American Philosophical Society

Mountain Growth, a Study of the Southwestern Pacific Region
Author(s): William Herbert Hobbs
Source: *Proceedings of the American Philosophical Society*, Vol. 88, No. 4 (Oct. 18, 1944), pp. 221-268
Published by: American Philosophical Society
Stable URL: http://www.jstor.org/stable/985450

Accessed: 05/10/2008 10:47

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=amps.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.

American Philosophical Society is collaborating with JSTOR to digitize, preserve and extend access to *Proceedings of the American Philosophical Society*.

http://www.jstor.org

MOUNTAIN GROWTH, A STUDY OF THE SOUTHWESTERN PACIFIC REGION

WILLIAM HERBERT HOBBS

Professor Emeritus of Geology, University of Michigan

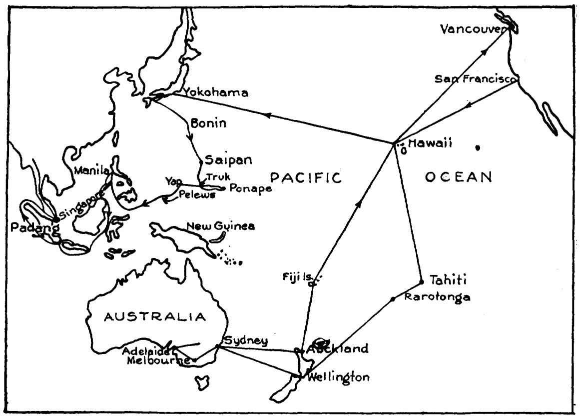
(*Read April 23, 1943*)

ABSTRACT

In most parts of the world where mountains are to be found, the history of their origin and manner of growth is difficult to decipher, and mainly for the reason that the history, if not already completed, is at least in a very advanced stage. We are in those areas dealing with conditions of erection which no longer obtain, and throughout this history other and destructive rather than constructive agencies have been in operation, and these agencies have largely effaced or else entirely removed the pertinent evidence. These agencies are grouped under the names weathering, erosion, and transportation, and they have left us only disfigured remnants of forms and structures which at one time would have laid bare the essential facts of the history.

These destructive agencies are largely within the realm of the atmosphere, and it is within that shell of our planet that most mountains undergo their erection.

In one region, that of the southwest Pacific, and in that alone, mountains have in very recent time been rising from the bottom of the deep sea, where they have been immune from the usual destructive agents, and they are there even today in an early stage of their growth. Impressed by the unique opportunity for study which was there presented, the author in 1918 began a preliminary study of the area, and in 1921 and 1923 he undertook for the purpose extensive reconnaissance cruises in the western and southwestern Pacific areas (map 1).



MAP 1. The author's cruises in the Pacific region in 1921 and 1923.

The proof that the mountains within this southwestern Pacific region are still in a vigorous growth which is not duplicated elsewhere, is supplied by the authoritative map of earthquake distribution (map 5). Only less important as evidence is the local effusion of now active volcanic vents which reveals general elevation while the presence of coast terraces reveals a local elevation, as barrier reefs do local subsidence. A very important aid has also been recently supplied by the extended use of the echo method for deep sea soundings (map 7).

The present study is treated in three parts: I, a general discussion of the nature of mountain growth; II, a special study of the mountain arcs of the southwestern Pacific area; and III, a study of the principal islands in the oceanic area of subsidence where crustal settlement has brought about the wrinkles or arcs.

CONTENTS

PART I, GENERAL

PART II, MOUNTAIN ARCS OF THE SOUTHWEST PACIFIC REGION

PART III, THE SINKING PACIFIC FLOOR

NOTE: Until World War II the islands of the Pacific had been vouchsafed comparatively little attention in American circles, as their importance commercially and strategically had been but lightly regarded. For purposes of description they now offer a difficult problem because of the many different names which have become attached to the same island and the different spellings of each which are in use. The multiplicity of names came about partly because of duplication in discovery, most frequently by unlettered whaling or other sea captains. Many of the names are of native origin and they have been phonetically rendered in several different languages. Though the discoverers have more often been either English or American, the superior atlases published on the continent of Europe and in general use for reference in our libraries, have brought much German or French spelling into our practice.

One or two examples may be mentioned. The Mariannes were discovered by Magellan and named by him the Ladrones (Thieves) because of his experience with the natives. The islands later took the Spanish name *Marianas*, but into wide use has come the word *Mariannes* (either French or English) and this form I have used. The Pelews or Pelew Islands were given the name Arricifos in 1543 by their discoverer, Villalobos. They were later given the English name Pelews, and still later sometimes Palau, perhaps because so many German scientists wrote monographs on them.

The first attempt to bring some order out of chaos was made by William T. Brigham, Director of the Bishop Museum at Honolulu, who in 1900 brought out his "Index to the Islands of the Pacific" (*Mem. B. P. Bishop Mus.* 1, no. 2; 170 quarto pp., maps). His usage I have rather generally followed.

World War II at once focussed the world's attention upon the Pacific region and, all too late when my maps and figures had been drawn, the National Geographic Society issued its superior series of Pacific maps. These maps, and the indexes to them which are now issuing, have been made standard by the approval of our army, navy, and air forces. Rather generally they adopt the original spelling, and so our Porto Rico becomes Puerto Rico.

PART I, GENERAL

1. THE ULTIMATE AND THE PROXIMATE CAUSES OF MOUNTAIN GROWTH

THE ULTIMATE CAUSE—A SHRINKING OF THE EARTH'S CORE

The lithosphere or outer rock shell of our planet seems to betray by its oblate spheroidal form, when this fact is considered in connection with its still continuing axial spin, an origin in a plastic condition. It is generally held that this early plastic spheroid through continued loss of heat into the surrounding space has become solid at least in the near-surface shells.

That the earth is now rigid throughout its mass, and probably also in a non-fused condition, would appear to be indicated by at least three observed conditions. These are:

1. The lithosphere is without generally appreciable tides like those of the sea. As measured by Michelson and Gale, the earth tides due to the pull of the sun and moon are of such small amplitude that they can be revealed only with use of the interferometer.
2. If the earth had a molten interior, it must, as reasoned by Kelvin, have long since ceased to spin on its axis.
3. The velocity of compressional earthquake waves which traverse the earth's interior has been repeatedly measured and found to be comparable to that of such waves traveling in the best tool steel. Confirmation of this is found in the period of precession or tilting of its plane of spin—precession of the equinoxes.

But if the earth's interior is not in a state of fusion, it does not follow that interior temperatures are not sufficient to melt rocks if they were under surface conditions of pressure. The outer rock shells are under high downward pressure (load), and it has been established that the melting point of all those rock types which have been investigated increases at a rate greater than that of the pressure from load.

The issue of lava from volcanic vents proves only that pockets (*maculae*) of molten rock exist at some moderate depth below the surface. If the geothermic gradient, or increase of earth temperature with depth that is found to obtain for the first few miles below the surface, should continue to as much as fifteen miles, all rocks would under surface conditions be fused even if in a dry state, and because of the water present at considerably lesser depths.

Wherever rocks below the earth's surface are at fusion temperatures, but maintained unfused and rigid by the load upon them, if this pressure of load should be locally removed, they would obviously become fused and yield a pocket or *macula* of *magma* (lava), and so supply a volcanic vent at the earth's surface.

Since, then, the earth's subsurface shells are doubtless at or above the surface fusion temperatures of rock (800° to 1500° C.), and since they lose heat into surrounding space, the earth must continue to shrink. Because of this contraction of volume, portions of the surface will move inward toward the center of form, and this will result in a reduction of the superficial area of the planet. The areas which have withdrawn most toward the earth's center are obviously the ocean bottoms, and from these great areas of settlement thrusts will be exerted outward toward and into the coastal areas of the continents.

The continually augmenting stress condition within the coastal regions of the continents is at irregularly recurring intervals relieved in great spasmodic mass jolts, earthquakes, and the face of the country is thus materially changed. At such times the behavior of all structures which are continuous, such as rails, pipes, curbs, wires, bridges, etc., are looped or buckled in such a way as to prove that a reduction in superficial area has occurred. There are no exceptions.[1]

THE OCEAN FLOORS THE AREAS OF SUBSIDENCE

Proof that the ocean floors were once farther removed from the earth's center of form, and have descended to their present positions as a result of a settlement, or subsidence which is measured in many thousands of feet, seems to have been afforded by the formation of encircling or barrier reefs about oceanic islands and by the atolls into which many hundreds of them have evolved.

THE EVIDENCE FOR THE DEPRESSION OF THE PACIFIC FLOOR

Quite independently the evidence for the depression of the oceanic floors during late geological time was pointed out by Charles Darwin and by James D. Dana, as a result of studies made by each when on long world cruises; by Darwin on H. M. S. *Beagle*, and by Dana on the United States (Wilkes) Exploring Expedition. The evidence as given by Darwin was illustrated by him in the now classic successive diagrams of figure 1.

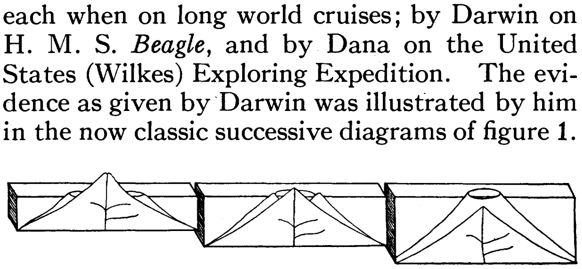


FIG. 1. Diagrams to illustrate the formation of encircling (barrier) reefs and atolls as a result of a subsiding ocean floor. (After Darwin.)

In all warm seas where the temperature of the water does not fall below 68° F., free-swimming, reef-building organisms, both animals and plants, attach themselves to the rocks of island shores and form fringing reefs (diagram at the left in fig. 1). All oceanic islands far from the continental shores are volcanoes, and most of these have or have had fringing reefs. The growth of the reef-builders is inhibited by water pressure at a depth much greater than that at 20 fathoms (120 feet).

If now a settlement (or a series of settlements) of the island takes place which does not exceed 120 feet, the reef colonies will continue to grow, and in the course of time the reefs will arrive at the surface as an encircling reef separated from the shore of the island by a ring-shaped lagoon (middle diagram of fig. 1). By repetition of such subsidences the volcanic island later becomes submerged, and the encircling reef is changed into an atoll—a rim of reef enclosing only a lagoon (diagram to the right in fig. 1).

Atolls are found by the hundreds distributed widely throughout the warm seas, and if the fundamental assumptions of the Darwin-Dana theory are warranted, there has been a settlement of the Pacific floor since late Cretaceous time which amounts in the aggregate to at least 10,000 feet. Since the theory was violently attacked in favor of a rival explanation of formation of atolls, offered by Sir John Murray and defended by a group of zoologists and notably by Alexander Agassiz and J. Stanley Gardiner, it is best to consider here briefly the results of a test to which the rival theories were subjected by the Royal Society of London. It had been early pointed out that since, according to the Darwin-Dana theory, the atoll evolved about a volcanic mountain of quite definite form, a boring put down through the atoll, if carried far enough, should

---

[1] Hobbs, W. H. A study of the damage to bridges during earthquakes. *Jour. Geology* **16**: 636–653, 1908.

——Studio dei danni prodotti dai terremoti ai ponti (Giulio Fornari, transl.). *Ingegneria Ferroviaria* **9**: 1–20, 1909.

——Construction in earthquake countries. *Eng. Mag.* **37**: 929–947, 1909.

enter the volcano at its base. A committee of the Society was set up under the chairmanship of Sir John Murray, funds were provided, the atoll of Funafuti was selected, and an expedition was sent out in a naval vessel to put down the bore-hole and obtain a core. At the time (1896) the oil industry had not brought the technique of rock borings to the perfection it has since attained, and after much difficulty the bore was carried to a depth of only 1,114 feet. Since it did not penetrate a base of volcanic rock, the test was inconclusive according to the criteria set up, and the many scientists who had had a part in studying the core and the marine life on the outer slopes of the atoll were forbidden to express in the official report[2] any opinion of the bearing of the results on the controversy. It is known, however, that the distinguished specialists, mainly zoologists, were practically unanimous in the opinion that the results furnished a definite proof of the essential correctness of the Darwin-Dana theory.[3]

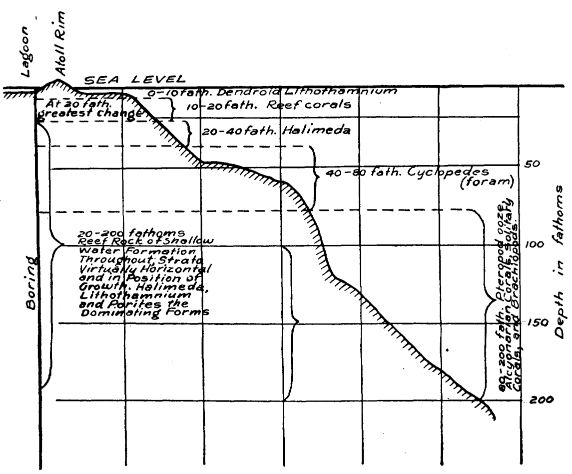


FIG. 2. Diagram to illustrate the conditions found at Funafuti, according to Sir Edgeworth David.

The reasons for this uniformity of view will be clear from the following results of the investigation:

1. To the bottom of the boring the organic remains encountered were all from organisms which are now living only at very shallow depths.
2. These organic remains were all found erect —quite undisturbed from their position of growth.
3. The core was throughout composed of dolomite (calcium magnesium carbonate), and this change from the original carbonate of lime (dolomitization) is recognized to be a near-surface oceanic process (fig. 2).

MARGINAL MOUNTAINS A CONSEQUENCE OF THE SETTLEMENT

The settlement of the ocean floors and the resulting reduction of their superficial areas may be given, then, as the probable ultimate cause of the push or thrust outward against the continental margins and the wrinkles set up there in the earth's face. For the Pacific area the measure of the subsidence is in the neighborhood of 10,000 feet, or near 2 miles. The testimony of the reefs supports the view that this has taken place since the late Cretaceous age of geological time, and so it corresponds to the earth's latest period of mountain-building, that which raised the great mountain welts of Central Asia and the lofty Cordilleran backbone of the Americas (map 2).

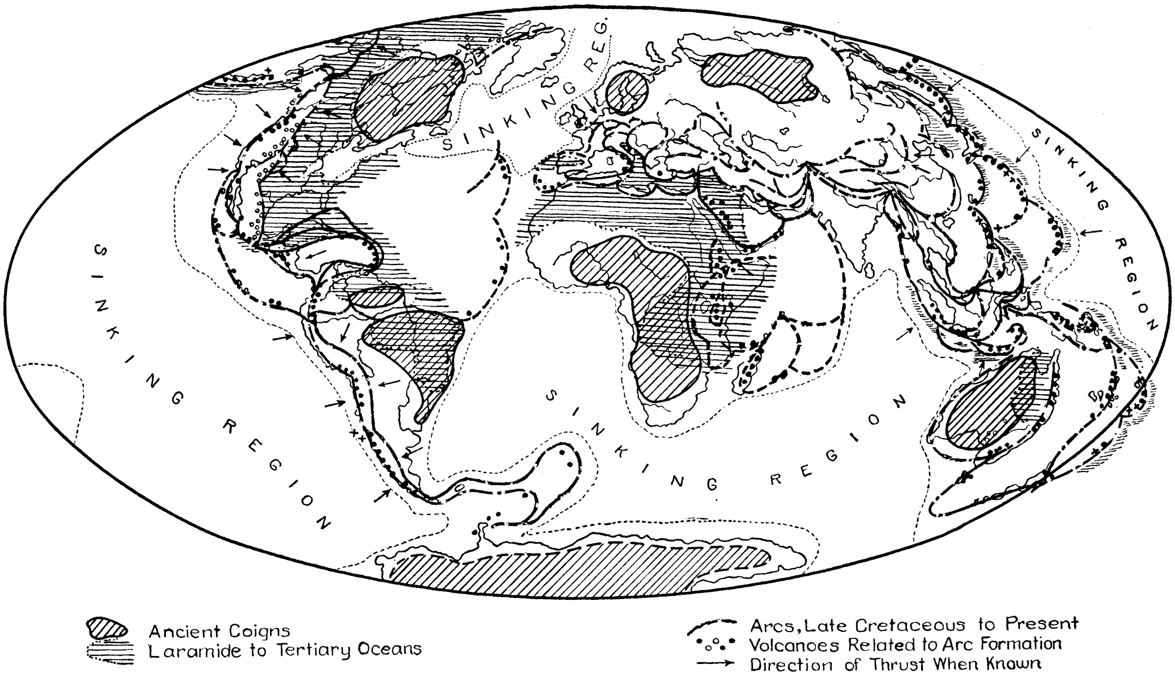
Like the newest series marginal to the present Pacific Ocean, the earlier mountains partake of the same characters so far as mutilation permits these to be read—it is an arcuate pattern everywhere peripheral to the ancient coigns at the hearts of the continental areas. The ranges nearest to the central coigns are shown through their mutilations by erosion to be the most ancient. From them there is a gradation in age outward until at the outermost marginal zone mountains are even now rising from the sea to the accompaniment of strong earthquake joltings and of catastrophic outpourings of volcanic lava.

The inner and older arcs are today represented only by their roots, mainly the plutonic crystalline rocks which consolidated slowly at depths far below the vents to which their material ascended to issue as lava. To the devastating earthquakes which marked their youthful history there has here succeeded the placid stage of senility. Growth has long since ceased, and destructive agencies have largely accomplished their work.

---

[2] *Report of the Coral Reef Committee of the Royal Society. The Atoll of Funafuti, Borings into a Coral Reef and the Results.* London: 1–428, text and maps, 1904.

[3] Such a statement was made publicly by Sir Edgeworth David to the Second Pan-Pacific Congress held in Australia in 1923 and confirmed to me by another of the experts connected with the study. With the core open for inspection, a symposium on coral reefs was included in the program led by Sir Edgeworth David, who had carried the boring down to its greatest depth. (See also E. S. Skeats, *Amer. Jour. Sci.* **45**: 82, 1918.)



MAP 2. The salient features in the earth's face—the mountains raised during the latest of the earth's mountain-building periods.

2. THE UNDERTHRUST OUTWARD FROM OCEANIC SETTLEMENT

UNDERTHRUST LANDWARD AS AGAINST OVERTHRUST SEAWARD

The erection of a fold or wrinkle within the outer shell of the earth, since it is brought about by unbalanced forces, may be *a priori* considered in either one of two ways. The ever accumulating active stress eventually is no longer balanced by a passive stress set up within the rock material. The static condition is thereupon transformed into a dynamic one and a fold is initiated. Such a fold could be formed either (1) by the active force directed from behind and above the fold, *overthrust*, or (2) by the active force directed from the front and below, *underthrust*. These contrasted views are represented in figure 3.

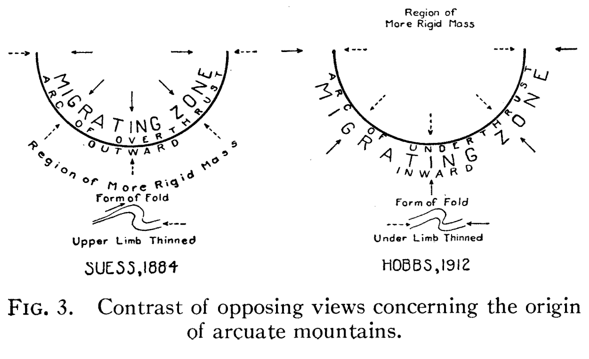


FIG. 3. Contrast of opposing views concerning the origin of arcuate mountains.

The first of these conceptions as a cause of the erection of mountain arcs is the older view and was for a long time the more widely accepted one. It was originally developed by the great Viennese geologist, Eduard Suess, first in 1875[4] and later in his famous masterpiece, *Das Antlitz der Erde*, issued in four massive volumes.[5]

The opposing view, that of underthrust from in front of the arc, was first advocated by Willis[6] and later by the author.[7]

It must be clear that the Suess view requires *a priori* a condition of tension in the interior of the continents unless material is brought in either laterally or from below during the growth of

---

[4] *Die Entstehung der Alpen.* Vienna, 1875.

[5] Published at Prague and Leipzig between 1885 and 1909 and translated into French, English, and in part into Italian.

[6] Willis, Bailey. Mechanics of Appalachian structure. *U. S. Geol. Survey, Ann. Rept.* 13, pt. 2, 1893.

——. *Research in China* 2, *systematic geology.* Carnegie Inst. Washington, 1907.

[7] Hobbs, W. H. *Earth features and their meaning:* 436–438. New York, 1912.

——. Mechanics of formation of arcuate mountains. *Jour. Geology* **22**: 71–90, 166–188, 193–208, 1914.

——. *Earth evolution and its facial expression,* chs. x and xi. New York, 1921.

mountains. When late in his study Suess came to treat the great Cordilleran mountain system of the Americas, his assumption of overthrust from the back encountered great difficulties which he could not harmonize with his theory.

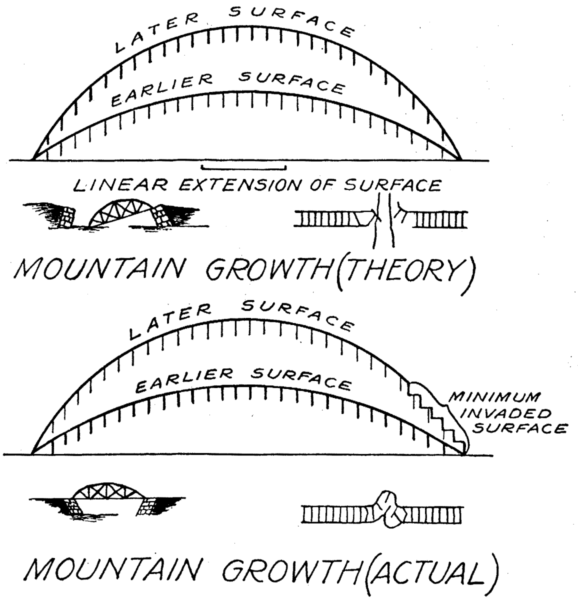


FIG. 4. Diagrams to illustrate the contrasted effects of tension (upper diagram) and compression (lower diagram) when present in rising mountain arcs. Below each is illustrated the effect on bridges and on railroads for each at the time of an earthquake.

The folds of the Andes were found to face outward on *both* flanks with the included area much circumscribed (map 1). He therefore felt obliged to consider the great Cordilleran system as an exceptional case which he designated the "Andean Structure."

Moreover, inasmuch as the process of folding augments rigidity, the Suess view of overthrust requires the outer arcs next the sea to be the more ancient and the others in succession more youthful, with the youngest of all next the coigns. Erosion effects and the seismicity unite in proclaiming loudly that the reverse is the fact. If the Suess view were correct, then in closely compressed folds the upper limb should be the thinner one, though the reverse is the rule (fig. 3, below).

COMPRESSION OF A MOUNTAIN ARC DURING ITS ERECTION

It would be natural to assume that mountain arcs in the process of erection should be in a state of tension for the reason that the anticlinal arch is thereby lengthened (see upper diagram in fig. 4). As a consequence the joints and any other openings of the rocks within the arch should in such case tend to open, and any continuous linear structures which traverse the arc should either be stretched or be torn apart with the rupture surfaces separated by a gap. Railroads and bridges, curbs, water and sewer pipes, and telegraph and telephone lines should all alike reveal this condition of tension. A study of such structures reveals, however, that without exception these structures have all been shortened at the time of earthquakes, and this whether they ran transverse to or along the arc.[8] Of hundreds of

FIG. 5. Buckling of rails on the approach to the Kisagawa railroad bridge after the great Japan earthquake of 1891.

FIG. 6. The Nagaragawa bridge after the great Japan earthquake of 1891. Though dropped into the river and given a sinuous course, all spans were still connected and the rails of the approaches indicated compression. (After Milne and Burton.)

---

[8] Hobbs, W. H. A study of the damage to bridges during earthquakes. *Jour. Geology* **16:** 636–653, 1908.

——. *Earthquakes, an introduction to seismic geology:* 183, 228–231, pls. XIV and XXII. New York, 1907.

examples examined from many earthquakes, there were no exceptions.

This apparent paradox is explained when the seaward margins of the arcs are examined, for a very considerable invasion of the area of the arc from the sea floor is everywhere indicated. On all coasts of the Pacific area, within which, as we have seen, a large subsidence has taken place, coastal staircases made up of successive strands are found on the seaward side of the arc. These represent elevations measured in hundreds or even thousands of feet and invasions of the arc which may run inland for tens of miles (figs. 4 and 7).

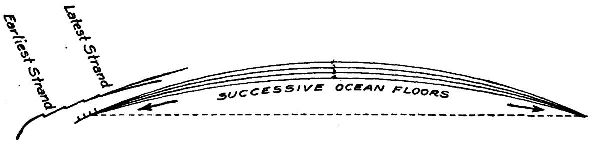


FIG. 7. Diagram to illustrate the relation of a progressive settlement of the ocean floor sector to the elevated Pacific strands.

Within these coastal staircases the "risers" are sea cliffs cut by the waves, and each represents the measure of uplift during a single strong earthquake or a series of closely related quakes.[9] The "treads" are many times as broad as the cliffs are high, and these measure the individual invasions from the sea floor to correspond to the earthquake or earthquake series which elevated the cliff at its back.

It would appear that at the time of each uplift the joints in the rock tend at first to open and suck down surface water, but are almost immediately jammed even closer together as the thrust comes in from the sea floor. It is characteristic of earthquakes that underground water is expelled at the surface in newly formed springs and from "earthquake fountains" which operate for hours and flood the country.

RESOLUTION OF THE UNDERTHRUST AT THE BOTTOM OF THE CONTINENTAL SLOPE

If we now consider once more the mechanics of the process when underthrust from the sea floor encounters the upward deviation along the continental slope, this must bring about a resolution of the thrust into a component thrust along the surface and one which continues the original near-horizontal direction (fig. 8). The former tends to lift the beds into an anticline, the latter to compress the arch when raised. The initial outward inclination of the surface which here starts the erection of the anticline was long ago given the name *initial dip* by Willis.[10] Successive stages in the process of erection of the anticline are illustrated in figure 8.

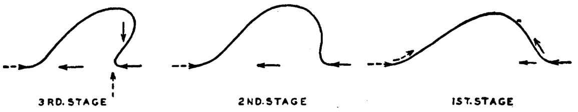


FIG. 8. Resolution of the underthrust from the sea floor where it encounters the continental slope.

