THE CENTURY EARTH SCIENCE SERIES

ARCHITECTURE OF THE EARTH

BY

REGINALD ALDWORTH DALY

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KIRTLEY F. MATHER, PH.D.
General Editor

ARCHITECTURE OF THE EARTH

By
REGINALD ALDWORTH DALY, PH.D.
Sturgis Professor of Geology
Harvard University

THIS is a very readable account of the make-up of the earth which affords a readily visualized picture of our planet. It is based on a new theory derived from forty years of research in the field, supplemented by continuous study of the world's geological and geophysical literature. It is the first book of its kind to give due weight to the latest and best results of investigations in both geology and earth physics.

The book presents an earth-model, analogous to the model atom of physics and the model star of astronomy, to illustrate the characteristics of the earth. In constructing this model the author takes into account both the earth's relief and the underground, invisible conditions which have created its surface characteristics. The author encourages independent thinking by comparing his model with other models built on theories different from his own.

Although primarily intended for use as a text in second-year college courses in general geology, physical geology, and structural geology, the book is of considerable interest and usefulness to chemists, physicists, engineers, and astronomers.

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PREFACE

The magical instruments of the astronomer reveal no element new to chemistry and show the earth to be a marvellously complete sample of the universe of matter, whether in planet, star, nebula, galaxy, or super-galaxy. Thus from earth science comes a better understanding of the universe. Geology, tracing the dramatic history of one of the celestial wanderers, deepens our concept of Time and still further broadens the foundation of a sound philosophy. Pierre Termier meant much when he wrote: "The earth declares the glory of God." He had devoted his life to a study of the stately processes that have governed the evolution of our globe through two billions of years. Yet, like other professional geologists, he found ordinary words inadequate for the new, unfamiliar ideas. Technical terms have had to be invented. Here is a difficulty when the geologist attempts to tell his story. Technicality puts a barrier between the specialists and the great public or even the beginner in the professional study of earth's history. For this trouble there is only one medicine—good-will. However, with good-will on both sides the geologist can share with others the thrills that spring from an incomparable moving picture.

The Norman Wait Harris Foundation of Northwestern University encourages effort of this twofold character: effort by the specialist to be an adequate reporter; effort by listener and reader to imagine truly the materials and processes that have made the earth what it is. The following pages represent the slightly expanded material of lectures on "The Crust of the Earth," given under the auspices of the Foundation in May, 1937. Special emphasis is placed on discoveries and clarifications made since the opening of the present century: crucially important discoveries by field geologists; clarifications due to the recent, spectacular growth of the young science of geophysics. More and more the exquisite tools of the modern physical and chemical laboratories are being used to guide the field naturalists in the interpretation of what he sees outdoors.

A leading purpose of this book is to summarize the new discoveries. There is offered to geologists and to other men of science a picture of the earth which has come out of a synthesis of facts, won by both observers in the field and their colleagues of the laboratory. The general reader will have trouble here and there in following an argument, but it is hoped that he too, without intolerable effort in an unfamiliar field, will be able to see how modern research is molding thought about our planetary home.

The writer wishes to record his appreciation of the great courtesy extended by Dr. T. W. Koch and other officers of the Harris Foundation and by members of the Geological Department of Northwestern University during the period of the lectures; also to Louise Haskell Daly and Professor Kirtley F. Mather for valued bettering of the manuscript, both in substance and expression; to Edward Schmitz for care in drafting many of the illustrations; to Dr. John M. Ide and Dr. Francis Birch of Harvard University for permission to quote new, in part unpublished records from their path-making researches on the physical properties of rocks; to various authors and publishers who have graciously permitted copying and re-publication of a number of drawings; and to others who have supplied original material for graphic illustrations.

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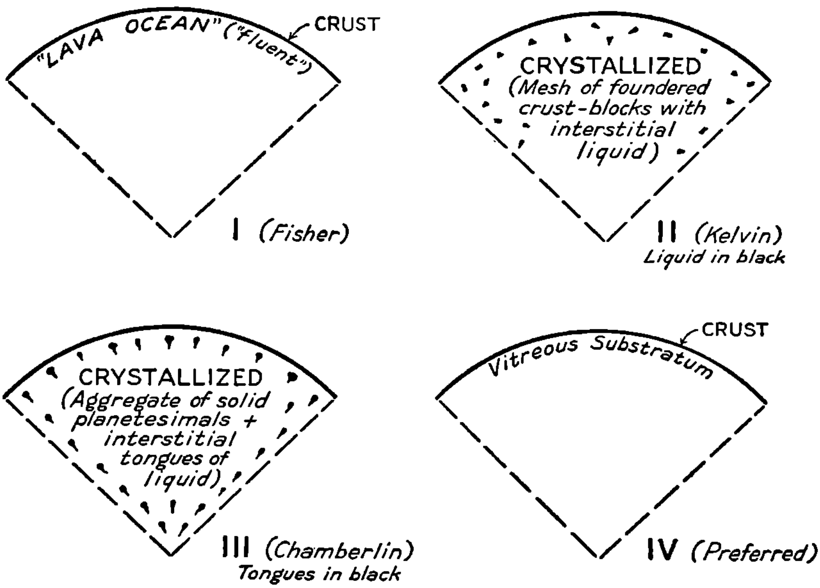
ARCHITECTURE OF THE EARTH

AN OUTLINE

JUST as astrophysics is making a new heaven for searchers of the stars, so geophysics is making a new earth for students of the rocks. In each instance it is a case of "is making," not "has made," a case of unfinished business. The secret of atom, star, or earth is within and invisible. The way to learn the secret is by a flank attack, using the method of the model. From the host of his experimentally derived facts the physicist builds up different models of atomic structure, and, while testing the degree of fidelity of each model to Nature's atom, develops new and powerful methods of research. The astronomer makes different mental models of a typical star, and, when examining their validity, is led to make ever more significant observations. So the geologist in his turn must be a creator of the earth, building better and better models, each suggesting new, vital methods of attack on his own complex problem. The best model is the one that works best. The perfect model, working infinitely well, is not for men now living. We must be content with partial success; and yet the history of geology, like that of physics or stellar astronomy, shows how the creation of even imperfect models has enormously stimulated discovery of essential facts.

Geology emerged as a science almost simultaneously with Laplace's famous suggestion about the origin of the solar system. His hypothesis heartened geologists to imagine an earth-model. Cooled from the fervent temperature of a condensing nebula, the planet, initially liquid, was supposed to have become endowed with a crust of frozen, crystallized, lava—a truly solid crust, which overlies a world-circling shell of liquid, mobile lava. See the earth-sector number One in Figure 1. This was the fashionable idea about the globe for a century, and was accepted by Osmond Fisher when he wrote his classic book "Physics of the Earth's Crust."

Model number One was tested by Lord Kelvin, George H. Darwin, and others, who showed that, against tidal forces, the globe is more rigid than steel and therefore can contain no general layer of highly fluent lava at the present time. Kelvin went farther and tried to account for this high rigidity. He assumed that the earth was originally so hot as to have been liquid to a considerable depth, if not from surface to center. He also assumed the liquid to have been of nearly or quite uniform composition. By radiation of heat to outer space the incandescent surface cooled rapidly, with the formation of thin patches of solid crust. These patches of new rock, having density



1. Sectors of earth-models.

greater than that of the underlying liquid, had to upend, like rammed battleships, and sink all the way to the bottom of the liquid layer, if not to the earth's center. Other patches formed and sank in a long succession, until the whole layer became crystalline, solid, and therefore rigid, except for small fractions of the original liquid that were trapped between the foundered slabs of crust. Sector number Two of Figure 1 gives the result diagrammatically, the black spots corresponding to the cells of residual, trapped liquid.

A generation later Chamberlin and Moulton announced their well-

2. Recent basaltic flow in the Kilauea sink, Hawaii.

known "Planetesimal" hypothesis—that the earth attained its present mass, not directly from a gaseous cloud, but by the accretion of solid particles and individual molecules. Those writers thought the earth's physical history to have been dominated by the compacting of the particles, and that the planet is essentially crystalline, solid, and therefore rigid. In effect they made a new model corresponding to sector number Three of Figure 1. There the little black tongues represent localized volumes of matter which Chamberlin supposed to have been melted by the heat of compression, the self-compression of the growing, gravitating globe.

At about the same time, forty years ago, the science of geophysics began its remarkable development. Its discoveries, together with the advance of geology itself, have shown fatal difficulties with the Planetesimal hypothesis, and have suggested another model, number Four of Figure 1, one that now seems to work best and the model to which we shall pay special attention. According to this latest conception a layer of the earth, beginning at depth no greater than about fifty miles or eighty kilometers, is too hot to crystallize. Thus there is a true crust, not necessarily of constant thickness but nowhere more than about fifty miles in thickness. The crust rests upon a continuous layer of non-crystallized, glassy or vitreous rock with the chemical composition of basalt, the commonest of lavas that emanate at volcanic vents. The Hawaiian basalt (Figure 2) shines in the sunlight because it is partly glassy, even after having been chilled to the temperature of the air. Our imagining brings us back to model number One, yet with a difference. Here, in number Four also, a true crust is postulated, but the layer just beneath it is not highly fluent, like lava at the moment of emission, and is endowed with some of the properties of a solid. This deeper layer or "substratum" yields under prolonged pressure almost as if it were liquid, and nevertheless shows high rigidity against short-lived forces and small stresses that were assumed by Kelvin and Chamberlin to prove solidity and crystallinity for the earth-shells in general. The vitreous basaltic substratum itself is relatively thin and rests on denser vitreous material. It is possible that the deeper and greater part of this intrinsically denser shell, the part beginning a few hundreds of kilometers below the earth's surface and itself resting on the so-called "iron core" of the planet, is crystallized by the high pressures of the interior. On the other hand, the iron core, beginning at the depth of about 3,000 kilometers and having a volume equal to about one seventh of the whole earth, may be actually fluid. In general, however, we shall be most concerned with the physical properties of the crust and the basaltic substratum.

The first of the succeeding chapters briefly describes the anatomy of the crust where it emerges from the ocean to form continents and islands, thus beginning the long job of testing the preferred model. The Greek poets built their own earth, and, like them, we shall visit the Olympians and question first Zeus, whose word is law. This august title fits the field geologist, for reasoning about the body of the planet must be guided by, controlled by, the facts of the surface.

The second chapter deals with the inaccessible, and much the greater, part of the crust; the third, with the deformations suffered by the crust during the ages.

The fourth and fifth chapters describe spectacular invasions of the crust by molten rock, risen from the deep interior of the globe.

The sixth chapter considers the reasons why, through geological time, the high-standing continents, the higher-standing mountains and volcanic piles, and the low-standing ocean floors are supported at their respective levels.

CHAPTER I

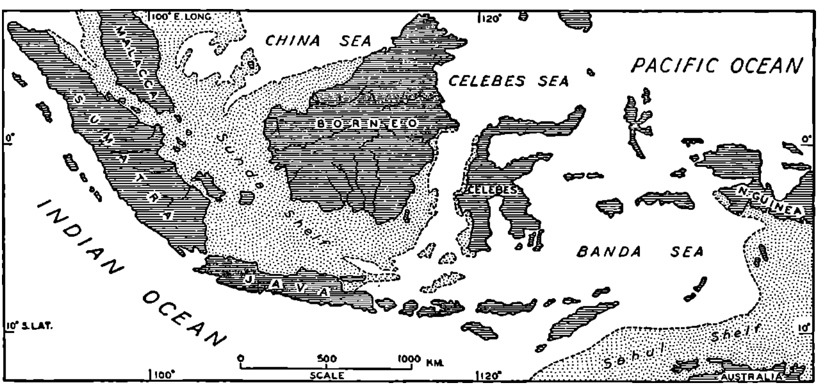
THE WORLD MAP

"Zeus the Controller"

THE projected inquiry about the true nature of the earth naturally begins with the known, observable part and then digs deeper and deeper into the unknown and much the greater part of the planet. Accordingly this first chapter will review the visible structure of the continents and the oceanic islands. The phrasing will be only in general terms.

The Continental Bucklers

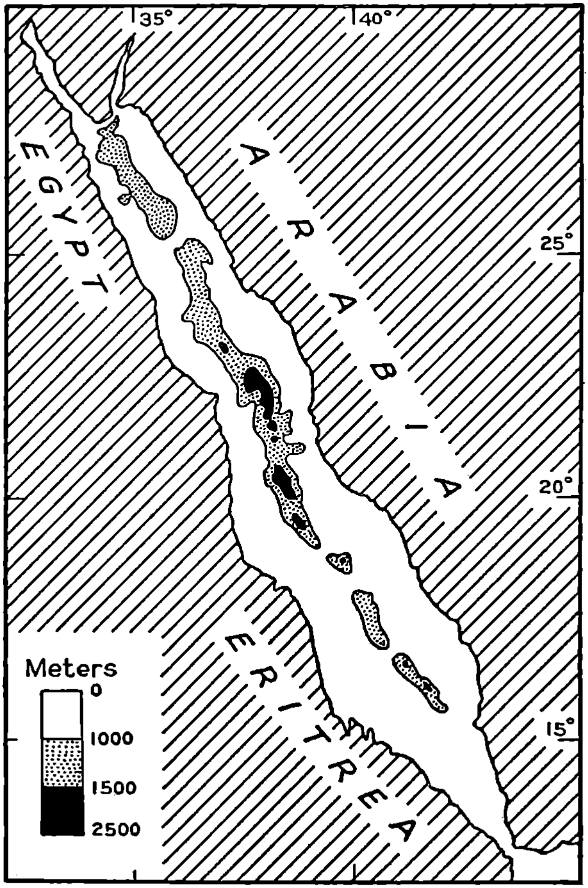
A continent is like a huge, curved buckler, resting on the body of the earth and flanked by the deep ocean. In average the surface of the



3. Map of the Sunda and Sahul continental shelves. After G. A. F. Molengraaff.

buckler is about four kilometers or two and a half miles above the ocean bottom. Regarded as bucklers, there are five continents: the two Americas, Australia, Antarctica, and the grandest of all, the "Old World" or the unit mass of Asia, Europe, and Africa.

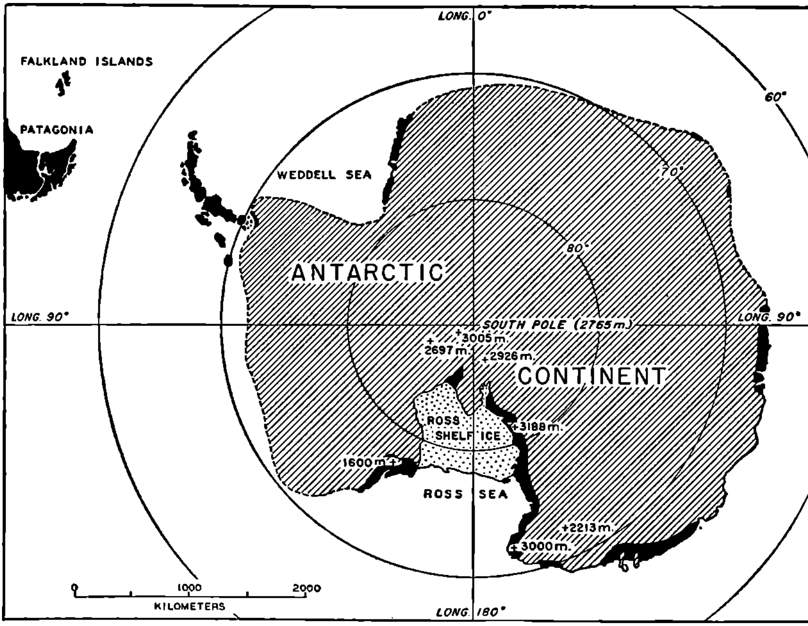
Here and there each buckler is overlapped by shallow salt water, forming what are called Seas of Transgression. Examples are Bering Sea, Hudson Bay, the Baltic Sea, Bass Strait separating Tasmania and Australia, and the seas on the Sunda shelf separating Sumatra



4. Map showing depths in the Red Sea

from Borneo and the Sahul shelf separating New Guinea from Australia (Figure 3).

Elsewhere the great ocean sends into the bucklers tongues of much deeper water, distinguished as Seas of Ingression. In illustration we glance at Figure 4, a map of the Red Sea. The stipple pattern covers areas where the depth of water is from 1000 to 1500 meters, and the black spots represent areas where the depth is from 2000 to 2500 meters. Twenty-five hundred meters is 8,200 feet. Other Seas of Ingression are the Mediterranean, the Sea of Japan, the deep Ross Sea of Antarctica (Figure 5), and the Gulf of Mexico.



5. Map of Antarctica and the Ross Sea. Ice-cap shaded; exposed rock in solid black; heights in meters.

Seas of Transgression are clearly underlain by the same kinds of rocks as those dominating in the dry lands of the continents, and the same relation holds for at least part of each Sea of Ingression. In general a continental buckler may be assumed to extend to the limit reached by its outermost Sea of Transgression—the sea covering the so-called continental shelf—and even beyond, to the line along which the continental slope merges with the floor of the deep ocean. Measured from the 1000-meter line of depth on the continental slopes, the bucklers are about 35,000,000 square kilometers more extensive than the continents indicated by the main shorelines drawn on a world atlas. The dry lands cover thirty per cent of the globe, but the total area of the bucklers covers forty per cent.

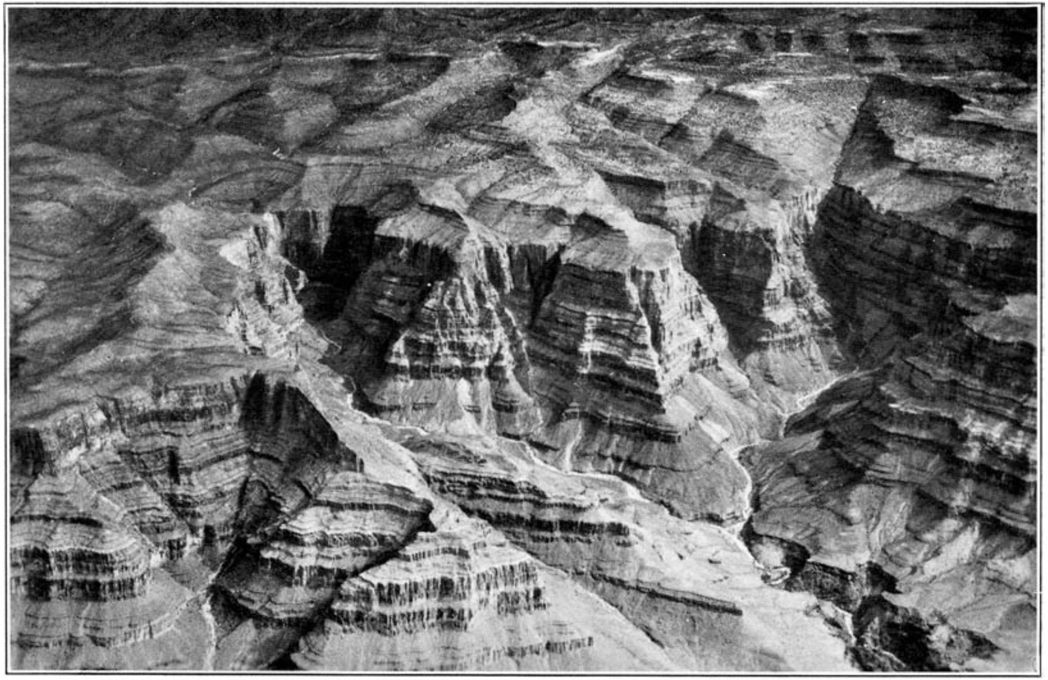
Sealevel has shifted up and down at intervals through geological time. At certain epochs the ocean trangressed the bucklers more widely than it does now; yet in general the buckler form was steadily preserved.

Visible Layers of the Crust

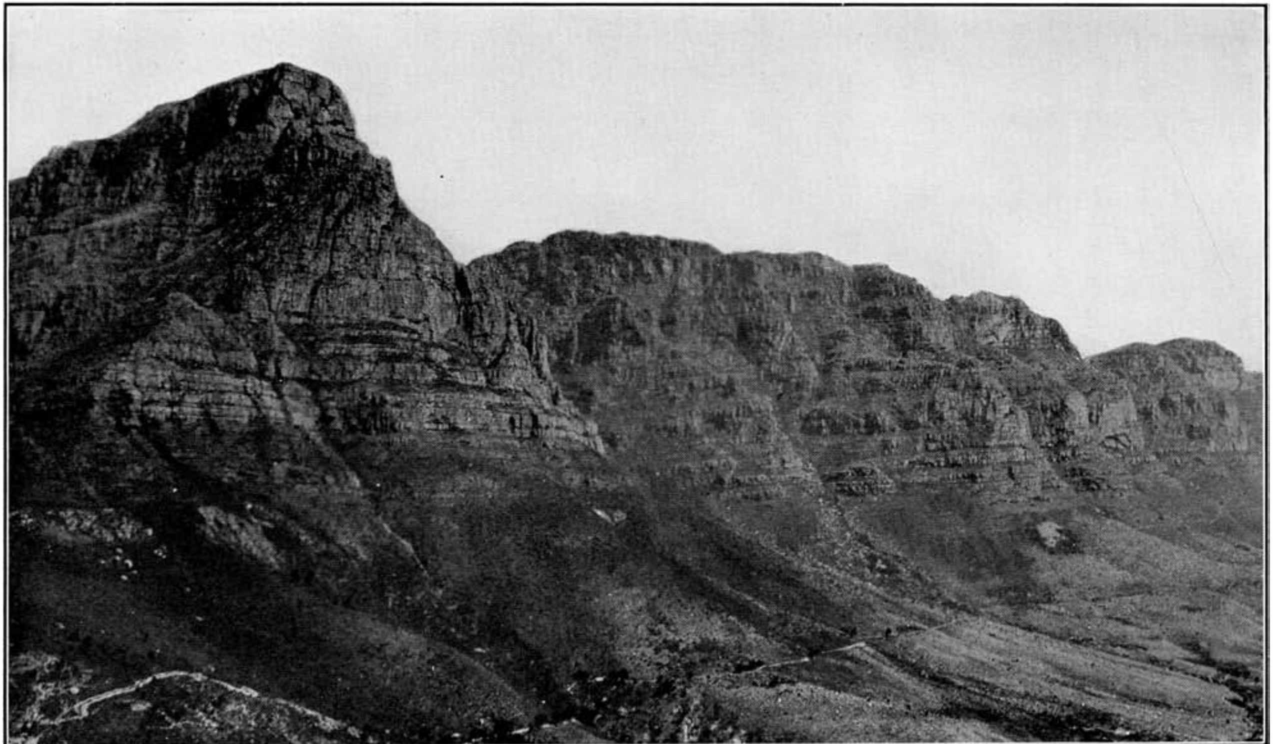
While mapping the length and breadth of rock formations, the field man does his best to measure their third dimension, thickness. He welcomes canyon walls and other cliffs, where he can foot-rule thicknesses of bedded formations, whether these strata lie flat as in the Grand Canyon district of Arizona (Figure 6) and in Table Mountain overlooking Capetown (Figure 7), or tilted out of their originally horizontal position as in the Cape Colony Range, not far north of the southern tip of Africa (Figure 57). He records the angles of dip, that is, the angles which the layering of the rocks makes with the horizontal plane. From the angle of dip and width of a series of beds a simple calculation gives the thickness of that series. As a rule such a book-like succession of rock layers keeps a nearly constant thickness for at least a few miles across-country, so that it is often legitimate to assume the series of beds to continue underground, in the direction of their diving or dip, to depths of thousands of feet or even several miles. Such deductions of the sleuth working only on the surface have been proved essentially correct in many cases where mines and tunnels were later cut through the bedded strata. Similarly prophecies by the field geologist concerning the underground extension of rocky beds have been tested by thousands of deep borings in the oil fields.

Although geologists have patiently gathered facts for two centuries, the accurate, detailed mapping of the lands may be said to have merely begun. However, campaigns of reconnaissance have shown that in principle the better known regions are samples of all lands whatever. It is thus possible to draw a comparatively simple picture of the continental part of the earth's crust, as viewed from the surface.

The picture is composed of four main elements: (1) a thick, con-

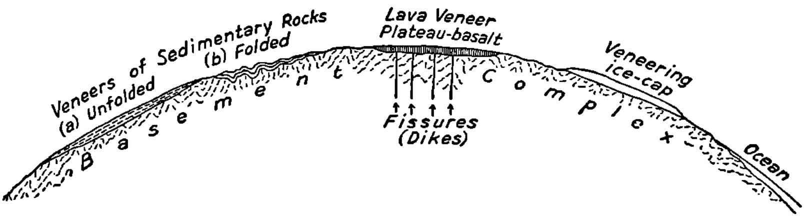


6. Layered, sedimentary rocks of the Grand Canyon District, Arizona. Airplane photograph by D. H. McLaughlin.



7. View of Table Mountain, above Capetown, South Africa.

tinuous assemblage of rocks called the "Basement Complex," this being partly covered by (2) regional veneers of layered sediments, either loose or hardened into rock; by (3) regional veneers of lavas that have flowed out of fissures in the Basement Complex and spread on the surface of the globe; and by (4) regional ice-caps and ordinary glaciers, themselves sedimentary from the snow-breeding atmosphere. See Figure 8.



