern Moluccas.*

increases as well. Probably this phenomenon is caused by the strong compression which the crust is undergoing here, as indicated by the formation of the marginal Timor trough, and more especially by the subsiding Sawu deep. For in this area the subsiding troughs had to become adapted to the limited space between the inner arc and the Australian continent, as contrasted with their free development more to the west. This phenomenon is clearly revealed by the narrowing deep-sea relief as shown on the bathymetric chart, Fig. 66, and in Kuenen's analysis of the submarine topography, Fig. 22.

BASINS AND TROUGHS BEHIND THE INNER ARC

We may now proceed to consider the downward wave on the continental side of the volcanic geanticlinal or inner arc (zone III of Fig. 64).

Two possibilities should be considered separately in respect of a supply of waste products from the surroundings.

One possibility is that the quantity of waste products equals or even surpasses the rate of subsidence of the bottom. The trough will then gradually become filled up and appear as a geosynclinal trough. During an ensuing stage of increasing compression the contents of the furrow will become folded (Fig. 58). It will be seen in Plate X that regions of this type actually occur on Sumatra and Java. They are called idio-geosynclines and constitute oil basins of high economic value. The strata underwent a moderate folding at the end of the Tertiary.

Owing to isostatic readjustment the idio-geosynclinal troughs rose slightly in the course of the ensuing period of decreasing compression, as mentioned in Chapter I.

It was pointed out that probably a contemporaneous sinking of such areas as the Java Sea, the Spermonde shelf and the shelf along the eastern coast of Borneo has taken place. This may perhaps be explained by assuming a migration of simatic matter towards the rising idio-geosynclines.

A comparison of Fig. 41 and Plate X clearly reveals that most of the igneous rocks of the Mediterranean clan are found in the idio-geosynclinal troughs. Possibly the ascending magmatic emanations reacted with much lime material from the marls and limestones that occur in comparatively great abundance in the geosynclinal troughs. On this view the location of the alkali-rock suites mainly along the concave side of the inner volcanic arc seems to be controlled by the occurrence of the limestone in the geosynclinal troughs, the sites of which are in turn predestined by the formation of crustal waves accompanying the downward-buckled belt.

The other possibility is that the rate of subsidence of the bottom exceeds the supply of sediments. In that case a deep-sea trough will originate and persist. The Flores trough might be cited as a possible example (Fig. 67). In the eastern part of the East Indies the situation is more complicated, on account of the double curvature of the arcs. But the deep basins may be explained in a similar way, their peculiar shapes being the result of a process of interference set up by the vortex-shaped arrangements of the buckled zone, as may readily be noticed from a comparison of Plate X and Fig. 22. The northern Banda Sea basin, for example, is, as it were, enclosed by the strongly curved zone of eastern and south-eastern Celebes. Instead of a continuous marginal deep, three separate basins developed along the convex front of this zone, marked *a*, *b* and *c* on Kuenen's map, and reproduced in our Figs. 22 and 68.

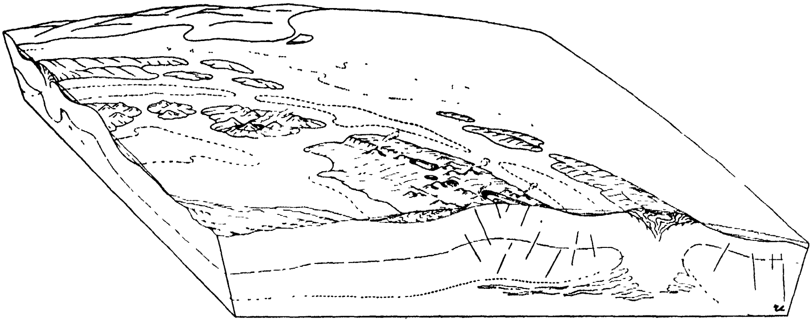


Fig. 67. *Schematic and tentative block-diagram of the double island-arc of the East Indies.*

Marginal deep (I*b*) along the convex side of the outer arc (I), 'intramontane' troughs (I*a*) along its concave side, the volcanic geanticline (II), and two types of depressions along the concave side of the volcanic inner arc, viz. in front an idio-geosyncline (III) and in the distance a deep-sea basin. The figures between brackets correspond with those of Fig. 64 and Plate X.