3. THE PATTERN OF A SYSTEM OF MOUNTAIN ARCS

THE RELATIVELY RIGID COIGNS WITHIN THE CENTRAL AREAS OF THE CONTINENTS

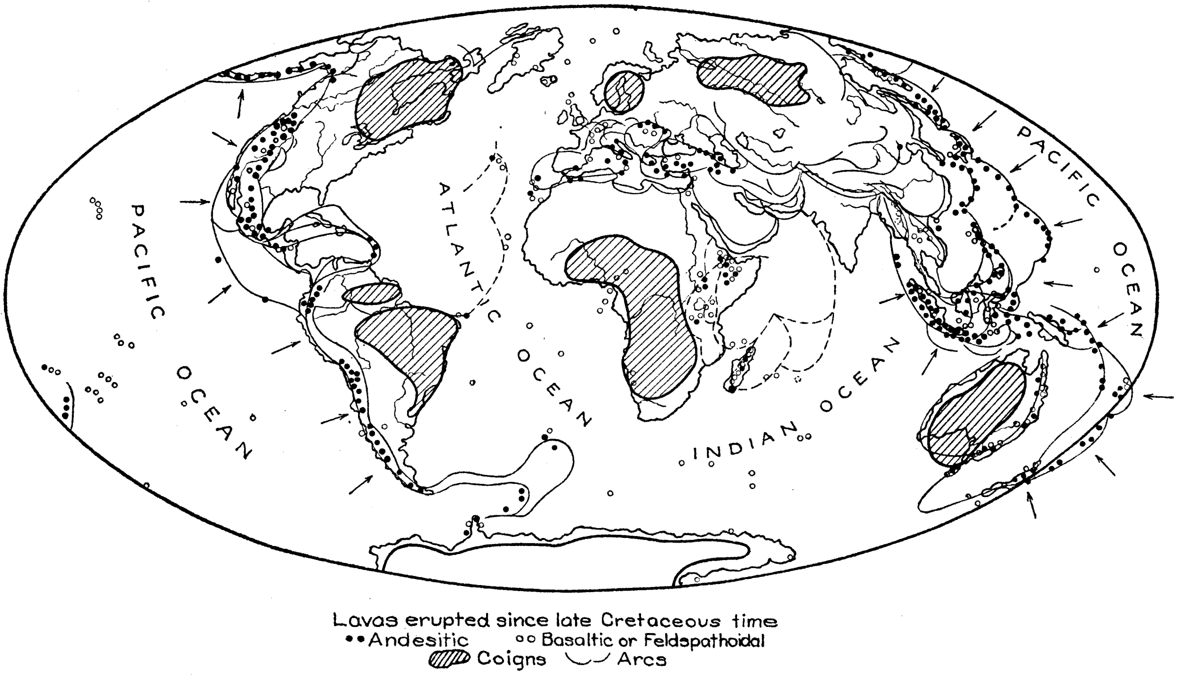
Upon the continents the most ancient rock formations of our planet occupy central positions with the mountains arranged in peripheral zones about them (map 3). These early platforms were by Suess designated as coigns. They consist essentially of Pre-Cambrian rocks, about which through the ages of later geological time the continents have grown to their present dimensions through peripheral enlargement. From two earlier mountain-building periods, those at the end of the late Pre-Cambrian and the Permo-Carboniferous, the mutilated mountain remnants do not permit us to restore the features except very imperfectly.

In the latest period of the mountains (map 3), the older series outlines the Tertiary ocean distribution, while the later series outlines the present oceans. The mountains of the latest development display a pattern of outwardly (seaward) convex arcs joined in cusps, as do garlands which are hung upon a wall (map 3). In positions where frontal protection has been afforded by a shielding coign (Australia), thrusts from two opposing directions have resulted in great lateral compression of the arcs (Netherlands East Indies). Successive chains in a single arc may be numerous as in the Seistan arc of Baluchistan (map 4).

---

[9] Hobbs, W. H. The rate of movement in vertical earth adjustments connected with the growth of mountains. *Proc. Am. Philos. Soc.* **62**: 63–73, 1923.

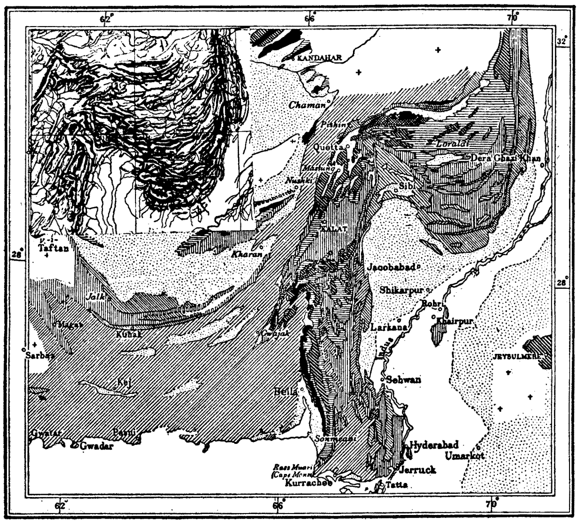
[10] Willis, Bailey. Mechanics of Appalachian structure. *U. S. Geol. Survey, Ann. Rept.* **13**, pt. 2: 246 ff., 1893.



MAP 3. The central coigns of the continents in their relation to the mountain arcs of the latest great mountain-building era.

THE LATEST ARC SYSTEM BORDERS THE PACIFIC OCEAN

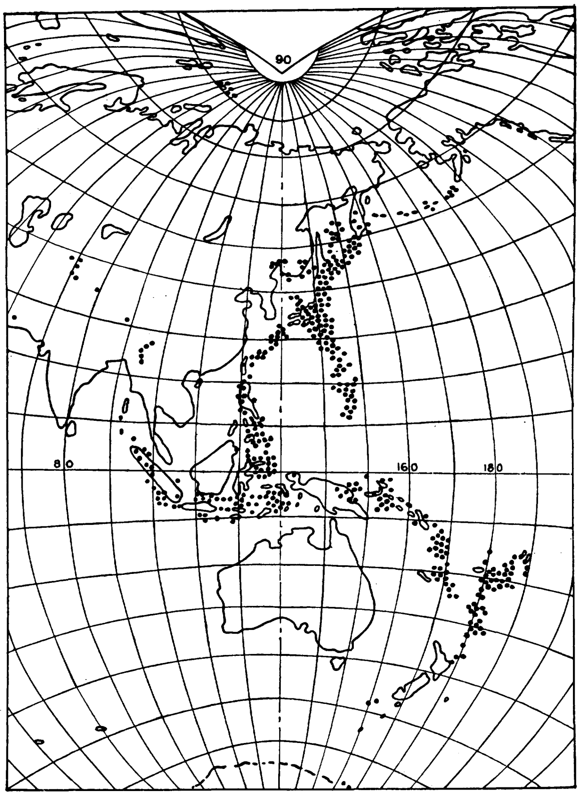
It is profitable to contrast the mountains which border the Pacific Ocean with those near the coasts of the Atlantic. The latter were formed in an earlier mountain-building period when the coast was in places in a different position from the present one. The infrequent earthquakes of the region indicate that mountain growth has ceased, and in those places where the former coast was in correspondence with the present one, the coastal staircase has been so mutilated by erosion as to be recognized only with difficulty. The Pacific border is by contrast the zone of greatest seismicity on our planet (map 5), and its coastal terraces betray only slight traces of erosional mutilation (fig. 9).



MAP 4. Successive mountain chains of the Seistan arc in Baluchistan. The mountain welts as features appear in the inset map, the flexures in the sedimentary formations in the main map. (After Vredenburg.)

From the map which exhibits the surface distribution of seismicity (map 5), it appears that earth adjustment is today at a maximum on the Pacific Ocean within two well-defined zones. These are on its western border from Japan southward to New Zealand, and on the opposite side of the ocean in the coast ranges of South America from Peru southward into Chile. Between these opposed borders of the Pacific Ocean lies its broadest expanse, and this includes nearly 180° of arc, as well as the galaxy of volcanic islands and atolls of Micronesia, Melanesia, and Polynesia—our earth's greatest region of crustal subsidence.

On the side of mechanics the arcuate form of the mountain ranges, always convex seaward, is



MAP 5. The earth's present-day seismicity of a part of our planet as indicated by teleseismic observations. The dots indicate intense seismicity ("earthquakeness"). (After Gutenberg and Richter.)

explicable on the basis of the directions of underthrust, which arrives in a broad converging fan of azimuths.

The earthquakes, which are the first manifestations to us of the jolting uplifts that produce the mountains on the rim of the Pacific, occur each within a segment which is comparable in extent to those of the arcs themselves. In this may lie the reason for the segmentation itself. Each greater earthquake within the Pacific's rim records the time when within that particular segment the stresses had accumulated sufficiently to overcome the resistance to adjustment inherent in the material. When this has been overcome, the potential energy is suddenly transformed into actual or dynamical energy and adjustment ensues. The stress condition is thus more or less completely relieved—completely for a central area and less so for sections increasingly distant from the central area.

Portions of the Pacific mountain rim most remote from that already relieved at the time of the earthquake are the ones most likely to find relief by the next succeeding earthquakes. Still later the probability of an early earthquake will be greatest for segments of the rim which lie midway between those already relieved of stress by definite earthquakes.

Such a sequence of successive great earthquakes occurred within the Pacific rim in the period 1906 to 1923, and better than any other it illustrates the segmentation of the zone of growing mountains.

For a considerable period the rim of the Pacific had been immune from a great earthquake when on January 29, 1906, one took place in Colombia, South America. A month and a half later (March 17) occurred the great earthquake in Formosa on the opposite side of the Pacific rim. Only a month later came the devastating California earthquake (April 15) about two-fifths the way from Colombia to Formosa. Dr. F. Omori, the great Japanese seismologist who had come from his distant home to study the San Francisco area of destruction, on his departure for Japan forecast in a press interview that the next great earthquake in the series would take place in Chile. Before his ship had arrived in Yokohama there occurred in Chile (August 17) the great Valparaiso earthquake, and on the same day but some hours later one in the Aleutian Islands.[11] These earthquake segments were each midway in portions of the Pacific rim then unrelieved. Dr. A. C. Lawson then forecast [12] that the next great earth-

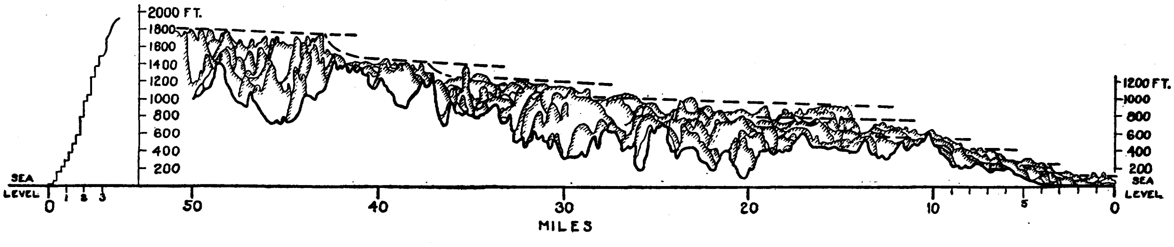
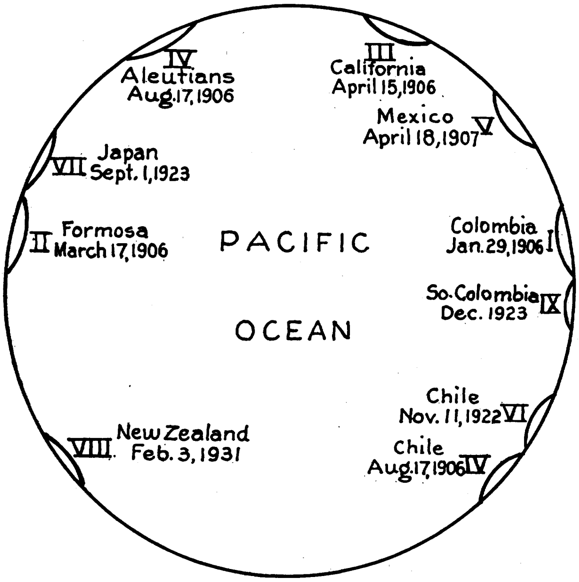


FIG. 9. Comparisons of raised terraces, Pacific and Atlantic. (From data by Tangier-Smith and Barrell.)

---

[11] *Bull. Japanese Earthquake Committee* 1 (1): 23, 1907.

[12] In a lecture delivered in March, 1907.



MAP 6. The successive segmental uplifts on the mountain rim of the Pacific within the period 1906–1931. (After Hobbs, 1909, except for segments VII–IX.)

quake would take place in Mexico, since there was there to be found the longest still unrelieved segment of the Pacific rim. His forecast was promptly verified on April 18 by the Guerrero earthquake. In April, 1909, I prophesied that the next great earthquake of the series should occur either in the Japan-Kamchatka segment or in that of New Zealand, since neither had yet been relieved.[13] This prognostication was doubly verified by the great Tokyo earthquake of September 1, 1923, and by the Napier, New Zealand, earthquake of February 3, 1931 (map 6).

If the initiation of the arcs composing the Pacific rim of mountains resembled in its segmentation the latest uplifts, the cause of the segmentation would seem to be found in the partial nature of the relief of stress at any one time. Once segmented, the reliefs at the time of successive later earthquakes would be likely to increase the curvature of the individual arcs.

4. MOUNTAIN ARCS ARE FLEXURES WITH A DOWNWARD-BENT PORTION (SYNCLINE) ON THE SEAWARD SIDE OF THE UPWARD-BENT PART (ANTICLINE)

IN EARLY STAGE FLEXURES ARE SYMMETRICAL, BUT LATER UNSYMMETRICAL WITH STEEPER LIMB ON THE SEAWARD SIDE

We have already seen that in the evolution of an anticline the profile is first nearly symmetrical, but soon becomes unsymmetrical with the steeper limb at the front. This lack of symmetry is increased with the continued compression of the anticline (fig. 8). Perhaps the best youthful arc to display the near symmetry is on the island of Curaçao off the coast of Venezuela (fig. 10). As the anticline continues to rise, it is compressed. This develops terraces on the front and usually a barrier reef on the back (fig. 11). A collection of

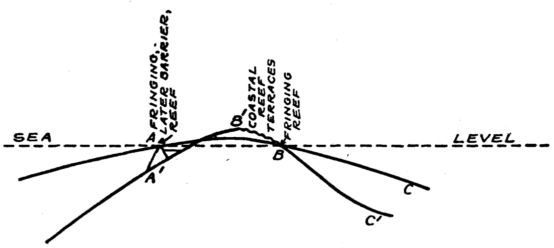
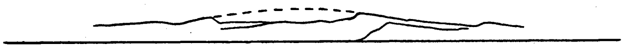
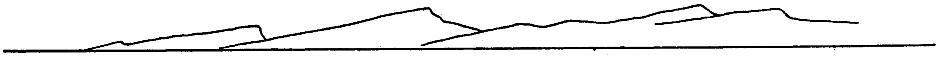


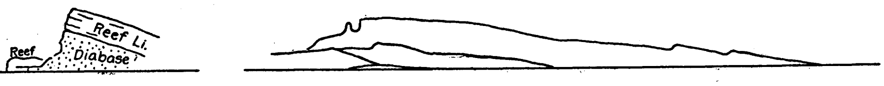
FIG. 11. Two early stages in the evolution of an island arc: *ABC*, early stage; *A'B'C'*, later stage.



Looking northeast from harbor of Willemstad



South coast, looking west from off Willemstad

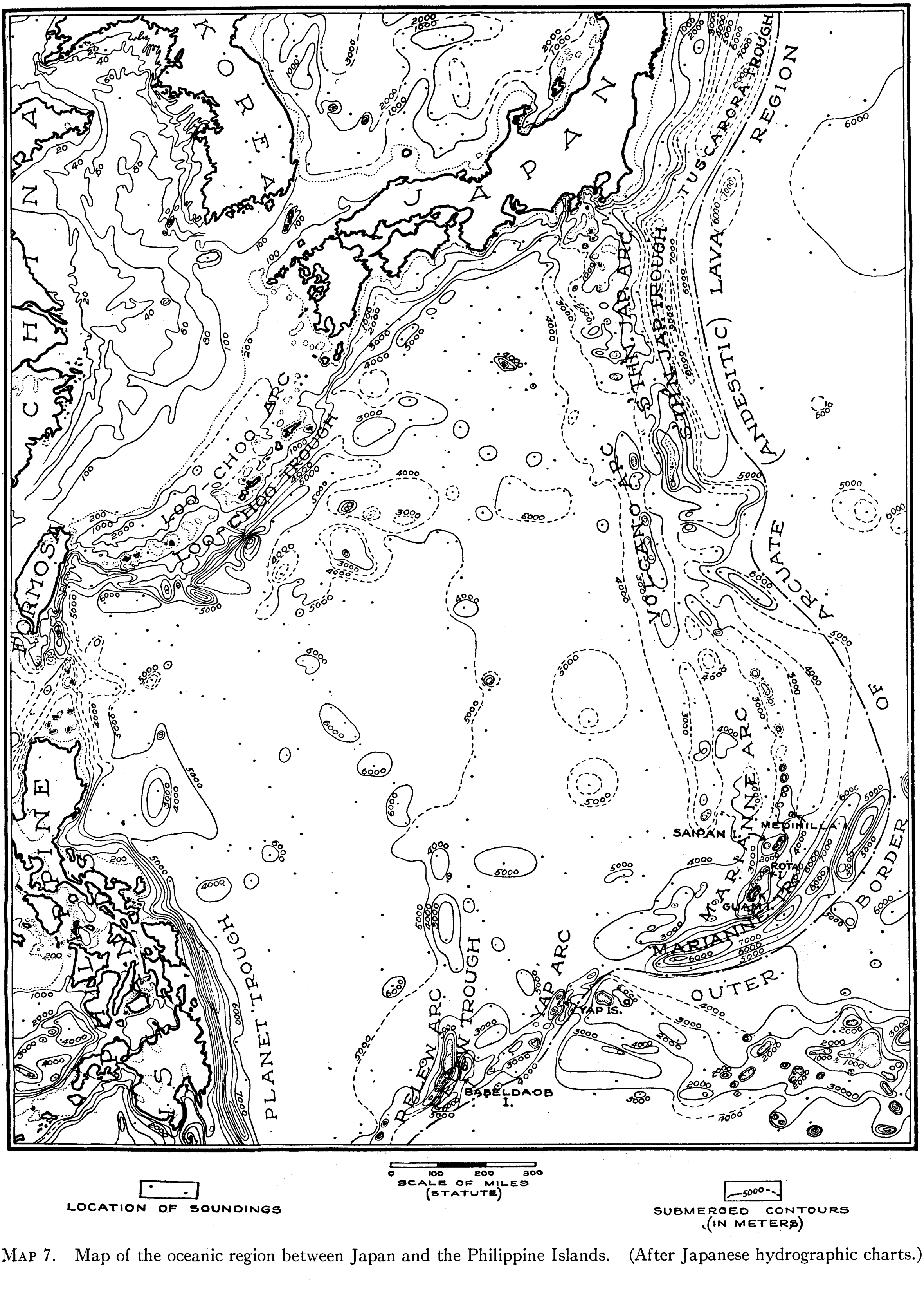


Below Fort Nassau, Schottegat South coast, looking east from off Willemstad

FIG. 10. The nearly symmetrical anticline of Curaçao. (From sketches by the author.)

---

[13] Hobbs, W. H. The evolution and the outlook of seismic geology (read April 24, 1909). *Proc. Am. Philos. Soc.* **48** (192): 289–290, map, 1909. This was repeated in lectures and in a press interview in the spring of 1923.



Map 7. Map of the oceanic region between Japan and the Philippine Islands. (After Japanese hydrographic charts.)

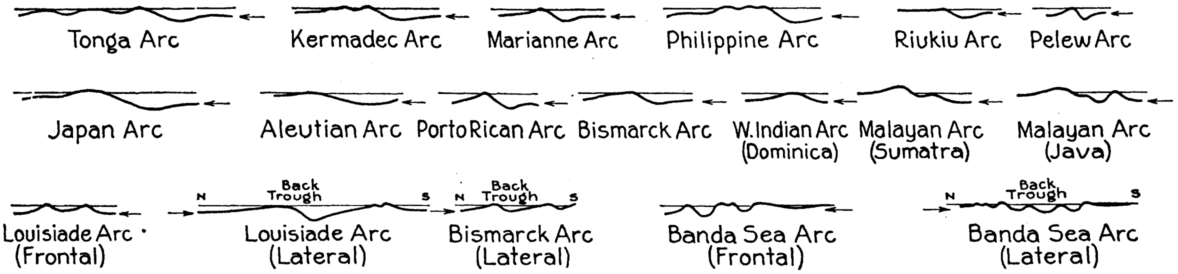


FIG. 12. Sections of rising arcs. Vertical to horizonal scales, 12: 1. → Direction of thrust.

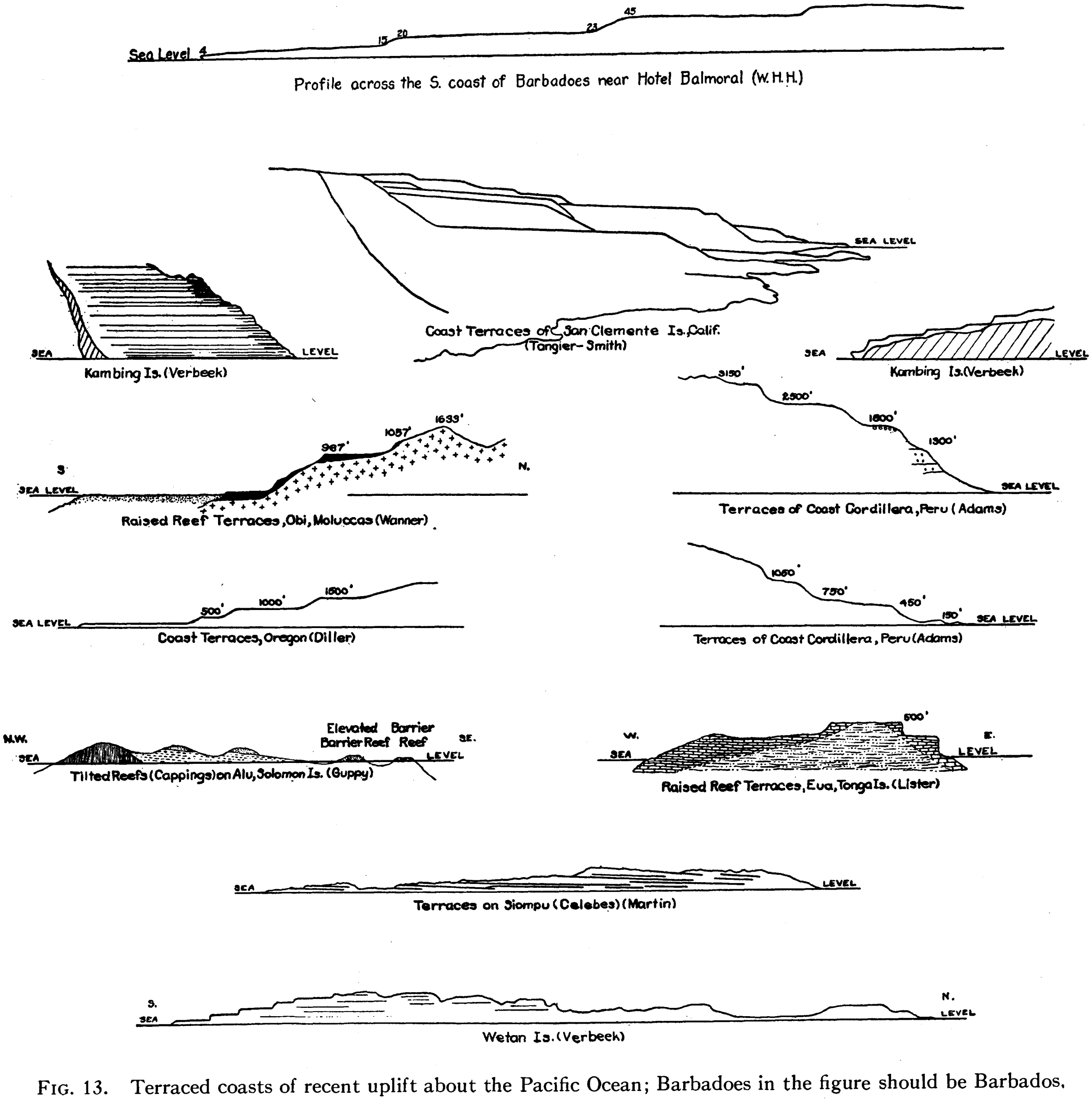
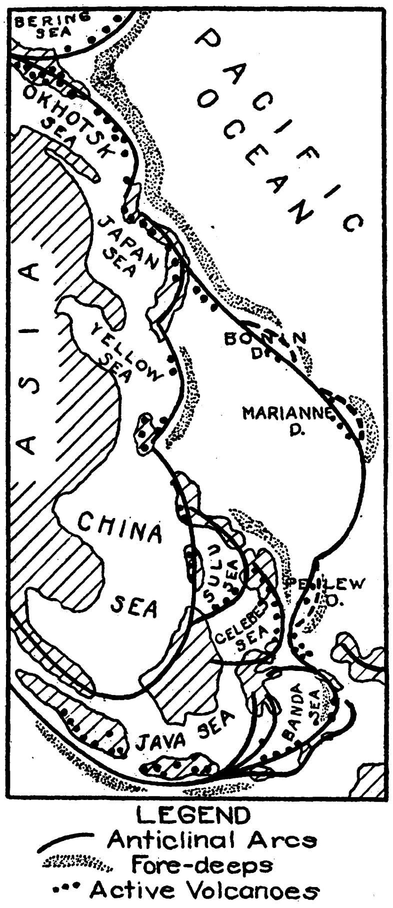


FIG. 13. Terraced coasts of recent uplift about the Pacific Ocean; Barbadoes in the figure should be Barbados.

profiles of early stages in the evolution of mountain arcs is included in figure 12.

Off the coast of Asia the pattern of the rising mountain arcs within the area to the southward of Japan is a relatively simple one of very flat curvature, always the indication of an early stage. In fact, nowhere else in the world can we find so many arcs in the stage of early youth. Here also soundings of the sea recently made by the echo method have come to our aid by revealing the features of the ocean floor to supplement those of the islands (map 7). In these youthful arcs the terraces are generally found on both sides wherever the arc has risen from the sea floor, and they may extend up to an elevation of a thousand feet or more (fig. 13). However, in proportion to the time which has elapsed since their elevation they have been modified by erosional agencies.



MAP 8. The position of the active volcanoes relative to the anticlinal arcs off the Asiatic coast.