8. Diagram illustrating relation between Basement Complex and rock veneers. Not to scale.

Basement Complex and veneering materials alike have been intruded at various geological epochs by molten rock, which has frozen, crystallized, within the crust. In many instances these invading rock-melts did not rise quite to the surface, but crystallized under cover. The covers had thicknesses ranging from hundreds of feet to many thousands of feet. After prolonged erosion of the roofs by running water, blowing wind, sawing waves of the ocean, or gouging glaciers, the newer masses of solidified lava or magma, as it is technically called, have been exposed to the air.

Figure 9 represents a tiny example of such injected lava. Here, cutting up through the limestone of a Montreal quarry, is a wedge of dark-colored rock, the top of a dike. The liquid evidently came from great depth in the earth, for only at the temperatures of great depth can rock be melted, liquefied, in situ. Small as it is, this pocket edition of a dike illustrates a major fact of physical geology, namely, the secular change of the earth's crust by the addition of frozen lava which has risen from deep levels in the planet.

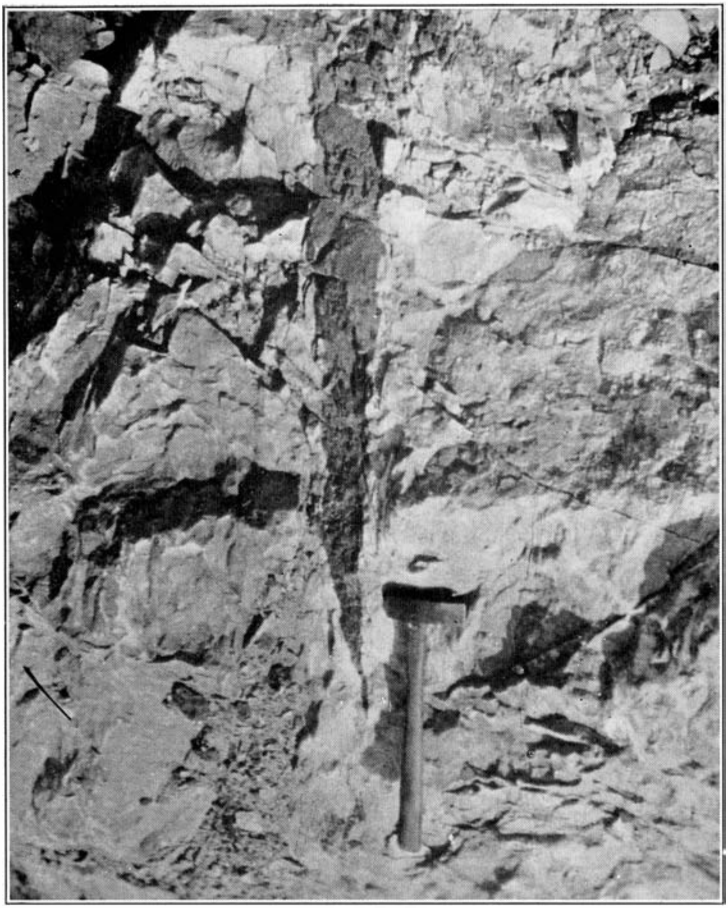
Figure 10 portrays a much larger dike of dark-colored rock, which in the molten state rose into the Basement Complex at a sea cliff of northern Labrador. The liquid filled a main fissure and also several branches of that fissure, the whole assemblage of cracks showing that then the rocks of the invaded Complex were cold and brittle. The size of the dike can be gaged from the height of the cliff, about 300 feet.

Thus the field maps and natural cross-sections of the rocks, together with cross-sections developed mathematically from surface outcrops, tell us much about the constitution of the outer part of the continental crust. In mountain ranges this probing may be safely carried on to depths of several miles, for in the ranges thick packets of rock beds were tilted and, after the tilting, made accessible by prolonged erosion. Let us now review two of the three master constituents of the visible continental crust—the Basement Complex and the crazy quilt of veneers. The group of once molten intrusive bodies will be specially considered in the fourth and fifth chapters.

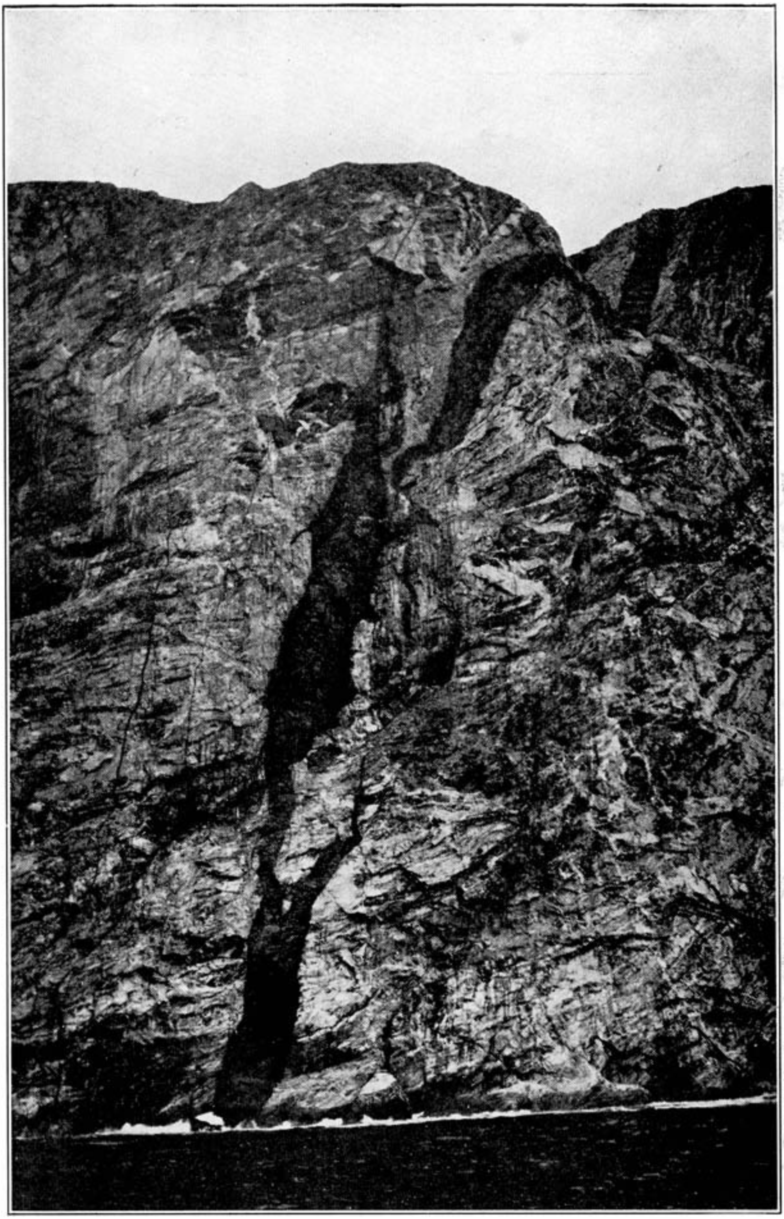
Basement Complex.—More than half of the continental map shows veneering rock, which expresses itself in the relief as plain, plateau, and mountain range. Beneath the veneering patches is the Basement Complex, the next course and the lowest course directly visible in this mighty masonry. The field geologist naturally emphasizes what he can see; hence the word "Basement." However, we shall learn that the Complex itself rests on other and quite different shells of rock, shells which also enter into the foundation of each continent and keep the surface of that continent high above the ocean floor. Remembering that the convenient word "Basement" is here used arbitrarily, we shall not be misled by it.

The superposition of veneer on Basement Complex can be actually seen on the faces of cliffs. In Figure 11, a photograph taken at the Cape of Good Hope, we note the old granite of the Complex capped by a thick cover of well-bedded sands, long ago hardened into strong sandstone. Another example is dramatically apparent on the northeast coast of Labrador (Figure 12). There the veneer is made of dark shaly rocks, lava flows, and ash-beds, the whole resting on the light-tinted, granitic rocks of the Complex. On the cliffs of the noblest of all canyons one sees the same ancient terrain blanketed by the eroded, flat-lying beds of the sedimentary veneer that extends far and wide in the State of Arizona (Figure 13).

At many places the Basement Complex crops out at the surface, either because it has never been covered up, or because any cover that



9. Top of a basaltic dike cutting limestone. Photograph by K. F. Mather.



10. Basaltic dike cutting Basement Complex at 300-foot cliff, Saeglek Bay, Labrador. Photograph by F. B. Sayre.

may have been formed in days long ago was later eroded off. This second case is well illustrated in the region surrounding Boulder Dam, down-river from the famed Grand Canyon of the Colorado. Figure 14 is a photograph taken at the height of nearly 10,000 feet and on a day when construction work on the dam had progressed no farther than the building of roads and light bridges across the river. Nearly all of the visible rock belongs to the Basement Complex, which at an earlier geological epoch was completely covered with thousands of feet of bedded sandstone, shale, and limestone. Since then secular erosion has here destroyed that veneer within the area photographed and has roughened the original, somewhat flatter surface of the Complex. The voracious Colorado River has cut its way down, hundreds of feet still deeper than the general surface of the scarred basement terrain.

On the map of Figure 15 most of each area left blank within the limits of Canada and the United States is an outcrop of the Complex; the shaded areas are those of veneers of sedimentary rock laid down in various old Seas of Transgression. From a recent study R. G. Moss [1] has estimated the thicknesses of the veneer and also the approximate depths where a boring machine would be likely to reach the surface of the buried Complex. From his maps the following figures have been culled. In the Adirondacks the Basement rocks reach the height of 5000 feet above sealevel. The surface of the Complex declines so that it is at sealevel in the Mohawk Valley; 10,000 feet below sealevel at the Pennsylvania-New York boundary; and 20,000 feet below sealevel in central Pennsylvania. In Louisiana the old surface is from 10,000 to 30,000 feet below sealevel. In Colorado it ranges from 12,000 feet above sealevel to 13,000 feet below sealevel.

The Complex is visible over vast areas in Brazil, around the Baltic Sea, in Siberia, China, India, and throughout much of the 11,000,000 square miles of Africa. It appears to form the chief part of the floor on which the huge ice-cap of Antarctica directly rests (Figure 5).

Elsewhere there are thousands of smaller outcroppings. In fact the Basement Complex is continuous under the veneers, continuous

[1] R. G. Moss, *Bulletin Geological Society of America,* vol. 47, 1936, p. 936.

from end to end and from side to side of every continent, even though locally pierced by younger bodies of intrusive, once-molten rock.

Thus the greatest of all visible terrains is nearly ubiquitous in the continental sectors of our globe. Now what of its composition and structure? Its structure represents one of the toughest problems of the geologist. He is manfully attacking the puzzle, but it will be long before he can improve on "Complex" as a descriptive name for this assemblage of rocks. The word honestly expresses bafflement, despite some genuine progress in unraveling the tangle of formations below the continental veneers.

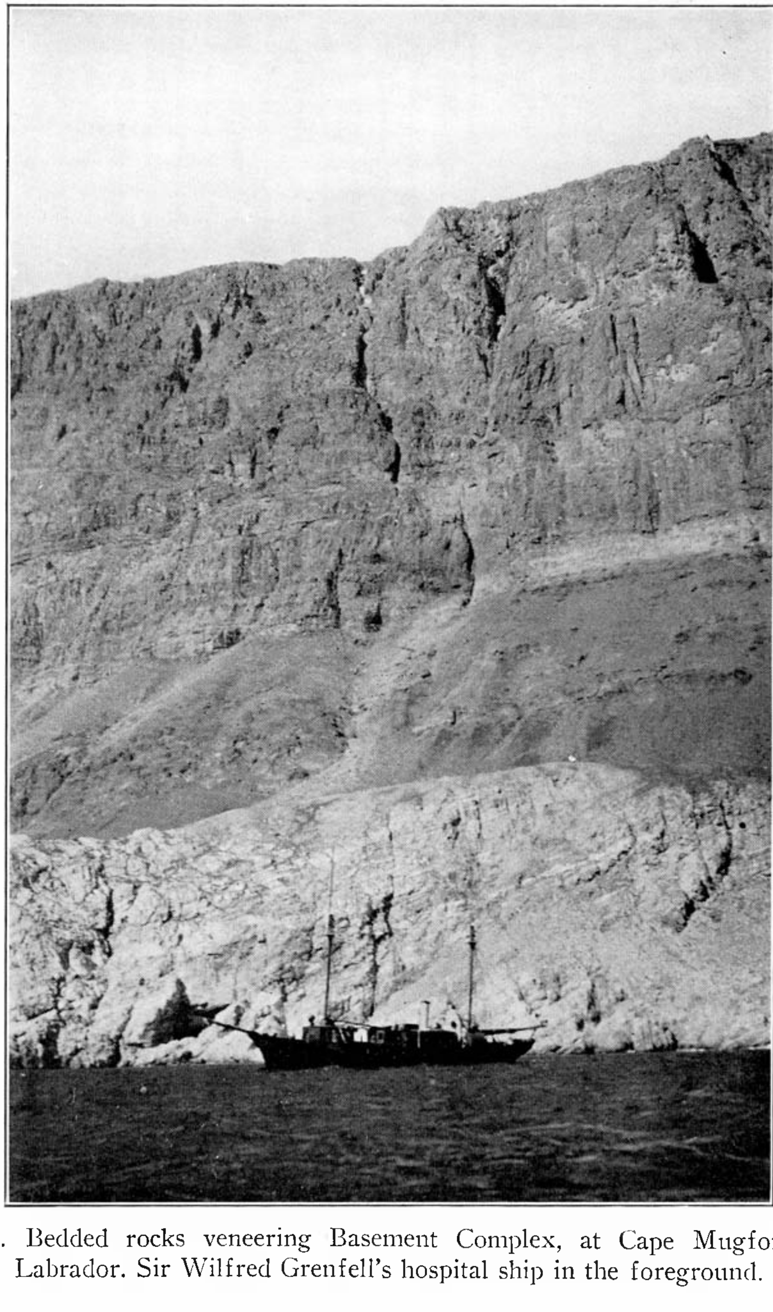
In general the rocks of the Complex can be matched, species for species, by those of the veneers themselves and by the intrusive masses that cut up through the crust. Like the veneers, the Complex contains extensive, thick beds of water-laid muds, sands, and gravels, beds of limestone, lava flows, and layers of volcanic ash, products of explosion. In both veneers and Complex the originally loose sediments were hardened to the strength of building stone, and in both cases these bedded formations were invaded from below, at intervals of both space and time, by molten granite. In both veneer and Complex, sediment, lava flow, volcanic ash, and granite have been squeezed, re-heated, and recrystallized. When the change leads to recrystallization the process is called metamorphism, and the resulting kinds of rocks are classed as "metamorphic."

The extent of the metamorphism, however, is quite different in the two cases. Drastic recrystallization of the veneering formations is local and confined to the comparatively narrow belts of mountain chains. On the other hand, recrystallization is almost universal throughout the Basement Complex and is not restricted to definite belts.

A second contrast: The dominant material of the veneers is sedimentary; that of the Complex is intrusive granite.

A third contrast: Over broad areas the rocks of the veneers have suffered relatively little disturbance since their original formation, whether as flat sheets of sediment or as lava flows; but nearly all of the layered rock and granites of the Basement Complex have been crushed, folded, thrust together, and upended. Figure 16 illus-

11. Sea-cliff at the Cape of Good Hope. The sea-cave, about seven meters in height, was quarried out of the granite by the breakers before a recent lowering of sealevel.



12. Bedded rocks veneering Basement Complex, at Cape Mugford, Labrador. Sir Wilfred Grenfell's hospital ship in the foreground.

trates how the layered rocks of the Complex were tortured by the crumpling pressure. A second example, on a larger scale, is found in a bit of the Complex in Southwest Africa. (Figure 17.) Here a thick packet of sedimentary rocks, including limestone beds marked "L" and sand-rock marked "Q," were powerfully folded. Apparently during the folding molten granite was injected between the beds, where it froze in the form of great pods, the pods themselves being twisted and bent as they crystallized. The earth's crust was plastic during a long period immediately following its first formation as a distinct earth-shell, and this plasticity was continent-wide. But structural turmoil of the same kind is found among the younger rock-beds of the veneers only in the narrow belts of the great mountain chains.

And there is one other difference between the two types of terrain. At intervals many of the bedded rocks of the veneers are charged with fossils, those invaluable "medals of creation" that tell the geologist the relative ages of the rock formations; the Basement Complex is almost wholly lacking in such manifest traces of life. When we consider the fact that about one half of the two billion years of the earth's history was occupied with the development of the Complex, we encounter one more leading problem of earth science. This long delay in the appearance of organic shells and skeletons among the stratified rocks was probably due in large part to the low content of calcium in the ocean during the first billion years of its history, for calcium (lime) is an essential component of the great bulk of fossil organic remains.

We shall not attempt to survey the many stages in the evolution of the Basement Complex, but for the purpose of this book it is well to consider what are the average composition and average density of the Complex.

The first step toward finding those values is to select a large, typical, well-mapped region where the Complex crops out at the surface. Then the areas occupied on the map of the region by the different kinds of rock are measured and reduced to percentages of the whole area. Knowing the average chemical composition of each kind of rock, the average composition of all the outcropping formations can be calculated. In this way the late J. J. Sederholm, Director of the Geological Commission of Finland and an exceptionally able student of the Complex, computed the average composition for well mapped Finland, which, in spite of small areas of veneering rocks, furnishes a good example of the Complex as a whole.[2]

Table I gives in percentages the relative areas of the types of rock in Finland.

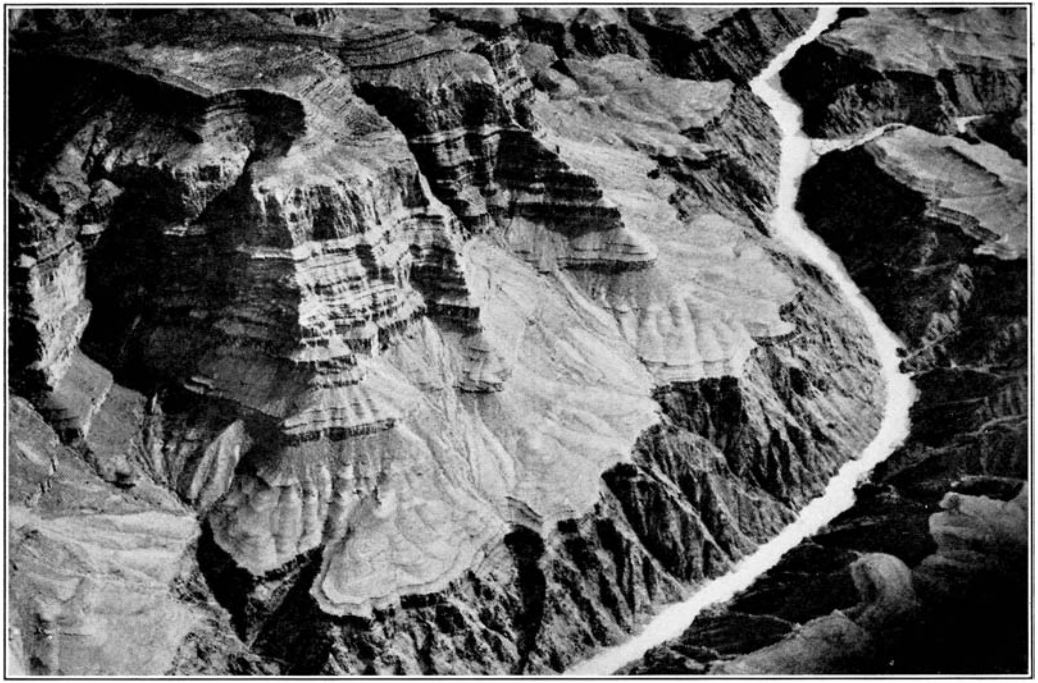
TABLE I

Granite	52.5
Intimate mixtures of granite, sediments, and old volcanic rocks	21.8
Granulites	4.0
Schists	9.1
Sandstones and quartzites	4.3
Limestones and dolomites	0.1
Basic rocks, unlike granite but also once-molten	8.2
	100.0

We need not stop to define the technical names in the table, nor to give Sederholm's values for the chemical composition of each kind of rock, but shall at once consider Col. 1 of Table II, where we read Sederholm's percentages of the different oxides represented in the average chemical make-up of the Finnish Complex. Column 2 gives the average composition of the Finnish granites alone; and Col. 3 the average composition of 546 granites collected all over the world.

From the chemical composition of the Finnish Complex its average density has been calculated with a close approach to accuracy. The density found is 2.72, the rock weighing 2.72 times as much as an equal volume of pure water. The average density of granite, the world over, is 2.67. Since the "basic" rocks of Table I are largely surface lavas and comparatively thin, the average composition of the Finnish Complex down to the depth of a few miles is nearly the average granite, and the corresponding density may be taken as 2.70, a value that must be close to the average for the Complex in every

[2] J. J. Sederholm, *Bulletin 70, Commission Géologique de Finlande,* 1925.



13. Basement Complex appearing beneath thick sedimentary veneer, in the Grand Canyon of the Colorado River. Airplane photograph by D. H. McLaughlin.

14. Basement Complex exposed by complete removal of veneering strata at the site of the Boulder Dam, Colorado River. Airplane photograph by D. H. McLaughlin.

continent. This figure is going to interest us when we shall consider the stability of the continents (Chapter VI).

TABLE II

CHEMICAL AVERAGES OF THE FINNISH COMPLEX AND OF GRANITES

(Reduced to totals of 100.00 per cent)

	1 Finland as a Whole	2 Finnish Granites	3 Granites of the World
SiO_2	67.70	69.42	70.18
TiO_2	.41	.39	.39
Al_2O_3	14.69	14.70	14.47
Fe_2O_3	1.27	1.08	1.57
FeO	3.14	2.49	1.78
MnO	.04	.03	.12
MgO	1.69	2.02	.88
CaO	3.40	1.44	1.99
Na_2O	3.07	3.24	3.48
K_2O	3.56	4.46	4.11
H_2O	.79	.66	.84
P_2O_5	.11	.07	.19
Rest	.13	...	...

The Rock Veneers.—We have seen that, except for local intrusions of once-molten, or igneous, rock, the Basement Complex is continuous, aboveground or underground, across each continent; that the veneering formations are highly discontinuous and made up of a great number of individual terrains; and that the most important of these are of sedimentary origin, their material representing the transported and then deposited constituents of rocks that were formerly molten. Thus in the final analysis all rocks whatever are made of originally igneous material and chiefly of granite of the Basement Complex. In a sense the face of a continent is dirty, covered more or less completely with the products of rock decay. Nature washes that face with rain, rivulet, river, and sea wave, trying, as it were, to drag the dirt out of sight, under the sea. Although never succeeding entirely, she has kept piling on the sea floor layer after layer of mud, sand, gravel, and river-borne salts, all derived by the agelong weathering of the lands. Under the pressure of their own weights these layers have become rocks, many of them approaching the parent igneous rocks in strength. Then, after much patient hiding of the rubbish beneath the clean, wimpling ocean, Nature has found her work undone by an occasional withdrawal of the sea. Thus new, sedimentary terrains, marine deposits, have been exposed to the downcutting rivers, as in the region of the Grand Canyon (Figure 6).

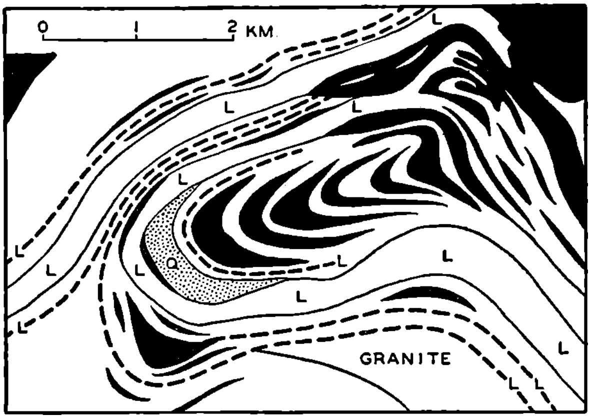
Other, generally less extensive veneers are composed of sediments that were laid down in freshwater lakes and along the courses of debris-carrying rivers or deposited by debris-carrying winds.

Commonly these deposits, whether marine or continental in origin, were accumulated in basins, the sediments having been supplied on all sides of each basin. Classic examples are the structural units presented by the Paris Basin and the Aquitanian Basin (Figure 18). Where the area of the deposit was broad, the floor on which the sediments were laid down slowly yielded under the new load, with further deepening of the original basin. Moreover, many basins were deepened by forces other than the weight of the inwashed sediments. Such additional depression invited the inwash of still more detritus from the surrounding uplands. By continuance of these processes the total thickness of many a basin deposit became great.