POSITIVE ANOMALIES OF ISOSTASY

A field of anomalies—with an average of $+20$ milligal.—covers the whole area of the East Indies outside the belts of negative anomalies. According to Vening Meinesz it is caused by lateral compression of the crust.

Strips of stronger positive anomalies run parallel to the negative zone, south of Java. And even the most complicated part of the Moluccas shows unmistakable evidence of a parallelism between belts of positive and negative anomalies. Their striking interrelation is a fundamental feature which calls for an explanation combining both negative and positive anomalies in a single synthesis.

The most important features may be summed up as follows. Comparing the gravimetric and bathymetric contours, one may notice some coincidences. A deep basin, such as the Celebes Sea, shows positive anomalies of more than 50 milligal. The same holds good for the deep Makassar Strait, the Gulf of Bone (between the southern and south-eastern arms of Celebes) and its continuation to the southern Banda Sea. From a further inspection, however, the following striking features may be noticed: (1) The relation to the submarine relief is not more than a rough approximation. (2) Neither the marginal deeps nor the troughs of the intramontane type (represented by 1, 2 and 3 in Fig. 22) show marked positive anomalies. (3) In the western and less complicated part of the archipelago zones of positive anomalies may be seen to run parallel to the strip of negative anomalies; nevertheless, the positive strips are not over the deep-sea furrow, but roughly coincide with elevations of the bottom. It seems obvious that the local coincidence of a ridge and a belt of positive anomalies is purely accidental.

Hence the cause of the positive anomalies must not be sought in crustal but in subcrustal phenomena. The following speculation may perhaps elucidate the problematic features just enumerated. The sial root penetrated downward into the heavier substratum. Consequently, the heavy masses of the substratum were pushed aside. The effects on surface features have already been discussed in previous pages. If it be assumed, however, that a deep-seated layer of heavy dunite was influenced in much the same way as the subcrustal layer of basaltic material, the result of the displacement of the heavy dunite would be revealed as a belt of positive anomalies on either side and at a comparatively short distance from the negative belt. The great depth of the process would explain why in one place the belt of positive

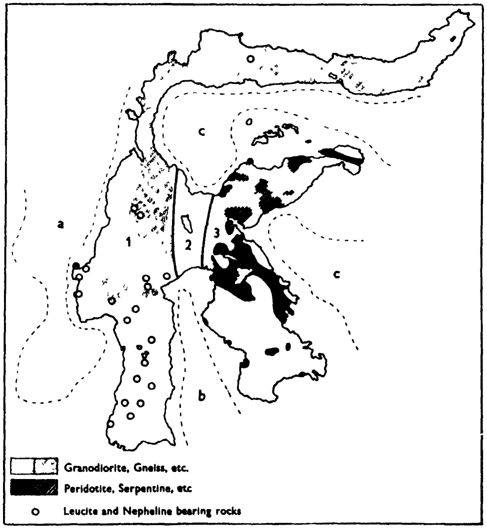


Fig. 68. *The inverted arcs of Celebes.*

anomalies corresponds to a ridge-shaped elevation of the crust, and elsewhere to a deep depression.

The general principle of this speculation may account also for the distribution of gravity in the complicated area of the Moluccas. Here a kind of interference between the interwoven negative zones might be expected. And, indeed, the highest positive values were found in the vicinity of the Sulu Islands, i.e. in the immediate vicinity of the greatest negative values. The sialic root is exceptionally broad and deep here. The adjoining positive field is also broader and the positive values higher than anywhere else, and this is what might be expected according to the theory.

It will be remembered that the occurrence of the volcanic belt on the inner side of the non-volcanic arc was explained as an effect due to the curved shape of the negative zone (p. 52). Probably a similar process of centripetal crowding influenced the subcrustal ultrabasic sima, and therefore the positive anomalies are strong and appear in partly interfering belts along the concave inner side of the negative zone. But they appear only in much fainter degree at its convex outer side, e.g. west of Sumatra and south of Java.