5. ACTIVE VOLCANOES ACCOMPANY THE ERECTION OF ARCS

VOLCANIC VENTS APPEAR ON THE BACK OF THE ARC

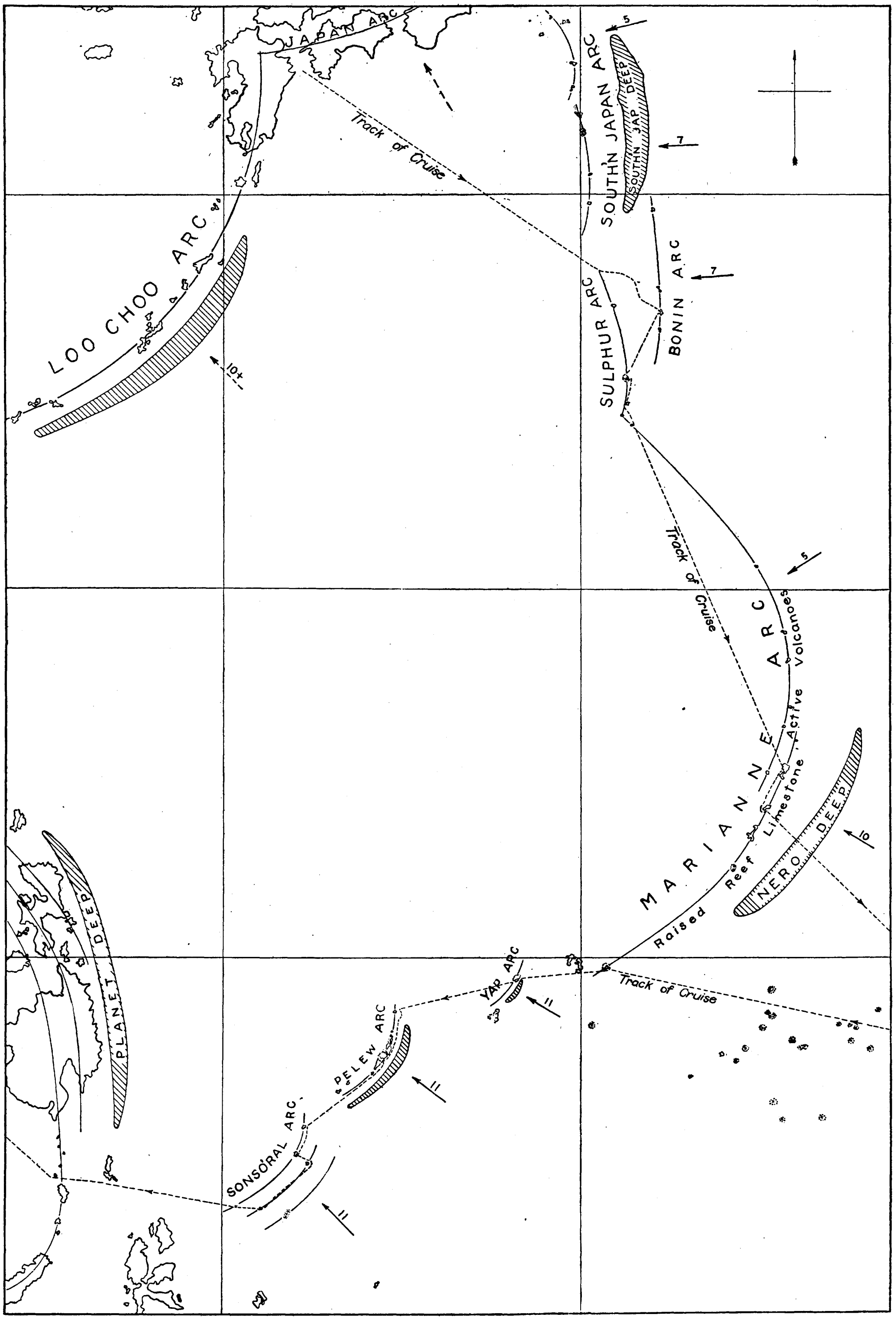
All mountain arcs of youthful stage are characterized by a line of active volcanoes which appear on the back (landward) side of the anticlinal arc (map 8).

The volcanoes have usually made their appearance before the anticline has risen above the waves. The Marianne arc supplies an illustration (map 9), as does the Iwo (Sulphur or Volcano) arc. Back on the continents, where erosion has removed the upper parts of the anticlines, most former surface features have disappeared and the volcanoes are no longer in evidence. In their place we find their roots, either the consolidated and generally crystalline rock that fills the pocket from which the lava was supplied, or that filling the pipe through which it ascended to the vent (map 10). In much-degraded mountain ranges throughout the world the maculae or reservoirs which were the source of the lava of an earlier stage are now represented by granitic cores (map 11).

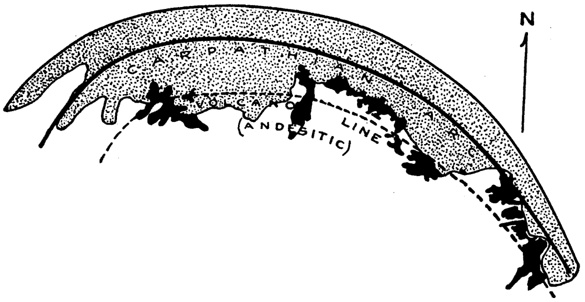
INITIAL LAVA EFFUSIONS HAVE THE COMPOSITION OF MUDSTONE—ANDESITE

The initial and early effusions from the volcanoes on the backs of mountain arcs betray but little range in chemical composition. Though lavas from all parts of the world vary in silica content from more than 80 percent to less than 40 percent, those exuded from the volcanoes of the mountain arcs fall near the average—from 60 to 65 percent of silica content. They thus correspond roughly in composition to a mud rock (shale or slate), and they are described as andesites. This is close to the average composition of rocks of all kinds, which is about 59 percent silica.

The later effusions from the vents on mountain arcs show, however, no such constancy of chemical composition, but they are as a rule much poorer in silica content (basalts), though sometimes richer (rhyolites) and often also richer in the alkali constituents (lenads, which contain as an essential constituent the minerals nephelene or leucite). Variety in composition, rather than constancy, is characteristic of the later extrusions. Rather generally the later extrusions issue from a later formed line of volcanoes farther back on the anticline (fig. 14) or even on a secondary anticline developed at the rear.



MAP 9. Outline map of the young arcs off the Asiatic coast between Japan and the Philippines.

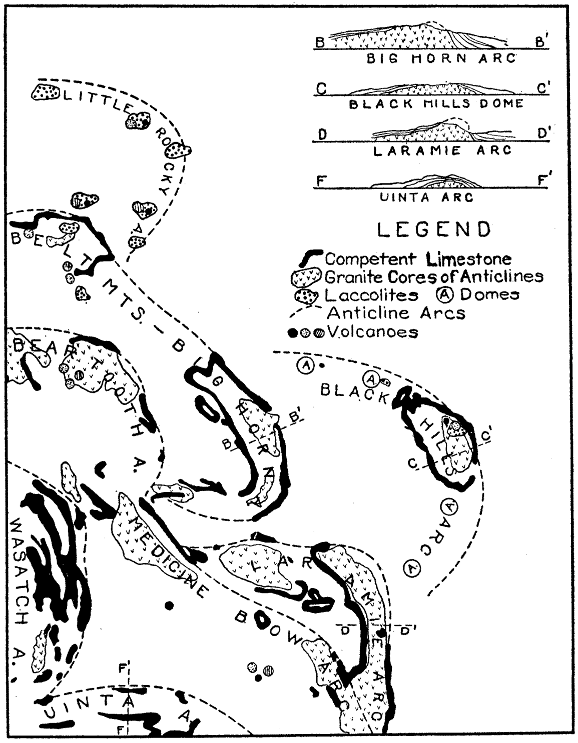


MAP 10. The Carpathian arc in southeastern Europe, with lava shown in black at the back of the anticline.

6. THEORY OF ORIGIN OF THE VOLCANIC EFFUSIONS

FUSION OF ROCK BENEATH A COMPETENT ARCH

In the opening section of this paper the reasons have been passed in review for the belief that the earth's interior is rigid and, in the near-surface shells at least, in a solid state, even though its temperature at depths of only a few miles is above the melting point of the rock.[14] The rock is kept in an unfused state only because of the superincumbent load, the weight of the rocks above. If a part only of this load were to be lifted off at any place, the rock beneath would at once become fused and produce a local pocket or *macula* of lava material, *magma*.



MAP 11. Denuded arcs off the front of the Rocky Mountains, showing, beneath a competent anticline of limestone, cores of granitic rock.

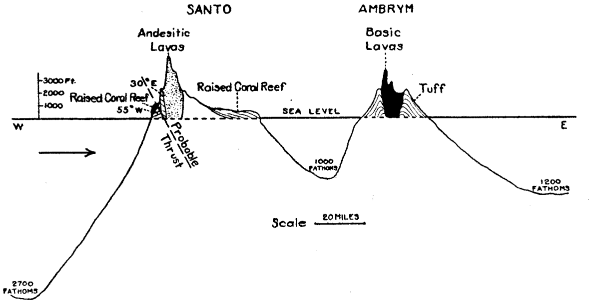


FIG. 14. Section across arc of New Hebrides. (After Mawson.)

There are two quite different geological processes known which seem competent to lift the load locally, and one of these is the formation of an anticline or upward bend in the rock strata such as forms in the initial stage of the growth of a mountain arc. An anticline is an arch, and if of strong rock such as limestone, it can sustain load as does the arch of a bridge.

Of the three main types of bedded or stratified rocks (sandstone, mudstone or shale, and limestone) formed as marine sediments, limestone is much the strongest, and the order of deposition is usually such that it lies over shale. When now an anticline is raised, it forms what is called a competent arch which lifts the load at least in part from the shale beneath. The shale (mudstone) thus fuses to produce a lava of intermediate silica content, andesite (fig. 15).

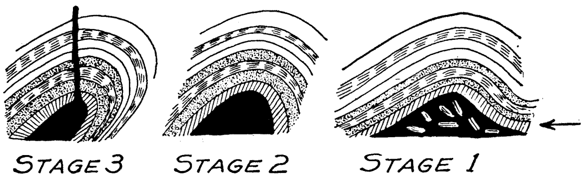


FIG. 15. Successive stages in the fusion of mudstone beneath a competent arch of limestone to produce an andesitic lava. The continued compression of the anticline forces the lava to the surface where it issues in a vent at the back of the arc.

In the laying down of marine sediments during a transgression of the sea over the land, the sandstones laid down near shore, and therefore at the bottom of the series, come to be gradually over-

---

[14] For a somewhat fuller discussion, see Hobbs, *Earth evolution and its facial expression*, chs. ii and iii, 1921.

laid by intermediate siliceous mudstones, then by pure mudstones, and from greater sea depths calcareous mudstones, and, lastly, pure limestones to form the top of the series. The pure mudstones are not only the weakest of the entire series, but they are also the most fusible. They should thus be the first to fuse under the competent arch of limestone and calcareous shale (fig. 16, at top).

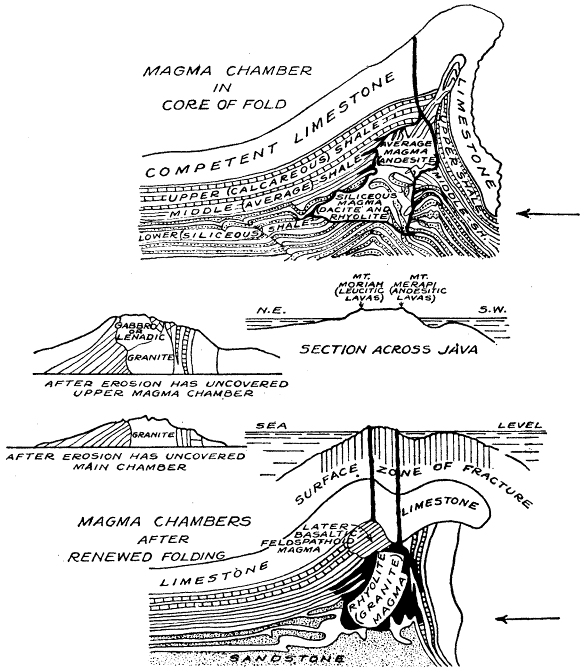


FIG. 16. Profiles to illustrate the possible fusion of shale beneath a competent arch of limestone in the raising of the anticline in a mountain arc (top). The later development of more siliceous and less siliceous lava types is also suggested (bottom). The uncovering of the lava cores by erosion is also illustrated (middle).

LAVA RISES TO THE SURFACE THROUGH THE CONTINUED COMPRESSION OF THE ANTICLINE

A continuation of the evolution of the arc and the resulting compression of the anticline acts upon the magma pocket as does a syringe held in the palm upon the included liquid. The lava is expelled from the pocket along a vertical conduit to the surface, aided by any available fissure in the limestone. Because of the unsymmetrical form of the anticline with steeper limb at the front, the volcanic vent will always be located at the back of the arc (figs. 14–16).

7. EVOLUTION IN THE PLAN OF THE ARC

EARLIER STAGES OF RELATIVELY FLAT CURVATURE WITH TROUGH AT THE FRONT

Comparison of many different arcs that are in different stages of development indicates that the evolution is from the simple to the complex. This is particularly to be observed in the curvature of the arc as displayed in the plan.

A very young arc approaches a straight line—its radius of curvature is very long. This is illustrated by the first stage in figure 17, in which the arc subtends an angle of only 45°. At this stage the arc is represented above the sea by a line of active volcanoes, the anticline still submerged, but a long and narrow trough is at the front. The Bonin, Iwo, and Marianne arcs, all to the south of the "elbow" of Japan, are examples (map 9).

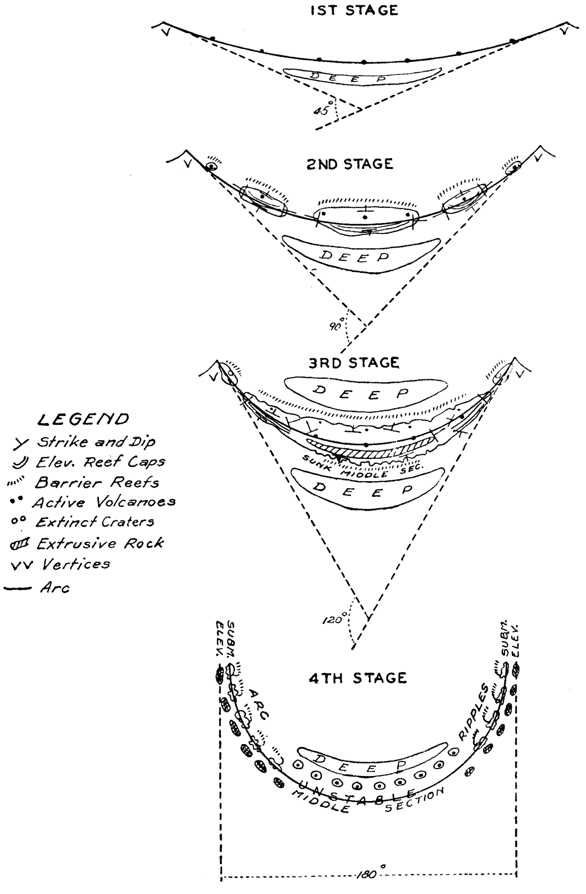
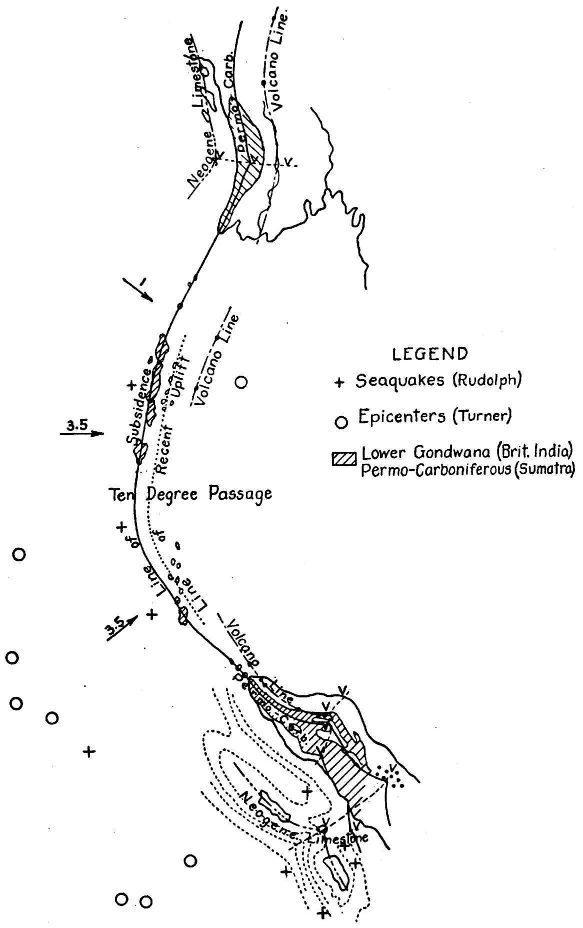


FIG. 17. Evolution in the plan of a mountain arc.

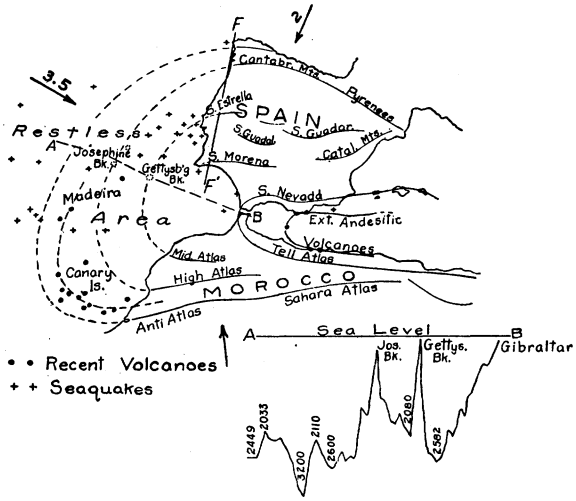
A second stage in the evolution is one in which the arc subtends a larger angle, where the anti-



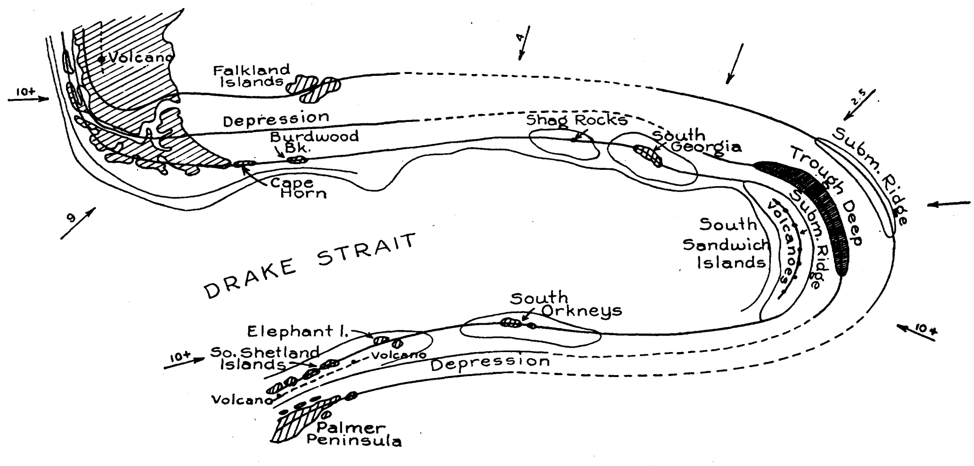
MAP 12. Plan of the Andaman arc.

cline is represented above sea level by a series of islands composed of either marine or volcanic sediments (tuff and agglomerate), or both. The trough is, as a rule, shorter and broader. The islands are terraced, especially on the front, and there are barrier reefs at the back. A seismic zone is accentuated at the front. The Andaman arc which joins Sumatra to Burma is an example (map 12).

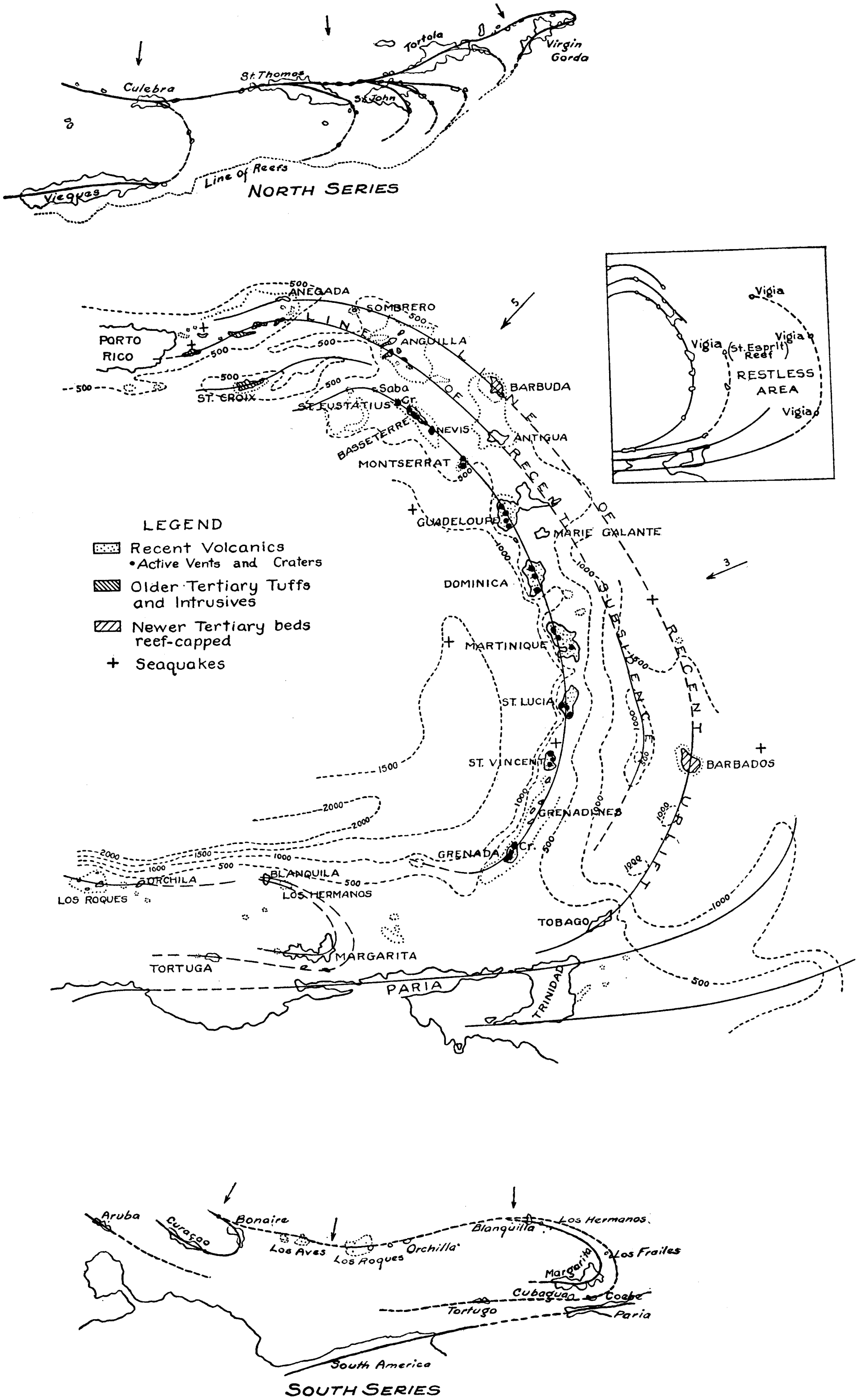
In a still later stage, here arbitrarily chosen as the third stage, the curvature of the arc is much sharper; the islands which represented the anticline in stage 2 and were the crests of its longitudinal wrinkles, have now been joined as the anticline emerged further. A new line of volcanoes has appeared behind the first one. The trough may be at the front or back or both, and the middle section of the anticline is very unstable. Off the front is a special seaquake zone, and there are records of many vigias—indicating islands which appear only to disappear, and perhaps later reappear.



MAP 13. The compressed Iberian-Mauretanian arc.



MAP 14. The compressed Drake Strait arc.



MAP 15. The extremely complex Antillean arc, with elaborate ripples at the north and south and vigias off the front (inset).

In stage 4 is represented the extreme development of the arc, one which subtends an angle of 180° or more. Of this stage there are a good many examples. They appear to represent two different classes. In one the front of the arc has been protected by a coign or other land mass, while the sides have been shoved toward each other by subsidences in two different oceans on opposite sides. The outstanding example is the Sunda-Banda arc between Australia and the mainland of Asia (map 27). Another example is the Iberian-Mauretanian arc (map 13), which, though not protected from the front, was compressed between an earlier sea at the south and the North Atlantic. Here the entire front of the middle section has dropped down along a great fault and now represents a peculiarly restless area in the sea.[15]

Two noteworthy examples of the other type are supplied by the compressed arc of Drake Strait between extreme southern South America and the Palmer Peninsula of the Antarctic Continent (map 14). In this extraordinary arc, though there was a minor lateral thrust from the North Atlantic at the north, the maximum thrust probably came from the Pacific Ocean at the back of the arc. The extremely complex Antillean arc probably was developed in a similar way, with the maximum thrust from the Pacific Ocean subsidence at the back at a time before the elevation of the Isthmus of Panama had closed the gap (map 15). Here, as in the case of the Iberian-Mauretanian arc, the entire front has dropped into the sea and over it there is now a notably restless area with records of vigias and extreme sudden changes of level.

RISING ARCS THE LOCUS OF STRONG EARTHQUAKES

As we have already noted, the erection of mountain arcs takes place at a rate which, measured by prevalent views of geological adjustments, is startlingly rapid. This is attested by the strong earthquakes at the instants in which uplifts of the lands have amounted in some cases to many tens of feet and subsidences at the bottom of trough deeps have been measured in as many hundreds of feet. As shown by the large-area and small-scale maps which display the distribution of earthquakes, these zones are identical in position with rising arcs of today (map 5). The large-scale maps of smaller areas likewise attest this identity. The *latest* arc to rise in any area is sure to be characterized by the *strongest* earthquakes (maps 25, 27). How important earthquakes may be in indicating the areas of adjustment, has been shown in study of the compressed arcs brought under review in the preceding section.