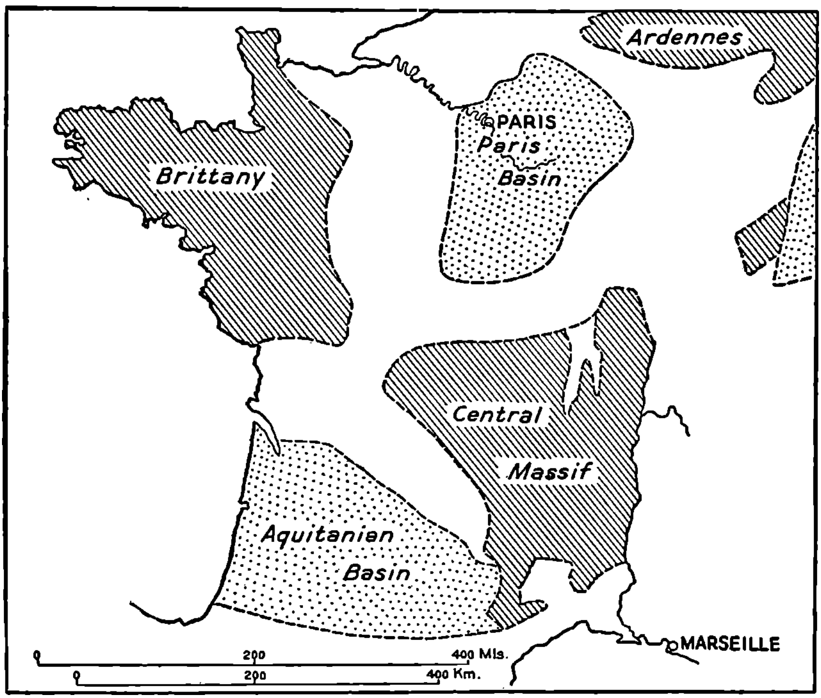
Thickest of all are the deposits that have accumulated in relatively narrow but elongated basins, some of which much exceeded 1000 miles in length. Basins of this kind, made by downwarping of the Basement Complex, are called technically "geosynclines," and their sedimentary fillings may be called "geosynclinal prisms." For the typical shape of the filling is that of a long, plano-convex prism with its convexity at the floor. An example is topped by the Ganges-Indus plain (Geosyncline of the Punjab) that fronts the Himalayan Range of mountains (Figure 19). See also Figure 59. The ground-plans of much more extensive and much older geosynclinal prisms are marked with a stipple pattern in Figure 20, a map of our own continent. It was out of the extraordinarily thick Cordilleran prism that the Front Range of the Montana-Alberta Rockies was made. A photograph (Figure 21) shows the eroded edges of some of the

15. Map of North America showing outcrops of the Basement Complex. After T. C. Chamberlin and R. D. Salisbury. Courtesy of Henry Holt and Company.

16. Crumpled bedded rock of the Basement Complex in the Wapussakatoo Mountains, western Labrador. Photograph by C. Tolman.



17. Deformed pods of granite (black) and sedimentary formations in Southwest Africa. After T. W. Gevers and H. F. Frommurze.

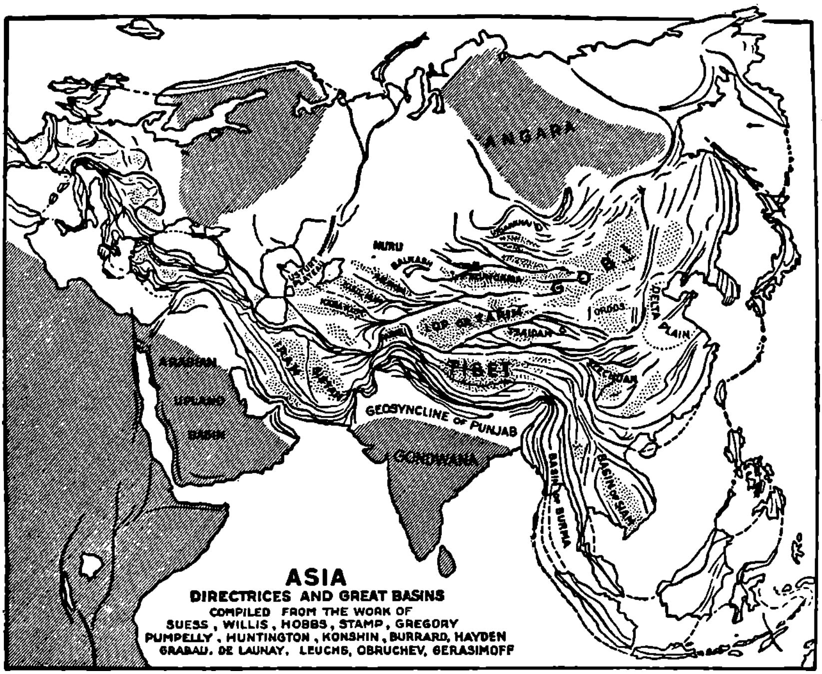


18. Map showing the position of the Paris and Aquitanian basins.

beds constituting this huge prism, with its measured thickness exceeding ten miles or sixteen kilometers.

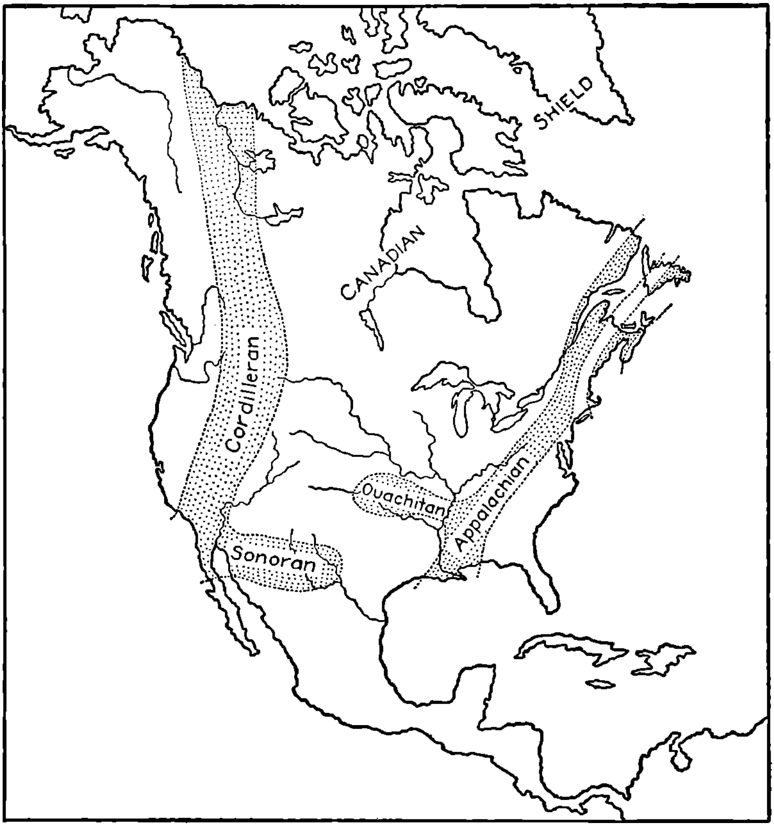
Geosynclinal prisms have peculiar importance because, as will be noted in the third chapter, they have determined the sites of mountain ranges and make up much of their essential substance.

All the basin deposits so far considered are intra-continental and



19. Map showing position of the Geosyncline of the Punjab. After C. P. Berkey and F. K. Morris.

nested in the Basement Complex or other old continental rocks. There are, however, thick deposits of another kind, those made of continental detritus that has been carried out to the open ocean. Such sedimentary material constitutes at least the upper part of the broad terraces called the "continental shelves." Fringing each of the continents and varying from ten to three hundred or more miles in width, these submarine benches gently slope out to the line where soundings register fifty to one hundred fathoms of water, and there, at the top of the so-called "continental slope," descend with relative rapidity to the general sea-floor, two miles or more below the surface of the water. The shelf does not, therefore, represent the filling of a basin from opposite sides, like the geosynclinal prism, but is a

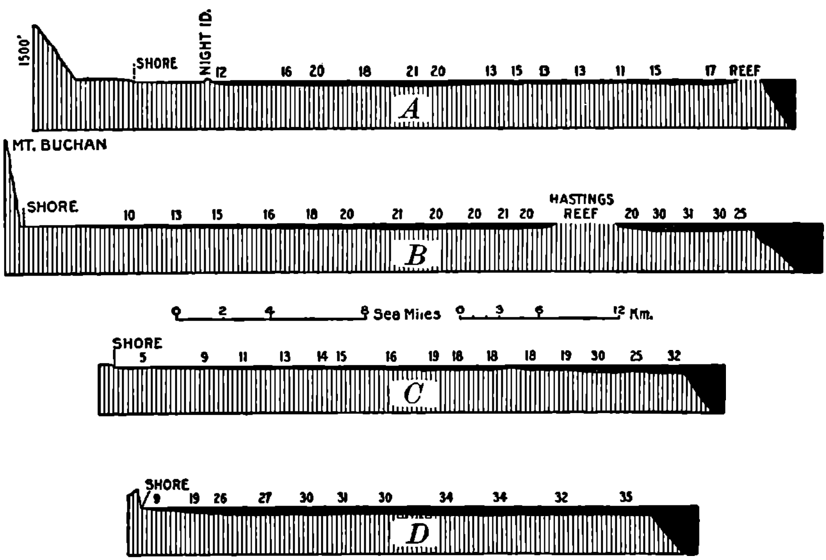


20. Geosynclinal prisms in North America. After C. Schuchert.

one-sided deposit, an embankment growing slowly outward, toward the abysmal depths of the ocean. Figure 22 portrays four cross-sections of the shelf off northeastern Australia. Here the water is shown in black. We observe that in the north, where the sea is warmer than farther south, the shelf carries local coral reefs on its back. Similar cross-sections illustrate the continental shelves and continental slopes (the fall-offs of the shelves) in six other parts of the world (Figure 23).

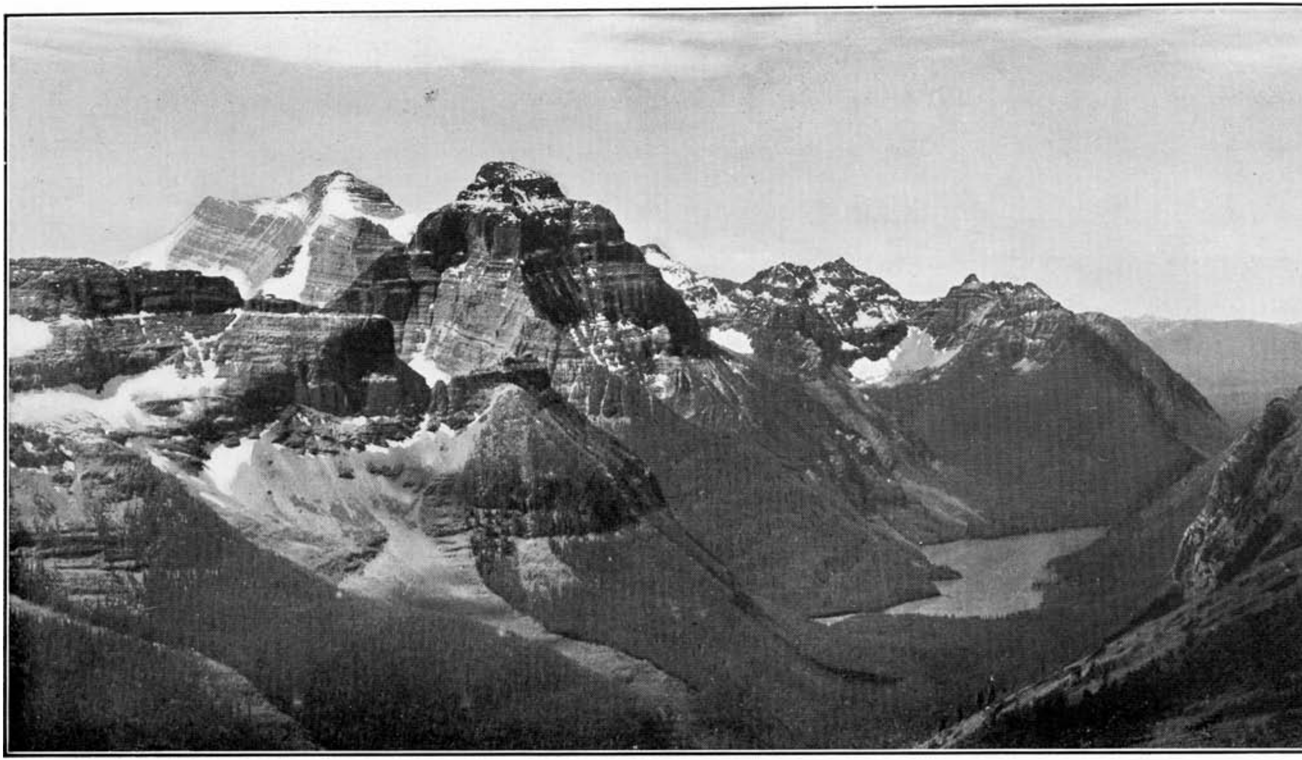
Let us now glance at the volcanic veneers, inquiring especially about their relations to the rest of the earth's body.

In this connection the nature of the lavas is of much importance. On the basis of chemical composition hundreds of species of lava have been distinguished and given as many different names in



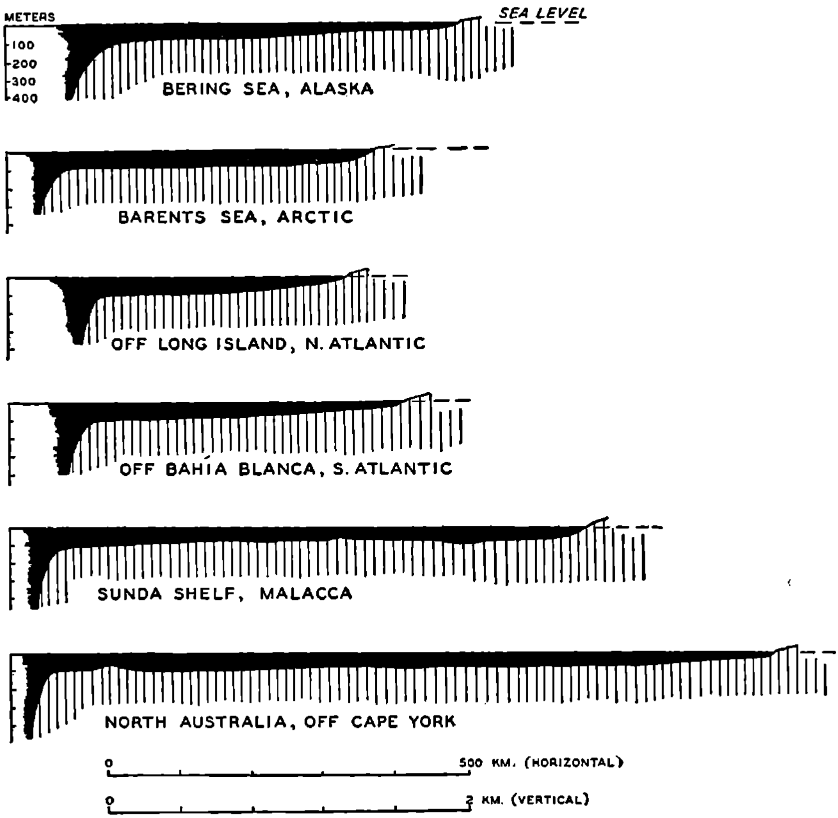
22. Cross-sections of the continental shelf, eastern side of Australia. Vertical scale about ten times the horizontal. Depths in fathoms (six feet to the fathom).

technical geology. With the chemical variation goes variation in the kinds and proportions of minerals that have crystallized out from the cooling liquids. One species, basalt, has, among all these erupted masses, the greatest total volume, by far the greatest. Most of the flooding basalt has issued from nearly or quite vertical fissures through the Basement Complex and the sedimentary veneers. The principle is illustrated at the extinct La Botte volcano of Central France (Figure 24). The line marked "Fault" in the little map is a fissure, up which molten basalt rose to run out on the surface, giving the successive flows marked "B."



21. View in the Front Range of the Rocky Mountains at the Boundary between Canada and the United States.

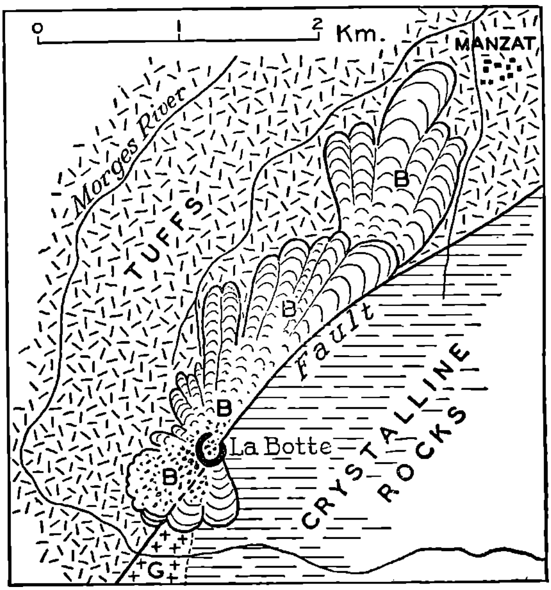
The basalt still left in the fissure freezes and forms a dike. The photograph of Figure 25 shows the polished surface of granite, split by a dike of diabase or frozen basalt. The light-tinted granite symbolizes the rock dominant in the top layer of each continental sector



23. Cross-sections of six continental shelves. Vertical scale 250 times the horizontal. Depths in meters (3.3 feet to the meter).

(Basement Complex). The strongly contrasted diabase symbolizes the invader that rises from great depth when the earth's crust is cracked through and through. This small, sixteen-inch specimen brings vividly to our eyes the two most voluminous types of rock known to science, and the black rock is one of the messengers that tells us what lies far below the ground we walk upon.

Here and there the continents have been fractured, and through thousands of cracks molten basalt has issued and run miles or scores of miles from the respective vents. Each flow quickly solidified and became in its turn a floor on which later flows ran and solidified. In this way many areas, each totaling tens of thousands of square miles, became deeply covered with flat-lying layers of crystallized basalt, new igneous rock. The Faroe Islands are remnants of one of these masses, and in Figure 26, a vertical cross-section drawn at



24. Eruption at a fissure; la Botte volcano.

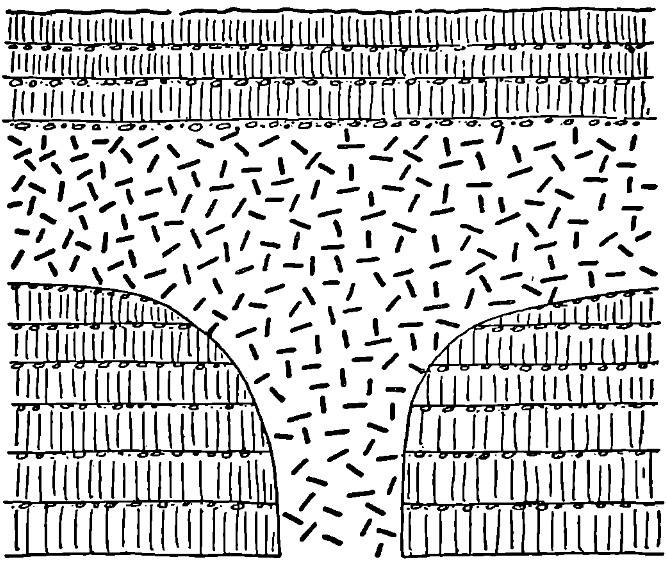
a sea-cliff in one of the islands, we see how the hachured basalt rose in a fissure and spread out at the surface to right and left of the fissure. After that flow solidified it was covered with younger flows, three of which are shown in the section.

The whole assemblage of "fissure eruptives" has the structure and also, commonly, the form of a typical plateau; hence the name "plateau-basalt" is often applied to the rock composing the tremendous volcanic piles. In the course of time rivers cut such a plateau to pieces, so that the observer can see the bed-like structure of the mass. For illustration see Figure 27, a photograph taken not far from the

25. Photograph of polished granite, cut by a dike of diabase (basalt). Specimen sixteen inches long.

celebrated Giants Causeway in northern Ireland. Another example is supplied in Figure 28, a view taken from a point nearly eleven thousand feet above sea and toward one of the 4000-foot cliffs of the Drakensberg, Basutoland, South Africa. In that cliff hundreds of superposed flows of plateau basalt can be counted.

At many points located on fissures, and at other points where there is no visible connection with fissures, the hot, gas-charged lava has bored or fluxed vertical holes out of which bombs, ash, and explod-



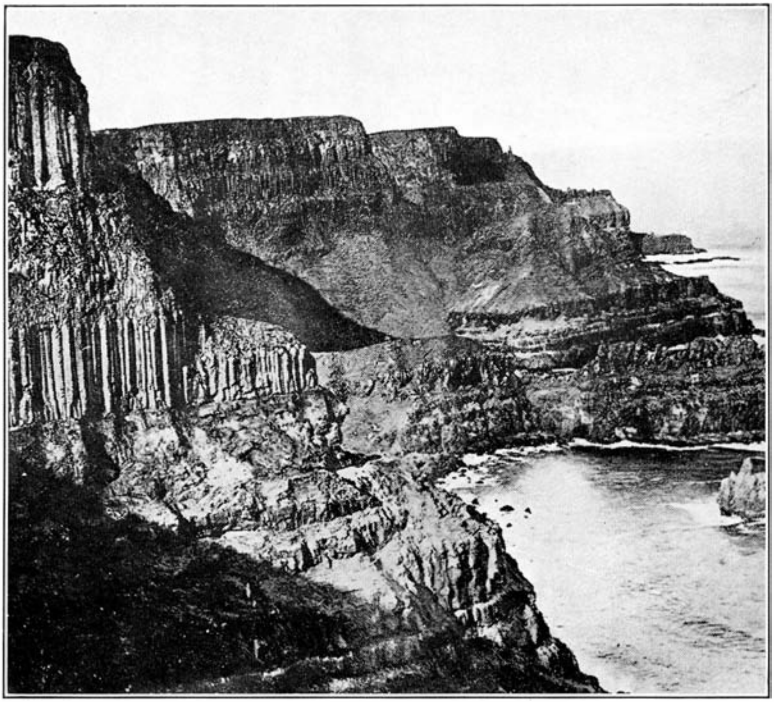
26. Cross-section of a basaltic flow, issuing from a fissure through older basaltic flows, each containing bubbles at top. Viderö, Faroe Islands. After F. Walker.

ing gases have issued. From these holes as centers flows have run out, and explosions have sent their rocketing projectiles in all directions; the results are "volcanoes of the central type." Mount Etna, the composite cone of Figure 29, is a classic example. At central volcanoes also basaltic flows are abundant, and it has become increasingly clear that most of the other kinds of lava represent modified basalt. In fact, for the last half billion years basalt has not only been dominating in surface volcanism; it appears also that basaltic liquid has been, except possibly at a few points, the only primary material engaged in volcanism of the central type.

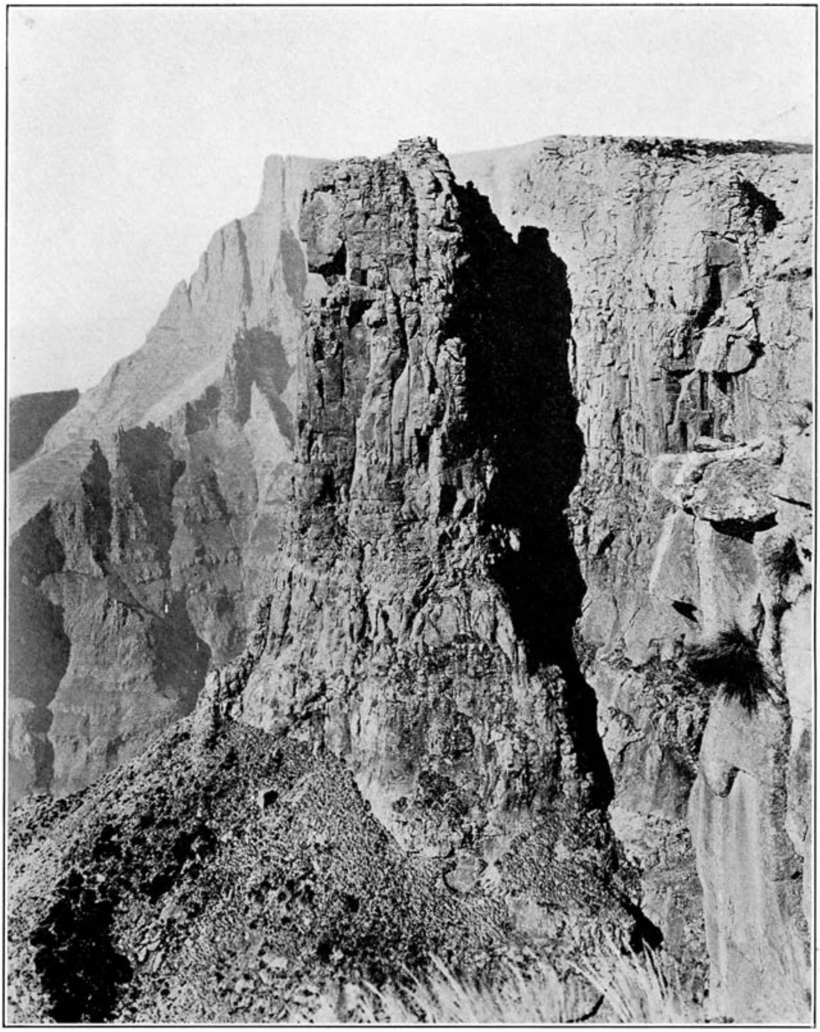
Another principal fact: Where the plateau-basalts have been piled up on a big scale, the floor on which they rest has been basined. There the earth's crust was bent down under the heavy weight of the superposed lava, just as geosynclines were deepened by the weight of inwashed mud, sand, and gravel. But for each basaltic plateau there was a second, still more important cause for the basining. When lavas totaling tens of thousands of cubic miles were transferred from depths to the surface of the earth, the solid crust-rock overlying the original home of the lavas had to sink, and sink most where the evacuation beneath and the accumulation of flows above were greatest; hence, because the earth's crust has limited strength, it had to collapse. It was basined merely because of the transfer of material from beneath it. A typical basin of collapse has minimum diameter measurable in hundreds of miles. This indicates that the eruptible basalt, when at its original level, extended at least as many hundreds of miles in the horizontal plane. Here, then, we have a direct suggestion that molten basalt may originate in a world-circling layer. Such basins of collapse are exemplified in the volcanic field of the northwestern United States. Figure 30 is a diagrammatic cross-section showing in principle how the old Cascade Mountain Range, composed of folded sediments and intrusive granite, was warped down, so that at the crossing of the Columbia River that old land surface is now below sealevel (SL) and buried under thousands of feet of basaltic and allied lavas. Details of topography and structure of the volcanic cover are omitted in the diagram.