THE INVERTED ARCS OF CELEBES

Doubtless the whorl-shaped pattern of the Moluccas is due to the presence of the continental block of Australia, including the Arafura Sea and New Guinea. The continental sial-masses, being much thicker and penetrating deeper than the comparatively thin sial-cover of the floor of the Indian Ocean and the sial-free bottom of the Pacific, must have considerably influenced the development of subcrustal processes towards the south-east and east. But a mechanical interpretation of the puzzling island arcs of the Moluccas is not yet possible. Our geological and geophysical knowledge of the adjacent regions is too scanty. This concerns especially New Guinea and Halmahera on one side, and Borneo on the other. From a geological point of view Celebes Island belongs to the Moluccas. Its remarkable four-armed morphology is due to a double arc which—unlike all the other arcs along the border of Asia—has its convex side turned towards the Asiatic continent. Obviously, the inverted position of the Celebes arcs is caused by the sum of the forces interacting in the region between Asia and Australia. Accordingly, for the time being, a mechanical interpretation of the inverted position of Celebes will be left out of the discussion.

But a few remarks may be made on some features which are intimately related to the inverted position of the arc and its position as part of the complicated pattern of the Moluccas. The theoretical deduction formulated on p. 51 was substantiated by the structural history of the western part of the East Indies and a large part of the Moluccas. Moreover, the main features of several other island arcs are in accordance with the theory.

At first sight, however, the theoretical scheme seems to break down if applied to Celebes. A belt of negative anomalies of isostasy coincides with the eastern and south-eastern arms of the island. These arms form an arc with its concavity towards the east. Hence—according to the theory—a volcanic 'inner' arc ought to be present, parallel to it, somewhere in the Banda Sea. But instead of a volcanic arc a deep-sea basin has developed east of Celebes and a volcanic zone has come into being on the opposite side. For the southern and northern arm of Celebes, as well as the uniting central part, are characterized by numerous manifestations of volcanism dating from Upper Tertiary to sub-recent times. The same zone is, moreover, characterized by the abundance of granodioritic rocks and gneisses. Similar rocks are conspicuously absent from the eastern arc, where serpentines, lherzolites and other basic or ultrabasic rocks have a wide distribution (Fig. 68). The central zone of the island, running north–south, formed a depression with marine sedimentation during the Upper Tertiary. It is now characterized by 'graben' and separated from the western part of Celebes by a zone of mylonites. Finally, three remarkable deep-sea basins must be mentioned. On morphological grounds Kuenen united them in a special class (*a*, *b*, *c* in Fig. 22 and in Fig. 68). Two of them, the Tomini and Bone basins, separate the eastern and western zones of Celebes; the other one—the basin of Makassar Straits—lies in front of the 'volcanic arc' (Fig. 68).

In an attempt to explain the unusual arrangement of these morphologic and tectonic elements, attention should be focused on the exceptional features of the Moluccas as a whole. We pointed out that the formation of the basin-shaped depression of the north Banda Sea was probably caused by interacting processes in the crust, due to the whorl-shaped arrangement of the zones of buckling. The accumulation of displaced dunite masses was thought to be responsible for the large fields of positive anomalies in the same region. Probably these processes hampered the development of a volcanic 'inner' arc east of the negative zone of Celebes. For the deeply subsiding crust under the Banda Sea basin acted as an antagonistic and dominant factor. And probably this effect was strengthened by the exceptionally strong accumulation of dunite in the same region (cf. p. 56). As a tentative explanation I therefore suggest that these co-operating factors suppressed the formation of an inner arc in this area. The basaltic material of the substratum that was pushed aside by the downward movement of the root under the eastern part of Celebes thus had to flow towards the opposite side, i.e. westward. And therefore, exceptionally, the total volume of sima that was displaced by the root had to flow towards the convex side of the arc, where it stimulated the development of the numerous granodioritic intrusions and volcanic manifestations found in the western part of the island.

The site of the dunite masses in the substratum is revealed by the fields and belts of strongly positive anomalies. In order to explain their distribution along the convex side of the negative zone the influence of all the major tectonic elements in the surroundings would have to be taken into account. Unmistakably the strongly negative zone between Celebes and Halmahera had a paramount influence on the site and shape of the positive field in the Celebes Sea and its connection with the positive belt in the Straits of Makassar.