PART II, MOUNTAIN ARCS OF THE SOUTHWEST PACIFIC REGION

1. THE BONIN ARC

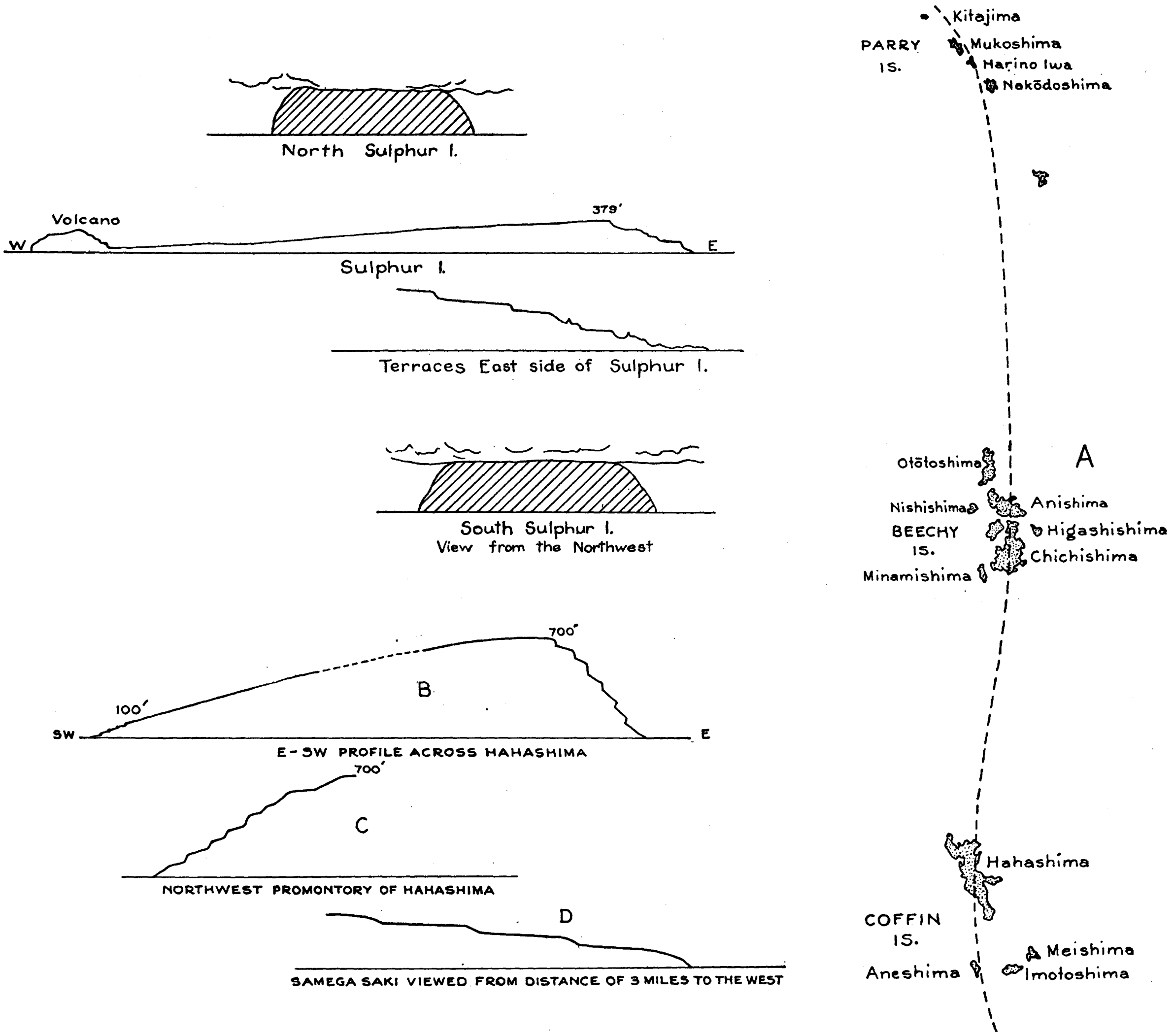
The Bonin (Ogasawara) arc, as shown at the right (*A*) in map 16, is not well outlined by the grouping of islands, and may indeed be in reality two arcs with a cusp at Hahashima, largest of the islands. All islands appear to be composed of andesite lava and andesitic tuff and agglomerate. Professor Wakemidzu, of the agricultural department of the Imperial University of Tokyo, has described the lava as augite andesite. There is a reef on the west coast of Chichishima, but none on the east coast. Specimens of the lava which I collected from near the port of Bonin, where it is found in pebbles (beach shingle) in an agglomerate together with madrepore and brain coral, were examined in thin section by Professor Walter F. Hunt, of the University of Michigan, and analyzed by Dr. R. K. McAlpine. It proves to be augite hypersthene andesite.[16]

The southernmost large island of the Coffin group is Hahashima (Mother Island). On its east coast, as reported to me by the director of the Museum at Bonin, is Sekimon (Gate of Star) promontory, which rises to about 700 feet above the sea and is terraced throughout, with the treads of the staircase dipping eastward as steeply as 50°. The promontory on the southwest (Okimuta) is only 100 feet high and, according to the same authority, has terraces with limestone cappings containing Tertiary fossils and with treads dipping 30° to the west. This would clearly indicate an anticlinal structure, and though I have often seen strongly tilted treads of this nature on arcs off the Asiatic coast, I have not found any as steep as 50°. I had no opportunity to land on the island. I sailed close to the northwestern promontory, which rises to about

---

[15] Hobbs, W. H. The unstable middle section of the island arcs. *Gedenkboek Verbeek, Verh. Geol.-Mijnb. Genootschap Nederland en Kolonien, Geol. Ser.*, **8**: 219–262, 4 pl., 19 fig., 1925.

[16] Hobbs, W. H., and Walter F. Hunt. Petrography of an area of the Western Pacific. *Proc. Third Pan-Pacific Sci. Cong., Tokyo,* **1926**: 711–715, 1926 (1927).



MAP 16. At upper left, profiles of the islands of the Iwo, Volcano, or Sulphur arc (from sketches by the author). At right (*A*) map of the Bonin arc (after a modern Japanese map). At lower left, profiles of Hahashima.

950 feet, with westerly dipping terrace treads up to about 700 feet (*C* in map 16). Samega Saki, seen from the north, was terraced on a relatively gentle slope (*D* in map 16).

According to Petersen,[18] the western coast of Chichishima is much cliffed with great stacks off shore, and this I was able to confirm.[17]

The departure of the line connecting the islands of the Bonin group from a perfect arc has raised the question of whether it is a single arc or two or more. There is a marked trough along its eastern front, but Japanese hydrographic charts generalize this into an exceptionally long trench extending nearly to the "elbow" of Japan and concave toward the east, a most abnormal feature. Kotô has clearly joined several arcs together in his monograph.[18] The islands are deserving of extensive study, which will be necessary in order to clear up the uncertainties.

2. THE IWO ARC

The Iwo, Sulphur, or Volcano arc is one of the most youthful to be found anywhere. Its position is south and west of the Bonin arc and be-

---

[17] Petersen, Johannes. Beiträge zur Petrographic von Sulphur Island, Peel Island, Hachijo und Mijakishima. *Proc. Third Pan-Pacific Sci. Cong., Tokyo,* **1926**: 24–54, pl. II, 1927.

[18] Kotô, B. The Rocky Mountain arcs in eastern Asia. *Jour. Faculty Sci. Imp. Univ. Tokyo* **3**, pt. 3, pl. VIII, 1931.

tween Japan and the Mariannes or Ladrones.[19] The three small islands which are comprised in this arc are in a north-south, nearly straight line with a trough on the seaward side (maps 9 and 16, upper left). The North and South Islands are "steep-to" lava domes, but the middle island (Sulphur Island) is made up of beds of volcanic tuff which rise to 379 feet and are inclined gently to the westward. Terraces are strongly developed on the higher east coast, and a small volcano still "smoking" is at the west end. We have here the usual indication of an anticline (fig. 10). The island has emerged so recently that there is as yet absolutely no indication of erosion, nor any appearance of reefs. When visited, both the North and the South Islands "had their hats on" (map 16), but they are obviously lava domes of augite andesite.[20]

3. THE MARIANNE ARC

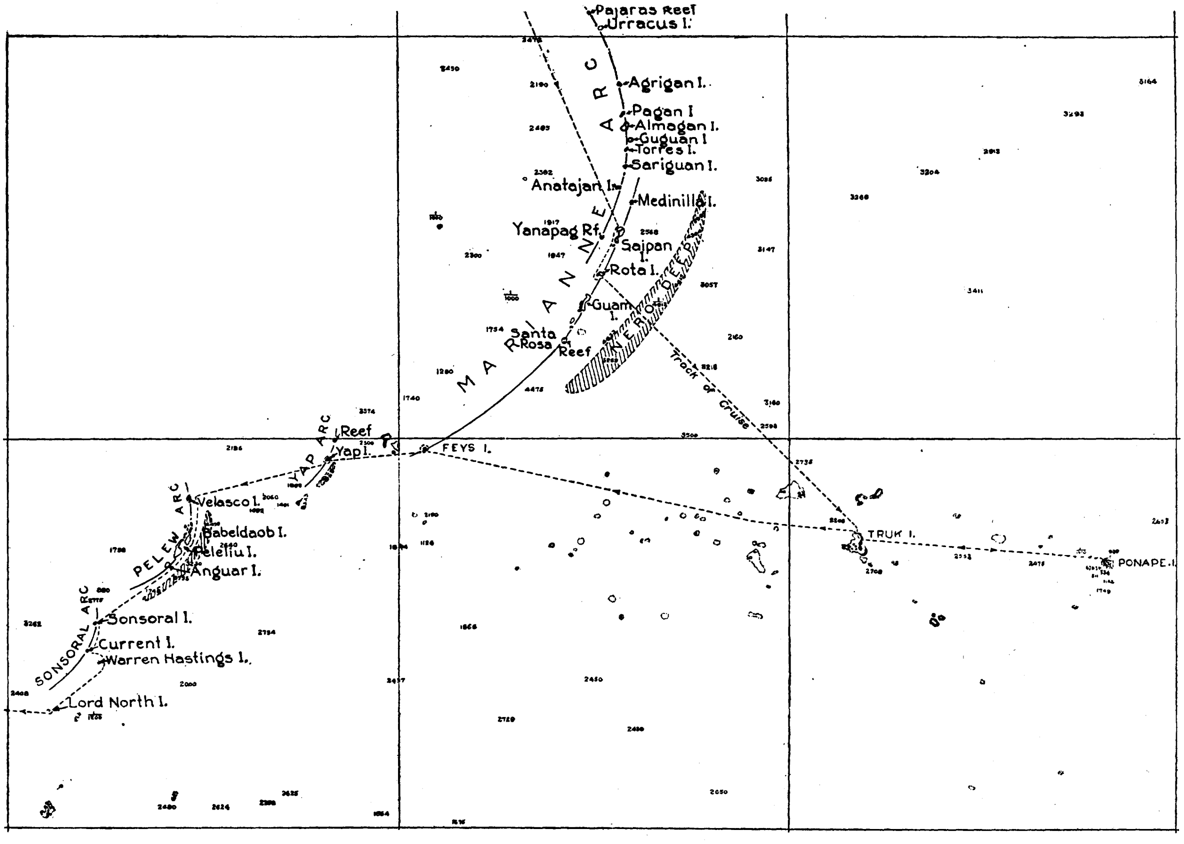
In contrast to the little-studied Bonin arc, which is somewhat difficult to outline, the Marianne (Ladrone) arc is a schematically perfect arc (map 17). It is about 700 miles in length and subtends an angle of about 45°. The southern section developed first, and its trough at the front is the profound Nero Deep, next to the Planet Deep the deepest in the world. Within this southern section of the arc are the islands of sediments, largely volcanic tuffs and reef cappings. In order from the north these are Medinilla, Saipan, Tinian, Aguigan, Rota, Guam, and in continuation southward Santa Rosa Reef, the raised atoll of Feys, and probably to be included Ululssi Reef.

Medinilla rises only about 50 feet above the sea and is terraced throughout. It is only about a mile in length, and on the southern and western

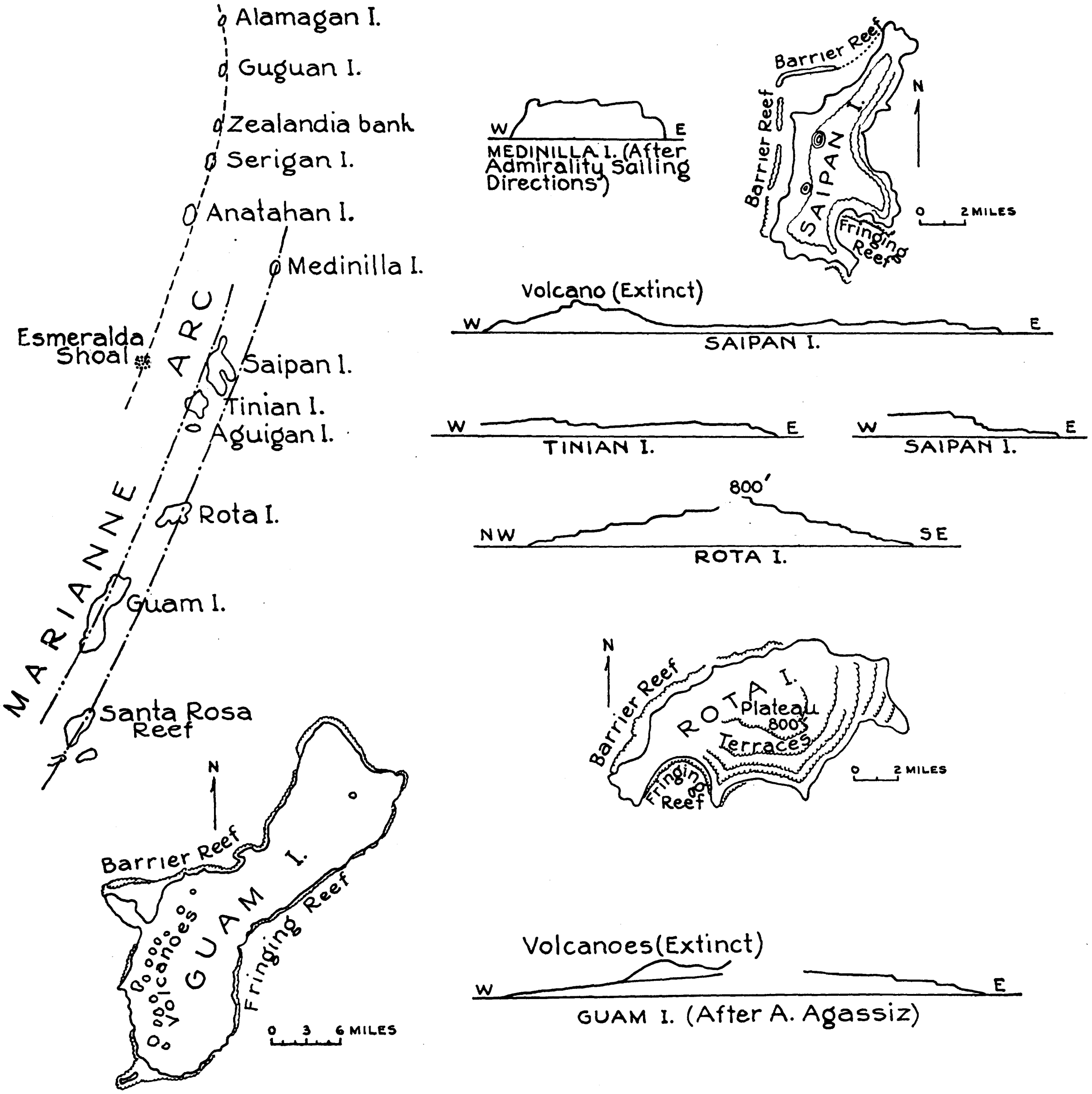
---

[19] The Iwo islands were practically without inhabitants, though a single canoe started out to our ship from the North Island. They were without any regular communication with the outside world and were visited by the *Matsumara Maru* in 1921 as the result of a destructive typhoon and the search for a Japanese liner which had not reported. War dispatches indicate great changes since 1921.

[20] Petersen, *op. cit.*



MAP 17. Arcs of the series from the Iwo arc on the north to the Sonsol arc at the south.



Map 18. The sedimentary islands of the Marianne arc.

coasts are extensive sea caverns. Saipan is terraced and with reef cappings (map 18 and fig. 18). The beds slope gently westward, with extinct volcanoes on the west coast. Offshore there are barrier reefs. The lava of the volcanic effusions is hypersthene andesite.[21] One of the volcanoes has an elevation of 1,345 feet.

Tinian, like Saipan, is terraced throughout and without any considerable evidence of erosion except by the waves (fig. 18*D* and *C*). West of Tinian a distance of 17 miles is Esmeralda Shoal, and, as there are depths of 25 fathoms close to the reef, it is doubtless a volcano of the line at the back and in evidence mainly to the northward.

Aguigan Island, 42 miles northeast of Rota, is flat and terraced with high cliffs. Rota is made up of great terraces with reef cappings, the one at the top of great breadth at an elevation of 800 feet (map 18 and fig. 18*E*′). With little doubt this is now an air base of the first rank. At the southwest of the island is the diminutive boat

---

[21] Tsuboya, K., *Japanese Jour. Geol. and Geog.* 9: 208–210, 1932.

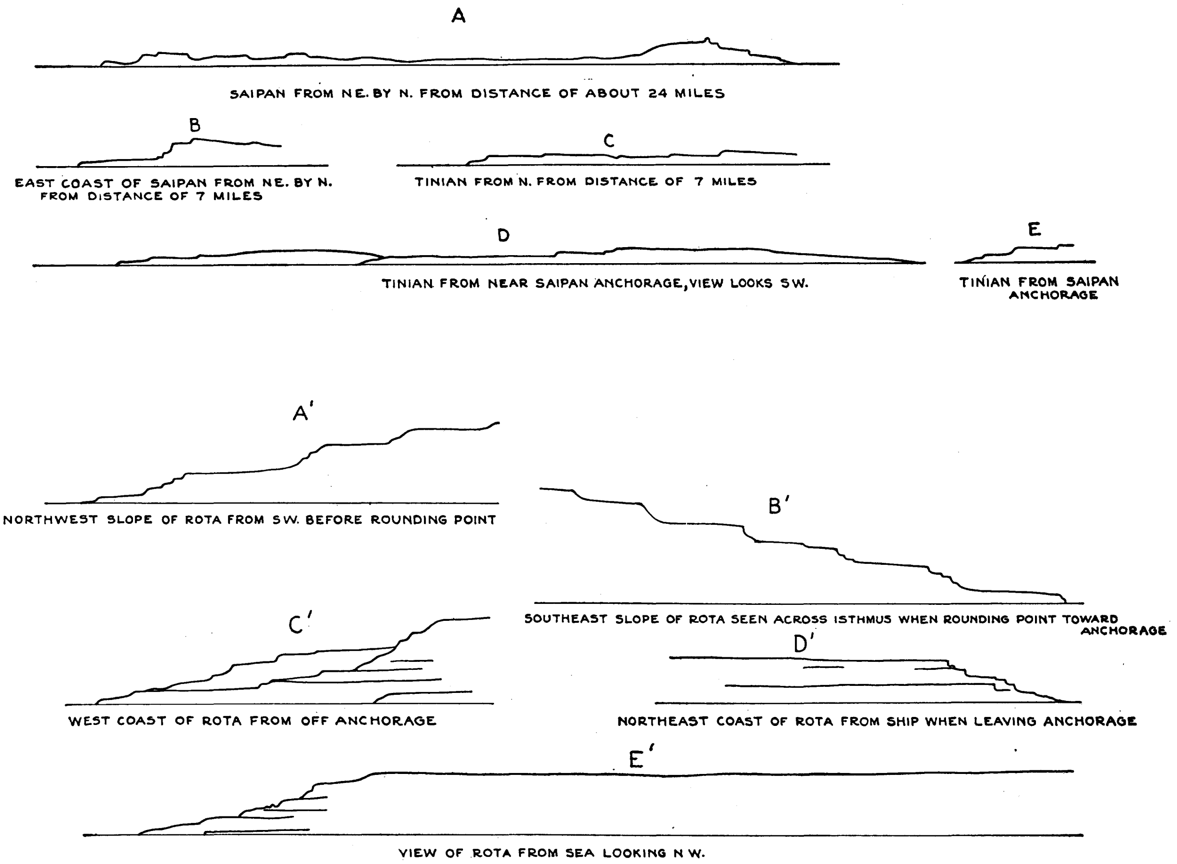
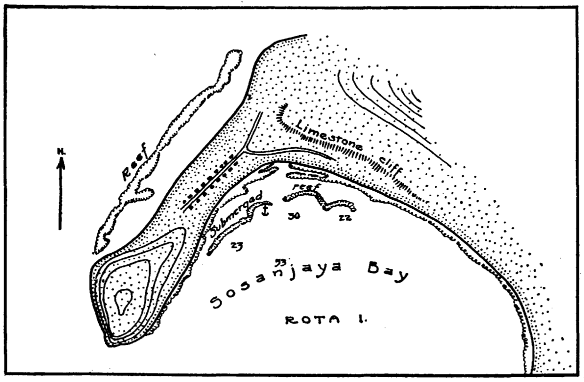


FIG. 18. Profiles of the islands in the anticline of the Marianne arc. (From sketches by the author.)

harbor of Sosanjaya Bay behind a barrier reef, and another offshore reef is west of the bar which has joined a diminutive "Gibraltar" to the island (map 19).

Guam, the largest island of the arc, is similarly terraced, as may be seen from high points on Rota. At the front Guam has a fringing reef, and at the back an offshore barrier reef, a part of which encloses the naval base. On this side also are extinct volcanoes (map 18). The lava is augite andesite, a large part of its exposures covered by reef cappings. According to Agassiz,[22] the peak of Ata Rosa, east of Agana, rises 150–200 feet above the general level of the island, and Mount Mokana, another volcano, has an elevation of about 600 feet.



MAP 19. Detail of southwestern Rota.

Beyond Santa Rosa Reef the arc of the Mariannes is probably joined to the raised atoll of Feys and beyond to Ululssi Reef. In the *Chikuzen Maru* I was able to circumnavigate Feys and photograph and sketch its profiles (fig. 19).

The western line of generally active volcanoes of the Marianne arc lies back of the sedimentary islands with their extinct volcanoes. The volcanoes have reared their heads above the sea only at the north beyond the front line of the arc.

---

[22] Agassiz, A. The coral reefs of the tropical Pacific. *Mem. Mus. Comp. Zoöl.* **28**: 367–375, pl. 195, figs. 2 and 3, pl. 197, fig. 1, and pl. 198, fig. 2, 1903.

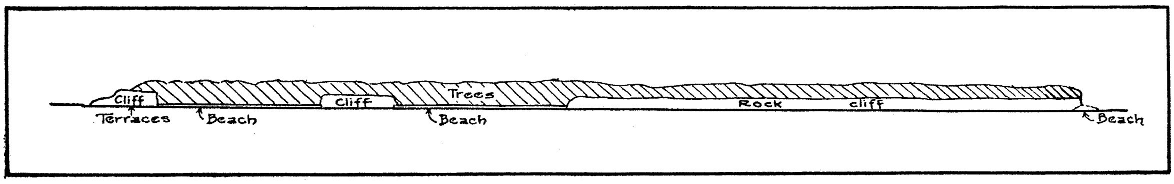


FIG. 19. The elevated atoll of Feys seen from the east. (Based on a sketch by the author.)

They are all steep-to islands and some of them are active volcanoes (map 17). The northern end of the line beyond Uracus is Farallon de Pajáras Reef, which is made up of lava (augite andesite).[23] The sections across the arc in the northern, middle, and southern portions are set forth in figure 20.

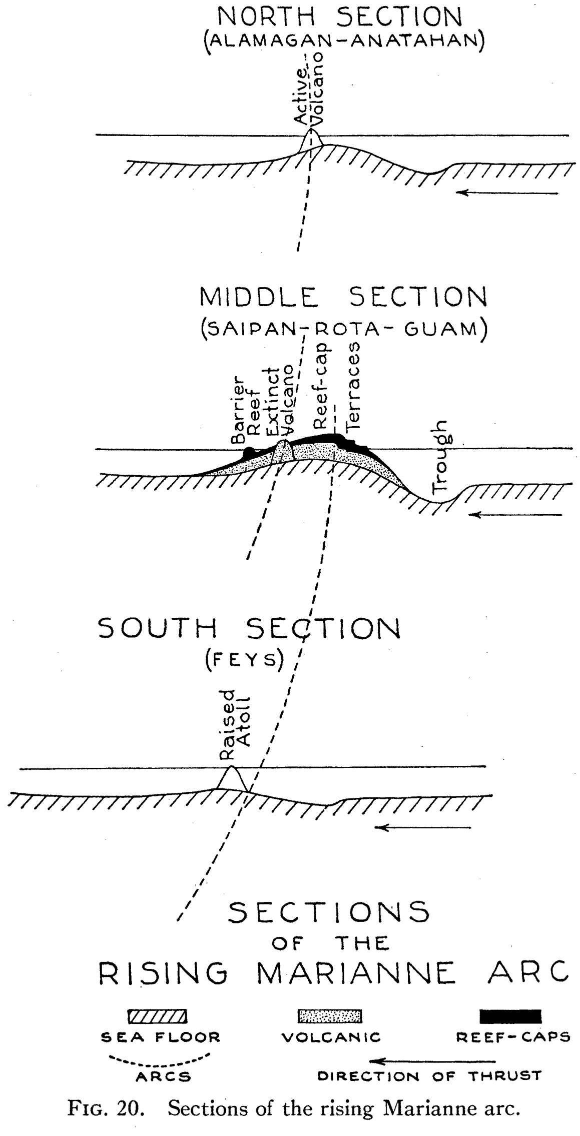


FIG. 20. Sections of the rising Marianne arc.

4. THE YAP ARC

The Yap arc lies between the Marianne and the Pelew (Palau) arcs (map 17) and consists of what was clearly a single island. That it is in reality an arc despite its odd outline is revealed by the definite trough at its front.

At the present time Yap consists of four islands: Rull, Tomil-Gamil (separated from Rull by the Lagereng Canal), Map, and Rumong, all close together. Their separation is due to a recent subsidence of Yap, which drowned the young streams, formed shallow estuaries through the reef, and in places through the volcanic core of the original island as well (map 20).

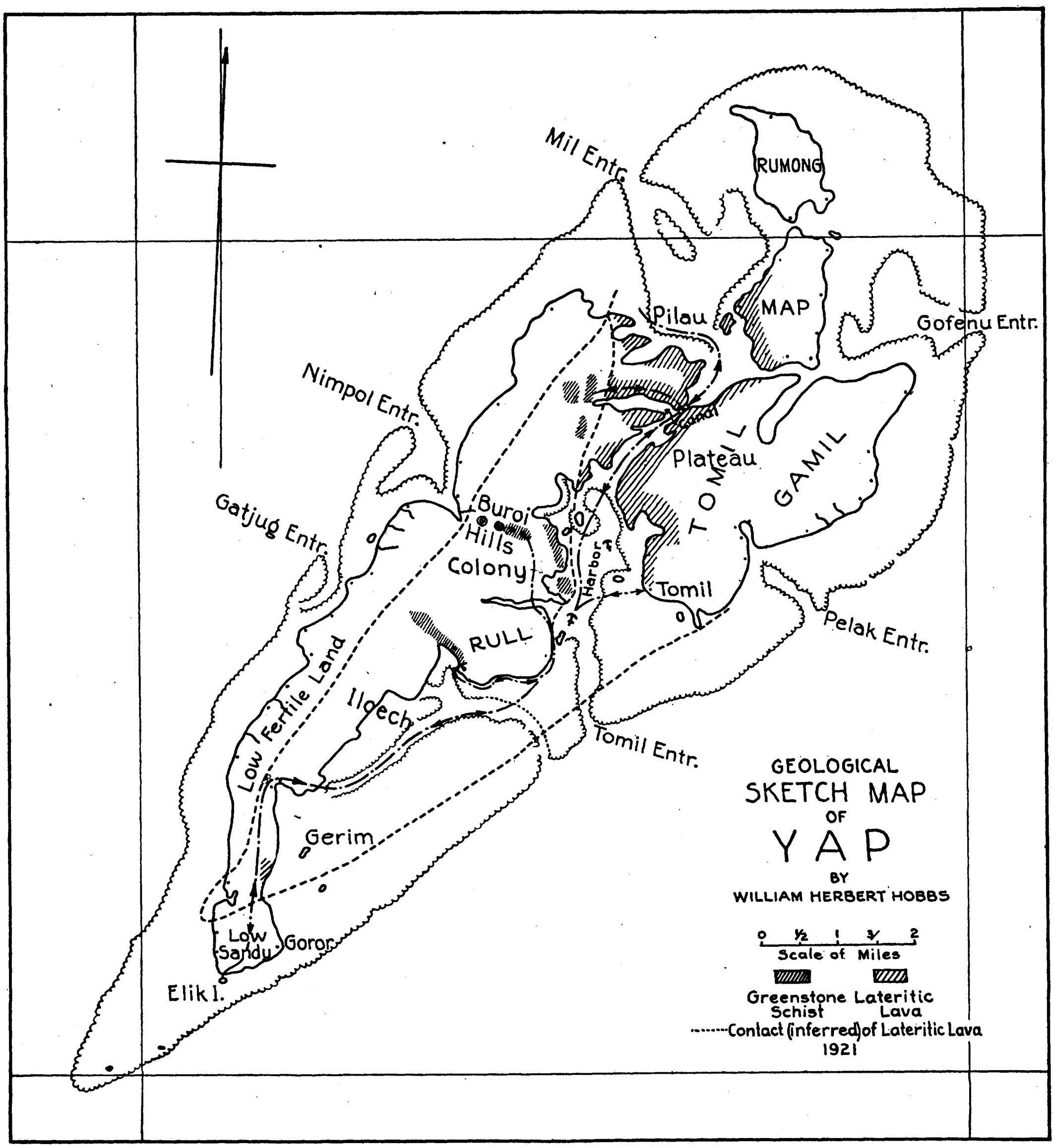
Together the four islands make a triangular area which trends northeast-southwest for about 7 miles and has its shortest side at the north. The area has a general slope to the northwest (fig. 21*C* and *D*) and has a maximum elevation of about 500 feet.