Field Geology in the Ocean Basins

So far we have been exploring the continental sectors. Let us now turn to the other two thirds of the globe. What can we learn from the islands of the deep ocean about the nature of the earth's crust and the underlying material? The outer limit of each continental buckler is in general at the foot of the continental slope, about 4000 meters or 13,000 feet below sealevel. To seaward of that slope the only visible rocks are those of the deep-sea islands. These are of



27. Plateau-basalt, fissure eruptions, near Giants Causeway, Ireland.

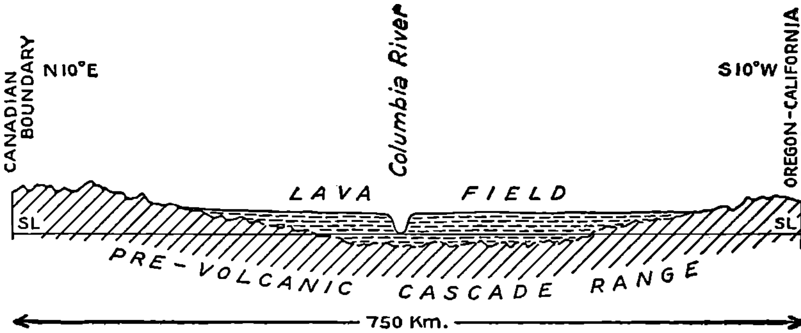


28. Cliff exposing edges of flows of plateau-basalt, Basutoland.

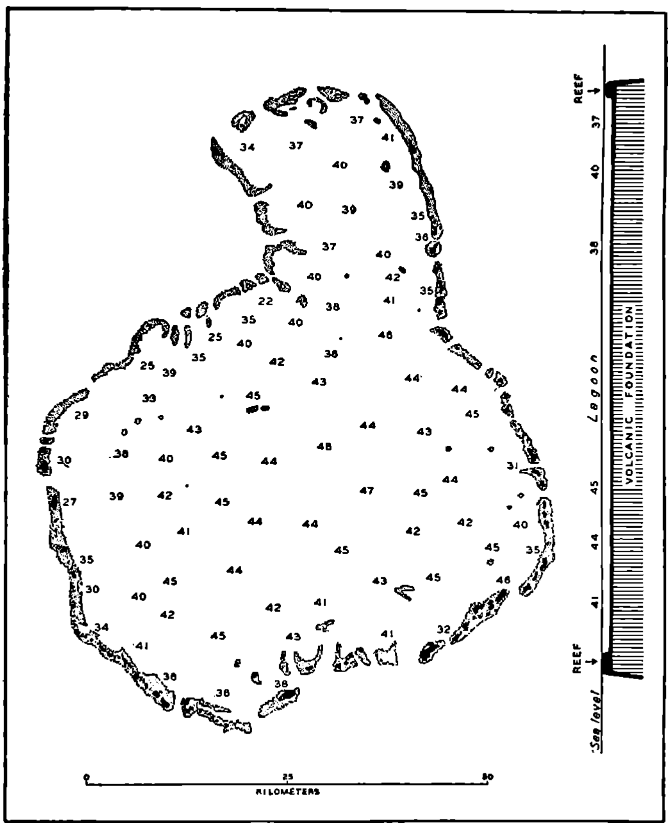
two kinds. Islands of the one class are wholly volcanic except for thin beds of limestone, precipitated chemically from the sea water and either interleaved with the lava flows and ash beds or deposited on these enormous cones after the volcanic action has come to an end. Of these limestones the thin cappings alone are commonly visible above sealevel. The islands of the other class contain quartz and other minerals that are essential constituents of non-volcanic formations of the continents. The two classes will be illustrated in order.

The volcanic islands far from the continents and lacking rocks of the continental type are small and isolated, so that it takes a skilful navigator to find one after his many days of sailing over the empty ocean. The utter loneliness of each island is one of the reasons why the landfall is so thrilling. In all the 35,000,000 square miles of the deep Pacific its two thousand or more volcanic islands total only about 70,000 square miles in area. The areal ratios for the Atlantic and Indian oceans are of the same order, while the Arctic Ocean is not known to be broken by a single deep-sea island. However, small as the islands may be and rarely as they lift their heads out of the veiling ocean, they give precious information about the sub-oceanic sectors of the globe.

More than half of the volcanic islands are so old that erosion by running water and battering waves has reduced them to shoals with surfaces 50 to 100 meters below sealevel. In many parts of the intertropical belt corals have taken root on these surfaces in comparatively recent time, and, with the help of other lime-secreting organisms, the corals have built up the living atoll reefs. As a rule the visitor to an atoll sees no other rock in place than reef limestone. Yet the outer submarine slopes of most atolls are so like those of the high islands that a volcanic origin is reasonably ascribed also to the stout pillars supporting these reefs. An illustration is found in the magnificent Suva Diva atoll of the Indian Ocean. The map of Figure 31 shows the reef awash by the stipple pattern; the dry, emerged parts of the reef by solid black; and the depths in the lagoon, marked in fathoms. The section on the right was made on a north-south line through the middle of the atoll. Here the organic material is shown in black, and the assumed volcanic foundation is shown



30. Basining of the floor under a thick pile of lava flows.

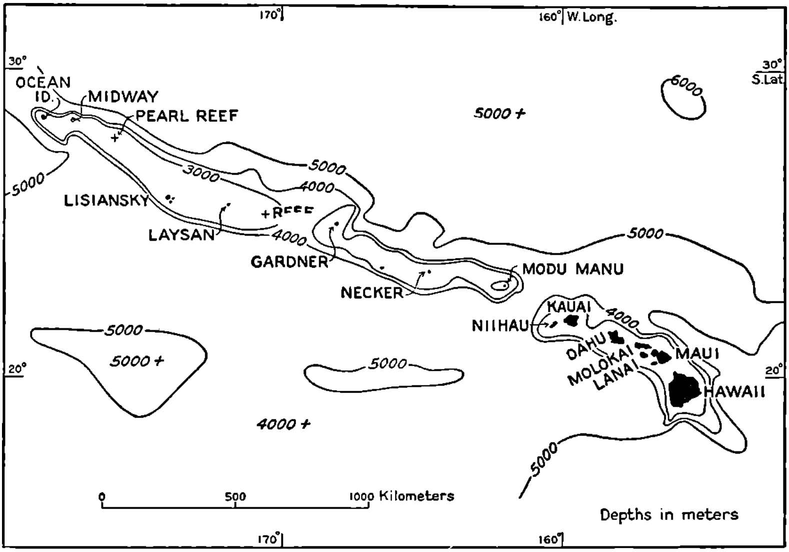


31. Map and section of the Suva Diva atoll, Indian Ocean. Depths in fathoms.

29. Mount Etna.

with vertical shading. The vertical element is exaggerated twenty-fold.

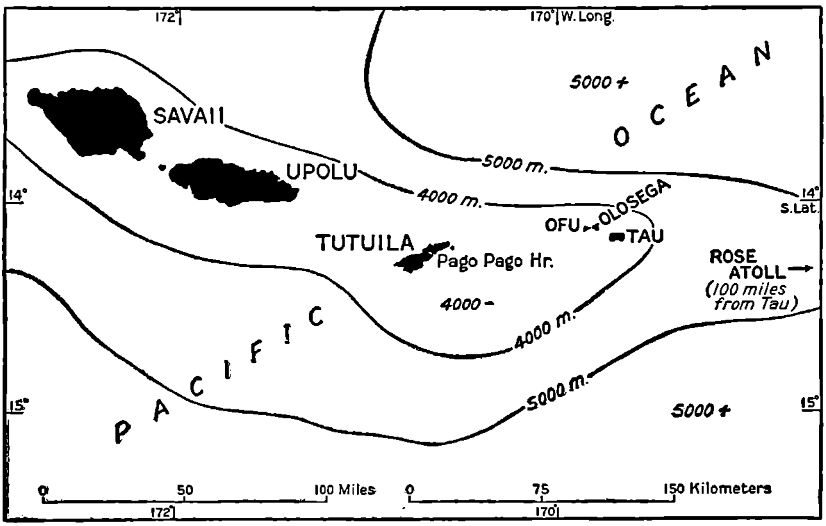
However, direct light on the mystery of the sub-oceanic crust is to be sought chiefly among the high islands. The Hawaiian group is informative. These mid-Pacific islands are strung on a line



32. Map of the Hawaiian Islands.

2500 kilometers or 1500 miles long (Figure 32). At the northwest end are the low Ocean and Midway islands, showing above sea only their thin cappings of limestone. At the southeast end is Hawaii, the highest deep-sea island in the world and still receiving additions to its volume as periodic eruptions of basaltic lava burst out on its flanks (Figure 87). No rocks of continental type have been found anywhere in the group. The high islands—Hawaii, Maui, Kahoolawe, Lanai, Molokai, Oahu, Kauai, and Niihau—are almost entirely composed of thin basaltic flows with subordinate interbeds of basaltic ash. One can see this layering as he walks up the picturesque gorges of Kauai or Maui. In the huge piles of basaltic rock are rare, small bodies of frozen lava which differ chemically from basalt and yet seem best interpreted as derivatives of basaltic liquid. Throughout the 400 miles from Hawaii to Niihau, then, the only visible rock, apart from the insignificant patches of limestone, is eruptive and originally basaltic. The low islands—Bird, Necker, Gardner, Laysan, Lisiansky, Midway, and Ocean—have submarine contour of the kind represented in the more southerly islands and presumably have been developed by a similar volcanic mechanism.

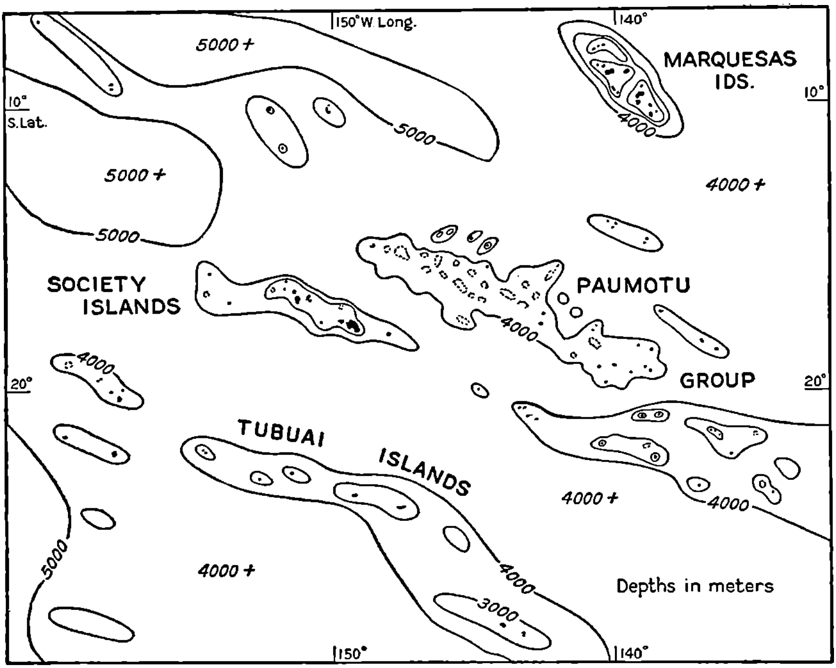
Four thousand kilometers south-southwest of Hawaii is Samoa, a group also showing a remarkable alinement (Figure 33). At the



33. Map of the Samoan Islands.

western end is Savaii, the highest and largest island, with a summit at 1858 meters above sealevel. Then come, in order, Apolima, Manono, Upolu (with the harbor of Apia, the home of Robert Louis Stevenson), Tutuila, Aunuu, Ofu, Olosega, Tau, and Rose Island. The last six named are under the American flag, Tutuila containing the capacious harbor of Pago Pago, a base for the United States Navy. Rose Island is an atoll capping a truncated volcanic cone, and is thus an analogue of Midway and Ocean islands of the Hawaiian group. Savaii is another Hawaii, as it includes the periodically active vent Matavanu, which, with its turbulent, fountaining lake of liquid basalt duplicates the wonderful features of the Hawaiian Kilauea and Mauna Loa.

The twin islands, Ofu and Olosega, are remnants of a single, formerly high cone, which appears to have been wrecked by gigantic landslides on both its northern and southern flanks. A somewhat similar explanation has been given for the remarkably straight, thirty-mile cliff on the north side of Molokai of the Hawaiian group. Along that cliffed line half of Molokai has slipped down, so as to have become quite drowned under the ocean.



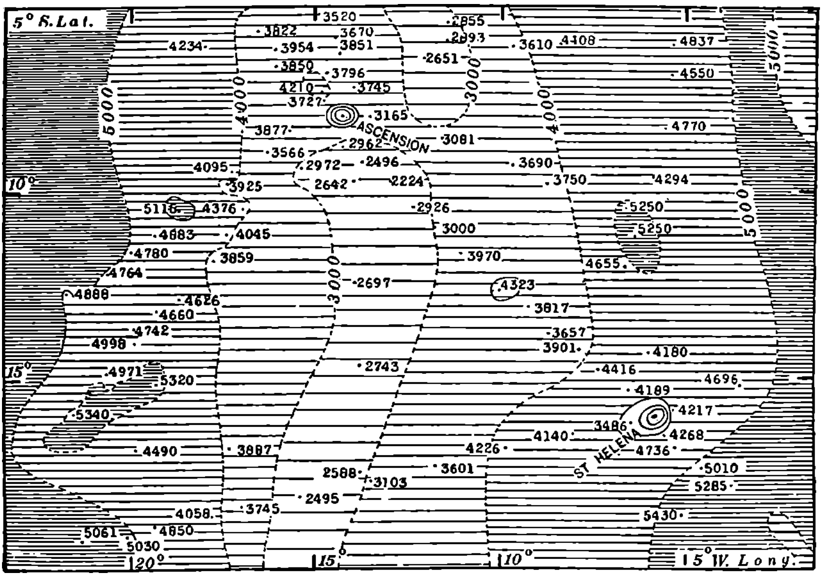
34. Map of elongated groups of islands in the central Pacific. Scale given by degrees of longitude (111 kilometers to one degree).

And the analogies between the Hawaiian and Samoan groups are not confined to the topographic relations, but are notable also in the details of rock composition.

Two thousand kilometers east of Samoa are the Society Islands (Figure 34), where again the great bulk of the lavas is basaltic.

Molten basalt was the material out of which other archipelagoes of the deep Pacific were largely or wholly built. The long list includes the Caroline, Chatham, Fiji, Galapagos, Gambier, Cook, Juan Fernandez, Kermadec, Marquesas, New Hebrides, and Tonga groups. Of essentially basaltic composition are a number of isolated cones, such as Campbell Island, Easter Island, Lord Howe Island, Norfolk Island, Pitcairn Island, and Rotuma Island.

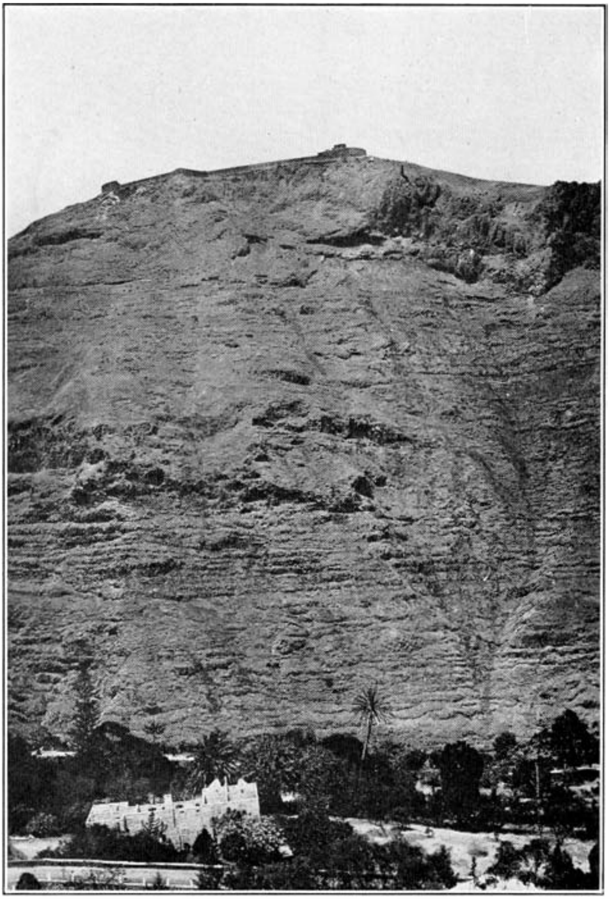
Not one island of the central Pacific has yielded a single piece



35. Map showing depths of water in mid-Atlantic and also location of Saint Helena and Ascension islands. Scale given by degrees of longitude.

of rock rich in quartz or indeed any of the rock types that abound in the continents, always excepting basalt and limestone.

Much the same story can be told about deep-sea islands of the Atlantic basin—Bermuda, Saint Helena, Gough, and Tristan da Cunha. In this smaller basin typical atolls, like Funafuti of the Marshall group, are lacking, but a well-boring has proved that the shelly limestone composing all of visible Bermuda is thin and rests on a high, broad, truncated volcano, essentially like the atoll basements of the Pacific. The volcanic rock found in the Bermuda borehole is a modified basalt.



36. Stream-cut cliff in Saint Helena Island.

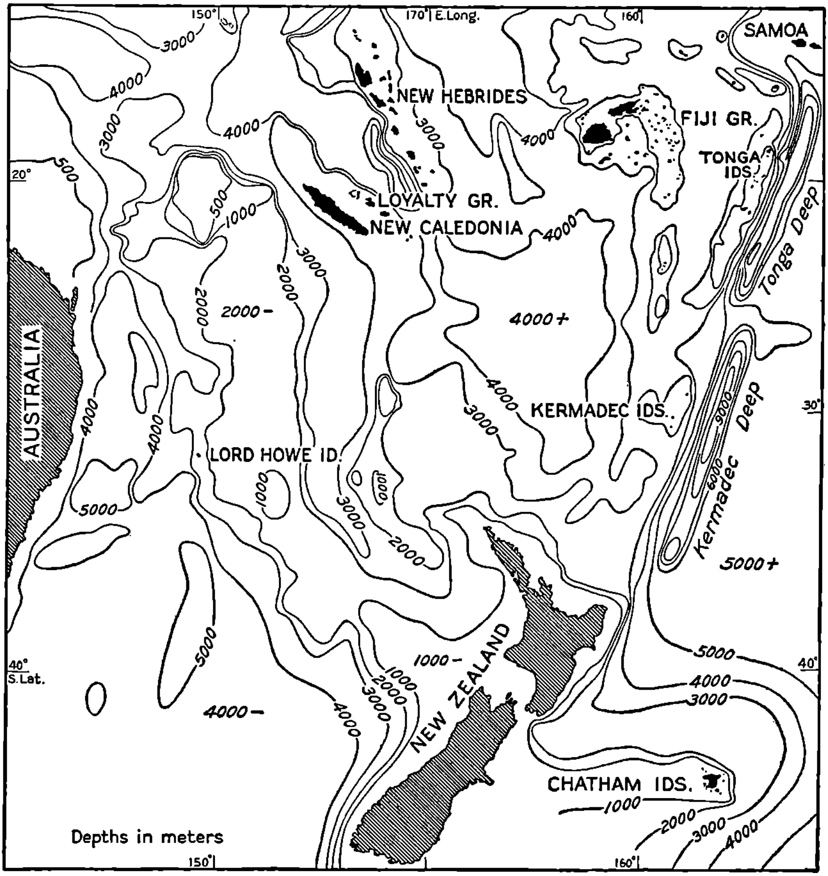
The lonely Saint Helena is in principle a duplicate of Tutuila, Samoa. On the map of Figure 35 we locate the island, a cone rising from the sea bottom where the depth exceeds 4000 meters, while Ascension Island rises from the bottom where it is 1000 meters higher, nearly on top of what is called the Mid-Atlantic Swell. The lightest shading on the map indicates this belt of relatively shallow water extending along the axis of the Atlantic basin. Later we shall have occasion to review some facts about Ascension. Like Ascension and Tutuila, Saint Helena is chiefly made up of countless thin flows of basaltic lava with occasional interbeds of basaltic ash, as illustrated in Figure 36. This photograph shows one steep wall of a valley not far from Jamestown, the one port of the island. Napoleon's body was temporarily buried near the buildings in the foreground. By mineralogical and chemical analyses it has been shown that in no important respect do the basalt and derivatives of basalt in Saint Helena differ from the basalt and derivatives of basalt in Tutuila Island, though the two islands are on opposite sides of the globe.

The deep-sea islands of the Indian Ocean basin are few in number. The list includes Réunion, Mauritius, Rodriguez, Kerguelen, and Christmas Island. See Figures 42-44. The last is a basaltic cone which has been reduced by erosion and then mantled with limestone. All the other islands are essentially basaltic in composition.

We turn now to the second great class of deep-sea islands, those containing non-volcanic rocks of kinds that abound in the continents. Although these islands contain some quartz-bearing or other types of rock characteristic of the continental bucklers, nearly all have been the scenes of volcanic action with outbursts of lava.

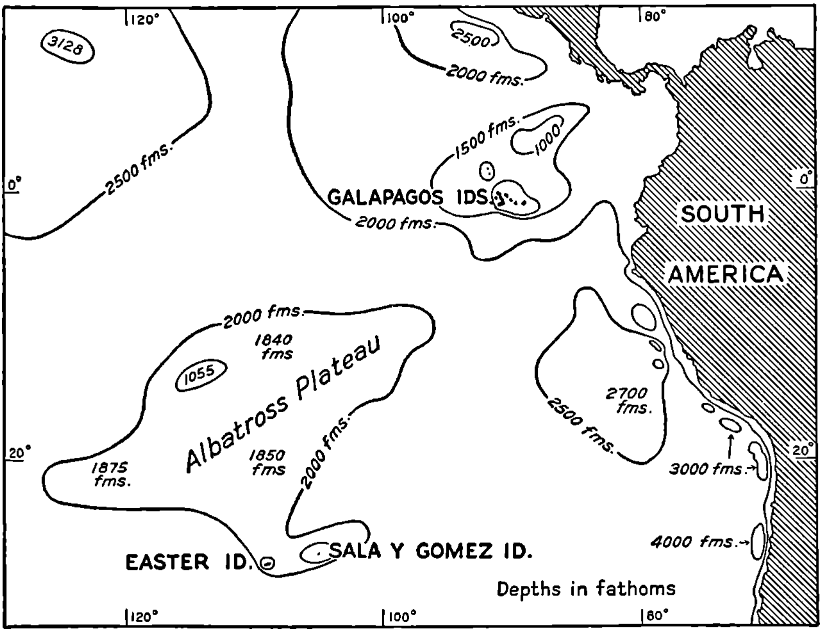
New Zealand, the largest of all, is much like western South America in constitution (Figure 37). In fact it seems possible that the New Zealand Alps are the emerged continuation of the mountain structure represented by the Patagonian Andes, the drowned mountain-arc of Falkland Islands and South Georgia, and the chain of West Antarctica. Throughout New Zealand continental types of rock dominate, but piled upon them and interleaved with them are masses of erupted lavas. These once-molten rocks themselves have almost as wide a range of composition as the eruptive rocks of America, Eurasia, or Australia, and here also common basalt is abundant.