But in order to understand the positive fields as a whole we ought to take into consideration the gravimetric data on land: on Borneo as well as on Celebes. It is, for example, uncertain whether the positive values in the Gulf of Bone and Makassar Straits may be interpolated so as to form a zone across the southern arm of Celebes, or whether the positive zone of the Gulf of Bone has to be united with the positive values in the Gulf of Tomini. A complete analysis of Celebes and its surroundings must therefore be postponed until more data become available. This applies also to the three deep-sea basins of Fig. 68, the presence of the idio-geosynclinal basins in east Borneo and south Celebes, and finally to the different aspects of the zone of 'graben' in central Celebes as compared with the deep-sea basins in its northern and southern continuation.

DESIDERATA AND UNSOLVED PROBLEMS

Early in the course of these lectures a number of open questions announced themselves. Some of them received an answer later, as further phenomena came up for discussion. But I believe that I have shown that most of them could only be answered tentatively by uniting the geological and geophysical results into one harmonious picture of the structural history of the East Indies.

The picture I have attempted to construct has, of course, the deficiences inherent in any human representation of an intricate pattern of the earth's crust. Personally, I am convinced that it is only of temporary value, something like a working hypothesis which has to be discarded as soon as new facts are revealed which are incompatible with our present views. Let us not forget that our knowledge of this vast area still leaves much to be desired. Repeatedly I have pointed out serious gaps in our knowledge. Let me, to conclude, draw your attention once more to some desiderata and unsolved problems.

Where are we to look for the continuation of the spinal column of New Guinea towards the west? Does that structural unit end without any connection with other structural zones of the Moluccas, or does it continue into Halmahera? Halmahera—an island the shape of which strongly reminds one of Celebes—and the area between Halmahera and New Guinea are, however, *terra incognita* from the point of view of structural history. A narrower net of gravimetric data in that area is another desideratum. And the same holds good for the surroundings of Buru, Ceram and Sumba. We are much in need of a structural and gravimetric map of the large island of Borneo, of the Philippines and the island-strings that connect these two regions. We want detailed geological profiles across Sumatra, Java, the islands west of Sumatra, Timor, Ceram, Buru, Borneo, New Guinea and a number of other islands. And still many more data are desired from most of the areas which are comparatively well known.

Volcanoes occurred in several areas where now only extinct volcanic ruins have been found, for example in southern Celebes and eastern Borneo, and even in marine Tertiary areas where no trace of their former existence is left in the morphology of the landscape, as in northern Dutch New Guinea. The distribution of plutonism and volcanism in the successive horizons of the Tertiary and older formations has not yet been summarized satisfactorily. Obviously our picture of the evolution of volcanism is only part of a much more complicated history.

In short, there are still a host of most interesting investigations to be carried out. When these and still many more gaps in our knowledge have been filled up, the picture which I have attempted to sketch undoubtedly will have to be augmented and altered in several parts. As data accumulate and our knowledge of this interesting archipelago grows, it will be possible to trace ever more completely the structural history of the East Indies.

REFERENCES

The following short enumeration of publications may serve as a key for further references.

Chapter I. SHALLOW SEAS

MOLENGRAAFF, G. A. F. *Geologie.* De zeeën van Nederlandsch Oost Indië, 1922.

RUTTEN, L. M. R. *Voordrachten over de geologie van Nederlandsch Oost Indië.* Groningen: Wolters, 1927.

UMBGROVE, J. H. F. Coral reefs of the East Indies. *Bulletin of the Geological Society of America*, 1947, vol. 58, pp. 729–778, contains an extensive bibliography.*

Chapter II. DEEP-SEA BASINS AND TROUGHS

KUENEN, Ph. H. Geological interpretation of the bathymetric results. *The Snellius Expedition*, vol. v, pt. 1, 1935.

KUENEN, Ph. H. Collecting of the samples and some general aspects. *The Snellius Expedition*, vol. v, pt. 3, § 1, 1943.

NEEB, G. A. The composition and distribution of the samples. *The Snellius Expedition*, vol. v, pt. 3, § 2, 1943.

RIEL, P. M. VAN. The bottom configuration in relation to the flow of the bottom water. *The Snellius Expedition*, vol. II, pt. 2, ch. II, 1934.

RIEL, P. M. VAN. Oxygen-content of the bottom water. *The Snellius Expedition*, vol. II, pt. v, ch. 1, 1943.