Except for the estuaries, Yap is entirely surrounded by a reef intermediate between a fringing and a barrier reef, and this reef is generally more than half a mile and for considerable distances as much as 2 miles in width. This indicates that after the erection of the arc to above its present elevation there has been a long stillstand period, after which a quite moderate subsidence drowned the young river valleys and yielded the shallow estuaries through the reef.

Yap is composed wholly of igneous and apparently effusive rock, which at the surface presents two widely different types, both greatly decomposed. One is an older augite andesite, now a red lateritic decomposition product, which occupied the eastern half of the inland complex; and this is in surface contact along a north-south medial line with a basic greenstone schist, in places talcose or actinolitic, which is the decomposition product of a black basalt. Blocks large and small of the latter are strewn over the surface of the greenstone schist, and apparently this rock is in place in the canal. With much probability

---

[23] Kaiser, Erich. Beiträge zur Petrographie und Geologie der deutschen Südseeinseln. *Jahrb. k. preusz. geol. Landesanst. u. Bergakad.* **24**: 114, 1903.



Map 20.

the contact of the intermediate and basic lava types along the medial line of Yap is one of superimposition of the basalt upon the andesite (map 20). According to both Kaiser[24] and Tsuboya,[25] there is to be found in the northwest island (Rumong) in a volcanic breccia blocks representing a considerable number of types of hypabyssal eruptive rocks related to the effusive types which so largely compose the island. These types are amphibole granite, amphibole syenite, gabbro, pyroxenite, and wehrlite.

---

[24] Kaiser, Erich. Einige Ergebnisse einer Reise nach den Karolinen und Marianne. *Verh. XIII deutschen Geographentages zu Breslau im Jahre 1901*: 167–179, 1901.

——. Alte Gesteine von den Karolinen. *Zeitschr. deutsche geol. Gesell.* **54**: 62–63, 1902.

——. Beiträge zur Petrographie und Geologie der deutschen Südseeinseln. *Jahrb. k. preusz. geol. Landesanst. u. Bergakad.* **24**: 93–110, 1903.

[25] Tsuboya, K. Petrographical investigation of some volcanic rocks from the South Sea Islands. *Japanese Jour. Geol. and Geog., Trans. and Abstr.* 9 (3–4): 207–208, 1932.

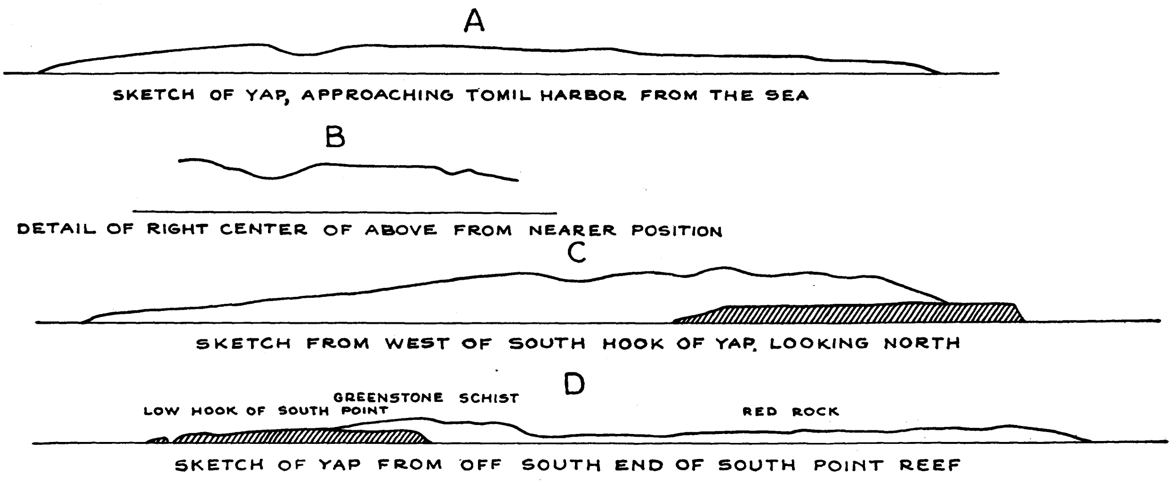


FIG. 21. Profiles of the island of Yap. (From sketches by the author.)

The schistosity of the greenstone schist strikes northeast with the arc and dips northwest, hence parallel to the surface of the effusive rocks where uneroded. It is with much probability parallel also to an original fluxion structure.

As already pointed out, both the effusive rocks of the island are greatly decomposed. Erosion has been much more effective in removing the lateritic andesite, as is evident from the profile of the island as seen from South Point Reef (fig. 21*D*). It supplies confirmation of the long still-stand of the island, which is in striking contrast with the history of the Pelew arc next to the southwest.

5. THE PELEW (PALAU) ARC

The Pelew arc is in a more advanced stage of development than the Yap arc. It is about 100 miles in length, as against the 12 miles of Yap, and it subtends an arc of about 120°. The main central archipelago of the Pelews is a little more than half the length of the entire arc, since this is extended northward by the atolls of Kossol, Kriangle, and Aruangle (Vigaruangle) in that order (map 21, inset), and southward to the elevated atoll of Anguar or Nguar, which is reported to have an elevation of 65 feet.

The main island of Babelthuap[26] is in the north central or middle section of the arc, and is made up very largely of a hypersthene and augite andesite lava with its corresponding volcanic sediments, a red tuff largely altered to laterite and interbedded with agglomerate and volcanic breccia, the latter generally underlying.[27]

Babelthuap is about 27 miles long and 14 miles wide. Its crest is near the east coast, which is steep and terraced, as was clearly to be seen when we were cruising offshore. It is in this eastern zone that most of the solid lava is found exposed. From offshore this massive rock can be seen to be cut by dikes of a black and more basic rock. In contrast with the east coast, the west coast is gently sloping and also but little eroded (fig. 22*G*, *H*, and *I*). As on Yap, the considerable erosion is restricted to the high country, here toward the east coast. Residual spines of the lava are reported there to attain an elevation of about 2,000 feet.

Near the base of the gradual west slope of Babeldaob are cinder cones (fig. 22*G* and *H*), which quite likely belong in a line of volcanoes to the west of the first, which appeared near the east coast. In its higher levels Babeldaob is re-

---

[26] The name is also spelled Babeldaob and means "the island much elevated," a most appropriate designation which may indicate that the natives were observant.

[27] Oebbeke, K. Beiträge zur Petrographie der Philippinen und den Palau-Inseln. *Neues Jahrb. f. Mineral., Geol. u. Paläontol.*, Beil. Bd. **1**: 492–495, 1881.

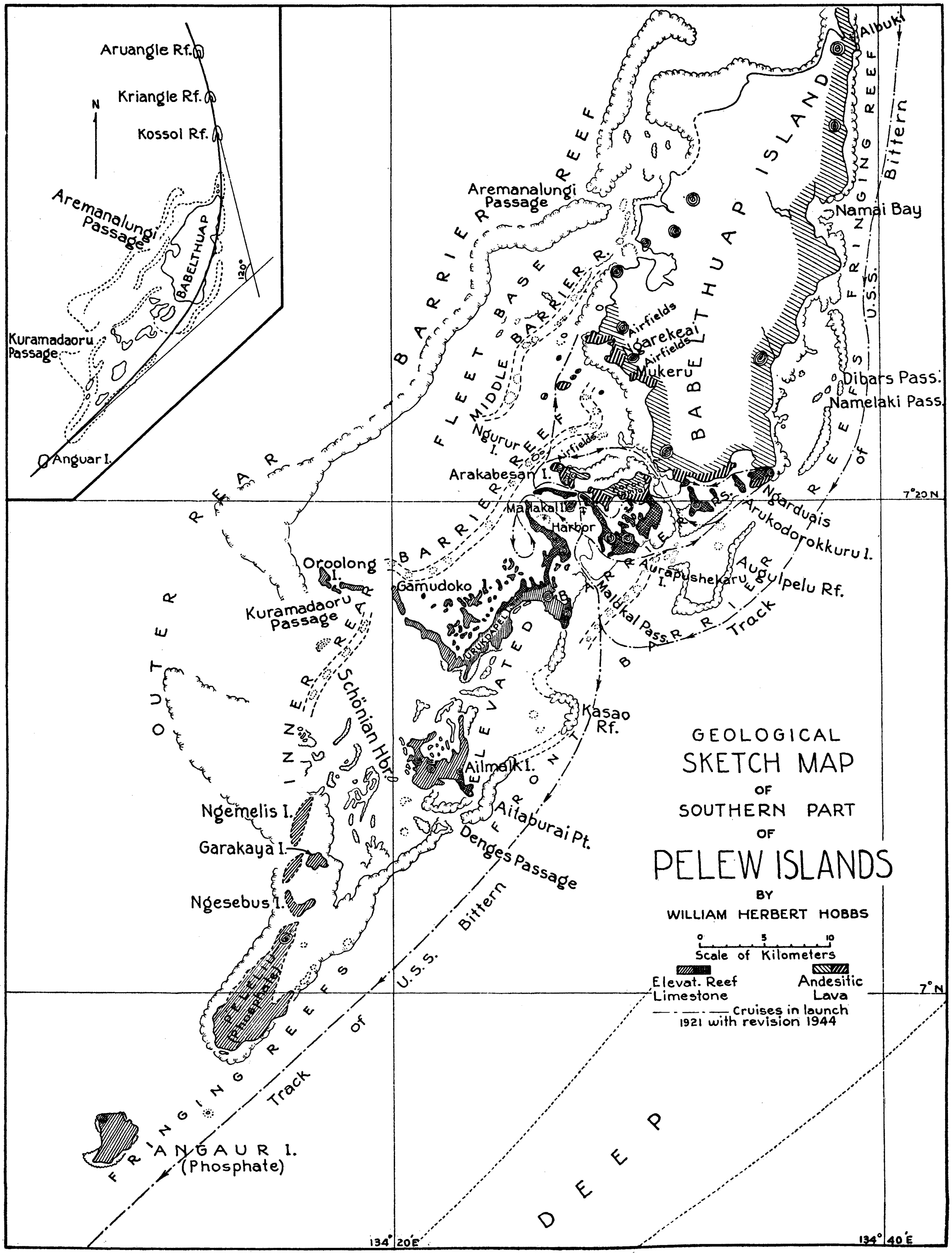
Kubary, J. Die Palau-Inseln in der Südsee. *Jour. Mus. Godeffroy* [Hamburg] **1**, Heft 4: 177–238, 1873.

Wichmann, A. Zur geologischen Kenntniss der Palau-Inseln. *Jour. Mus. Godeffroy* [Hamburg] **3**: 255–259, 1875.

Kaiser, Erich. Beiträge zur Petrographie und Geologie der deutschen Südseeinseln. *Jahrb. k. Preusz. geol. Landesanst. u. Bergakad.* **24**: 113–114, 1903.

Krämer, Augustin. Studienreise nach den Zentral—und Westkarolinen. *Mitteil. deutsch. Schutzgebieten*, **21**, Heft 3: 179–186, 1908. (Maps of Yap and Palau).

Tsuboya, K. Petrographical investigations of some volcanic rocks from the South Sea Islands. *Japanese Jour. Geol. and Geog., Trans. and Abstr.* **9**: 202–212, 3 pl., 1932.



MAP 21. Geological sketch map of southern part of Pelew Islands. (Based on the Japanese hydrographic chart issued July 7, 1917.)[28]

---

[28] The U. S. hydrographic chart 1260 (1916) was also carried on the trip, but I was able to effect corrections in the position of the northern atolls, some of which are incorporated in hydrographic chart 5423 (1926).

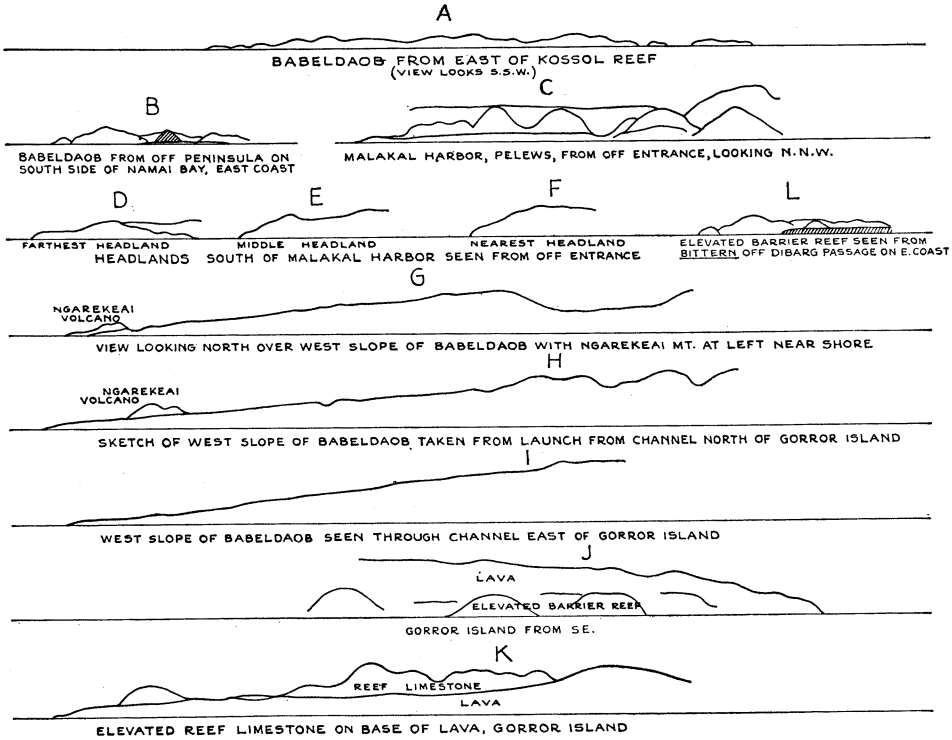


FIG. 22. Profiles of Babeldaob and other islands of the Pelew archipelago. (After sketches by the author.)

ported to be a barren trenched plateau which has been but little explored by geologists. However, there have been found overlying the tuff there, as well as near the west coast, ferruginous clays and a greenish-gray non-calcareous bedded marine sediment largely of organic origin.

The andesitic lava of Babeldaob is extended southward in the islands of Korror, Arakabesan, and Malakal, and as a basement to many of the other islands, which for most of their emergent portions are elevated barrier reefs. In these smaller islands also are exposures of an amygdaloidal melaphyre which may be related to the basic dikes seen cutting the eastern cliffs of northeast Babeldaob. Wichmann (*op. cit.*) reported also blocks of syenite granite, probably from volcanic breccia as was the case at Yap.

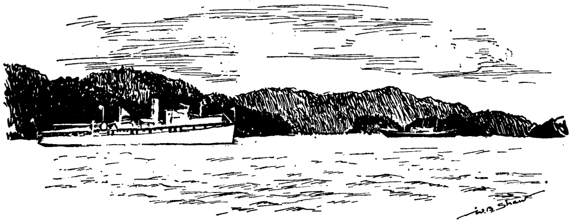


FIG. 23. The anchorage in the harbor of Malakal, showing high elevated barrier reefs at the back. In the foreground the U. S. mine sweeper *Bittern*, and at the right in the middle distance the *Chikuzen Maru*. (Pen sketch by Shaw after a photograph by the author.)

Encircling Babeldaob and the smaller lava islands are long chains of elevated barrier reefs, whose crests rise to elevations of 200 to 300 feet and which display the once submerged contours little changed, probably the most remarkable display of such structures to be found anywhere in the world (map 21 and figs. 22 (bottom), 23, 24*B* and *C*, 25, and 26). The channels between the reefs and the "sugar loaf" ranges are beautifully displayed. Though so little eroded, they reveal the stages in the interrupted process of elevation. Sea caverns cut in the sides of the reefs, cliffs, and even stacks are displayed in many of these elevated reefs.

My reading has revealed no description by a geologist of the extreme western reefs of the archipelago. We are therefore fortunate in having a rare account of these reefs by shipwrecked British seamen and their officers.[29] They found

---

[29] Keate, George. *An account of the Pelew Islands situated in the western part of the Pacific Ocean, composed from journals and communications of Captain Henry Wilson and*

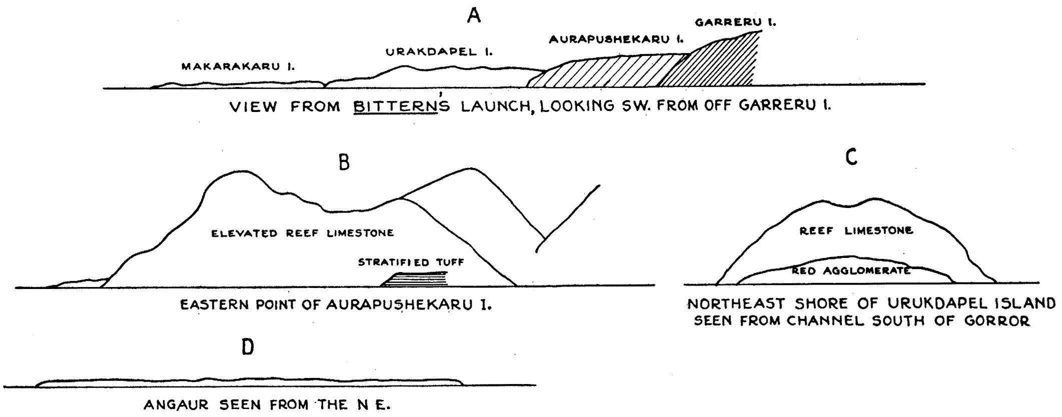


FIG. 24. Profiles of islands in the Pelew arc. (From sketches by the author.)

their way in the ship's boats to Oroolong Island, obtained supplies Crusoe fashion from the wreck, built a pinnace, and made their escape. They built an observatory on the island and from it made the careful sketch of the reefs to the eastward with the compass bearing of each "sugar loaf" (fig. 26).

The several elevated barriers (one at the front and at least two at the back), with the caves and cliffs upon them to mark the levels of ocean strands carved by the waves during their interrupted elevation, considered also with due regard to the fact that those in the middle front section are now being rapidly undermined by the waves during a subsidence—these facts reveal to us much of the late arc history.

The sequence of the vertical adjustments, in summary, seems to have been about as follows for the South Babelthuap - Korror - Malakal section of the arc:

1. Upward rising arc of andesitic lava with the usual terraces on front, and formation of barrier reef at the back. This later developed into

FIG. 25. View from the summit of Malakal island, looking northward over an elevated reef to Arakabesan island (andesite lava) in the middle distance, and beyond in the distance to the low west flank of Babeldaob (andesite tuff). (Pen drawing by Shaw after a photograph by the author.)

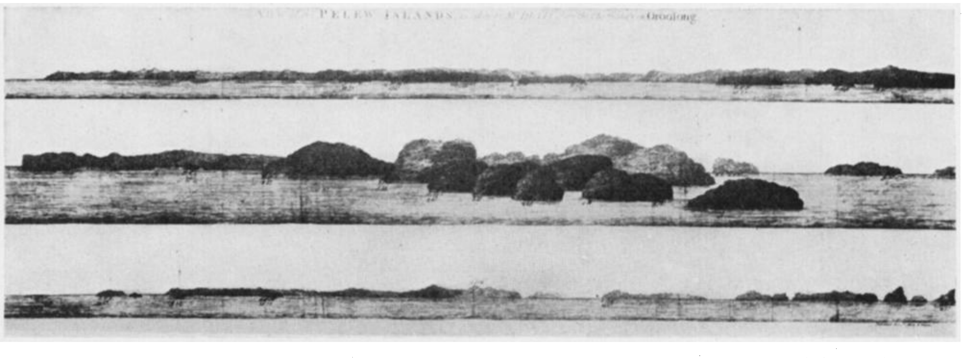
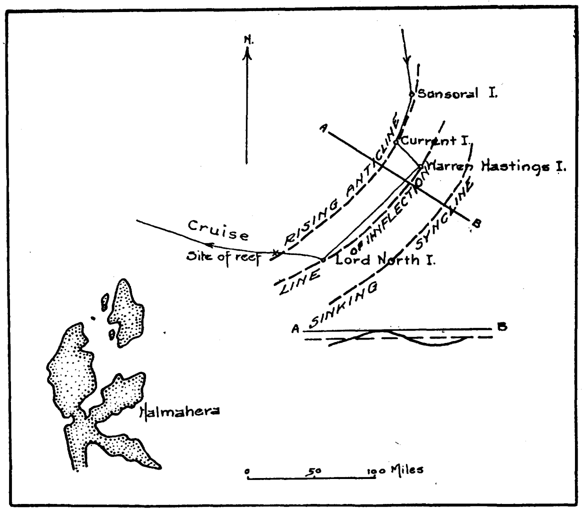


FIG. 26. Panoramic view of the elevated reefs of the inner barrier and of Gamudoko and Arukdapel Islands from the "observatory" on Oroolong Island, which is just inside the Kuramadaoru Passage through the Outer Rear Barrier Reef of the Pelew Islands. Date, 1783. (From Keate, 1788.)

---

some of his officers, who, in August, 1783, were there shipwrecked, in the Antelope, a packet belonging to the Honourable East India Company. London: 1–377, 1788. (See fig. opposite p. 288.)



MAP 22. The Sonsol group of atolls.

the longitudinal wrinkles (map 21, inset), with the atolls Kossol, Kriangle, the Aruangle at the north and the elevated Anguar at the south.

2. Later renewed lateral compression of the arc and development of barrier reef around the south of Babelthuap and its offshore lava islands, at the same time that a barrier reef developed off the front and a second one off the rear.

3. Renewed thrust from the front of the arc caused the islands with their encircling barriers to undergo an interrupted elevation.

4. The next succeeding thrusts came from the ends to produce further longitudinal wrinkling and a renewed subsidence in the cross synclines.

6. THE SONSOL ARC

To the southward of the Pelew arc and in the direction of the arcs of the Netherlands East Indies lies the inchoate arc of Sonsol. It consists of a few atolls and reefs. A still rather indefinite arc, it is made up (map 22), it would seem, of a front line consisting of Warren Hastings Island (also known as Merir and Pulo Marière) and Lord North Island (called also Neville and Tobi). The back line in the group consists of Sonsol Island (called also Sonsoral and St. André) and to the southwest of it Current Island (also known as Pulo Anna and Bur). Profiles of the islands made during a cruise near them are given in figure 27.

We approached the Sonsol group of islands in the *Bittern* from the north, intending to pick up Sonsoral on the port side. It was sighted on the starboard side, which may indicate that its position on the chart needs correction. The island is wooded and appears to be an elevated atoll. Our lookout in the crow's-nest said the island appeared hollow at the top, and I estimated its height to the tops of the palms to be about 100 feet. It is inhabited, and ten canoes of very wild-looking natives came out to the ship to trade.

Current Island is nearly circular and of about the same size as Sonsoral Island. It is a raised atoll, probably somewhat higher than that island. No natives appeared.

Warren Hastings Island is low, and the trees are wholly on a low reef of the east side, which is extended in a north-south direction. Lord North Island is similarly low, and the trees are on a north-south reef of the east side, but they extend also along the southeast side of the atoll as well. No natives were seen at Warren Hastings Island, but at Lord North Island five canoes of natives came out to barter. The Sonsol island group as a whole probably represents the earliest possible stage in the initiation of an arc.

7. THE RIUKIU (LOOCHOO) ARC

The arcs which have thus far been brought under consideration, from the Bonin arc at the north to the Sonsol arc at the south, comprise an outermost and latest series erected by late

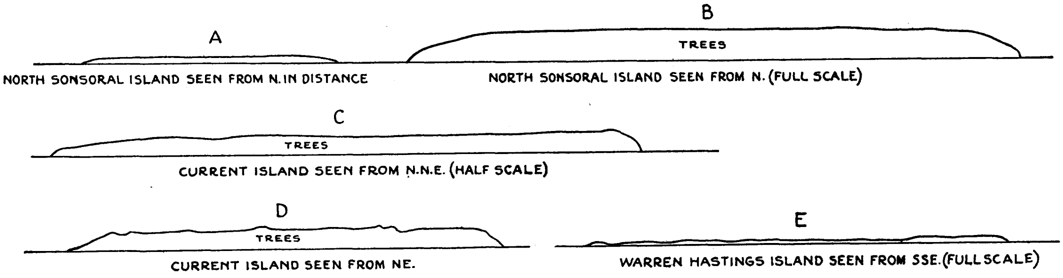
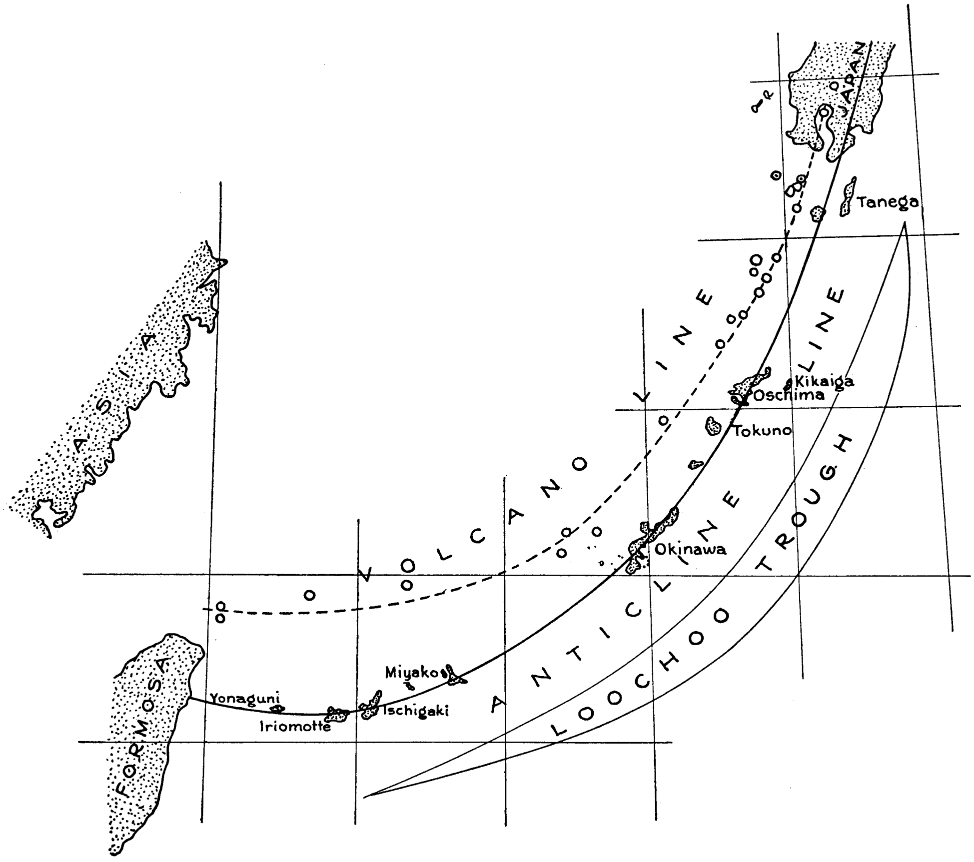


FIG. 27. Profiles of islands in the Sonsol group. (From photographs and sketches by the author.)