New Caledonia and the large members of the New Hebrides and Fiji groups are clearly more or less isolated blocks of continental rock, penetrated by eruptive masses (Figure 37). Most of the small



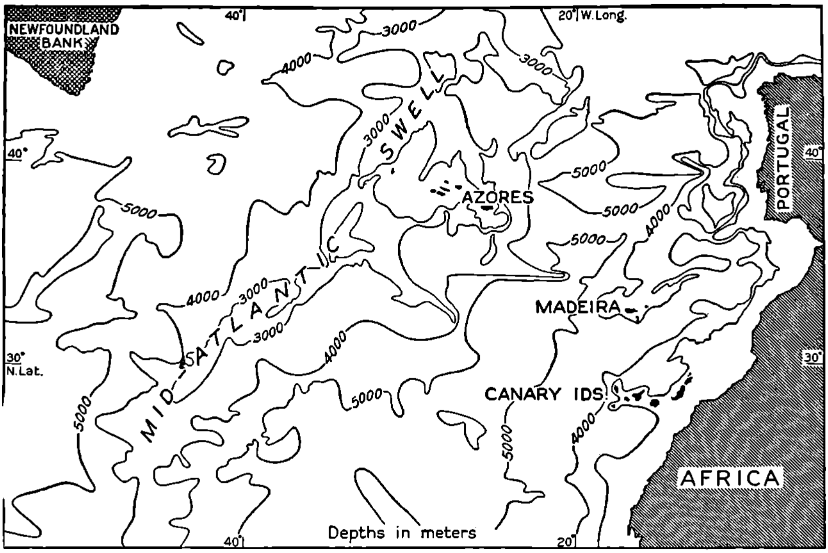
37. Map of islands in the Southwest Pacific. Scale given by degrees of longitude.

islands of Fiji are essentially volcanic in their visible parts, the eruptives including, besides basalt, many cones, flows, and ash-beds of andesitic lava. At least some of this andesite, like the trachyte of Samoa, Hawaii, or Saint Helena, is regarded as having originated from basaltic liquid. The Kermadec Islands are basaltic and andesitic, but in the volcanic ashes pieces of granite have been found. Such volcanic bombs show that the visible piles of Kermadec lava, like the Fijian volcanoes, rest on rock formations which have representatives in the adjacent Australia. These discoveries, together with the irregular submarine topography (see Figure 37), suggest the presence of drowned continental rocks, more or less continuous throughout the 2000 kilometers from New Zealand to northern Fiji.

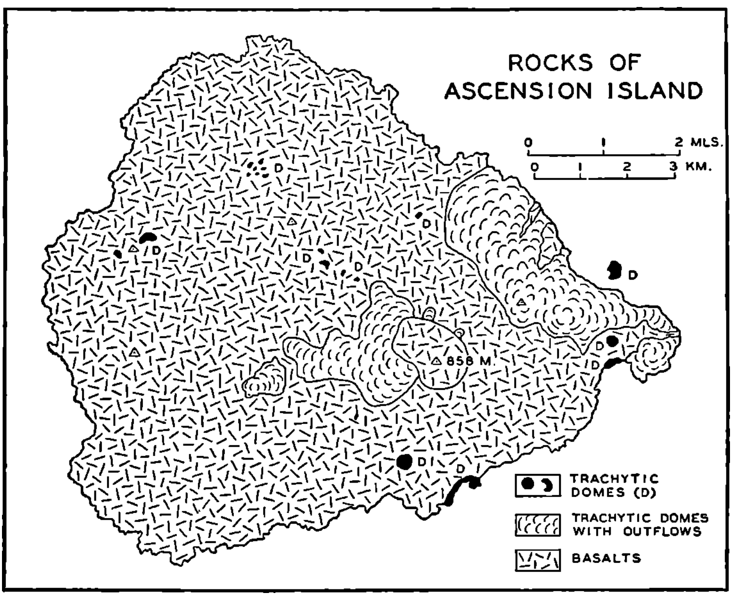


38. Map showing Easter Island in relation to the Albatross Plateau. Scale given by degrees of longitude.

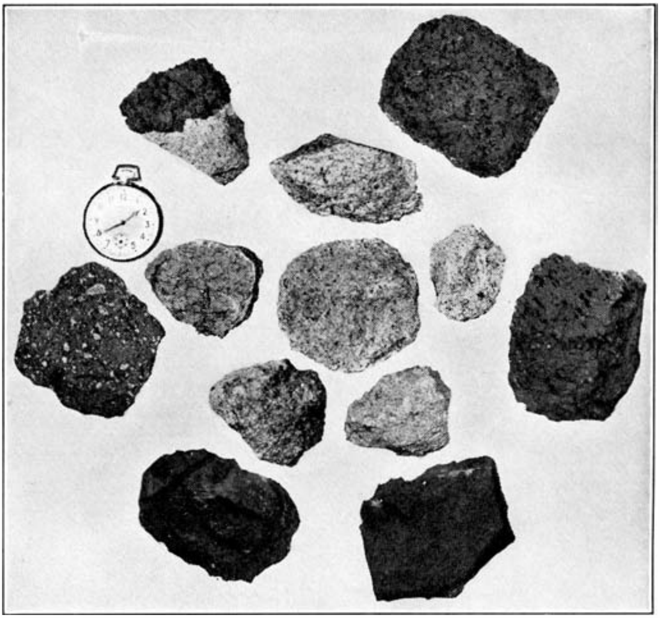
About 2000 kilometers from the eastern end of the Paumotu (Tuamotu) swarm of islands and 3000 kilometers from the shore of South America is Easter Island, which merits special attention. We locate it in the southern part of the map, Figure 38. The island is to be rated as a composite basaltic cone, but among all the islands of the Pacific, far from continental land, it is unique in exhibiting flows of the glassy lava known as obsidian. When analyzed the obsidian turned out to be the chemical equivalent of granite. During a recent field study M. C. Bandy was able to show (personal com-



39. Map showing the Azores Islands in relation to the Mid-Atlantic Swell. Scale given by degrees of longitude.



40. Geological map of Ascension Island.



41. Photograph of specimens of basalt and of granitic bombs thrown up in volcanic vents of Ascension Island.

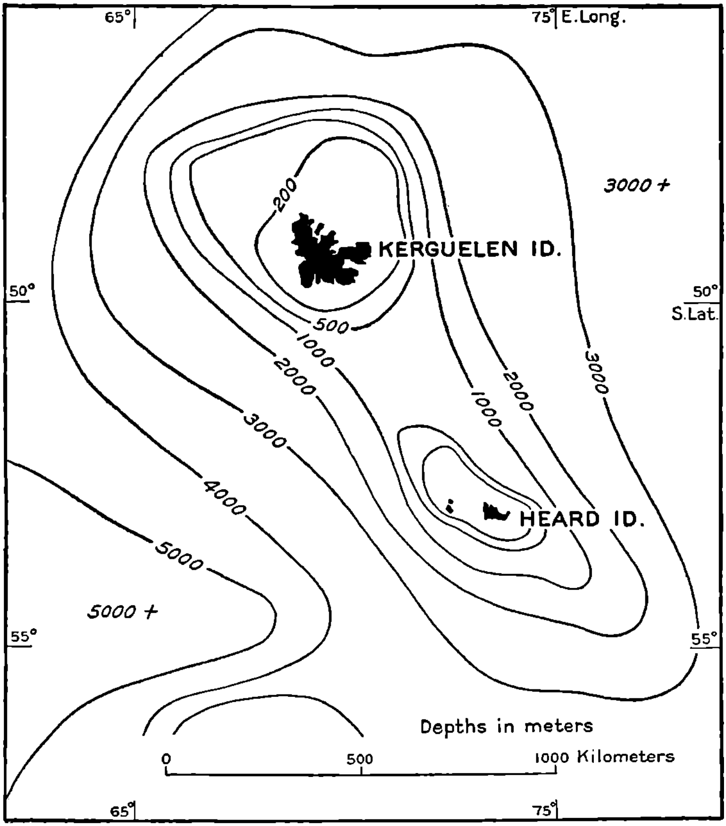
munication) that obsidian composes three short flows emanating from vents which had been opened through the huge pile of basaltic flows. Why lava with the chemical composition of granite should have been emitted at a point so far from the nearest continent is a question of profound interest for the geologist. Is this remarkable glass a derivative of original basalt, or is it the product of reaction between hot basaltic liquid and old, crystalline granite underneath the Easter Island cone? These queries can not be answered definitively, but it is significant that the island cone rises from the submarine Albatross Plateau, which is covered by little more than 3000 meters of water, that is, water 1000 to 2000 meters shallower than that on most of the Pacific floor. The relatively high stand of the Albatross Plateau seems best explained by assuming it to be the top of a thin patch of continental rock. Such a wide patch, like the actual continents, would be supported at the observed level by the higher density of the surrounding crust. In the next chapter we shall learn that most of the sub-Pacific crust is probably crystallized basalt, with a density about ten per cent greater than the density of granite. The assumption described has some independent support from studies of the velocities of earthquake waves as they run through the rocks under the surface of the Albatross Plateau. Thus there is something to be said for the idea that the Easter Island obsidian is the product of reaction, perhaps mere re-melting, of old granite when it was invaded at great depth by hot basaltic liquid.

The Mid-Atlantic Swell presents a problem much like that of the Albatross Plateau. On the map of Figure 39 we see a more northerly part of this gently winding bulge of the Atlantic floor, a bulge 7000 miles long. Its continuation to the south is represented in Figure 35. The Swell actually reaches the surface in the Azores Islands, which inclose visible formations made of typical continental rock.

Farther south along the bulge is Ascension Island, mapped by the author in the year 1921. It was found easy to corroborate Charles Darwin's discovery of many granitic fragments in Ascension, bombs thrown up by violent volcanic explosions.[3] Basalt, indicated by

[3] R. A. Daly, "The Geology of Ascension Island," *Proceedings American Academy of Arts and Sciences,* vol. 60, No. 1, 1925, p. 19.

hachures on the map (Figure 40), is dominant, but trachytic lava in small volumes has been erupted so as to fill older basaltic craters and to make short stubby flows from fissures. A photograph (Figure 41) shows a number of granitic bombs, light-tinted and surrounded by specimens of the darker-colored basalt. It seems best to assume



42. Map of Kerguelen Island, Indian Ocean.

that these fragments of granite had been torn off from a submerged terrain, thinner than a continental buckler but of similar composition.

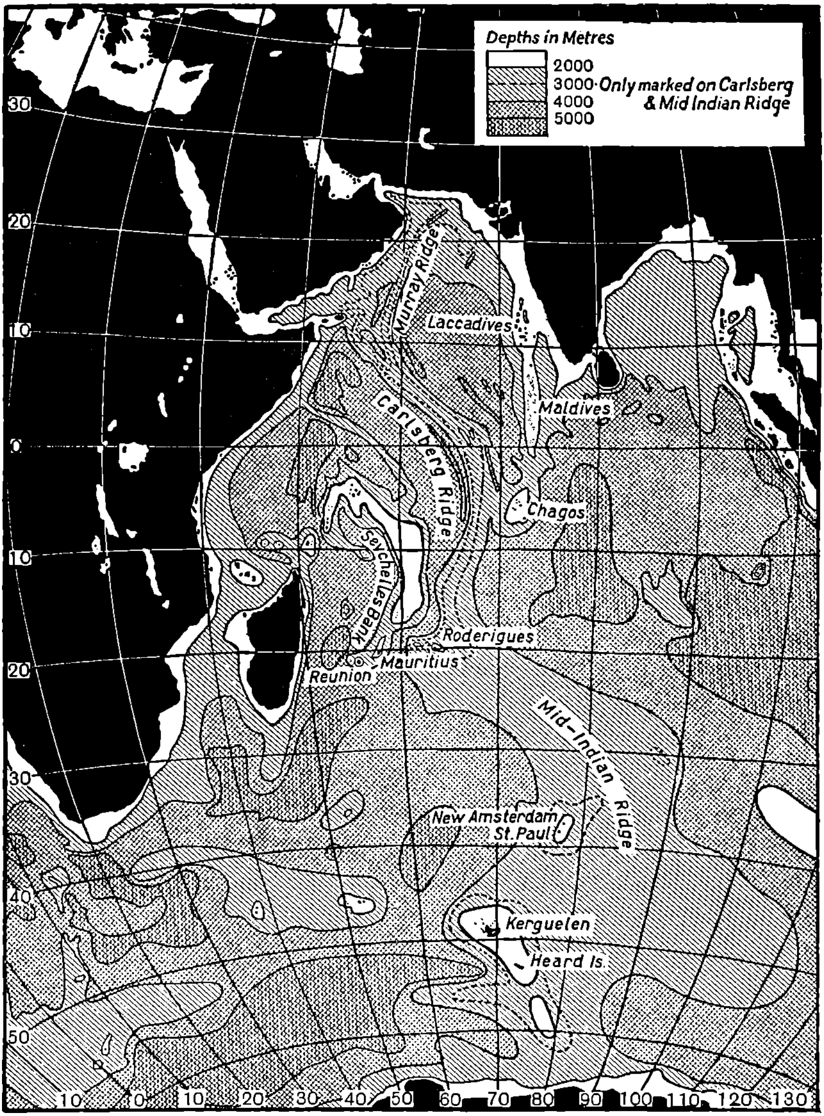
Kerguelen Island of the Indian Ocean is an analogue of Ascension (Figure 42). Although a composite of basaltic eruptions, Kerguelen is reported to bear outcrops of formations characteristic of the continents. Here the sea floor rises in the form of a submarine plateau, 600 miles long, 300 miles wide, and covered by water less than 400 meters deep. This comparatively high-standing block of the earth's crust might be regarded as an outlier of the Antarctic continent, from which, however, it is separated by a belt of deep water 700 miles wide.

Recent soundings by the John Murray Expedition have shown that the floor of the western half of the Indian Ocean is strongly varied, its "swells" including the "Mid-Indian Ridge," the Seychelles "Bank," and the "Carlsberg Ridge" with its offshoot, the "Murray Ridge" under the Arabian Sea. Since the Seychelles "Bank" is known to be largely or wholly granitic, it seems highly probable that the "ridges" also represent great patches of drowned continental rock.[4] See Figure 43. In fact, the geologist is likely to regard these projections from the general floor of the Ocean as representing fragments of the ancient "Gondwanaland," which until the close of the Paleozoic Era connected Africa, India, and Australia.

It is of interest to note that the John Murray Expedition dredged up fragments of basaltic lava on the Carlsberg "Ridge" and also from the deep basin to the northeast, where the water is 4800 meters deep. Similarly the German explorers on the "Meteor" had found pieces of basaltic lava in their dredge when hauled up from the top of the mid-Atlantic Swell where the water is 2000 meters deep.

In review, it is clear that all rocks visible in the oceanic sectors of the globe belong to types also well represented in the continental sectors, but the accent is different. Most of the visible part of the continent is granitic; the visible deep-sea island is chiefly made of basaltic lava flows and basaltic debris of volcanic explosions. Since all basalt, whether of continent or island, was originally molten, it must have come from great depth. Again, the average basalts of the islands in the Pacific, Atlantic, and Indian Ocean basins closely resemble one another and also the average basalt of any and all continents. Both of these fundamental facts are at once understood if the sources of all the basaltic masses are to be referred to a world-circling, vitreous substratum immediately beneath a continuous, world-circling crust. Why the substratum basalt is eruptible and

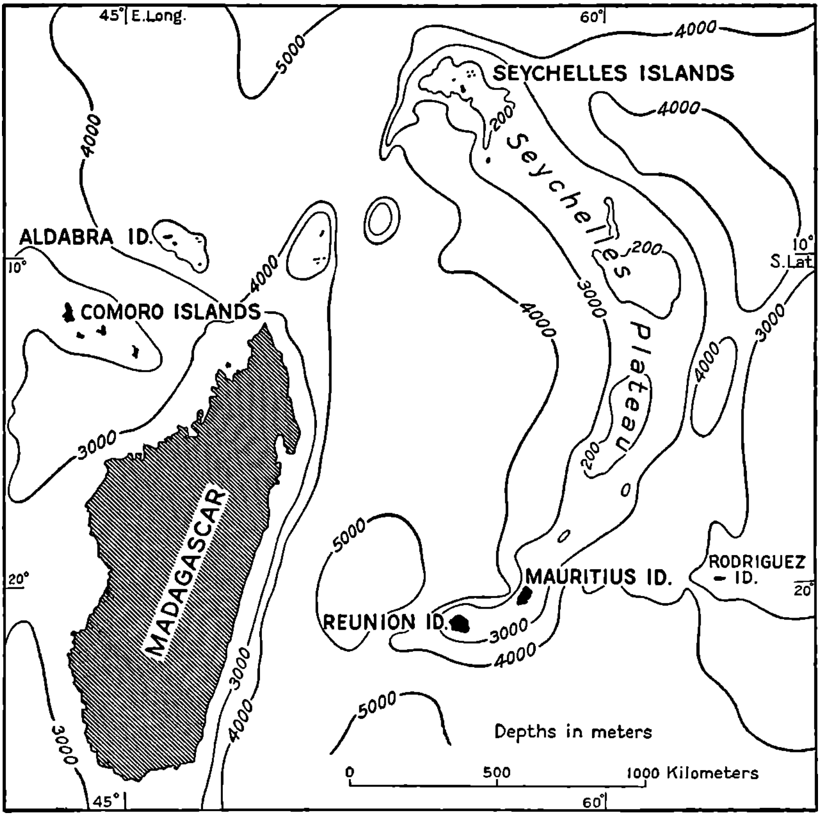
[4] J. D. H. Wiseman and R. B. S. Sewell, *Geological Magazine,* vol. 74, 1937, p. 219.



43. Relief of the floor of the Indian Ocean. Courtesy of J. D. H. Wiseman and R. B. S. Sewell and the Editor of the *Geological Magazine*.

why it has risen through the crust are problems to be specially discussed in the third, fourth, and fifth chapters.

On the other hand, our survey of the deep-sea islands has taught us comparatively little about the constitution of the crust below the open ocean. Islands of the Seychelles (Figure 44), Azores, and



44. Map of the Seychelles Plateau.

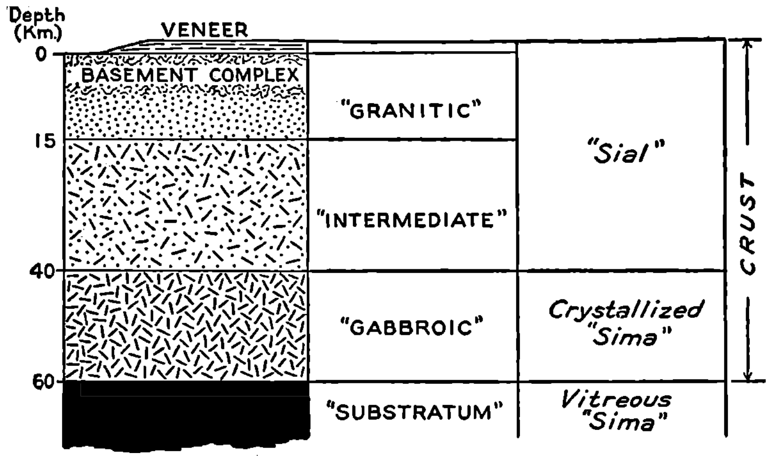
Fiji groups expose to the air ledges of quartz-bearing and other rocks that are characteristic of the continental bucklers. The submarine topography suggests that each of those formations is merely the emerged top of local patches of continental rock. Similar patches under Kerguelen Island, Ascension Island, and the Tonga Islands are suggested by the presence of quartz-bearing bombs in the respective volcanic piles. In general, however, the volcanic islands of the central Pacific and of the deeper parts of the Atlantic basin have yielded no fragments of continental rock, so that over one half of the earth we have no direct clue to the composition of the crust. To find real clues we must look elsewhere. That we shall do as we pursue our main theme, particularly in the next chapter and also the last chapter of this book.

Summary

From the topographic and geological maps of the earth have come facts bearing on our principal topic, namely, the validity of a particular idea about the constitution of the outer solid earth. We have visualized the continental bucklers with their flat-lying and crumpled veneers of layered sediments, old and young, and bedded lavas, old and young; and the infinitely varied structural disorder of the Basement Complex. We have found that granite is the fundamental stuff out of which both sedimentary veneers and Basement Complex are made; that at some, as yet undetermined, depth or depths below the surface of each buckler, during at least the last half billion years, basalt has been steadily or temporarily in the molten state and capable of eruption into and through the overlying crust of the earth; that erupted basalt is the staple material in the thousands of deep-sea islands; and that extensive "swells" and "plateaus," varying the relief of the ocean bottom, are probably topped by relatively thin layers of rock characteristic of the continents.

The only voluminous material common to the visible rock outcrops of both buckler and ocean basin is basalt, and the direct suggestion of the world map is that basalt constitutes a deep, eruptible layer extending all round the globe, a complete earth-shell. Later chapters will add much strength to this suggestion, and, as a kind of résumé of this first chapter and also as a concise statement as to what we are going to find about the make-up of the outer earth, the diagrammatic section of a continent, Figure 45, may be inspected. So far we have dwelt on the physically visible. The diagram is intended to anticipate what we shall find during the argument of the next chapter, when we shall try to make the physically invisible mentally visible.

The Basement Complex passes down into, is part of, a 15-kilometer layer with properties throughout essentially like those of the visible Complex, so that the layer (stippled in the drawing) may be called the "granitic" layer. Below that is a second layer, to be referred to as "intermediate," because it is of composition intermediate between granite and basalt. And then comes the third layer, which in chemical composition approximates to gabbro, a crystallized form



45. Diagrammatic cross-section of the different layers constituting the earth's crust in continental sectors.

of basaltic liquid, and may for convenience be named the "gabbroic" layer. The three layers or shells together make up the continental part of the crust of our earth-model, a crust assumed for the present epoch and one which, in constitution and thickness, can hardly have changed much during the last few millions of years. On the other hand, it is most unlikely that any such model could represent well the conditions when the earth was young or during certain revolutionary epochs when the great mountain chains were built. How the proposed model would have to be changed to fit those ancient conditions in detail is beyond the scope of this book.

Below the crust is the fourth layer, according to the main hypothesis to be discussed—a world-circling shell made of glassy, noncrystallized basalt. The next step is to examine the sanctions for sending the plummet of theory so far below the thin skin of the earth which one can actually see.

CHAPTER II

PLUMBING THE DEPTHS

"A Call for Athena the Wise"

Introduction

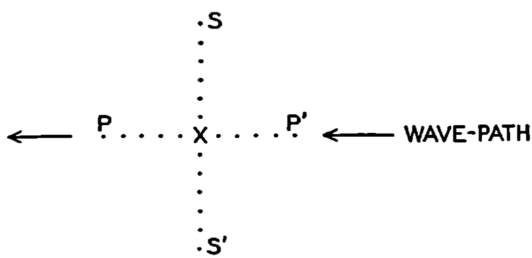
THE men who map the rocks can make shrewd judgments about the underground extension of visible formations, but such inferences can be safe to a depth that is only a little more than one one-thousandth of the earth's radius. What lies beyond? The field geologist, unaided, can make no adequate answer. He therefore calls in a colleague, the geophysicist, one of whose aims is to devise means of diagnosing the interior of the globe.

At the present time the most promise is extended by a geophysical method which has some resemblance to the X-ray technique of medicine and surgery. The method is founded on the speeds of earthquake waves at different levels in the earth. So from seismology, the science of earthquakes, has come light. What have seismic messengers from the depths so far reported concerning the nature of the outer layers of the planet? This, the subject of the chapter we are now entering, is complex, and it is well to note at the outset that the mode of attack in question now gives only approximate results, not the more accurate idea of the earth-shells which future research may be expected to furnish.

Earthquake Waves

Seismographs are sensitive instruments designed to make records giving the speeds, kinds of vibration, and energies of earthquake waves as these rush along each layer of the earth's body. Earthquakes are either natural or artificial. When the crust, previously in a strained condition, is suddenly fractured by the strain, the earth's body suffers a violent jar. Or it may be jarred by a volcanic explosion or by the explosion of a big charge of dynamite. From any of these centers of shock three kinds of elastic waves are set going in the solid rock.

The fastest wave runs out in all directions, with nearly the same speed as that with which sound waves travel through the same rock. As the wave travels, the particles of the rock vibrate to and fro in the direction of the wave's path or "ray." In illustration see Figure 46, where a particle of the rock, initially at the point X, oscillates between the points P and P′ when this wave is passing. Because the to-and-fro motion is along the wave-path, a wave of this



46. Diagram illustrating the respective displacements of a rock particle by Push wave and Shake wave.

kind is often called a Longitudinal wave. Again, since the first effect on the particles of the solid is to press or push them together, the alternative name, Push wave, has been coined.

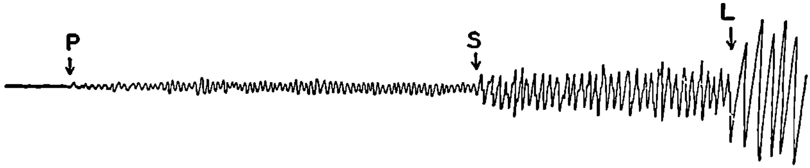
After an interval of time a second, slower kind of elastic wave, sent out from the same center of shock, arrives at the recording instrument. Now the rock particles are vibrating, not parallel to the wave-path but at right angles to it—in the diagram between the points S and S′. The motion is somewhat like that of a particle in a carpet when being shaken from one end. Hence this has been called a Shake wave. Because the motion is across the wave-path seismologists use the alternative name, Transverse wave.