UMBGROVE, J. H. F. On the time of origin of the submarine relief in the East Indies. *C.R. du Congr. Intern. de Géogr. Amsterdam*, 1938, tome 2, § II*b*, pp. 150–9.

WICHMANN, A. Der Vulkan der Insel Una-Una. *Zeitschr. Deutsch. Geol. Gesell.* 1902.

Chapter III. VOLCANOES

A great number of papers were used in the preparation of this synopsis. Special reference ought to be made of the series of memoirs: *Vulkanologische en Seismologische Mededeelingen* (*Dienst van den Mijnbouw in Nederl. Indie*), vols. I–XII, 1919–30. *Bulletin of the Netherlands East Indies Volcanological Survey*, nos. 1–94 (1927–41) and the following papers:

BEMMELEN, R. W. VAN. De tektonische structuur van Sumatra. *Natuurk. Tijdschr.*, vol. XCIV, 1934.

BEMMELEN, R. W. VAN. The volcano-tectonic origin of Lake Toba. *Ing. Nederl. Indie*, 1939.

BEMMELEN, R. W. VAN. On the origin of the Pacific magma types in the volcanic inner arc of the Soenda Mountain system. *Ing. Nederl. Indië*, 1938.

STEHN, C. E. Beobachtungen an Glutwolken des Vulkans Merapi. *Handel. 7e Ned. Ind. Natuurwet. Congr.* 1936, pp. 647–56.

UMBGROVE, J. H. F. Het ontstaan van het Diengplateau. *Leidsche Geol. Mededeelingen*, vol. III, 1929.

UMBGROVE, J. H. F. Het vulkaan eiland Oena-Oena. *Leidsche Geol. Mededeelingen*, vol. III, 1930.

UMBGROVE, J. H. F. The Sibajak volcano. *Zeitschr. für Vulkanologie*, vol. XIII, 1931.

WILLEMS, H. W. V. On the magmatic provinces in the Netherlands East Indies. *Verhandel. Geol. Mijnb. Genootschap.* (Geol. Série), vol. XII, 1940.

Chapter IV. STRUCTURAL ZONES

UMBGROVE, J. H. F. Geological history of the East Indies. *Bulletin of the American Association of Petroleum Geologists*, no. 22, 1938, with additions from several more recent papers by numerous authors.

Chapter V. GEOPHYSICS

1. *Seismology*

GUTENBERG, B. and RITCHER, C. F. Depth and geographical distribution of deep-focus earthquakes. *Bull. Geol. Soc. America*, vol. XLIX, 1938.

GUTENBERG, B. and RICHTER, C. F. Seismicity of the Earth. *Geol. Soc. of America* (Spec. Paper), vol. XXXIV, 1941, and *Bulletin*, vol. LVI, 1945.

VISSER, S. W. On the distribution of earthquakes in the Netherlands East Indian Archipelago. *Verhand. Kon. Magnet. en Meteorolog Observatorium, Batavia*, vol. XXII, 1930.

VISSER, S. W. Seismic isobaths in the East Indian Archipelago. *Geol Beitr. zur Geophysik*, vol. LIII, 1938.

VISSER, S. W. *Seismologie.* Groningen: Noorduyn, 1943.

2. *Gravimetric results*

VENING MEINESZ, F. A., UMBGROVE, J. H. F. and KUENEN, Ph. H. *Gravity Expeditions at Sea* 1923–1932, vol. II. Publication of the Netherlands Geodetic Commission, Delft, 1934.

VENING MEINESZ, F. A. The Earth's crust deformation in the East Indies. *Proc. Kon. Acad. v. Wetensch. Amsterdam*, vol. XLIII, 1940.

Chapter VI. SYNTHESIS

UMBGROVE, J. H. F. Island arcs in the Western Pacific. *Geogr. Jour.* vol. CVI, pp. 189–209, 1945.

UMBGROVE, J. H. F. *The Pulse of the Earth* (2nd. ed. The Hague: Nijhoff, 1947), ch. VII, Island Arcs, with extensive bibliography.

* Plate III, C is from a paper by the present author entitled 'The first days of the submarine volcano near Krakatoa' (*Leidsche Geol. Mededeelingen*, vol. II, 1928). Plates III, D, V, B and VIII, B are photographs by the present author not published in previous publications.

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