MAP 23. The Riukiu arc.

thrusts from the Pacific floor. An earlier series lies farther back toward the continent of Asia (maps 7 and 9), and they join the island of Kiusiu in southwestern Japan to New Guinea. In order they are the Riukiu (Loochoo) arc, the Philippine arcs, and the Sunda-Banda arc series. From northwestern New Guinea, where they are joined to the outermost series, they continue as a single series eastward through the Admiralty, Solomon, Santa Cruz, New Hebrides, New Calodonia, Fiji, and Tonga-Kermadec islands into New Zealand.

The Riukiu arc (map 23) is in a youthful stage similar to the Marianne arc. It joins Kiusiu to Formosa or Taiwan. Behind the deep Riukiu trough, a series of islands made up of Paleozoic and Tertiary sediments comprises the anticline crest, behind which in the normal position is a line of generally steep-to volcanoes which have erupted andesite lava. Of the sediments in the anticline, the later ones are at the front.[30] This front of the arc is strongly terraced with reef cappings, though neither barrier reefs nor atolls are at the back.

8. THE PHILIPPINE ARCS

Inasmuch as the outermost series of arcs off the Asiatic coast have so recently emerged from the sea, their surface features either betray little of the ravages of erosional agencies other than the notching by the waves, or they retain sufficient remnants of the anticline surface to permit in-

---

[30] Yoshiwara, S. Notes on the raised coral reefs in the islands of the Riukiu curve. *Jour. Coll. Sci. Imp. Univ. Tokyo* 16: 1–14, 2 pl., 1901.

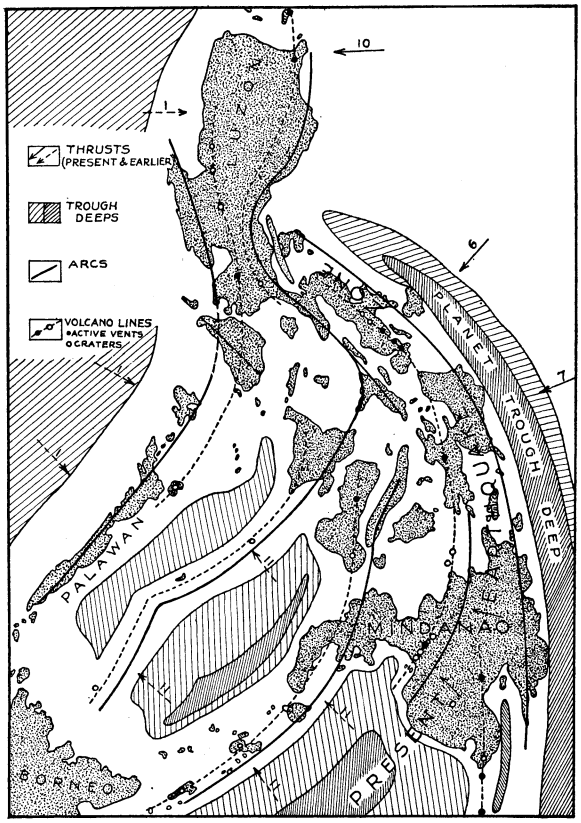
——. Geologic structure of the Riukiu (Loochoo) curve, and its relation to the northern part of Formosa. *Ibid.*: 1–67, 4 maps and tables of profiles.

Richtofen, Ferdinand von. Geomorphologische Studien aus Ostasien, III, Die morphologische Stellung von Formosa und den Riukiu-Inseln. *Sitzungsber. k. preusz. Acad. Wiss. Berlin* 11: 944–975, 1 pl., 1902.

ferences to be safely drawn concerning their tectonic structure.

We turn now to an earlier and older series of arcs where erosional and transportational agencies have played a large part in obliterating original anticline surfaces, and where, in our attempts to decipher tectonic structures developed during mountain growth, we must rely more upon other factors, and especially on those learned from study of the younger and less modified arcs. Of these clues, those of greatest importance relate to the position of the lines of volcanoes both extinct and active, and to the position of troughs in the neighboring sea floor. The trends of the dominant ranges, with due regard to the strikes of the sedimentary rock formations, are of the greatest service in deriving the arcuate pattern, and this is very apt to be displayed in the trends of the relatively narrow islands.

Now that we feel assured in assuming that the thrusts which developed the arcs came from sinking sea floors at the front, and knowing, further, that the convexity, of the arc itself and the greatest convexity of the anticline profile both face seaward, we assign first importance to these facings. As regards the order of sequence in formation of arcs which are concentrically festooned, study of the zones of strong earthquakes should in all cases reveal the clue.



Map 24. The series of mountain arcs of the Philippines.

In now applying these criteria to the series of Philippine arcs, which with exception of northern Luzon belong in a single concentric arcuate group (map 24), we learn at the outset from study of the earthquake map[31] that the outermost arc next to the great Planet Trough Deep is the latest to have been formed (map 25). Probably the greatest earthquake intensity in the islands has been concentrated in the Agusan Valley north of Davao along the continuation northward of a narrow sea trough in the Gulf of Davao.[32] The Philippine rocks are all of Tertiary age or younger.

The arc which passes through the Bataan Peninsula in extreme western Luzon and is continued southwestward, passes through Mindoro and Palawan (the last two islands formerly were joined together). While it conforms in its arcuate convexity to the other arcs of the series, yet it is nevertheless abnormal in that the line of volcanoes, which includes the active volcano Taal southeast of Manila Bay, lies on the east (seaward side) of the anticline. It is the only case of its kind anywhere known to me. Luzon, in contrast to Palawan, is still very seismic (map 25), and the structure lines of Mindoro seem to run with the island or directly across the Palawan-Bataan structure.[33] There is here a suggestion that an early-formed arc ran southeastward with the Mindoro structure into Panay, the island to the southeast, which would conform to the early pattern, and that the late sinking of the great China Sea to the west, 1,000 miles across and with depths in excess of 5,000 meters, has superimposed a Bataan-Palawan arc upon the older one and so raised a line of volcanic vents on the back.

The other Philippine arcs, four in number, which have culminated in the one next to the

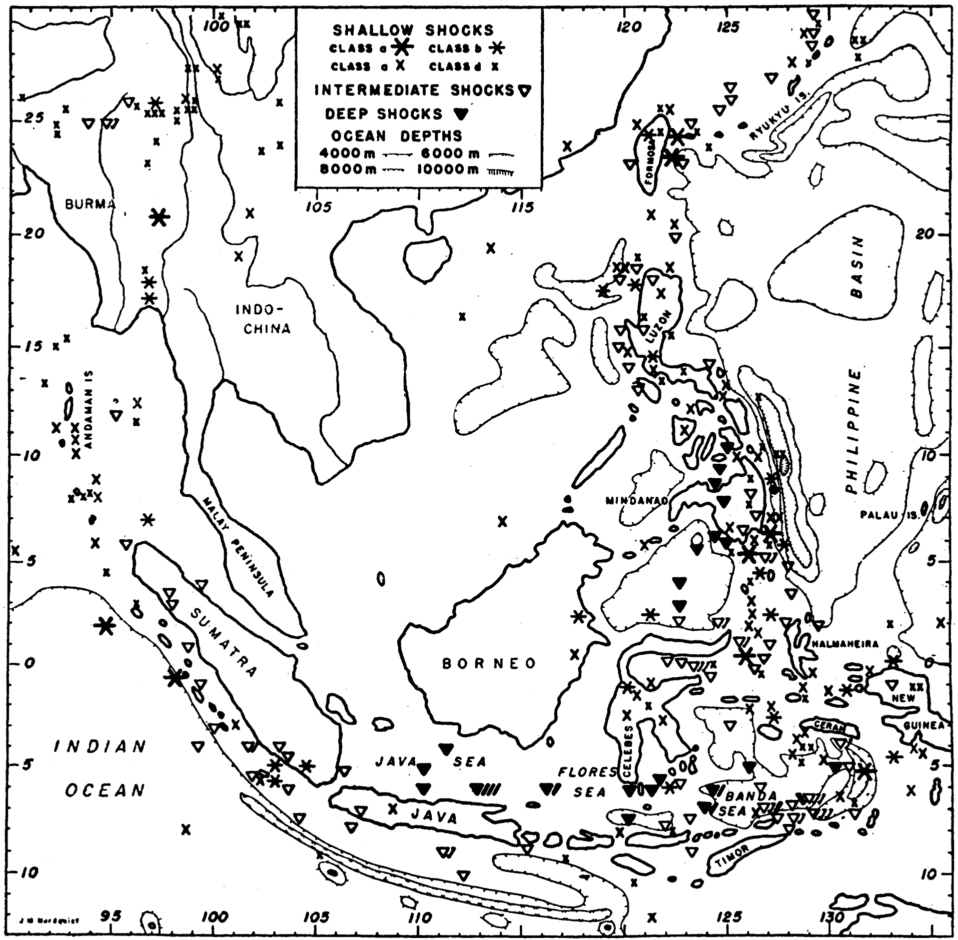
---

[31] Gutenberg, B., and C. F. Richter. Seismicity of the earth. *Geol. Soc. Amer., Spec. Paper* 34: 56, fig. 9.

[32] Smith, W. D. *Geology and mineral resources of the Philippine Islands*: 205–206. Manila, 1924.

[33] Smith, W. D. The essential features of the geology of the Philippine Islands. *Philippine Jour. Sci., A., Chem. and Geol. Sci. and Industries*, 5 (5): pl. II, 1910.

——. *Geology and mineral resources of the Philippine Islands*, pl. 37, 1924.



MAP 25. Earthquake map of the Philippine Islands and the Netherlands East Indies. (After Gutenberg and Richter.)

Planet Trough (fig. 28), are all quite normal, with trough to seaward and with the volcano line landward from the anticline.

The Planet Trough has an extreme depth of 9,788 meters (31,811 feet) or over 6 miles. An interesting proof that this great depth has arisen through local subsidences is furnished by the sediments dredged by the ship *Planet* from the bottom. *Over* the deposit of minerals clearly derived from the augite andesite lavas was a 3½-inch calcareous deposit of brown clay containing well preserved shells of *Globigerina*. Since calcareous sediments are all dissolved before reaching a depth of 6,000–7,000 meters, the local subsidence has been in excess of 2½ miles.[34]

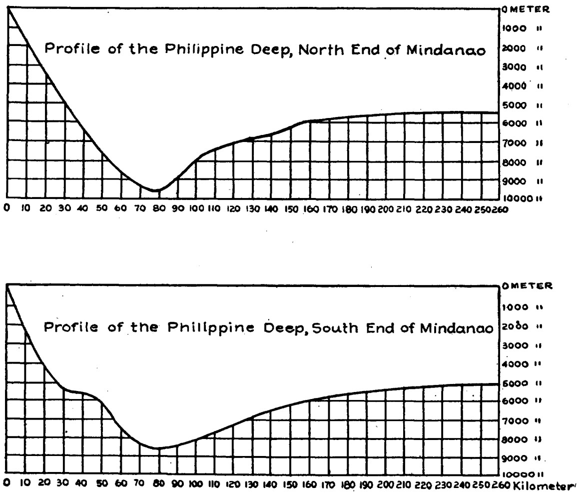


FIG. 28. Profiles across the Planet Trough east of the Philippine Islands.

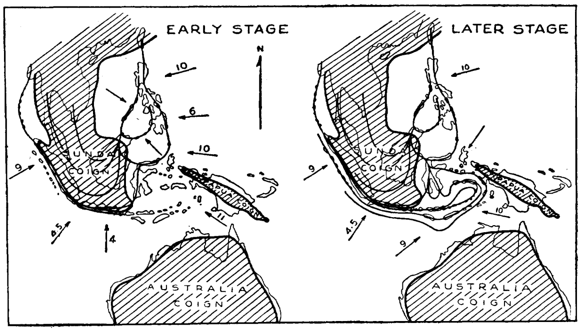
---

[34] Smolenski, J. Ueber die Entstehung der heutigen Tiefen des Philippinen Grabens. *Bull. Acad. Sci. Cracovie, Cl. Sci. Math. et Nat., Ser. A, Sci. Math.*: 586–601, Nov.–Déc., 1916.

All the early eruptions are of augite andesite, and there are later effusions of basalt.[35]

9. THE SUNDA-BANDA ARC SYSTEM

The Sunda-Banda arc system is unique, since it has been evolved, not as the result of a thrust from one ocean area toward a continent, but because of active thrusts from two oceans located on its opposite sides—a thrust from the Pacific basin lying to the northeast and another from the Indian Ocean off to the southwest (map 26).



Map 26. The evolution of the Sunda-Banda arc system.

The Malay Peninsula, then as now, was extended southeastward by the Sunda Bank or platform which acted as a coign.[36]

In the Sunda part of the arc the thrusts appear to have come first from the Indian Ocean area, and these developed a double anticline on Sumatra and Java, the earlier one now being the most developed (map 27 and fig. 29). In addition to the two anticlines developed upon the larger islands there are two which are submarine ridges at the front. The inner one comes to the surface in the Mentawie chain of islands off central Sumatra, also in Soemba, Timor, and Ceram of the Banda region. Nias in the Mentawei chain is an anticline with the steep side on the south and with terraces on the north which are so recent that the color of the coral reef caps still shows.

The outer submarine ridge emerges in its eastern portion in Aroe and in the "bird beak"

---

[35] Iddings, J. P. The petrography of some igneous rocks of the Philippines. *Philippine Jour. Sci.*, Sec. A, **5**: 155, 1910.

[36] There is a voluminous literature relating to the structure of the Netherlands East Indies, beginning with the great works of R. D. M. Verbeek and coming down to works by the distinguished group of later official Dutch colonial geologists and mining engineers. Some of the more important of the later general works are the following.

On earthquake distribution:

Kemmerling, G. L. L. De aardbeving van Bali op 21 Januari, 1917. *Jaarb. Mijnwezen Nederl. Oost-Indië* **46**, *Verh.* **1**, 1917. Batavia, 1918.

Visser, S. W. On the distribution of the earthquakes in the Netherlands East Indian Archipelago, 1909–1919. *Verh. Kon. Magn. en Meteorol. Observatorium* [Batavia] **7**: 1–77, 3 maps, 1921.

——. Inland and submarine epicentra of Sumatra and Java earthquakes. *Ibid.* **9**, 1922.

Maps:

Abendanon, E. C. Geologische Schetskaart van Nederlandsch Oost Indië samengesteld in opdracht van het Koninklijk Nederlandsch Aardrijkskundig Genootschap. In six sheets. Scale 1 : 2,500,000. The Hague, 1914.

Atlas van Tropisch Nederland. (Issued by the Netherlands Geological Society in collaboration with the Topographical Service of the Netherlands East Indies.) The Hague, 1938.

De Bussy's Atlas Van Nederlandsch Oost Indië voor Kantoor, school en Hus. Amsterdam, 1919.

On structure of the archipelago:

Kotô, B. On the geological structure of the Malayan Archipelago. *Jour. Coll. Sci. Imp. Univ. Tokyo*, sec. **11**, pt. 2: 83–120, 1 pl., map, 1899.

——. The Rocky Mountain arcs in Eastern Asia. *Jour. Fac. Sci. Imp. Univ. Tokyo*, sec. II, **3**: 131–172, maps, 1931.

Suess, Eduard. *The face of the earth* (*The Oceanides*) **4**: 291–327. Oxford, 1909.

Volz, Wilhelm. *Der malaiische Archipel, sein Bau und sein Zúsammenhang mit Asien. Sitzungsber. phys.-med. Soc. Erlangen* **44**: 177–204, map, 1912.

Molengraaff, G. A. F. Folded mountain chains, overthrust sheets and block-faulted mountains in the East Indian Archipelago. *Comptes Rendus Cong. Géolog.* Internat., 12th Sess., Canada, 1913: 689–702, 1914.

——. De geologie der zeeën van Nederlandsch Oost-Indië. In: De Zeeën van Nederlandsch Oost-Indië: 272–357, maps and plates. Leiden, 1921.

Brouwer, H. A. Geologische Oversichtskaart van den Nederlandsch Oost-Indischen Archipel. *Jaarb. mijnwezen* Nederl. Oost-Indië **44**, *Verh.* **2**: 272–354, 7 maps. Batavia, 1917.

——. The geology of the Netherlands East Indies, *Univ. Michigan Studies, Sci. Ser.* **3**: xii + 160, 18 pl., 17 fig., 1925.

——. The major tectonic features of the Dutch East Indies. *Jour. Washington Acad. Sci.* **12** (7): 172–185, 1922.

Gogarten, E. Die Vulkane der nördlichen Molukken. *Zeitschr. f. Vulkanologie, Ergänzungsb.* **2**: 1–298, 1 map, 1918.

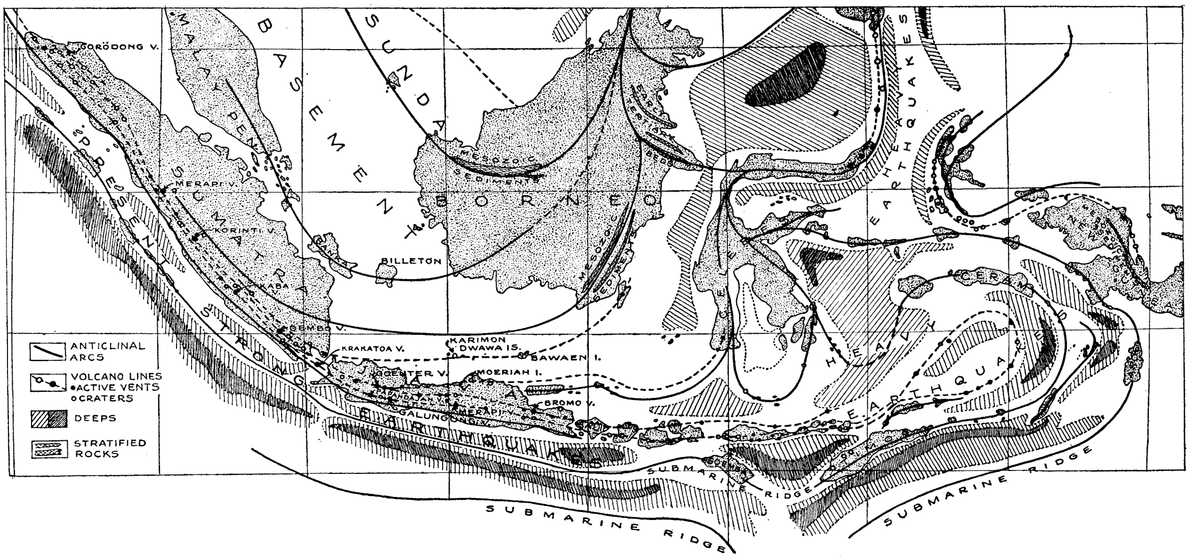
Hobbs, W. H. The unstable middle section of the island arcs. *Gedenkboek Verbeek Verh.* (*Supra cit.*, footnote 16).

Rutten, L. M. R. *Voordrachten over de Geologie van Nederlandsch Oost-Indië:* 1–839, illus. Groningen and The Hague, 1927.

Vening Meinesz, F. A. *Relevé gravimétrique maritime de l'archipel indien. Relation entre l'intensité de la pesanteur et l'activité tectonique de l'écorce terrestre.* (Publication de la Commission géodésique néerlandaise.) Pp. 1–6, map. Delft, 1931.

——. Modern deep-sea research in the East Indian Archipelago. *Geog. Jour.* **58**: 95–121, map, 1921.

Umbgrove, J. H. F. Over het Ontstaan van den Indischen Archipel. *Tijdschr. Kon. Nederl. Aardrijkskundig Genootschap*, ser. 2, **52**: 17–24, map, 1935.



Map 27. The principal arcs of the Sunda-Banda system. (Based on *Atlas van Tropisch Nederland*, 1938.)

Fig. 29. Geological section across Java. (After Verbeek and Fennema.)

of New Guinea; thence it turns westward through Misool, Obi-eil, and Soela into the middle eastern prong of Celebes.

The lines of active volcanoes follow closely parallel to the latest formed anticlines—the submarine ridges which have today the heavy earthquakes. The gap in the line of active vents north of Timor is apparent only since they are covered by reef caps.[37] Farther back are lines of extinct vents which correspond to the older anticlines on the larger islands. The lavas from the series of young volcanoes near the southern coasts of the larger islands are exclusively andesites and rather generally augite andesites. The older volcanoes near their northern coasts, though in association with older andesitic eruptions, reveal that their later effusions were more varied and especially alkaline.[38]

The southern coasts of Java and Sumatra are marked by elevated strands in terraces, but these show downward as well as upward adjustments of the coast. On the Java south coast there is a strand of Miocene age at an elevation of nearly 1,000 meters and a strand of Upper Eocene age near present sea-level.[39] There are extensive barrier reefs off the north coasts of the smaller Sunda islands (Bali, Lombok, Soembawa, Flores, Soemba), but nowhere do they occur on the southern coasts.[40]

10. THE ARC SUCCESSION IN THE PHILIPPINE-SUNDA-BANDA ARC SYSTEM

As may be seen from maps 24 and 26, the Philippine and the Sunda-Banda arc systems are parts of a common complex, for the easternmost and latest anticline of the former, with its volcano line on the west, continues through the two

---

[37] Brouwer, H. A. On the non-existence of active volcanoes between Pantar and Dammer (East Indian Archipelago), in connection with the tectonic movements of the region. *Proc. Kon. Akad. Wetensch. Amsterdam* 21 (6–7): 795–802, 1917.

——. On reef caps. *Ibid.*, pp. 817–826, 1918.

——. Ueber Gebirgsbildung und Vulkanismus in den Molukken. *Geol. Rundschau* 8: 197–209, 1917.

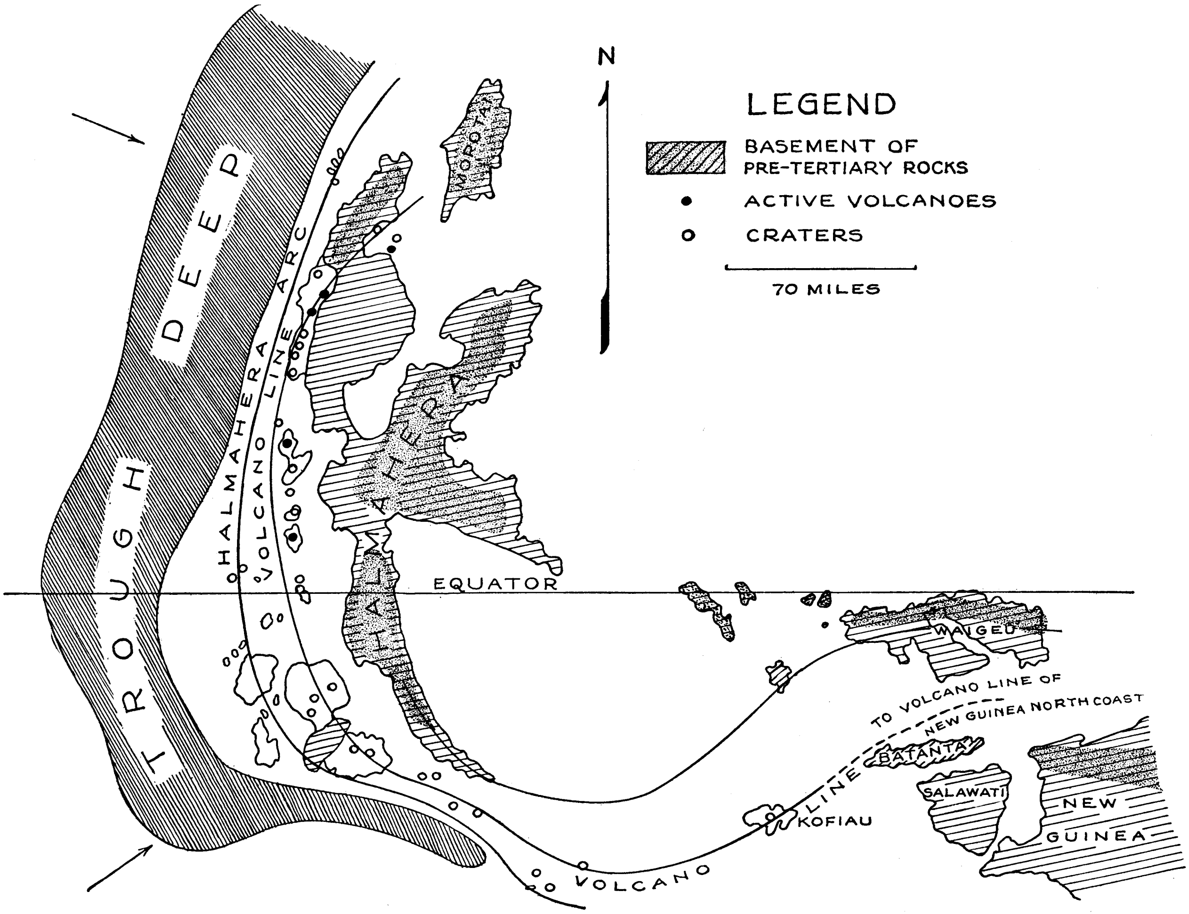
[38] Rinne, F. Beiträge zur Petrographie der Minahassa in Nord-Celebes. *Sitzungsber. k. preusz. Akad. Wiss. Berlin* 24: 474–503, 1900.

Brouwer, H. A. Ueber leucitreiche bis leucitfreie Gesteine vom Gunung Beser. *Centralbl. f. Mineral., Geol. u. Paläont.* 1914 (1): 1–7, 1914.

[39] Martin, K. *Sammlungen des geologischen Reichsmuseums in Leiden*, N. F., Ser. I, 9: 73, 1914.

——. Mesozoisches Land und Meer im indischen Archipel. *Neues Jahrb. f. Mineral., Geol. u. Paläontol.* 1: 107–130, 1907.

[40] Niermeyer, J. F. Barriere-riffen en Atollen in de Oost-Indiese Archipel. *Tijdschr. kon. Nederlandsch Aardrijksk. Genootschap*, ser 2, 29: 881, 1912.



Map 28. The Halmahera arcs.

northeastern prongs of Celebes in the system of the latter. The arcs of Halmahera to the eastward are not represented in the Philippines, but form the connection with the outer series of arcs which started southward from the "elbow" of Japan and was continued through the Bonin, Iwo, Marianne, Yap, Pelew and Sonsol arcs to this junction with the Sunda-Banda system (map 28). They also form their junction[41] with the Bismarck Archipelago and its continuation eastward and then southward as far as New Zealand. The excessive compression of the Banda section of the Sunda-Banda arc system—it subtends an angle of no less than 212°—seems clearly to be due to thrusts coming mainly from the northeast and the southwest, with partial protection afforded at the front by the Papuan and Australian coigns (see map 26).

11. THE BISMARCK ARCHIPELAGO-SOLOMONS-NEW HEBRIDES ARCS

Comparable to the Banda arc in the measure of its compression is the Bismarck Archipelago[42] section of the arcs lying to the eastward, but the former was nearly symmetrical, whereas the Bismarck Archipelago has an entire lack of bilateral symmetry. The positions of anticlines, troughs, and volcano lines, and those of the terraces and reefs as well, clearly indicate that the arcs here face to the southeast, and that the major of the two opposing thrusts came from that direction (map 29).