Both Push and Shake waves are body waves, spreading through the body of the earth in all directions from the center of shock.

Still slower than the Shake waves is a set of induced waves that travel along the upper surface of the shocked layer of rock. These

Surface waves are longer than either of the other two kinds, and as a rule cause larger swings of the recording pendulum of the seismograph.

All three kinds of waves record their arrivals graphically at a seismographic station, in a so-called seismogram. In principle a seis-



47. Illustrating one type of seismogram.

mogram is illustrated by Figure 47, where the arrows point to the instants of the different arrivals. Time is represented by the horizontal dimension, and we see that the impulses corresponding to the Push, Shake, and Surface waves arrive at the seismograph in that order.

Now, from such machine-written records the seismologists are able to deduce the elastic properties of the earth's crust and deep interior and also something of their structure. Let us see how it is done.

The speeds of earthquake waves in a perfectly elastic rock depend on three properties of the rock: first, its density; second, its rigidity, that is, its elastic resistance to a shearing force; and, third, its volume compressibility, that is, the amount by which a unit cube of the rock is compressed by a unit of all-sided pressure upon the cube. Comparison of the actual wave-velocities with those calculated from equations (1) and (2), assuming perfect elasticity for the rocks, is being used to tell the kinds of rock that constitute the earth all the way down to the center, 4000 miles down.

$$(V_s)^2 = \frac{R}{D} \quad \cdots\cdots\cdots\cdots \quad (1)$$

$$(V_p)^2 = \frac{K + 4/3\ R}{D} \quad \cdots\cdots\cdots\cdots \quad (2)$$

In the equations V_s and V_p respectively represent the velocities of the Shake and Push waves; D represents the density of the rock traversed by the waves; R represents the rigidity; and K represents the so-called bulk modulus or the reciprocal of the volume compressibility.

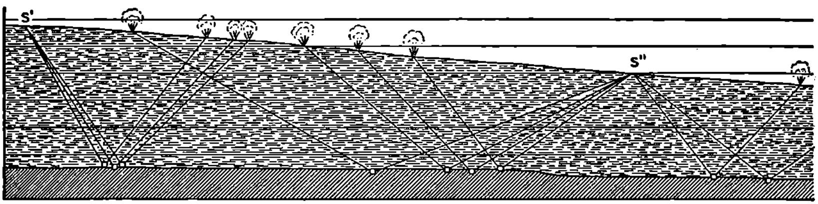
We recognize a person at the other end of a telephone wire by a property of his voice. The seismologist recognizes the species of rock in a given layer of the earth by one or other or both properties, the rigidity of that layer and its compressibility.

This recognition demands preliminary information of two sorts. One must know, first, the velocity of an earthquake wave at the depth concerned; and, second, the wave-velocities that would characterize all types of rock that can conceivably exist at that depth. The seismologist himself furnishes the first kind of information. The physicist in the laboratory furnishes the other kind, by reporting instrumental measurements of the density, rigidity, and compressibility of the many species of accessible rocks when exposed to high pressures and temperatures. For each accessible type of rock the physicist calculates the wave-velocity. That type whose calculated wave-velocity most closely matches the velocity of the earthquake wave in the shell of the earth which is being investigated is considered to make up this inaccessible layer.

The words "layer" and "shell" have been used advisedly, for the seismologist has found what he calls "discontinuities" in the earth, that is, levels where there are rapid changes in the physical constitution of the rocks. By discontinuities the crust is divided into successive layers or shells. This fundamental fact has been proved in two different ways.

The first method is that of reflection, analogous to echo-sounding in the ocean. A powerful dynamite explosion is set off at an instant which is known to a small fraction of a second. Elastic waves rush away from the center of explosion in all directions. If at some deep level there is a discontinuity or break in the material, the waves are reflected back from that level or interface, their times of arrival at the surface being registered by a seismograph. The average speeds of Push wave or Shake wave in the rock above the discontinuity are also determined by the seismograph. With the use of all these data the depth of the discontinuity can be found by a simple calculation.

For example, the thicknesses of great glaciers have been thus measured. The vertical cross-section of Figure 48 shows above, with horizontal shading, glacial ice; and, with diagonal shading, the rocky floor beneath. Points where timed dynamite explosions were made are indicated graphically. Two locations for the seismograph are marked at S′ and S″. The drawing is copied from a memoir



48. Section of the Greenland ice-cap, showing method of determining its thickness by the reflection method.

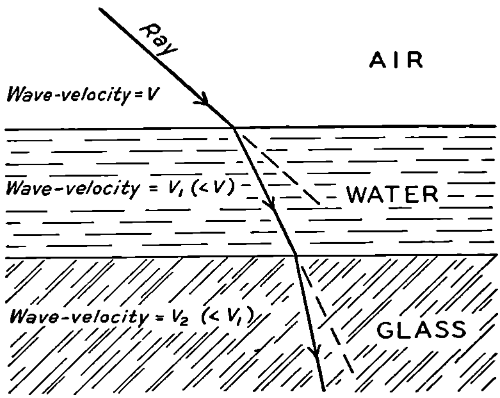
detailing this field proof that the Greenland ice-cap is more than a mile thick.

Such reflection-shooting, as it is called, is now commonly preferred in prospecting the ground for beds of rock where deposits of petroleum, natural gas, rock salt, sulphur, and other valuable materials lie hidden. Millions of dollars are being spent on research of the kind.

Artificial explosions have too little energy to give records from which the location of discontinuities at great depth can be determined. On the other hand, the incomparably more violent shocks at the "foci" of natural earthquakes do furnish the required information.

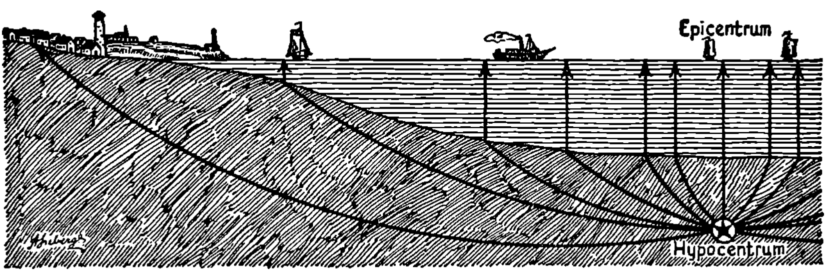
The second method of finding discontinuities, the levels where contrasted earth-shells meet, is that of refraction. Here again the elastic waves from both dynamite explosions and from centers of natural shocks are being used. Suppose a wave, sent down from the point where the blow was struck, to penetrate a discontinuity. If a wave-ray meets the plane of the discontinuity at any angle differing from a right angle, the ray is bent or refracted at that interface. In the same way a beam of light is refracted when it penetrates the boundary between air and water or water and glass (Figure 49).

With increasing depth in the earth the particles of the rock are jammed together by the growing pressure. Hence the rock becomes more rigid and also less compressible as the depth increases. Referring once more to equations 1 and 2, we see that as a rule the wave-



49. Diagram illustrating the principle of refraction.

velocity must increase with increase of depth, even in an earth-shell which is of quite uniform composition. Hence a wave is continuously refracted as it dives into the earth-shell or rises through that shell.

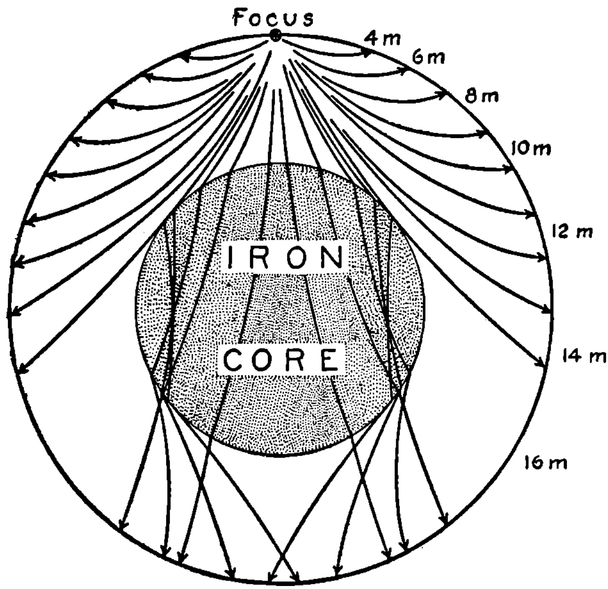


50. Diagrammatic section illustrating refraction of an earthquake wave with center of shock at "Hypocentrum" (focus). After A. Sieberg. Courtesy of G. Fischer, Jena.

Figure 50 illustrates the case. At the star, figured to represent the center of an earthquake shock, waves are set traveling in all directions. Some of their paths are drafted in heavy lines. These lines are bent systematically upward, since they portray the normal case where a given wave travels faster the deeper it goes.

Figure 51 is a diagrammatic section of the earth, including the so-called iron core. The drawing illustrates the principle of important refraction at master discontinuities. We note that a wave, set going near the surface, plunges downward, suffers one or more abrupt refractions at discontinuities as well as continuous refraction in any individual shell traversed, and ultimately emerges at the earth's surface.

A chain of seismographs, ranged out from the region of shock,



51. Section through the center of the earth, showing the paths of earthquake waves, their refractions, and some of their times of arrival at the surface, in minutes (m). After A. Sieberg; courtesy of G. Fischer. Jena.

registers the times of arrival of this emerging ray at the respective points on the surface. Of course, with increasing distance from the center of shock, a Push wave or Shake wave emerges at later and later instants. If the whole path of either wave through the rock above a given discontinuity is known, the wave-velocity in the rock just beneath that discontinuity and also the depth at which the change of material takes place can be computed. How such calculation is made is a matter too involved for present description.

Since we are inquiring particularly into the reality and constitution of a terrestrial crust, a caveat should be filed. The computed thickness of, and wave-velocity in, any of the outermost earth-shells are subject to some inaccuracy, if there be even small mistakes in estimating the wave-path and wave-velocity above any one of the overlying discontinuities. Improvement in instrumental equipment and increasingly accurate seismograms are gradually narrowing the chances of error, but it is still impossible to be sure of absolutely exact positions for the discontinuities above the depth of 100 kilometers.

The Continental Sectors

After thus reading many messages from the earth's interior, seismologists have concluded that there are three principal layers under the continental surfaces and above the depth of about 60 kilometers or 37 miles. The thickness of the uppermost layer including the Basement Complex has been variously estimated at from 10 to 25 kilometers, the more recent and more accurate estimates tending toward the smaller value. The differences are partly due to insufficient data, partly to the fact that the discontinuity is not perfectly sharp, and partly to real changes of thickness from one continental region to another. We shall take 15 kilometers or 9.3 miles for the thickness of the uppermost layer.

The bottom of the second layer is placed by different authorities at depths ranging from 35 to 45 kilometers, a good value being 40 kilometers or 25 miles. This gives 25 kilometers for the thickness of the second layer, which itself seems to be composed of sub-layers. The total thickness of the two main layers, namely, 40 kilometers, was in mind when the crust-substratum hypothesis was imagined in the form stated in the first chapter. See Figure 45. At the 40-kilometer level the pressure is about 11,500 atmospheres or nearly 80 tons to the square inch, and the temperature is roughly estimated at 900° Centigrade.

Elastic Properties of Rocks

So much for the seismological half of the detective method and for some of its results. We shall now consider the other half—experiment on the elastic properties of all accessible types of rock that can be reasonably imagined to enter into the constitution of crust and substratum.

To reproduce the conditions below the earth's surface, the experimenter has to expose his specimens of rock to high pressure and high temperature simultaneously. The job of measuring the rigidity and compressibility of rock at room temperature and high pressure is not easy. Measurement at high pressure for specimens heated above 500° Centigrade is still more difficult. One reason is the danger of collapse of the retaining steel cylinders when weakened by the heat. Nevertheless much progress has been made through the researches of L. H. Adams and colleagues in the Geophysical Laboratory of the Carnegie Institution at Washington,[1] and the more recent studies by P. W. Bridgman and F. Birch and colleagues at Harvard University.[2] The Harvard results are specially noteworthy because of the high sensitivity and accuracy of the apparatus used, and also because many of the investigations there were conducted with the rock specimens at relatively high temperatures. In both laboratories the maximum pressures employed were of the same order as those ruling along the 40-kilometer or 25-mile level. At Harvard the compressibility of a number of rock types has been measured under the conditions of temperature as well as pressure prevailing about 15 kilometers below the surface, and from the results this elastic property can be closely estimated for the same rock specimens when supposed to be at depths considerably greater. Measurements of the rigidity have been made on many specimens under the all-sided pressure of 4000 atmospheres and at temperatures of 30° and 100° C. It is planned to extend the study so as to cover much higher temperatures.

[1] L. H. Adams and E. D. Williamson, *Journal Franklin Institute,* vol. 195, 1923, p. 520; *Smithsonian Report for 1923,* p. 241; *Journal Washington Academy of Sciences,* vol. 21, 1931, p. 381. L. H. Adams and H. E. Gibson, *Proceedings National Academy of Sciences,* vol. 12, 1926, p. 275, and vol. 15, 1929, p. 713.

[2] P. W. Bridgman, *American Journal of Science,* vol. 7, 1924, p. 81; vol. 10, 1925, p. 359; vol. 15, 1928, p. 287. F. Birch and R. R. Law, *Bulletin Geological Society of America,* vol. 46, 1935, p. 1219. F. Birch and R. B. Dow, *ibid.,* vol. 47, 1936, p. 1235. J. M. Ide, *Proceedings National Academy of Sciences,* vol. 22, 1936, p. 81 and p. 482; *Journal of Geology,* vol. 45, 1937, p. 689. F. Birch, *Journal of Applied Physics,* vol. 8, No. 2, 1937, p. 129. F. Birch and D. Bancroft, *Journal of Geology,* vol. 46, 1938, pp. 59, 113.

The Crystalline Sima.—Among the results we shall first pay particular heed to those from which one may deduce the kind of rock immediately underlying the 40-kilometer discontinuity. At this level the velocity of the Push wave suddenly jumps to about 7.8 kilometers per second, and the velocity of the Shake wave jumps to about 4.35 kilometers per second. Where these rapid increments of speed take place, there is evidently a change from a less rigid and more compressible rock above to a more rigid and less compressible rock below. What is the kind of rock below the break described? In other words, what is the kind of rock constituting the third and lowest layer of our continental crust?

There are two laboratory methods of attacking the problem, one founded on what is called the dynamical elasticity of rocks and the other founded on what is called the statical elasticity.

The principle underlying the dynamical method has for the first time been effectively applied to many types of rock by J. M. Ide and F. Birch at Harvard University. Their apparatus, involving forced vibration of a rod of each kind of rock, gives the velocity of sound in the rock, the quantity called Young's modulus (E), and also a value for the rigidity (R) of the rod.

First, measurements on many specimens at the temperature and pressure of the laboratory were made. The densities of the specimens were also determined. In connection with our present problem we are to be specially concerned with the results for specimens of crystallized basalt, called diabase and gabbro. Since these particular rocks have been proved to be almost perfectly homogenous and elastic, the velocities of the elastic waves in each can be computed with approximate accuracy by the use of equations connecting E, R, and D.

From Sudbury, Ontario, specimens of gabbro (also called norite) were obtained and were tested. Using only the dynamically determined values of E and R, the wave-velocities given in line A of Table III were calculated. Using the dynamically measured E and also W. A. Zisman's value for the (statical) compressibility of this gabbro at one atmosphere of pressure, the wave-velocities given in line B were calculated from another set of equations. Line C states the actual velocities in the Sudbury gabbro, at and just beneath the surface, as measured by the Harvard seismologist, L. D. Leet.[3] He used seismographs that recorded the pulses from accurately timed explosions on the rock ledges at Sudbury.

TABLE III

DEDUCED AND ACTUAL WAVE-VELOCITIES IN GABBRO

	Shake Wave (km/sec)	*Push Wave (km/sec)*
A. Laboratory	3.57	5.93
B. Laboratory	3.53	6.16
C. Field-seismograph	3.49	6.22

The close agreement of values affords good hope that the laboratory dynamical method can foretell very nearly the wave-velocities to be expected in an earth-shell made of crystallized basalt.

The next step was to determine the effect of high pressure on the velocities in various types of rock, these still being at temperatures no higher than 30° Centigrade. We shall consider sample values for diabase, gabbro, dunite, and pyroxenite. Both diabase and gabbro are composed essentially of the minerals feldspar, pyroxene, and olivine. The two rocks are, however, distinguished by different arrangements of these crystals. Dunite may be regarded as crystallized basalt minus feldspar and pyroxene, and pyroxenite as crystallized basalt minus feldspar and olivine.

From their manuscript notes, Professor F. Birch and Dr. D. Bancroft have kindly released for present publication the values shown in Table IV. Here the all-sided pressures on the specimens are given in kilograms per square centimeter (one kilogram per square centimeter is about one atmosphere or fifteen pounds to the square inch), and the computed velocities of the Shake or Transverse waves to correspond are entered. Assuming that the acceleration of the wave-velocities established for the interval between 3000 and 4000 units of pressure obtains at still higher pressure, the velocities of the waves at 11,500 kilograms (the pressure at about the 40-kilometer level in the earth) would be those given between brackets.

[3] W. A. Zisman, *Proceedings National Academy of Sciences,* vol. 19, 1933, p. 653. J. M. Ide, *ibid.,* vol. 22, 1936, pp. 81 and 482. L. D. Leet, *Physics,* vol. 4, 1933, p. 375; *Bulletin Seismological Society of America,* vol. 26, 1936, p. 129.

TABLE IV

LABORATORY DETERMINATIONS OF VELOCITIES OF THE SHAKE WAVE

(Average values at 30° C.)

Kind of Rock	*All-sided Pressure* (kg/cm²)	*Wave-velocity* (km/sec)
Vinal Haven diabase	1	3.28
	1000	3.87
	3000	3.90
	4000	3.91
	(11,500	3.99)
Maryland diabase	1	3.60
	1000	3.77
	3000	3.81
	4000	3.83
	(11,500	3.98)
French Creek gabbro	1	3.39
	1000	3.90
	3000	3.96
	4000	3.98
	(11,500	4.13)
Mellen gabbro	1	3.35
	1000	3.70
	3000	3.72
	(11,500	3.87)
Webster dunite	1	4.12
	1000	4.48
	3000	4.55
	4000	4.57
	(11,500	4.72)
Stillwater pyroxenite	1	4.47
	1000	4.52
	3000	4.54
	4000	4.56
	(11,500	4.71)

Since the temperature increases with depth, the effect of temperature on the wave-velocity must also be tested. This rather difficult investigation is now under way. Already it appears that the effect somewhat offsets the contrary effect of the high pressure ruling at the deep level.

We recall, now, that the Shake wave just below the 40-kilometer level has been estimated by the seismologists at 4.35 kilometers per second, or higher than any value given in the Table for either diabase or gabbro. On the other hand, the actual seismic velocity might lead us to prefer dunite or pyroxenite for the third layer. However, such preference would be reached without our having taken account of several facts, not yet mentioned but to be weighed after we have studied the results of measuring the effective elasticity of rocks by the statical method.

This older laboratory method is based on measurements of the (statical) compressibility of rocks. Of the many data only those will be noted that bear directly on the problem of the third layer in the continental sectors of the earth. It appears that the choice of material for this layer must be a comparatively dense and little compressible type of rock. Among the types actually studied are again the four species, diabase, gabbro, dunite, and pyroxenite. The measurements at the Harvard laboratory have given their compressibilities when the specimens were at room temperature and under high pressure. Column 2 of Table V states the results for an all-sided pressure of 11,500 atmospheres. For the corresponding depth in the earth, 40 kilometers down, the temperature has been estimated at 900° Centigrade. Preliminary experiments on diabase show that heating to 900° increases the compressibility about five per cent. Assuming the same percentage in all four instances, the statical compressibilities of diabase, gabbro, dunite, and pyroxenite, if placed under the conditions ruling at the 40-kilometer level in the earth, come out with the values given in the third column of the Table.

Let us suppose for the moment that some one of these four types of rock composes the third layer in the continental crust. The compressibility of the material at the top of the layer is stated in the third column of the Table. The corresponding velocity of the Push wave has been calculated and entered in the fifth column.

Table V

Velocities of the Push or Longitudinal Wave, Computed from Laboratory Measurements of Compressibilities

Kind of Rock	*Density of Rock*	*Compressibility (in ten millionths per kg per sq. cm) at depth of 40 km and at temperature of:*		*Wave-velocity (km per sec) at depth of 40 km and at temperature of:*	
	1	2 20° C.	3 900° C.	4 20° C.	5 900° C.
Diabase, Vinal Haven	2.96	10.7	11.2	7.4	7.2
Diabase, Maryland	3.01	10.5	11.0	7.4	7.2
Gabbro, French Creek	3.03	10.5	11.0	7.3	7.2
Gabbro, Mellen	2.87	10.3	10.8	7.6	7.45
Pyroxenite, Transvaal	3.29	8.0	8.4	8.1	7.9
Dunite, Webster	3.275*	7.8*	8.2	8.3	8.0

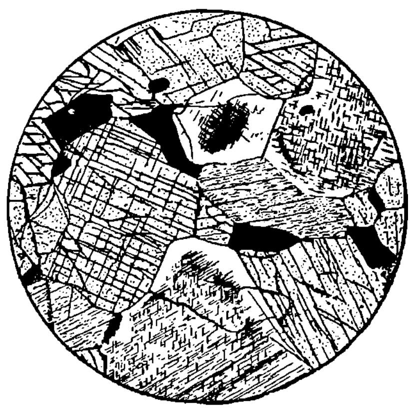
* Values given by L. H. Adams and H. E. Gibson, Geophysical Laboratory in Washington.

Now we make the comparison toward which we have been aiming. The actual velocity of the Push wave, given by the seismologists for the 40-kilometer level, is about 7.8 kilometers per second. The velocity deduced for the accessible diabase or gabbro, when exposed to the same physical conditions, is 7.2 to 7.45 kilometers per second. The actual velocity is five to eight per cent greater. On the other hand, the specimen of dunite or pyroxenite, if affected by temperature in the same way as diabase, would give nearly the actual velocity at the deep level.

Thus the measured compressibilities, like the measured rigidities matching the wave-velocities of Table IV, suggest at first sight that the third layer of the continental crust is not crystallized basalt, but either dunite or pyroxenite. In fact, some workers on the fundamental problems of physical geology are basing their thought on the assumption that this earth-shell is actually crystallized dunite and many hundreds of kilometers thick. However, that conclusion has been made without due regard to several considerations that tend to modify it.

In the first place, the rocks investigated are loose-textured or porous to a degree that can not be represented in the inaccessible rock of the third layer. Each rock specimen is made of multitudes of crystals. In all the specimens there are open, albeit sub-microscopic, cracks between the adjacent crystals, and a much greater number of cracks appear as gaping cleavages in the rock minerals. A camera lucida drawing of a thin slice of diabase illustrates the case (Figure 52). The banded laths are feldspar; the fatter grains between the feldspars are pyroxene. Evidently there are physical breaks where

52. Internal structure of a diabase, magnified. After A. Osann. Courtesy of Die Schweizerbartsche Verlagsbuchhandlung, Stuttgart.



53. Internal structure of a pyroxenite, magnified. After A. Harker. Courtesy of Methuen and Company.

the two kinds of crystals meet, and there are other, perhaps even more important, breaks located at the cleavages appearing as cracks in the pyroxene. Figure 53 is a similar drawing of a thin section of pyroxenite, the pyroxene being accompanied by some black oxide or iron. Once more we note abundant cleavage cracks.

It must be very different with the inaccessible rocks whose nature we are trying to detect. In general these rocks, from the time of their solidification, that is, for untold millions of years, have been under high pressure and at relatively high temperature. Under such conditions the intergranular openings must be practically negligible, and it is likely that at depths exceeding twenty kilometers open cleavages do not exist at all. At these depths cleavage is potentia., not actual or "realized."

In contrast, open cleavages are expected in minerals that have formed from rock-melts near the earth's surface where pressure is low. Moreover, if rocks, originally solidified at great depth, are lifted, and eroded so as to be brought into contact with the atmosphere, the composite rocks are strained by the mere change of pressure upon them, and they are strained still more by changes of temperature in the air alongside. Now all such changes open cleavages in rock-forming minerals. Hence the specimens from ledge or quarry are more flawed, more compressible, and less rigid than their mineralogical equivalents at great depths. Finally, it should be noted that the cracks in laboratory specimens are not completely closed even by the application of an all-sided pressure of 12,000 atmospheres, unless the material has been simultaneously heated to a temperature hundreds of degrees higher than any hitherto reached in these experiments.

Absolute closure of cracks in gabbro would, therefore, give that rock a lower compressibility and higher rigidity than those experimentally found for gabbro taken from ledge or quarry. But the lower the compressibility, other things being equal, the faster must a Push wave travel in the material; and the higher the rigidity the faster must the Shake wave travel. Hence it seems altogether likely that gabbro, crystallized at and below the depth of 40 kilometers, would transmit Push waves at a rate faster than 7.2 to 7.45 kilometers per second, the values calculated for accessible gabbro and stated in column 5 of Table V. And we recall that the actual rate at the top of the third layer of the continental crust does not exceed 7.8 kilometers per second.

Since open cleavages in the minerals of a rock lower the rigidity of that rock, we can now see why the Shake waves in the gabbro at the depth of 40 kilometers or more should be faster than those in specimens of gabbro, the accessible rock, when under the conditions of the laboratory experiments.

A second fact: geologists have found that, where gabbro and diabase were intensely squeezed and also heated, because pinched in mountain folds, the rocks have been recrystallized into denser and less compressible types of rock. Of these garnet-bearing gabbro and amphibolite are examples. Indeed, some authorities have suggested that the third layer is in chemical composition a gabbro, but recrystallized under the high pressure and temperature at and below the 40-kilometer level. Such material would give wave-velocities comparable with those deduced for the dunite of the laboratory specimens.

Again, there are reasons for suspecting that the crystals constituting the lower half of the crust are elongated in the horizontal direction. If so, our problem has a third complication. Some geologists believe that such elongation is the natural result of recrystallization under the dead weight of the overlying part of the crust. And in the next chapter we shall find that mountain-making is accompanied by horizontal shearing in the deeper, hotter part of the crust, with the conceivable result that the longer axes of the crystals, old and new, have there come to lie preferably in the horizontal plane. The deep-lying rock may therefore have special rigidity and compressibility, effective in the transmission of the horizontally running earthquake waves. Until this possible influence is evaluated, a final conclusion as to the chemical nature of the third layer is premature.

There is a fourth question. For the lowest layer of the continental crust the stated velocities of the Push waves and Shake waves—7.8 kilometers per second and 4.35 kilometers per second respectively—are really rough averages for a considerable thickness of the layer, in which each wave-velocity increases with depth, so that the velocities at the top of the layer are smaller than the corresponding averages. How much smaller? This query can not be answered until the network of seismographic stations has been made closer than it is now in any continental region. Worth noting is the latest estimate of H. Jeffreys for the velocity of the Push wave in the third layer, namely, 7.7 kilometers per second.[4]

Thus, in view of various uncertainties, it seems unsafe to consider the third layer as composed of olivine crystals alone (dunite rock), pyroxene crystals alone (pyroxenite rock), or a mixture of olivine and pyroxene crystals (peridotite rock). On the other hand, the laboratory experiments suggest doubt that the third layer is pure

[4] H. Jeffreys, *Earthquakes and Mountains*, London, 1935, p. 45.

basaltic material. In fact, there are some field observations from which it is not unreasonable to deduce a composite character for the layer. Large bodies of peridotite are visible in New Caledonia, New Zealand, and a few other regions. Those bodies, rising from deep levels, were injected into at least the upper part of the earth's crust. Doubtless there are other, invisible, masses of injected peridotite, and they may be most numerous in the third layer. How and where the extra-heavy rocks originated are still unsolved problems, but the exotic, injected character is clear. If in this way the third layer has come to include a notable proportion of peridotite, the wave-velocities just below the 40-kilometer level should average higher than the velocities expected in purely basaltic material.

Whatever be the correct explanation of the wave-velocities in the third layer, one conclusion seems unavoidable: the facts of earth science forbid belief that a layer of crystallized dunite or peridotite, hundreds of kilometers thick, begins at the depth of 40 kilometers. But the facts of the world map can be accounted for, if dominating crystallized basalt begins there, and at the depth of about 60 kilometers is underlain by non-crystalline or vitreous basalt. The main purpose of the following chapters is to illustrate the worth of these speculative ideas.

Looking back, we see that the problem is charged with uncertainties on the experimental side. One needs to know more about the exact wave-velocities involved; about the effect of temperature on the elasticity of rocks; about the high-pressure forms of basaltic material; and about the influence of cleavages and other cracks as well as pores on the rigidity and compressibility of rock at and above the pressure and temperature appropriate to the 40-kilometer level in the earth. While awaiting more precise information, it seems right to follow the lead suggested by the facts of geology, to take a risk, and assume the third layer of the continental crust to be chiefly basaltic in composition. To emphasize that dominance of basaltic material, the layer will be called "gabbroic." An alternative technical name for it is "crystallized Sima," the word "Sima" being mnemonic of two abundant elements contained, namely silicon and magnesium. See Figure 45.

The Sial.—Again from seismological data and from those of laboratory experiments on specimens from ledge and quarry, the nature of the two layers above the crystallized Sima has been deduced. The top layer, extending from the surface of the Basement Complex to the 15-kilometer level, appears to be chiefly granitic and may be called the "granitic" layer. Judging from the wave velocities, the second layer has an average composition between those of granite and basalt, and, also for this reason, may be referred to as the "intermediate" layer.

The two upper layers are commonly treated as one, to which may be applied the name "Sial," mnemonic of its two most abundant elements, silicon and aluminum. See Figure 45. The rocks of the Sial are relatively light, both per unit of volume and also with respect to color. The granite of Figure 25 symbolizes it, while the black dike of the same photograph symbolizes the Sima.

The Vitreous Substratum.—How thick is the third or "gabbroic" layer under the continents? What lies beneath it? Once more we go to the seismologist for help. His detective method when applied to material below the depth of 40 kilometers is valid, provided that he can ascertain the character, wave-transmitting power, of all the overlying rocks with high precision. Here there are still some difficulties, but it is hoped that the necessary refinement of measurements will soon be attained. Meantime we must be content with probabilities, approximate diagnosis, founded on the best available figures for the geometrical and physical properties of the earth's outermost shells.

Besides wave-velocities we need to know what are the temperatures in the depths. Below the depth of a few kilometers the rate of increase of temperature with increase of depth can not be directly measured. At the lower levels the rate is calculable if certain quantities are known. These include: (1) the rate of increase of temperature with depth for rock at the surface; (2) the age and initial temperature of the earth; (3) the rates of conduction of heat in the different shells; (4) the extent to which new heat was generated and is now being generated within each shell by radioactivity; and (5) the extent to which internal temperatures have been re-distributed by convection or overturning of the deeper shells during geological time.

Not one of those values has been exactly determined. Question number four is specially troublesome. Physicists believe that the breakup of the radioactive elements in rocks and the resulting generation of heat is not affected by the high pressure or the high temperature of the interior of the globe. Yet there is no obvious way of finding how those elements and the associated heating are now distributed in depth. Moreover, specialists in this field of study are strongly suspecting that the body of the young earth was long heated by elements which, because of their rapid disintegration, are not now discoverable in the chemical analyses of rocks. For several reasons, then, the relative importance of original heat and the heat of radioactivity, true furnace heat, is unknown. In consequence there remains a grievous uncertainty about the increase of the earth's temperature even to the comparatively small depth of 100 kilometers.

TABLE VI

CALCULATED TEMPERATURES (APPROXIMATE) IN THE EARTH'S CRUST

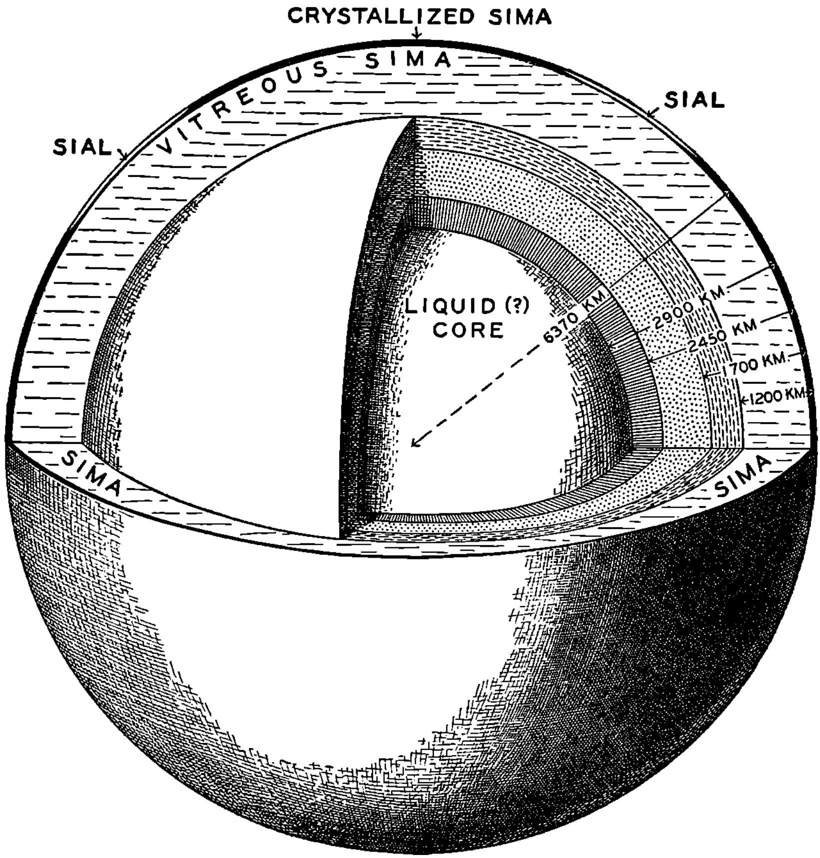
Depth in Kilometers	1 *Present Hypothesis*	2 *Holmes*	3 *Adams*
0	10° C.	10° C.	10° C.
30	760	800	630
60	1330	1206	960

TABLE VII

ESTIMATED RATE OF INCREASE OF TEMPERATURE
(degrees Centigrade per kilometer of depth)

Depth in Kilometers	1 *Present Hypothesis*	2 *Holmes*	3 *Adams*
0	28°	38°	35°
30	22	18	15
60	16	11	10

That and the other uncertainties leaves us with a Gordian knot, one that can not now be untied even with all the resources of mathematical physics. On the other hand, the known facts seem to permit the hypothesis that a layer below the depth of about 60 kilometers in the continental areas is too hot to crystallize. Let us cut the Gordian knot by making this hypothesis in the specific form indicated by the figures in column 1 of Table VI and column 1 of Table VII. There reasonable estimates of the temperatures and rates of increase of temperature at three levels are given. Columns 2 and



54. Diagram illustrating the shelled nature of the earth.

3 of the same tables give estimates made respectively by A. Holmes and L. H. Adams. All three columns refer to continental regions.

The preferred estimate of the temperature just below the 60-kilometer level, namely 1330° C., means that basalt can not there be frozen but must be in the glassy or vitreous state. The thermal conditions assumed by Holmes or Adams also imply a completely vitreous state for basalt if at depths somewhat exceeding 60 kilometers.

The suggested relation of the crust (crystallized Sima under the oceans and crystallized Sial plus Sima under the surfaces of the continents) to the non-crystallized Sima of the substratum is represented in Figure 54. This stereogram incidentally recalls the conclusion of some eminent seismologists, that in spite of the enormous pressure upon it the core of the planet behaves like a mobile liquid. It may be noted also that, since the drawing was made, much improved data have led to doubt that the discontinuities marked at the depths of 1200, 1700, and 2450 kilometers are properly placed. However, the diagram still serves to illustrate the idea of crystalline crust and vitreous substratum. We shall see later that the basaltic substratum can have but moderate thickness and that it overlies denser material, probably of the kind represented in peridotite or else stony meteorites. It is further possible that the lower part of this denser, "ultra-basic" matter has been crystallized by pressure.

The fundamental hypothesis of true crust and basaltic vitreous substratum has been formulated, not merely because it seems permitted by known geophysical facts, but also because it appears to be in principle essential to an understanding of the great changes which have affected the outer earth during geological time. In fact the general idea has been tested by its fruits and has not yet been found wanting. There is apparently no more promising way to attack the main problems of earth science. In subsequent chapters the hypothesis will be examined in the light of geological observations and principles; now we shall consider tests of a more purely geophysical character.

In the first place, some geophysicists dismiss the possibility of a vitreous substratum because the Shake waves of earthquakes are transmitted at all levels in the earth down to the top of the iron core. The argument runs as follows. Although one must ascribe effective solidity to cold glass, melted rock at and above 1330° C. must be a true liquid, even when pressed by the weight of 60 or more kilometers of rock. At one atmosphere of pressure basaltic lava is fluent, like the fountaining basalt of Kilauea, Hawaii (Figure 106). Non-crystalline basalt even at 17,000 atmospheres, the pressure ruling at the 60-kilometer level, is supposed by the skeptical authorities to be likewise a true fluid. But a fluid can not transmit a Shake wave. Nevertheless Shake waves are transmitted at depths of 60 kilometers and more; hence it is argued that the earth-shell topped by the 60-kilometer level can not be vitreous basalt.

The argument is not convincing until its proponents show that Shake waves can not be propagated in melted basalt where this is exposed to a minimum pressure of 17,000 atmospheres.

Here one of Ide's experiments is suggestive. He has found (personal communication) that a column of pyrex glass at one atmosphere of pressure and at 700° C. transmits sound waves at very nearly the same velocity as at 20° of temperature. Yet at 700° the glass, when exposed to stronger forces, or to small forces applied for longer periods than those corresponding to the sound experiment, behaves much like a highly viscous liquid; the column was almost ready to buckle under its own weight. But the elastic forces involved in the transmission of earthquake waves are small and of short periods of application. Ide believes it is reasonable to hold "that the effect of high pressure will be to increase considerably the temperature at which the material ceases to support vibrations." He is further of opinion that the "proposed basaltic substratum should transmit vibrations, like a rigid solid, up to very high temperatures. Certainly it will do so to 700° C. without any assistance from the pressure." Thus he too conceives the substratum glass to be like the pyrex glass of his experiment, in that the rigidity is high "so far as rapid vibrations are concerned, at temperatures where it behaves like molasses for slow vibrations."

From recent experiments M. P. Volarovich of Moscow concludes that up to the temperature of 1100° C. molten basalt, even at only one atmosphere of pressure, has effective rigidity and can transmit Shake waves (personal communication).

Pitch offers an analogy. Against small pressures applied for short periods of time, pitch reacts as an elastic solid; it is brittle and can be made into a tuning-fork which will give out a musical note. Yet against long-continued pressure pitch reacts like a liquid with high viscosity. The initial rigidity of pitch at room temperature is high, and in the tuning-fork this rigidity is relaxed at a low rate because the stresses set up in the material are both small and of short duration. Since both of these conditions are met in an earth-shell when set vibrating by some sudden shock, and since in addition there is the stiffening effect of many thousands of atmospheres of all-sided pressure, it seems logical to consider the described objection to the idea of a glassy substratum as ill-founded. The relevant experiments by Ide and by Volarovich appear to support the conception that the glass of the imagined substratum has the so-called "restoring force" necessary for the transmission of earthquake waves, even if that glass be nearly or quite as weak as water against permanent stress.

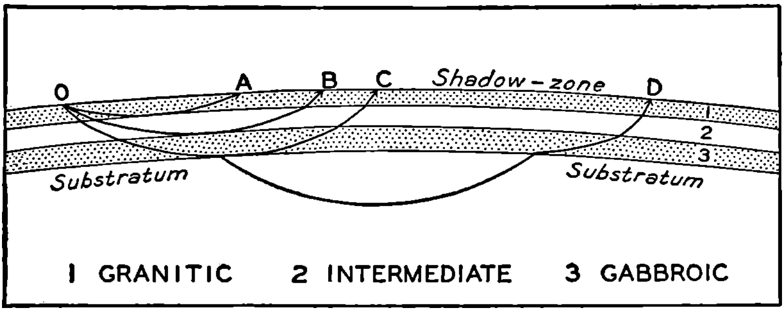
Again, the existence of the glassy shell below a 60-kilometer crust has been questioned, because some earthquake shocks center at depths as great as 600 kilometers. Some seismologists, though not all, hold that the material above that depth must be credited with much strength and therefore crystallinity; otherwise, they believe, it could not accumulate enough stress to produce the deep fractures, sudden displacements, and the associated blows to the earth's body. Yet P. W. Bridgman's recent experiments at the Harvard Laboratory of Physics have proved that such accumulation of breaking stress is not dependent on the crystallinity of the substance concerned; and the analogy of pitch shows that the brittleness of a substance or the possibility of its sudden fracturing does not mean that the substance has ultimate strength.

We turn now to a third geophysical test of the idea of a glassy substratum, a test for the future, one that will need some new seismological equipment and a Maecenas with vision to supply that equipment.

To make the idea more readily grasped, a cross-section of the continental crust, curved as in Nature, has been drafted (Figure 55). We recognize the layers, 1, 2, and 3, of the crust, as well as the substratum. Just above the bottom of the third or "gabbroic" layer, the Push wave travels at the rate of about 8.0 kilometers per second. At and just below its top the substratum, because glassy, is more compressible than the crystallized third layer, and so much more compressible that the influence of its lower density on the wave-velocity is more than counteracted (see equation 2 on page

44). Hence at and near the top of the substratum the Push wave should travel at a rate a little smaller than 8.0 kilometers per second. Seismographs placed at the earth's surface along the line of the section should register this drop in wave-velocity at the 60-kilometer level. They should also show an increase of wave-velocity with increasing depth in the substratum itself, because the compressibility of basalt-glass diminishes with the addition of pressure. Now, we ask, how will the seismographic records at the different stations be affected?

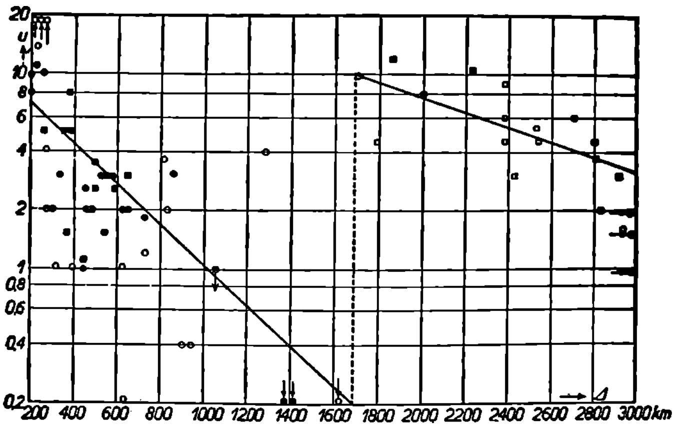
Let us assume a powerful dynamite explosion in a quarry situ-



55. Section illustrating the principle of the "shadow-zone." After L. D. Leet. The section does not indicate the composite nature of the second layer, and does not show the relative thicknesses of the upper layers quite to scale.

ated on the surface of the "granitic" layer, number 1 of Figure 55. Elastic waves rush away in all directions. By refraction their paths or rays are bent in the successive layers so as to make curves with convexity downward. Moreover, the rays must be specially bent in the same sense as they pass from the "granitic" layer into the "intermediate" layer, number 2, and again as they pass from the "intermediate" layer into the "gabbroic," number 3. On the other hand, a ray passing from the "gabbroic" layer into the substratum, where its velocity is slightly lower, must be bent in the opposite sense, and so plunge deeply into the substratum. Since here again the wave-velocity slowly increases with depth, the ray reverts to its forward direction of bending; that is, the ray now begins to bend up in a curved path, just as in the overlying, crystalline layers. Accordingly, after reaching the lowest part of its path, the racing wave is brought by refraction once more to the surface. There its time of arrival is registered at a seismographic station.

To illustrate more specifically, let us trace four particular wave-rays. Three of them dip down to, but no deeper than, the three respective discontinuities. They reach the surface at the points marked A, B, and C. But consider a fourth ray, whose path just above the bottom of the third layer is slightly steeper than ray C.



56. Change of amplitude of the Push wave as it emerges at increasing distance from a center of shock. After B. Gutenberg.

That fourth ray enters the substratum and is so refracted that it emerges at the distant point marked D. Note the important point: on the surface between the points C and D no seismograph could record any direct Push wave. The same failure of registration would be found also in the case of the Shake wave. In both cases we should have, between the stations at C and D, what the seismologists call a "shadow-zone." It is as if the region between C and D was shielded against the impact of the earthquake wave by some opaque mass. We think of the analogy offered by the shadow of a house in bright sunlight.

Now B. Gutenberg,[5] a leading seismologist, has long been suspecting a shadow-zone for a continental sector, beginning about

[5] B. Gutenberg, *Grundlagen der Erdbebenkunde,* Berlin, 1927, p. 138.

800 kilometers from the center of shock and ending about 800 kilometers farther away. He points out that even in the shadow-zone Push waves diffracted along the boundary between layers 3 and 4 should appear at the surface, but the energy of the diffracted wave should be very small when compared with the energy of the direct Push wave. The more energetic the wave the greater is the swing or amplitude of the motion in the registering seismograph. From many seismograms Gutenberg measured the changes in amplitude as the Push wave emerges at greater and greater distances from the center of shock, and plotted the values as in Figure 56. Here the amplitude is indicated by the vertical dimension of the diagram, the distance from the center of shock by the horizontal dimension. We note the marked decrease of amplitude in the interval of distance between 800 kilometers and 1600 kilometers. At the latter distance the amplitude suddenly jumps to high values, as expected at the outer limit of a shadow-zone.

After an independent study I. Lehmann has come to what is in principle a similar conclusion regarding the zone of greatly lowered energy for the emerging Push waves.

Although cautious about interpretation, Gutenberg has himself deduced the possible existence of a vitreous substratum beginning at the depth of 60 or 70 kilometers.

In view of all the facts, it seems clear that this third geophysical test of the substratum hypothesis may be one of the most valuable of all, and that there is urgent need for its application with all possible thoroughness.

If we assume the existence of a shell of vitreous basalt, how thick should this fourth layer be? What underlies it? In attempting answers to these questions we make a mental journey into an Erebus that grows darker with every mile of descent.

Geophysicists do give us a few rules for guidance. They have evidence that below the depth of 100 kilometers each individual earth-shell is nearly or quite uniform in chemical composition, if sampled in a horizontal direction, while probably showing a slow, systematic increase of heavy elements with increase of depth in that shell. The compressibility of each shell has been rather closely determined. We know, further, that the density increases with depth, not only because of change in chemical composition, but also because the material is compressed under the weight of the overlying shells. There is increase of temperature with the depth, though at rates that still escape evaluation; the temperature of the iron core is doubtless at least 5000° C., and may considerably exceed that figure. The average density of the earth is 5.52, that of water at room temperature and pressure being unity. The distribution of densities must be such as to give the fixed quantity known as the earth's moment of inertia (rotational inertia).

Further, the speculative choice for the material beneath the basaltic layer is naturally made among known species of rock. Since the intrinsic, that is, chemically determined, density must exceed that of basalt, there is but a narrow range of choice among the terrestrial species. In fact attention is now being concentrated on those few types that contain a large percentage of the heavy mineral olivine. As we have seen, some authorities emphasize one particular species, dunite, made up of practically nothing else but crystals of olivine; others think rather of peridotite, composed of crystals of pyroxene as well as olivine. However, the earth's moment of inertia shows that, not only must the vitreous basaltic shell be relatively thin, perhaps nowhere more than a few scores of kilometers in thickness, but also that any underlying shell of dunite or peridotite can not extend down all the way to the iron core of the earth. On the other hand, the moment of inertia can be accounted for, if the iron core is overlain by a thick shell of material chemically like the iron-bearing stony meteorites, which also carry a considerable percentage of olivine. Incidentally it may be noted again that possibly some part of this deep-lying shell is crystallized by the high pressure affecting it.

In summary, we have found that study of earthquakes seems not to invalidate our picture of crust and substratum in the continental sectors of the globe. A more positive reason for retaining the preferred earth-model is its power to meet other tests, both geological and geophysical. They will be reviewed in the following chapters, but this one may well close with a brief account of seismological observations regarding the oceanic regions.

The Sub-oceanic Sectors

It is well to recall some facts we learned in the first chapter. Sea water makes seventy-one per cent of the earth's surface. Of the 361,000,000 square kilometers of crust-rock thus inaccessible to the field geologist, one tenth seems clearly to represent the slightly drowned edges of the visible continents. About two tenths of the ocean appears to rest on broad but relatively thin sheets of rock similar in general composition and density to standard types of rock found throughout the dry land of the continents. The remaining, deeper part of the ocean, with an area half that of the whole earth, offers to the geologist's hammer only the rare island volcanoes and their thin sheaths of shell-beds or organically formed or other sedimentary rock. Of these isolated structures the geologist can see no more than their very tops.

Direct information regarding the nature of the crust under the deep ocean is thus exceedingly, pitifully, limited. We found that all the islands rising from the deep ocean bear basalt as their dominant lava, that is, rock nearly or quite identical with the plateau-basalt of the continents. If our reasoning so far is sound, we are logically forced to entertain the idea that the island volcanoes also have been fed from a vitreous basaltic substratum, endowed with the temperature necessary for the eruption of liquid basalt.

Few seismographic stations are established on the islands. One of them is on Upolu Island of the Samoan group. There it has been found that the velocities of the Push and Shake waves, just below the thin mud of the ocean floor, are those expected if the rock there is crystallized basalt.