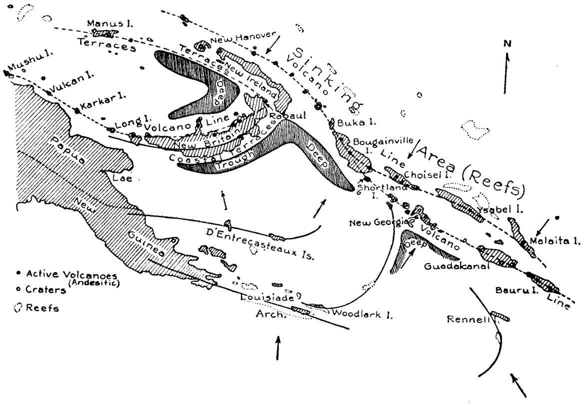
Within these arcs there is the evidence that in late Pliocene to Recent times the islands have

---

[41] Gogarten, E. Die Vulkanen der nördlichen Molukken. *Zeitschr. f. Vulkanol.*, Ergänzungsb. **2**: 1–298, 1 pl., 1918.

[42] For the most detailed large-scale map of this archipelago, see R. H. R. Parkinson, *Dreisig Jahre in der Südsee, Land und Leute, Sitten und Gebraüche im Bismarckarchipel und auf den deutschen Salamoinseln.* Stuttgart: 1–876, 56 pl., 141 fig., 4 maps, 1907. (Double-page map of New Britain at p. 20 and of New Ireland at p. 248.)

risen from the deep sea a distance of at least a mile and a half, for marine deep-sea deposits containing shells of pteropods and *Globigerina* are found interbedded with the Recent volcanic tuffs and agglomerates. Today earthquakes bring about uplifts and subsidences equal to any in the world, and the coasts bob up or down in accelerated tempo.



Map 29. The Bismarck Archipelago - Solomons arcs.

When in the early 1880's Guppy visited the Solomons,[43] Treasury Island, which lies southwest of Choiseul, had been uplifted 5 feet during an earthquake, and a little earlier 7 to 8 feet. On Ugi Island, 400 miles away, there had been a drop of 15 feet. Earlier, however, the coast had risen to reveal a marine terrace at an elevation of 200 feet. On Treasury Island reef-capped terraces are at an elevation of 400 feet. Evan Stanley, after his second visit, this time with the Campbell Brown Expedition, stated that in the then recent earthquake the southern coast of New Britain had risen 20 feet, at the same time that the northern coast had sunk 2 feet.[44] In an earlier published report[45] he had written:

> New Britain is the axis of an old fold . . . which has suffered tilting from south to north. As the northern coast line subsided, volcanoes built up deposits of tuff, cinder and lava to an average height of about 3,000 feet. . . . Along almost the entire length of the southern coast line terraces of coral limestone and raised beaches may be seen up to altitudes of at least 1,500 feet.

The volcanoes erupted mainly augite andesites. Lavas and volcanic agglomerates were deposited and interbedded with marine sediments, Pliocene marls and grits, to indicate they erupted in the Pliocene and later. In New Ireland the sediments are folded "outward"—as in New Britain the facing is to the south.

In the Shortland Islands of the Solomons, pteropod ooze of deep-sea origin overlies the andesite lava, and this indicates that these islands must have been elevated from 4,500 to 6,300 feet, or probably about a mile. Bauru (San Christoval) Island at the extreme southeast end of the Solomons is 70 miles long and rises to an elevation of 4,100 feet. The coastal rim is a reef-capped wave-cut terrace 15 to 20 feet above sea-level, probably raised during a single earthquake, and such terraces extend upward to about the 500-foot level. On the south side the island rises precipitously, the front of the arc. The core of the island is of plutonic igneous rocks (diorite, gabbro, diabase, etc.), covered by volcanic extravasations.[46]

Bougainville Island at the opposite end of the Solomons is 110 miles long and 30 miles wide, and its volcanic peaks attain elevations of 7,000 to 10,000 feet.

Guadalcanal appears to have a core of plutonic rocks, like its neighboring island of Bouru, with volcanic cones reared above them. It is 80 miles long and 25 miles wide and has rivers flowing on flatter country on the northern side.

Florida Island, to the north of and near Guadalcanal, gives evidence by its excellent harbor that it has undergone a recent subsidence. It is largely made up of andesitic tuffs with reef cappings over foraminiferal limestones up to elevations of 900 feet.

Our knowledge of the New Hebrides is based largely on the explorations of Sir Douglas Mawson.[47] The history of these islands is one of almost continuous uplifts. According to Mawson, landslips in the soft rock of the mountains are almost continuous. Almost everywhere are elevated wave-cut terraces. On Santo they go

---

[43] Guppy, H. B. Observations on the recent calcareous formations of the Solomon group made during 1882–4. *Trans. Royal Soc. Edinburgh* **32**: 545–581, 2 pl., 1885.

——. Notes on the characters and mode of formation of the coral reefs of the Solomon Islands, etc. *Proc. Royal Soc. Edinburgh* **13**: 857–904, 1886.

——. *The Solomon Islands, their geology*, etc. London: 1–152, map and plates, 1887.

[44] Reported to the Second Pan-Pacific Science Congress convened in Australia in 1923.

[45] Stanley, Evan R. Notes on the structural relationships of the volcanic rocks, late Tertiary and Mesozoic deposits of New Guinea. *Rept. Australasian Assoc. Adv. Sci.*, **16**: 285, 1923.

[46] Marshall, Patrick. Oceania. *Handb. Region. Geol.* **7** (2), Heft 9: 17, fig. 6, 1911.

[47] *Proc. Linnean Soc. New South Wales*, 1905.

up to elevations of 1,000 feet, and in the Torres group they occur throughout, or up to 1,230 feet. Efate also is terraced to its crest at 700 feet. Between the New Hebrides and the Solomons lies the Santa Cruz island group with similar characteristics.

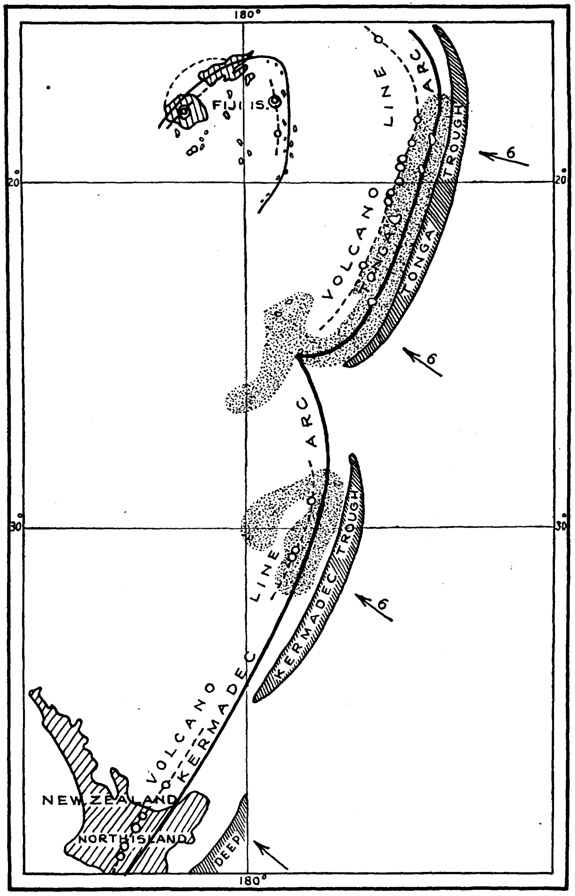
New Caledonia, which lies to the southward of the New Hebrides, is by contrast to them relatively stable. It represents the earlier anticline, while the New Hebrides constitute a near parallel one of more recent elevation, and now offer it protection from a major thrust which comes from the broad expanse of the Pacific lying to the northeast. Between lie the Loyalty Islands, and they, like New Caledonia, have a trough to the northeast as a facing. The Solomons at the west received their major thrust from the south and faced in that direction; but here farther to the east the major thrust was from the northeast with the facing of the arc in that direction. For the Solomons the thrust from the north may have been held off by the Carolines, Marshalls, and Gilberts, whereas for the New Hebrides no such shield existed.

12. THE TONGA-KERMADEC ARCS

The Tonga-Kermadec arcs to the northward of New Zealand face east-southeastward across a vast expanse of deep sea which is without obstruction as far as remote South America. In this respect these arcs resemble the Marianne arc, and like it they are in a youthful stage, are nearly rectilinear, have profound narrow troughs at the front and lines of steep-to volcanoes at the back (map 30).

Southward the Kermadec arc is continued into the easternmost arc of the North Island of New Zealand (map 31), and northward the Tonga arc probably makes connection with the New Hebrides section of the Bismarck Archipelago - Solomons - New Hebrides arcs (map 32), through a now submerged compressed arc like the Fiji arc and off its front.

Our knowledge of the Tonga geology is due largely to Lister,[48] and of the Kermadec arc, to Oliver and Speight.[49]



Map 30. The Tonga-Kermadec arcs, with their relationships to New Zealand and to the Fiji arc.

The Tonga anticline takes its course in the normal way through a front line of islands which rise to an elevation of 500 feet and are composed of sediments, and these are faced by a staircase of terraces, reef-capped and with broad plateaus at the top. Between this frontal anticline and the line of steep-to volcanoes at the back, there is a middle line of islands made up of volcanic tuff laid down in the sea and lacking the frontal terraces of the front-line islands. Like the sediments of the Bismarck - New Hebrides anticlines, which were reared far out from a continental slope and had therefore to form their wrinkle on the floor of the deep sea, the sediments of the Tonga-Kermadec arcs are deep-sea sediments.

The Fiji, Tonga, and Kermadec arcs are all loci of heavy earthquakes which have accompanied the later adjustments in the anticlines. Angenheister,[50] who has mapped their distribu-

---

[48] Lister, J. J. Notes on the geology of the Tonga Islands. *Jour. Geol. Soc. London* **47**: 590–617, 1 pl., figs., 1891.

[49] Oliver, W. Reginald B. The geology of the Kermadec Islands, *Trans. New Zealand Inst.* **43**: 524–535, 4 pl., 3 fig., 1911.

Speight, R. Petrographical notes on the rocks of the Kermadec Islands. *Ibid.* **42**: 242–254, 1909.

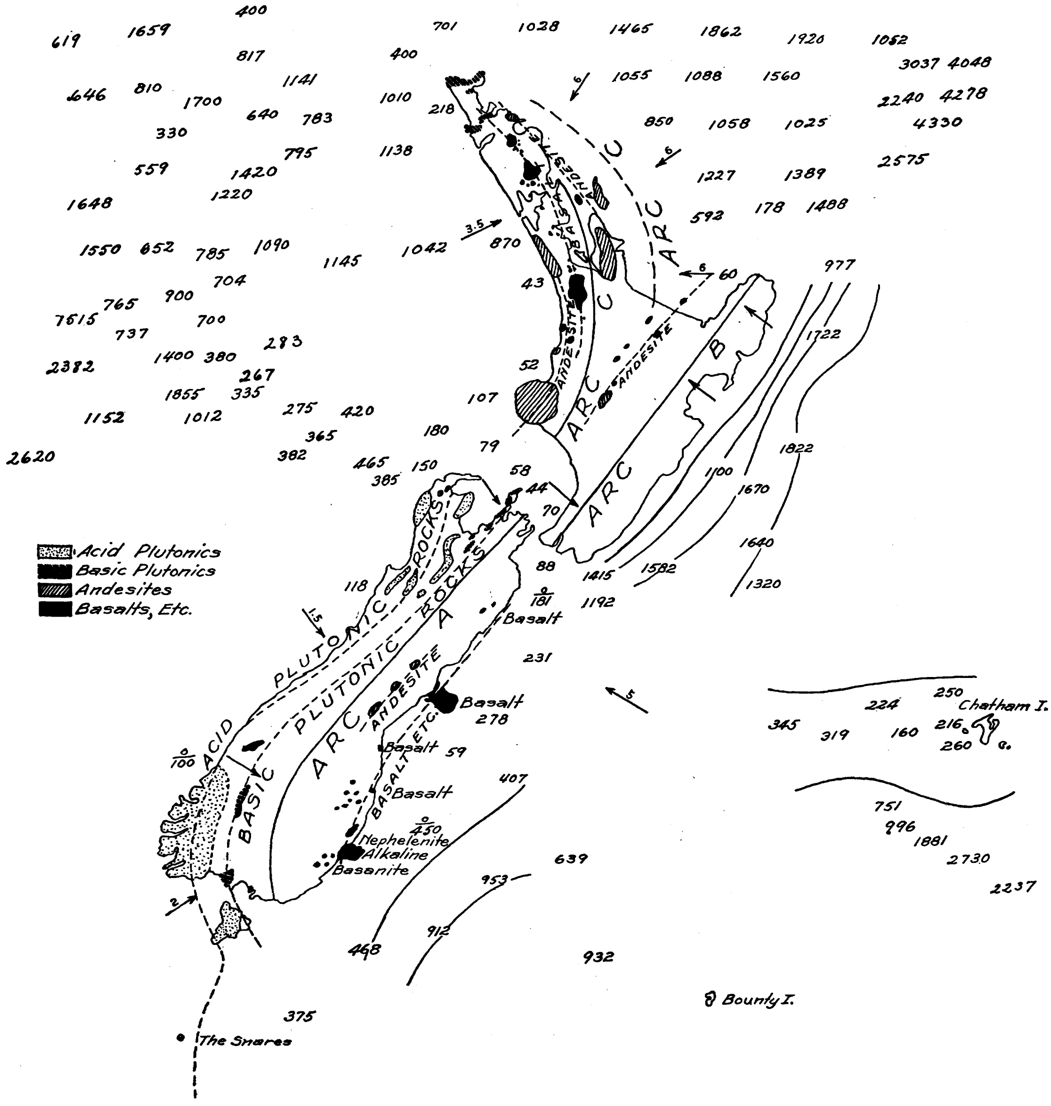
[50] Angenheister, G. A study of Pacific earthquakes. *New Zealand Jour. Sci. and Tech.* **4** (5): 210–235, map, 1921.

tion, has shown that the strongest earthquakes have occurred on the undersea portion of the outer limbs of the Tonga and Kermadec anticlines. Another seismic zone of much importance is in the eastern wing of the Fiji arc. Samoa, near but located outside the belt of arcs and on the broad sinking floor of the Pacific, is relatively stable. The southwest wing (Vitilevu) and also that side of the Tonga arc (Tongatabu) have sunk.[51] However, it has been clearly shown[52] that the algebraic sum of the oscillations, upward and downward, in the Fiji group of islands since Pleistocene time has been an extensive uplift.

13. THE NEW ZEALAND ARCS

New Zealand, a considerable land mass with mountains in excess of 12,000 feet elevation, and containing a core of sediments as old as the Cambrian, does not lend itself to a wholly satisfactory treatment of its mountain history by the methods of arcuate study alone.

The South Island, which exposes the core of ancient rocks within the deep fjords and valleys of the southwestern highland (Southern Alps), is



MAP 31. The arcs of New Zealand. Ocean depths are in fathoms.

---

[51] Ladd, Harry S., and J. Edward Hoffmeister. Recent negative shift in the strand line in Fiji and Tonga. *Jour. Geol.* **35** (6): 442–556, 14 fig., 1927.

[52] Foye, W. G. Geological observations in Fiji. *Proc. Am. Acad. Arts and Sci.* **54**: 145, 1918.

somewhat set off from the North Island, which is connected up directly with the Kermadec arc only some 500 miles away. Here the dominant thrust which produced the arc came from the east (arc *B* of map 31), with a trough at the front and a line of andesitic volcanoes at the back.

The northwestern prong of the North Island by its convexity of curvature (dotted arc *C*) indicates that the thrust which reared it came from the northeast, and it faces there a great expanse of the Pacific, extending to the Americas. A line of lava extrusions from andesitic volcanoes is in a rear position. This anticline (dotted *C*), if ever pushed up above the sea, has since subsided; but behind it, following the course of a mountain backbone of the peninsula, is a parallel volcano line which has exuded basaltic lava of a later series. This is represented farther to the northwest by the corresponding granitic types of deeper-seated origin. A later and at the time dominant thrust came from the sea lying to the southwest. This might explain the andesitic effusions found along the southwest shore of the peninsula, and perhaps also some of the basaltic lavas along its medial line.[53]

The South Island is separated from the North Island by a great transverse fault in Cook Strait, along which the North Island has been shifted to the southeastward. In this older land mass to the south the structure reveals that the thrusts which raised the islands came in the northern section, where there was shielding from South Sea thrusts by the coign of Australia. Farther south no such shield was interposed, and heavy thrusts came in in a west-southwest direction from a vast expanse of sinking sea. This has produced a convex face of the arc *C* (map 31) in that direction.

The first anticline to rise produced the lofty range of the Southern Alps, now deeply dissected in the great fjords and deep valleys of the southwest. Of the volcano lines of this arc we can find only the roots—the granitic textured rocks of acid, basic, and ultrabasic stocks which, laid bare by the deep dissection, reveal the reservoirs only from which the earlier volcanic vents were supplied. In the secondary arc which was later erected at the rear (figs. 14 and 16), the front line of andesites and the rear one of basalts are both present, the latter following closely the line of the coast.

PART III, THE SINKING PACIFIC FLOOR

1. THE LAVA EFFUSIONS

With New Zealand, the long and in part double line of young mountain arcs beginning at Japan comes to an end at least so far as visible evidences are concerned. Across the South Seas beyond New Zealand lies that part of the Antarctic continent which, least known of the unknown, is yet thought to be like other parts of South Victoria Land, a block-faulted region.

To the eastward of the arcs which have now been passed in review lies the vast central area of the Pacific Ocean, in area nearly a third of the superficies of our planet. In sharpest contrast to the arcuate islands, those of the central Pacific area are without noteworthy alignment, though distinguished geologists, beginning with J. D. Dana, mixing arcuate islands with the others, have with rather indifferent success sought to arrange them in series of parallel straight lines regarded as fractures. All the islands are either volcanoes or atolls, now generally regarded as volcanoes, which have subsided as earlier reefs have risen over them to form the atolls.

When the lavas which these mid-Pacific volcanoes have erupted are subjected to petrographical and chemical study, it is found that they are in sharpest contrast to those from arcuate mountains. As we have seen, the arcuate mountain lavas of all earlier effusions are andesites, and nearly always pyroxene (augite) andesites. Sometimes a non-aluminous pyroxene (hypersthene) in part replaces the aluminous pyroxene (augite). It is the later extrusions only which in the case of arcuate mountains show variation from the rule that they are exclusively andesite—of intermediate chemical composition.

The lavas erupted from islands of the mid-Pacific are exclusively non-intermediate in composition; they are basic—basalts. Sometimes they are also alkaline as well, and, if so, the alkali constituents are either sodium or potassium, which are present largely in the minerals nephelene or leucite (see map 3).

Already convinced that the artificial distinction made by petrographers between "Atlantic"

---

[53] For the geology and geography of New Zealand see the following works:

Park, James. *The geology of New Zealand*, etc. Christchurch: 1–488, 27 pl., 145 fig., col. geol. map, 1910.

Marshall, P. *The geography of New Zealand.* Rev. ed. Christchurch: 1–447, illus. (no date).

Cotton, C. A. *Geomorphology of New Zealand, pt.* 1, *systematic.* Wellington: 1–462, illus., 1922.

Marshall, P. The igneous rocks of New Zealand. *Gedenkboek Verbeek* (*supra cit.*, footnote 16): 357–367, 1925.

and "Pacific" igneous rocks had been falsely based, in 1921, with the aid of Miss Ellen Stevenson, then instructor in geology at the University of Michigan, I assembled the chemical analyses of arcuate mountain lavas from the Pacific belt (776 separate approved analyses) and prepared the composite arcuate mountain lava.[54] This composite was found to be chemically closely in correspondence with the average mudstone or shale (see *antea*, p. 233, concerning a probable fusion of shale beneath a competent arch in a rising anticline).[55, 56]

The contrasts and parallels appear in the following table:

	Arcuate Mountain Lava				Fault Block Lava			
	1	2	3	4	1′	2′	3′	4′
SiO_2	58.29	59.09	56.69	57.76	49.52	47.62	47.92	42.74
Al_2O_3	16.97	15.35	16.47	15.22	15.89	15.20	13.59	11.13
Fe_2O_3 FeO	6.94	6.88	2.67 4.87	6.74	11.50	4.50 8.85	2.80 9.67	3.96 9.66
MgO	2.83	3.49	5.07	2.76	5.04	4.90	6.04	11.63
CaO	6.06	5.08	9.06	3.07	7.27	8.42	9.20	13.04
Na_2O	3.55	3.84	2.08	1.25	4.03	3.20	2.98	2.64
K_2O	3.20	3.13	0.43	3.21	2.18	1.25	1.67	1.20
Others	2.16	3.14	2.23	9.99	4.57	5.69	5.96	4.35
	100.00	100.00	99.72	100.00	100.00	99.63	100.04	100.35

1. Arcuate mountain (fold) lava. Composite of 776 analyses.
2. Average magma. Composite of 5,602 analyses.
3. Andesite, Malakal Island, Pelews. Analyst, B. A. Soule.[56]
4. Average shale. Composite of 114 analyses.

1′. Fault block lava. Composite of 188 analyses.
2′. Basalt lava, Moen Island, Truk Archipelago. Analyst, B. A. Soule.[56]
3′. Basalt lava, Chogach Rock, Ponape. Analyst, B. A. Soule.[56]
4′. Basalt lava, From Lele Island, Kusaie. Analyst, R. K. McAlpine.[56]

A possible explanation of the basic character of the fault-block lavas is suggested by their origin in the adjustments in position of blocks within a mosaic at the time of earthquakes. Though in a sinking area where the average movement is a downwardly directed one, there are yet certain blocks which with regard to their immediate neighbors move upward, or at least downward by a smaller amount (fig. 30, lower profile). Moved relatively upward, the heavier upper strata of the block separate from the lower, only to be immediately caught in the jamming compressional thrust. This tends to hold the upper beds suspended as in a vice, lifting the load in part from the lower and inducing fusion. Later the load is applied to the fused mass, tending to lift it to the surface along a marginal fracture.

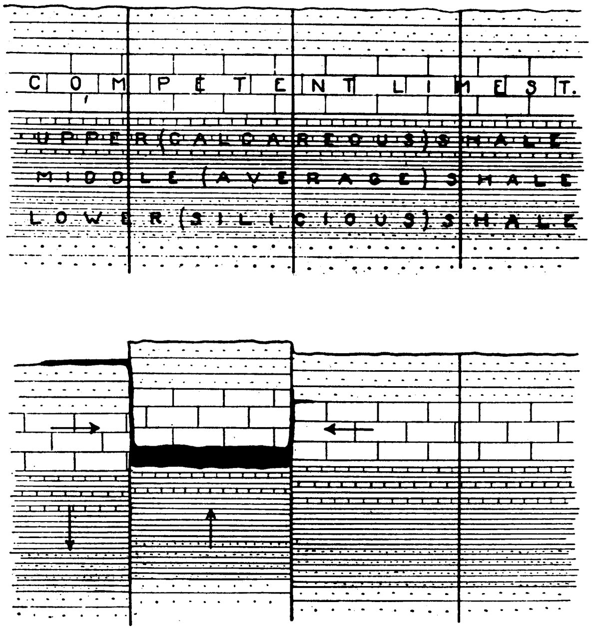


FIG. 30. Diagrams to illustrate a possible origin of fault-block lavas.

2. THE PARTITION LINE BETWEEN MOUNTAIN ARCS AND THE SINKING FLOOR

That a sharply defined boundary separates the area of arcuate mountains from that of the sinking Pacific floor off its front, was first recognized by Marshall,[57] and by the present author[58] it was extended to Japan (map 32).

---

[54] Hobbs, W. H. Lava composition in relation to earth physiognomy. In: *Earth evolution and its facial expression*, ch. xiii, especially pp. 171–173, 1921.

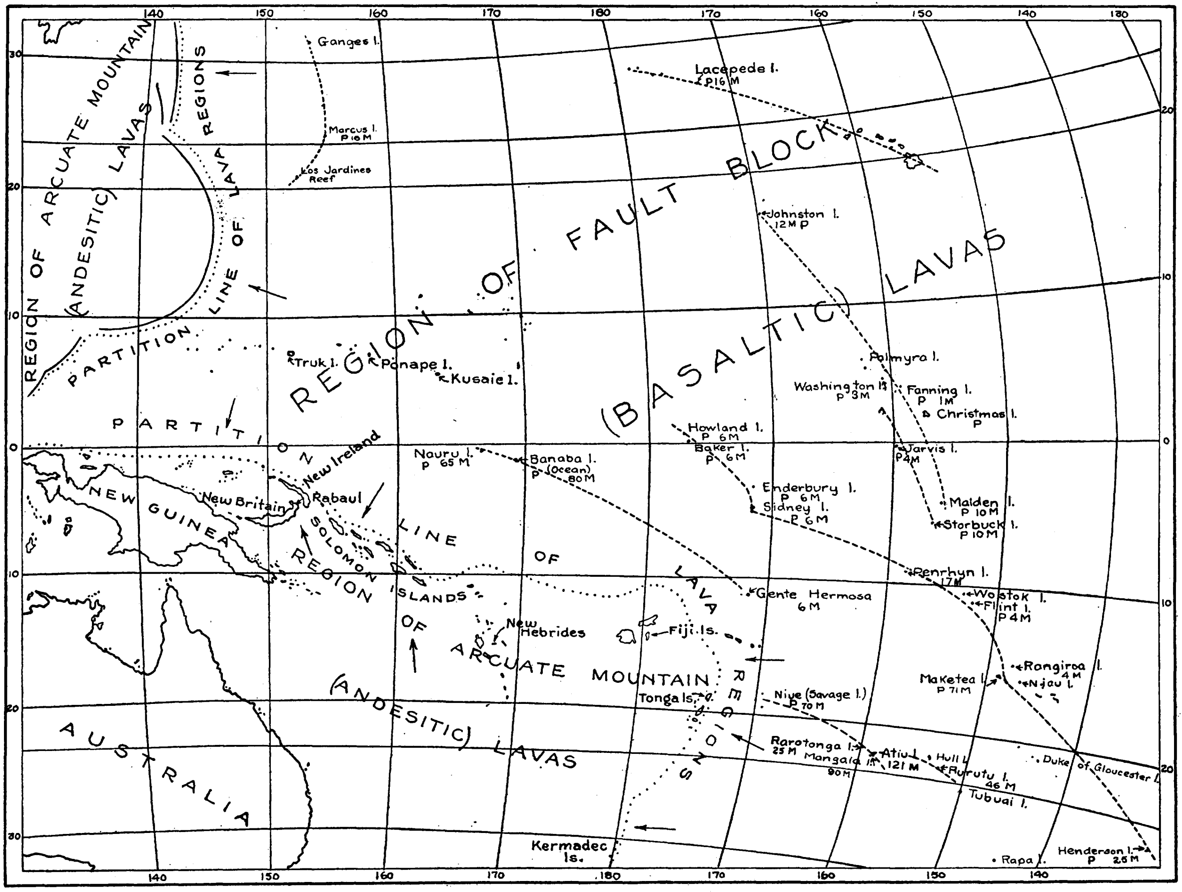
——. Contrasted lava types of the Pacific region. *Second Pan-Pacific Sci. Cong., Australia*, **1923**, **1**: 838–842, 1926.

[55] Hobbs, W. H. *Earth evolution and its facial expression*, chap. iii. New York, 1921.

[56] Hobbs, W. H. and W. F. Hunt. Petrography of an area in the western Pacific. *Proc. Third Pan-Pacific Sci. Cong., Tokyo*, **1926**: 715, 1927.

[57] Marshall, P. Ocean contours and earth movements in the south-west Pacific. *Rept. and Proc. Australasian Assoc. Adv. Sci., 12th Meeting, Brisbane, Sec. E:* 432–450, folding map, 1909.

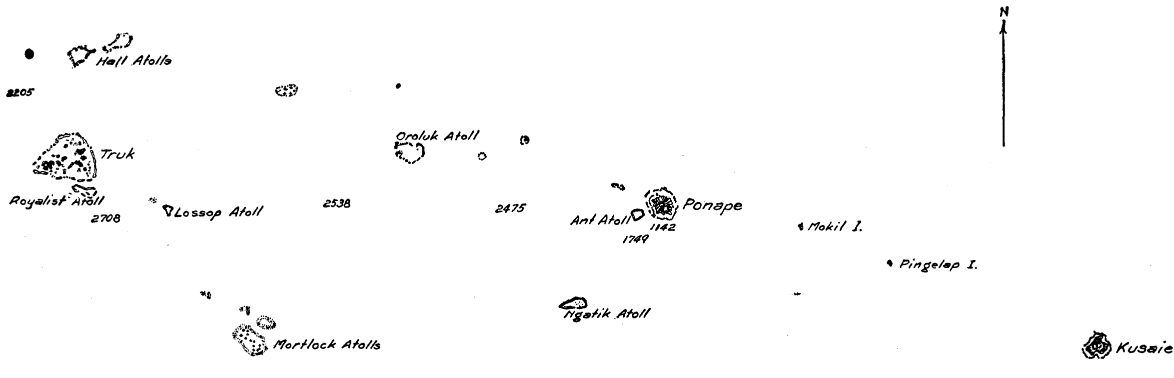
[58] Hobbs, W. H. Contrasted lava types of the Pacific region. *Proc. Second Pan-Pacific Sci. Cong., Australia*, 1923, 1: 842, 1926.



MAP 32. The regions of arcuate mountains with andesitic lavas contrasted with the region of fault-block adjustments with basaltic lavas.

3. BASALTIC VENTS IN THE SOUTHWESTERN PACIFIC FLOOR

Scattered throughout the broad expanse of the sinking Pacific floor are volcanic lava mountains which rise on steep slopes from generally profound depths. The slopes may in some cases be as high or higher than 30°. Of atolls, which are believed to be based on volcanoes, there are literally swarms, as, for example, in the Tuamotu or "Dangerous" Archipelago, and in those of the Gilberts and Marshalls. Much the most extensive of the lava islands are those of the Hawaian

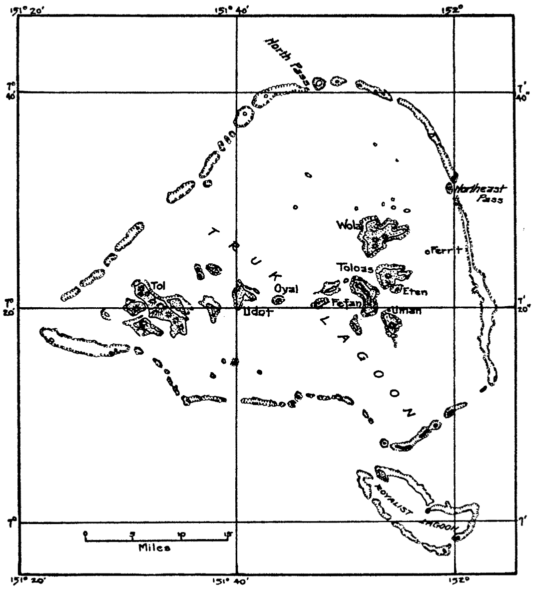


MAP 33. Map of the eastern Caroline Islands—the lava islands of Truk, Ponape, and Kusaie with associated atolls.

group, but the most important in the western section are those of the eastern Carolines—Truk, Ponape, and Kusaie (map 33).

4. TRUK

Of the basaltic volcanoes in the Caroline group, the largest is Truk, the great naval base of Japan. Among volcanic islands it is unique. It consists of an outer reef, the emergent portions of which rise at most 10 to 15 feet above the sea. The enclosed lagoon is roughly triangular, and 30 to 40 miles across. There are four entrances for vessels, two of which are indicated on map 34. The others are at the south and west.



MAP 34. Archipelago of Truk and the neighboring Royalist Atoll. The conical lava islands within the lagoon have fringing reefs. The lagoon has depths of generally more than 25 fathoms and less than 50 fathoms, and there are many reef islands.

FIG. 31. Characteristic lava islands in the Truk lagoon. At the right is Eten, now truncated for an air field, and at the left Uman. (Pen sketch by Shaw from a photograph by the author made in 1921.)

The character of the ten islands of massive olivine basalt within the lagoon is indicated in figure 31. Other sectional panoramic profiles, made from the ship when east of the eastern passage through the reef, and from 5 miles north of the north entrance, are reproduced in figures 32 and 33, respectively.

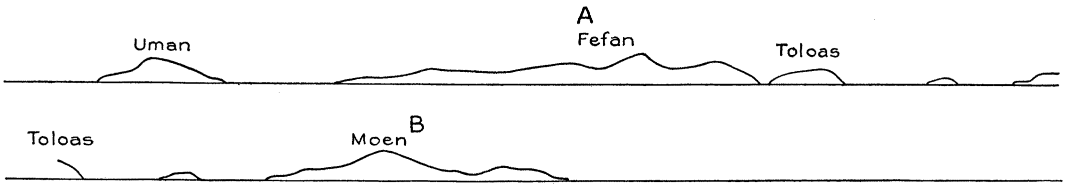


FIG. 32. Sketch of Truk, looking west from ship east of eastern passage. (*B* is continuation of *A* northward.)

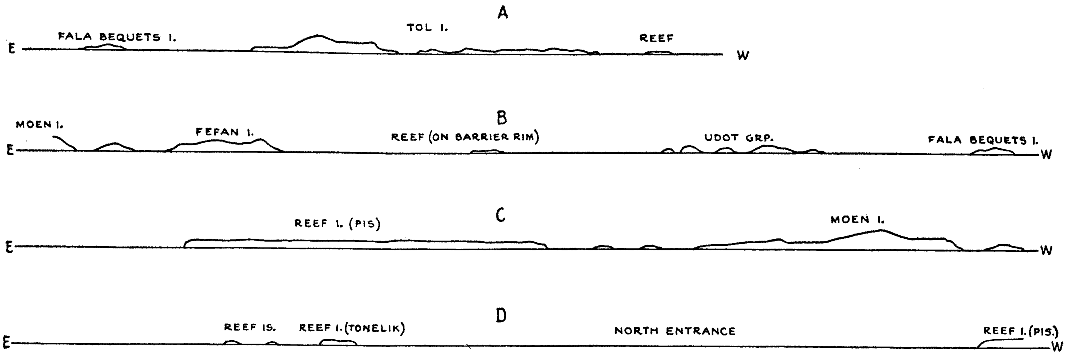


FIG. 33. Panorama of Truk from ship about 5 miles north of north entrance.

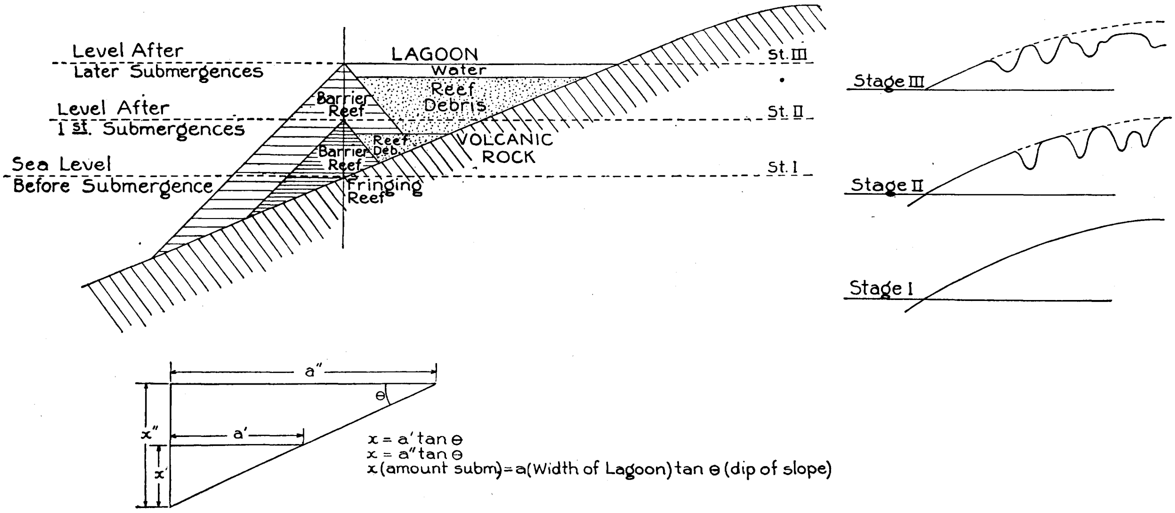


FIG. 34. Profiles of the encircling reef development and of the denudation of the lava dome of an earlier Truk Island, represented in three consecutive stages.

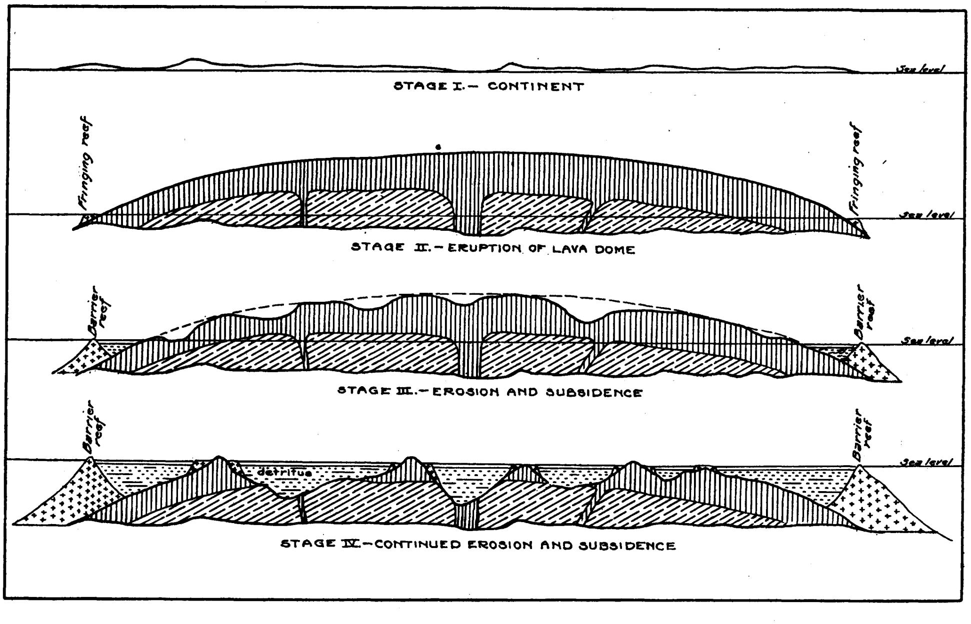
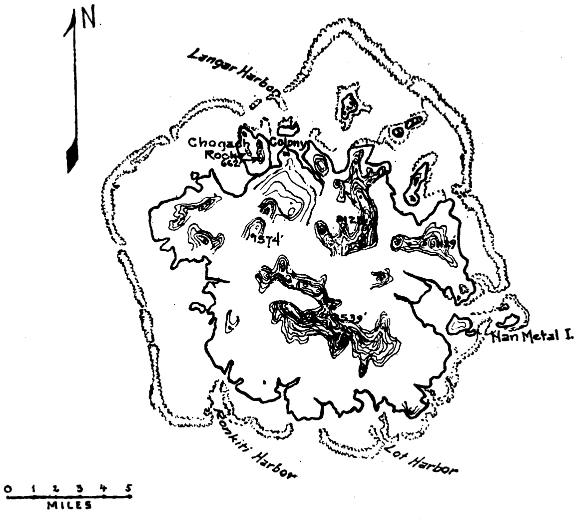


FIG. 35. Profiles to show stages through which an original Truk Island has passed to produce the present archipelago through reef formation, degradation of the lava dome, and subsidence.

The origin of the Truk Archipelago is explained through reef growth, denudation, and continued subsidence of volcanic extravasations in the form of a lava dome. Arbitrarily chosen stages I, II, and III in the formation of the encircling reef about the dome and of denudation are represented in figures 34 and 35. In figure 34 an original low continental area is represented as receiving large extravasations of basaltic lava in the form of a dome (stages I and II). Settlement and upgrowth of the encircling reef has produced the dissected island of stage III, and by further subsidence the archipelago of stage IV, which exists today.

5. PONAPE

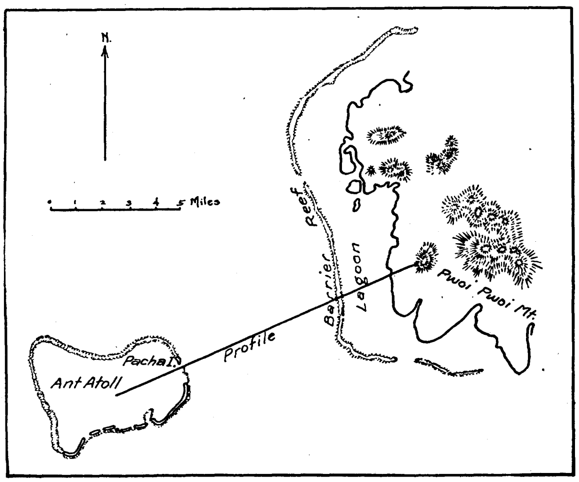
Ponape offers perhaps the world's most perfect example of an encircling or barrier reef. It sur-



MAP 35. The islands of Ponape in the eastern Carolines.

rounds this dissected lava dome, situated nearly on a direct line connecting Truk with Kusaie and somewhat east of the central position (map 35). Ponape has a maximum elevation of 2,579 feet and is made up of massive olivine basalt which grades into a nephelene basanite.[59] The principal entrance through the reef (and this admits large vessels) is at the north into Langar Harbor, the naval base under the dominating Chogach Rock, 937 feet high, which is cliffed on three sides, the north flank cliff actually overhanging (fig. 36*C*). Entrances through the reef which accommodate smaller vessels are off Ronkiti and Lot at the south of the island.

Compared with Truk, the degradation of the Ponape dome is small and the exudations which built it up must have been much later. This is confirmed by the lagoon width, which here averages only 2½ miles.



MAP 36. Western Ponape with Ant Atoll.

Off to the west-southwest of Ponape a distance of less than 10 miles is the perfect atoll of Ant (map 36). Because of the interesting relationship here displayed between a typical barrier reef and a typical atoll, soundings were undertaken and a section was made which extends from the summit of Pwoi Pwoi Mountain on Ponape to the center of the Ant lagoon (fig. 37).

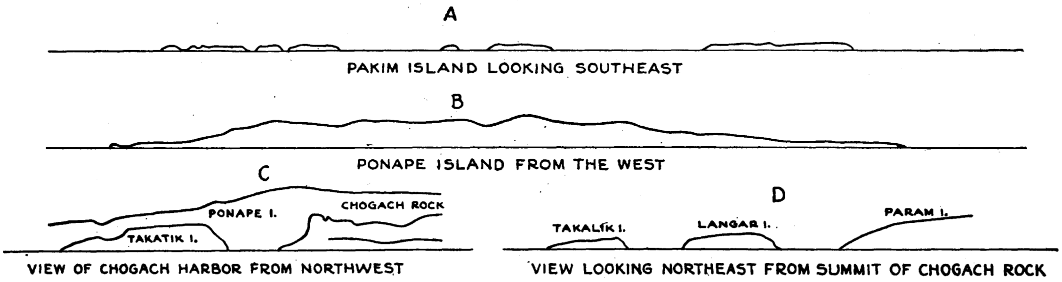


FIG. 36. Profiles of the island of Ponape. (From sketches by the author.)

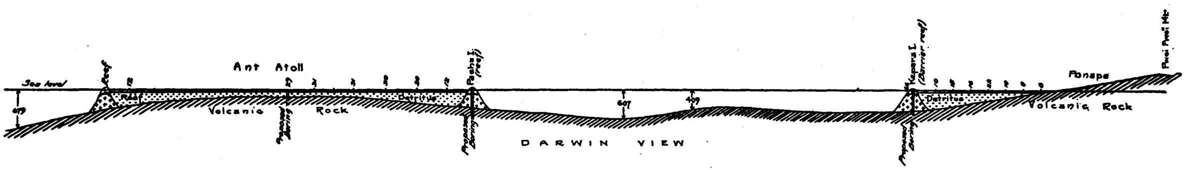


FIG. 37. Section from Pwoi Pwoi Mountain on Ponape to the center of Ant lagoon.

---

[59] Hobbs and Hunt, *op. cit.*

Also to display the striking contrast between the large degradation on Truk and the relatively small amount which Ponape has undergone, the profiles of figure 38 are given.

Though I did not ascend to the highest point of Ponape, I was convinced from conversations with Chief Nanpei of the Ronkiti tribe of natives, an educated native who speaks English, that the island is what its profiles proclaim it, a craterless lava dome. Its probable later history is indicated in figure 39.

6. KUSAIE

The island of Kusaie I did not visit, and I am therefore compelled to depend upon others for such knowledge as I have of it. The profiles in figure 40 are from photographs by various visitors to the island.

The lagoon of Kusaie is narrow, ½ mile to a mile in width, as against the 2½-mile-wide lagoon of Ponape and the very much wider one of Truk. The summit of Kusaie is relatively flat-topped and at an altitude of 2,100 feet. The island is, like Ponape, nearly circular in outline, here with an extension in an east-west line of 7 miles, and in a north-south line of 5 miles.

Captain U. Aoki, in command of the *Matsuyama Maru*, was good enough to collect a specimen of the lava from Lele Island near the harbor of Kusaie. This has been studied in thin section

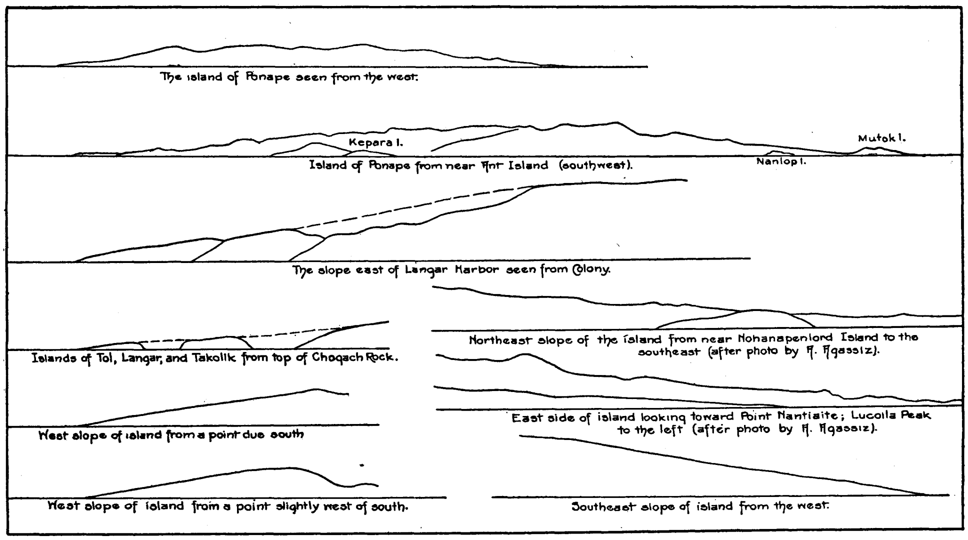


FIG. 38. Profiles of Ponape. (From sketches by the author.)

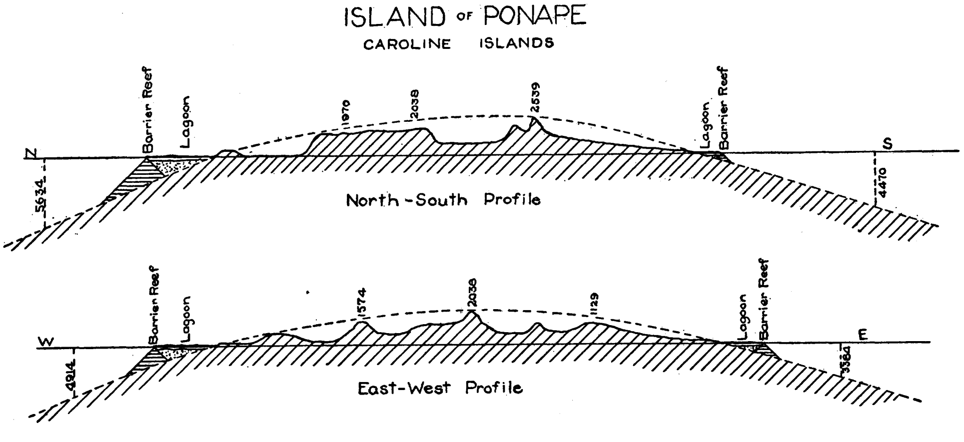


FIG. 39. Sections across Ponape.

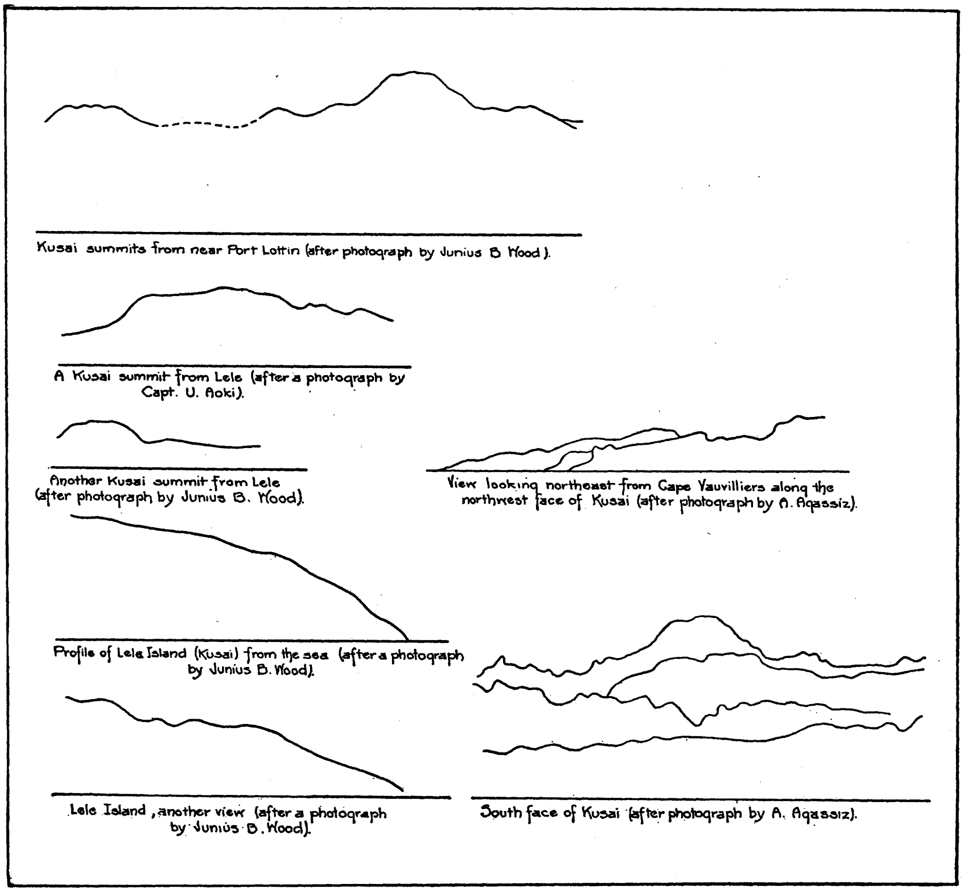


FIG. 40. Profiles of Kusaie, a lava dome in the eastern Carolines; Kusai in the figure should be Kusaie.

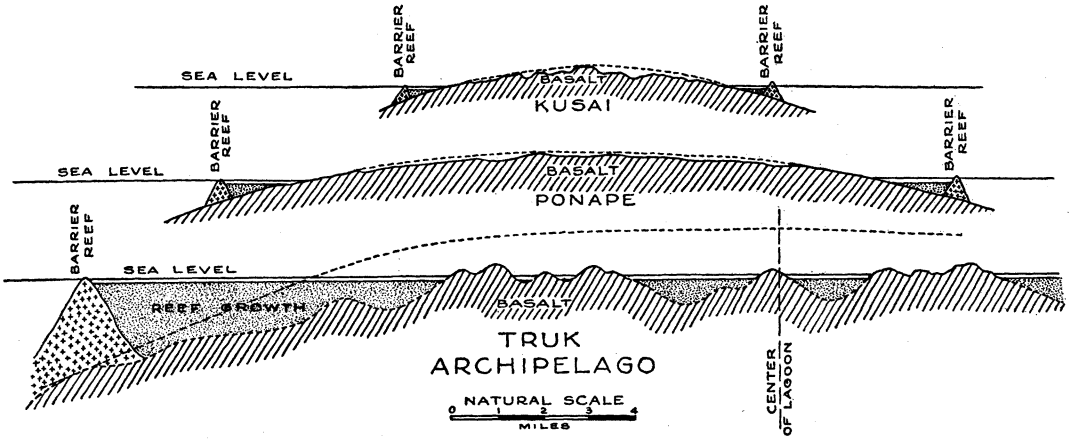


FIG. 41. Generalized profiles of the volcanic islands of the eastern Carolines; Kusai in the figure should be Kusaie.

by Hunt[60] and found to be olivine basalt, confirmed by the chemical analysis by R. K. McAlpine.

The three islands of Truk, Ponape, and Kusaie are represented by the generalized profiles on figure 41 to show their relationship.

7. SUMMARY AND CONCLUSIONS

There are two major types of mountains: (1) arcuate (folded) mountains, which form near the margins of vast subsiding areas, the basins of the oceans; and (2) extravasation mountains formed along fractures within the subsiding areas.

The arcuate mountains appear to develop where there is an initial dip in the surface of the ocean floor. The early pattern to rise is a series of arcs which are convex toward the subsiding area, from which the actuating thrusts are directed. In profile in the early stage they are made up of a flattish anticline behind a well-defined deep syncline, a trough of the sea. As the anticline evolves further, volcanoes rise at the back of the crest and exude lava of an intermediate composition, andesite—the composition of mudstone or shale. Terraces, which in tropical seas are veneered with reef limestone, are notched on the rising front of the anticline, while barrier reefs are forming on the sinking back. In later stages the arc is of sharpened curvature, and erosion mutilates more and more the model of its surface.

Within the Pacific region the youngest folded mountains compose a festooned rim which is marked by a belt of excessive seismicity and is sharply set off from the vast subsiding region at its front. This partition line, which separates mountains of the two major types in the southwest Pacific area, starts near Japan, continues east of the Marianne and Pelew Islands; then north of the Bismarck, Solomon, New Hebrides, and Fiji Islands; and, then turning southward, borders on the east the Tonga, Kermadec, and New Zealand Islands.

---

[60] Hobbs and Hunt, *op. cit.*