Seismologists have corroborated that conclusion by the result of a quite different kind of investigation. Hitherto we have sought the meaning of the speeds of Push and Shake waves at depth, but something more can be learned from the Surface waves. Surface waves are those which an earthquake shock sets traveling along the surface of the earth's crust. Now it has been found that these waves travel more slowly across a continent than across any basin of the deep ocean. For example, W. Hiller determined the velocities of one kind of Surface waves, in kilometers per second, to be as follows: across Europe and Asia, 2.87; across the Atlantic sector, 3.58; and across the Pacific sector, 3.69. The differences of velocity are those expected if the continental part of the crust has the three-layered constitution, while the sub-oceanic part is basaltic or "gabbroic" and has little or none of either the "granitic" or "intermediate" material.

Independent studies of the Surface waves, by G. Angenheister, P. Byerly, D. S. Carder, B. Gutenberg, and T. Matuzama have yielded a similar result for the greater part of the Pacific and Arctic oceans and for deep-water areas of the Atlantic and Indian oceans.[6] The somewhat lower velocities of the Surface waves crossing the North Atlantic, the northwestern part of the Indian Ocean basin, and the broad area covered by the submerged Albatross Plateau, west of South America, seem to indicate rock of continental type under those parts of the world ocean. And we saw that in some at least of these instances there is direct, visible evidence that granitic rock, relatively thin and yet of notable extent, is represented.

On the other hand, it is doubtful that the Surface waves will ever furnish a check on the hypothesis that the "gabbroic" layer under the mud of the deep ocean lies directly on a shell of its own composition, but so hot as to be still vitreous. More promising is the outlook for studying the question by the use of properly placed networks of seismographic stations on the islands of the deep sea. There, as in the case of the continents, we should expect evidence of a shadow-zone. Such costly research is also for the future.

Meantime we are not without some clues. First from cosmogonic theory. All the best theories of the earth's origin imply initial fluidity of the rock, from the surface downward. When the planet was in the fluid state, the lighter elements must have been more or less concentrated toward the surface, the heavier elements sinking, until approximate equilibrium was established. An early consequence of this gigantic metallurgy was a layer of basaltic liquid. If this is a true picture of the young earth, the non-crystalline or

[6] P. Byerly, *Bulletin Seismological Society of America,* vol. 24, 1934, p. 299. D. S. Carder, ibid., p. 265.

vitreous basalt must have made a complete earth-shell, partaking of all sectors, continental and oceanic. While some of this shell has frozen into the "gabbroic" layer, the cosmogonist has not found, either in theory or fact, any reason why we should not postulate at moderate depth a world-circling couche of basalt, still vitreous.

Secondly, more direct warrant for extending the vitreous substratum from the more accessible continental sectors to the oceanic is found in the recent proof that all round the globe there is a nearly or quite uniform velocity for the Push wave at the depth of 100 kilometers. If special research should ultimately demonstrate glassy basalt at about that depth under the lands, it would be hard to assume any other material below the ocean.

Summary

A single chapter is all too short for the great detective story of the underground. Its telling would be simpler if it were not for some residual uncertainties. The velocities of Push and Shake waves at all depths within the outer 100 kilometers of the earth are not yet known with the desired exactness. On the other side the laboratory physicist still has trouble in accurately determining how far the elasticity of the deep-lying and therefore inaccessible rocks differs from the elasticity of accessible, chemically similar rocks at the same pressures and temperatures. Already the coöperation of seismologist and laboratory elastician has greatly narrowed the diagnostic problem and is sure to narrow it still further. Already it looks as if the rock between the 40-kilometer and 60-kilometer levels approximates in chemical composition more closely to basalt than it does to dunite, the material now assumed to exist at this depth by most workers in geophysics. To indicate the real affinity, the layer has been named "gabbroic," gabbro being a known form of basaltic liquid when crystallized at considerable depth. An alternative name is "crystallized Sima" (Figure 45).

Similarly, by comparing seismological and laboratory data, the "intermediate" and "granitic" layers, which in the continental sectors of the globe successively overlie the "gabbroic," have been identified. The first two are made of the less dense kinds of rock, and we are to see that their buoyancy on the earth's body makes the dry land of the continents and larger islands possible. This profoundly significant fact of Nature prompted the invention of the technical name "Sial" to cover those two top layers in the continental sectors.

From the geological map of the world, from a statistical study of volcanic eruptions and the associated structures, and from testimony of the thermometer in mines and bore-holes, we have found it probable that the "gabbroic" layer rests upon vitreous basalt, that is, upon what may be named "non-crystalline Sima." Probable but not proved. Absolute proof is bound to be difficult. Here is a future job for the seismologist: to test the reality of the "shadow-zone" suspected by Gutenberg. Meantime let us see if the hypothesis of a vitreous substratum has special power to explain the responses of our rugged old earth to body forces that have fashioned the majestic structures visible at the surface.

CHAPTER III

THE CRUST DEFORMED

"Labors of Hercules"

Introduction

WE ARE now to set our earth-model another examination. We want to know how the planet, supposed to have a true crust and a vitreous substratum, would behave when exposed to deforming forces. This subject is vastly too broad for full outlining. We shall specialize on only its most spectacular phase, the formation of mountain chains. Here is a double mystery, for there are really two questions involved. First, how is the structural turmoil characterizing the belts of mountain topography to be explained? In illustration, why were the beds of rock in the Cape Colony Range (Figure 57) twisted up out of their originally horizontal position? Second, why do mountains stand high above the general surface of the continent?

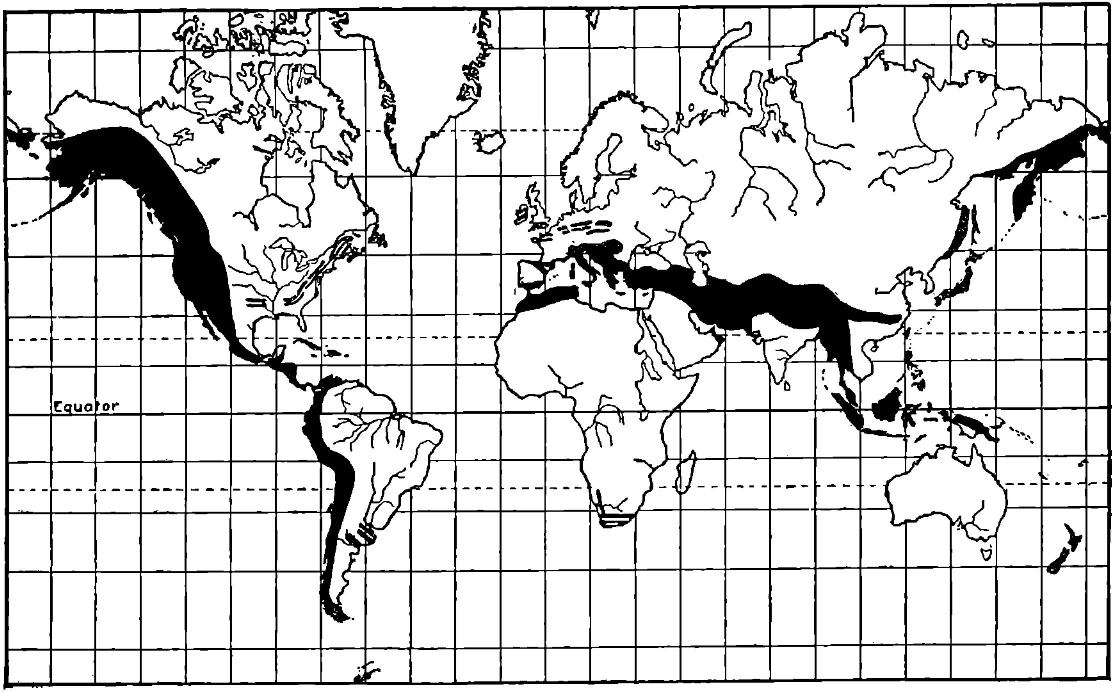
Whatever be the mode of origin, both the inner structure and the uplift of a mountain chain mean that stupendous energy was expended. This fact becomes ever more impressive to geologists who study the internal structure of mountain chains. The wonder grows. Whence came the energy for the almost inconceivable work done? The source of the horse-power is the chief topic of the present chapter, particularly in relation to the crust-substratum hypothesis.

Characteristics of Mountain-structures

The discussion may well begin with a review of principal facts.

First, mountain-structures have been developed in zones. Even the mightiest covers but a small part of the earth's surface, and the structures are elongated in belts like those of the familiar mountainous reliefs.

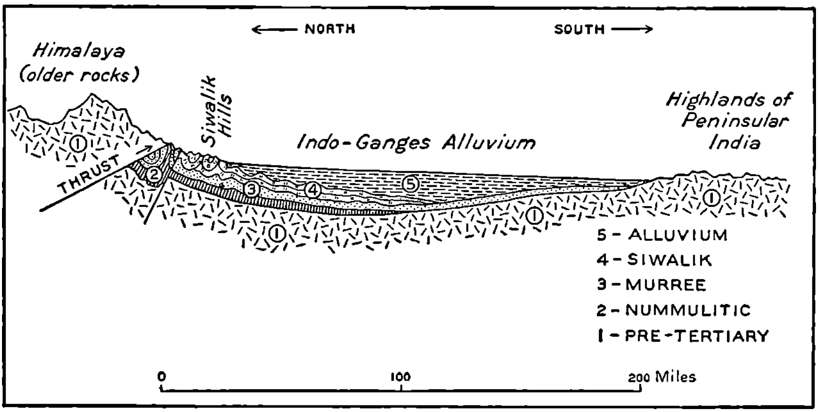
57. Upturned sedimentary beds of rock in the Cape Colony Range.



58. Map locating mountain chains. Mercator projection.

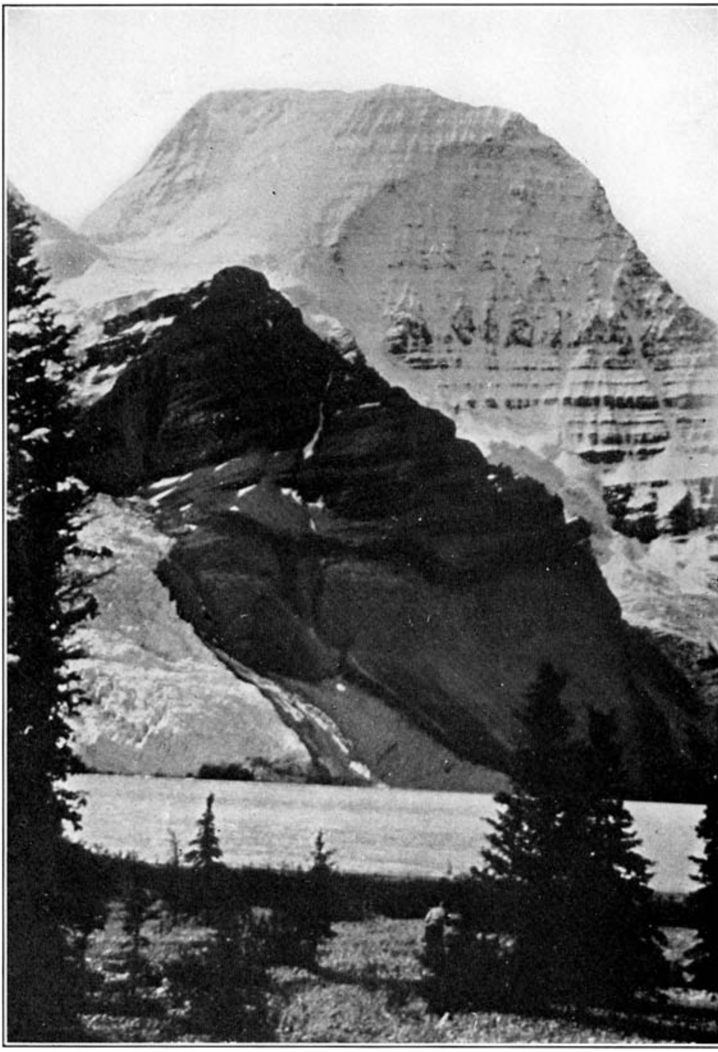
Second, the old, eroded chains as well as the high, geologically young systems are located within the continental segments of the earth's crust, and for the most part are confined to three composite belts. The map of Figure 58 shows in solid black the general distribution of the younger chains, and with broken lines that of some of the older chains. One belt is peripheral to the Pacific Ocean. Another belt is more decidedly intra-continental, and, although sinuous and interrupted by the Atlantic, stretches in an east-west direction across Eurasia and North America. The third belt is also intra-continental, and extends across South Africa into South America, again with an interrupting Atlantic Ocean.

Third, each mountain chain originated at a geosyncline and was in large part made out of the corresponding geosynclinal prism. We remember from the first chapter that a geosynclinal prism is the mass of layered mud, sand, and gravel filling a geosyncline or elongated downwarp of the earth's crust. Figure 59 is the cross-



59. Cross-section of a geosynclinal prism in northern India.

section of a great prism, which is being thickened at the present time with the burden of alluvium brought down from the Himalayas by the Indus and Ganges rivers. We note on the left some dislocation of the beds making up this new prism. In fact, northern India is an uneasy region, because the Himalayan block and peninsular India have been slowly approaching each other, as if beginning to crumple the whole of the young prism between them. It may be added that



60. Photograph of Mount Robson.

the Himalayan chain itself was born in a geosynclinal prism, much wider and much older than the one made of formations marked 2, 3, 4, and 5 in Figure 59.

Almost all or quite all of the rock beds composing any one of the major prisms were deposited below sealevel, as for example were the shales and limestones visible in the Rocky Mountains of British Columbia and Alberta (Figure 60).

Fourth, study of the sedimentary rocks in the deformed prisms shows that, during the mountain-making process, the sides of each geosyncline were brought nearer together by many tens of kilometers. Some expert students of mountains believe that the narrowing may be rated in hundreds of kilometers.

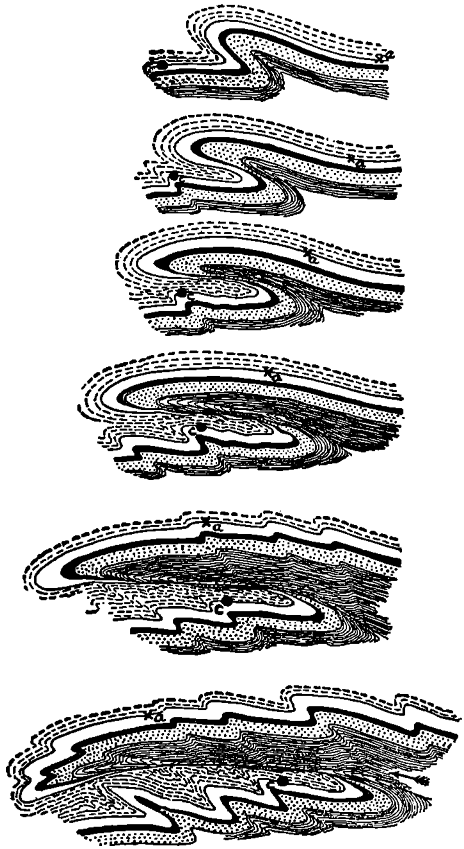
Fifth, horizontal compression of the geosynclinal prism as a whole is further indicated by the visible attitudes of its beds. Originally flat-lying, many of these have been folded by pressure directed horizontally across the axis of the prism. Such folding means shortening of the width of the prism.

Still more striking is the case where an arch-fold or anticline is thrown over on its side. See the uppermost of the cross-sections in Figure 61. If the lateral pressure keeps up, the overthrown fold ruptures, and one packet of beds is sliced and thrust over another, as in the lower cross-sections. Less flexible layers of the rock are more likely to rupture without folding, and, as compression continues, the broken edges move past each other. The new relation is called technically an overthrust or an underthrust, depending on which of the two broken blocks was displaced more than the other with respect to some fixed point in the earth. The principle of thrusting is illustrated in Figure 73.

Figure 62 exemplifies thrusting in the heart of the highest of all ranges, the Himalayas. The bedded rocks on the left were pushed up and over younger rocks on the right, the plane of scission and thrust being located in the oblique zone of shadow.

Sixth, the described close-folding, overfolding, and rafting-together by thrust affected geosynclinal prisms and the underlying Basement Complex, that is, rocks of relatively low density. Hence in young mountain-built belts there was accumulation, thickening, of the lighter components of the earth's crust. In other words, each young mountain chain has a "root" of comparatively light rocks. The evidence that such roots exist will be given later.

Seventh, important mountain-building seems to have been regu-



61. Cross-sections of asymmetrical mountain folds and of thrusted slices. After A. Heim and C. K. Leith. Courtesy of Henry Holt and Company.

larly accompanied by the rise of molten rock into the deepening root of the structure. After the old bedded rocks were well folded and thrusted, the liquid continued to invade the roots, rising still higher toward the surface. The invasions were on a grand scale. Their cause will be a subject of inquiry in the fifth chapter.

62. Thrusting of older rock so as to overlie younger rock; at Lebung Pass, central Himalayas. After D. N. Wadia. Courtesy of Macmillan and Company.

Eighth, still later, when huge volumes of the subterranean lava were already cooled and solidified, each of the composite mountain-structures was slowly uparched, its surface finally reaching a height far above its surroundings. There was a long delay between the manufacture of the mountain-structure and the final uplift that has given the topographic dignity which we associate with mountainous land. A formerly depressed belt becomes an elevated belt; low places have become high places.

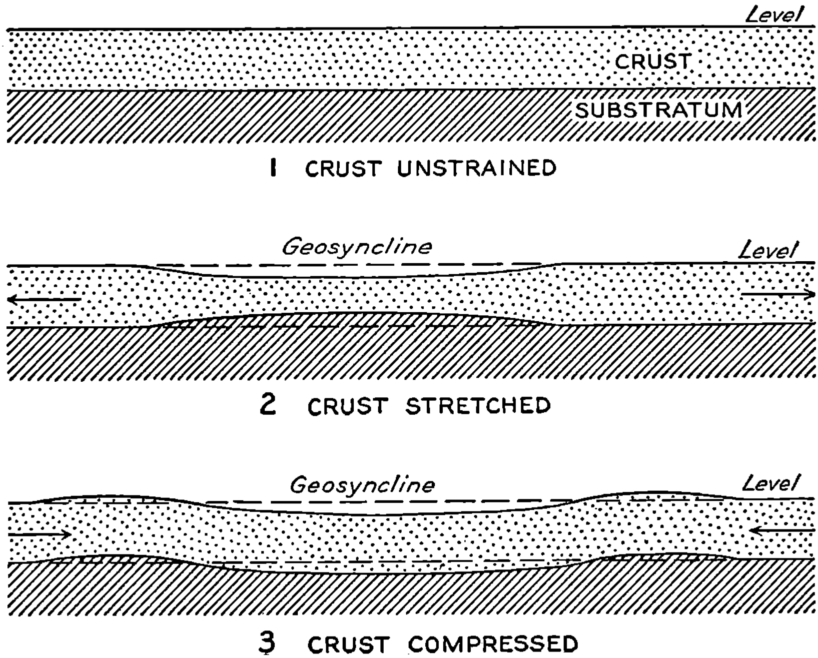
In review, we see that the geosynclinal prism is parent to the mountain-structure, and the geosyncline is grandparent. A good theory of mountains should, therefore, account for the geosyncline, the antecedent basin or trough, and also for its sedimentary filling, the geosynclinal prism.

Geosynclines

Two different origins have been proposed for the geosyncline. Some students of the problem attribute the downwarp of the surface to stretching of the earth's crust. They suppose the crust to have been thinned at the geosynclines, somewhat as a rope of plastic sugar is thinned in a candy-pull. See Figure 63. Where the crust was so thinned locally the surface dropped; hence the geosyncline. There are cogent reasons why this hypothesis is not acceptable, but they will not be detailed on the present occasion.

Much more compelling is the opposite view, which ascribes the geosyncline to horizontal compression of the crust. Compare the lowest of the cross-sections in Figure 63. The arrows represent pressure which is competent to buckle the crust, that is, to warp it up and down in the form of waves. Many a local, thin bed of rock, initially horizontal, has been so bent by pressure from its two ends. The earth's crust is too thick to buckle in this simple way where the crust is initially quite level. It would rupture rather than bend. Analysis shows, however, that, after the crust is so fractured, continuing pressure causes the part of the crust on one side of the plane of rupture to press down the part on the other side of that plane, where a geosynclinal downwarp is generated. On the other hand, buckling without through-going rupture may be possible where the crust, under sufficient horizontal compression, is initially and considerably out of level.

During the geosynclinal downwarping, however conditioned, subcrustal matter must flow away, horizontally, from the belt so affected. The belt should have deficiency of rock matter, and the neighboring belts of upwarping should have excess. In fact studies

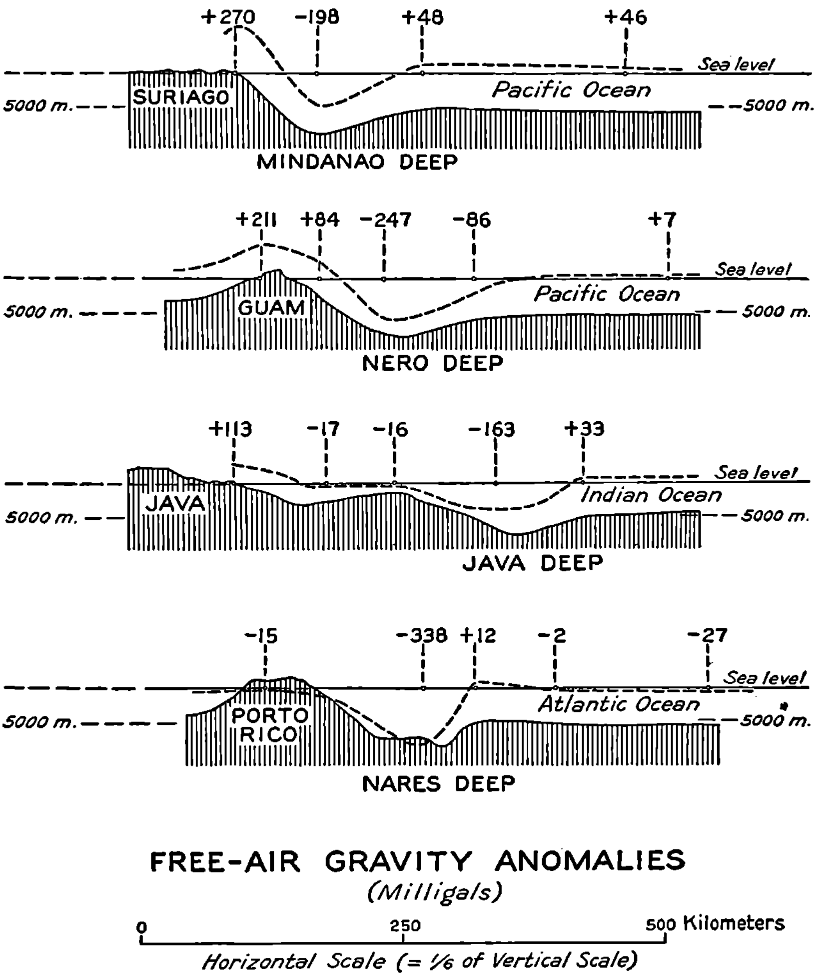


63. Diagrammatic cross-sections illustrating theories of the origin of geosynclines.

with the gravity pendulum show these two deductions to accord with reality. The pendulum measures the force of gravity at the point where the instrument is swung. F. A. Vening Meinesz[1] has adapted the principle in a masterly way and with his special apparatus has obtained many remarkably accurate values of gravity at sea, when observed in a submarine. In general each observed value at sealevel was found to differ from that expected at the same latitude and longitude as given by the best available formula for

[1] F. A. Vening Meinesz, Gravity Expeditions at Sea (*Netherlands Geodetic Commission*), Delft, 2 volumes, 1932 and 1934.

the sealevel figure of the earth. The differences between the observed and calculated values of gravity at sealevel are called technically "Free-air anomalies." The occupied stations at sea include some that were located over deep geosynclines in the East Indies and north of Porto Rico. Cross-sections of these large topographic features are seen in Figure 64. Solid rock is represented by shading.



64. Sections of oceanic Deeps, showing deficiency of matter and their origin in downwarping of the earth's crust. A milligal represents about one millionth of the force of gravity at the earth's surface.

Where the depth of the ocean exceeds 5000 meters along each narrow strip we have a geosynclinal downwarp. The broken line and figures of each section indicate the run of the Free-air anomalies. Where the bottom of the ocean drops, we see that the anomalies bear a minus sign. Now, from a strongly negative anomaly students of the earth's gravity deduce a notable deficiency of matter under the corresponding station. Hence we conclude that the geosynclines are downwarps of the kind anticipated, if the broad troughs were caused by horizontal compression of the earth's crust. It may be added that the candy-pull hypothesis quite fails to account for the negative values of the Free-air anomalies.

Other observations affirming the compression hypothesis come from experiments in the laboratory. Of the efforts to imitate Nature's way of making geosynclines mention will be made only of the experiments of G. R. MacCarthy and P. H. Kuenen.[2] Both of these investigators designed apparatus embodying a crust and plastic substratum.

To represent the earth's crust, MacCarthy used horizontal layers of wax, mixtures of paraffine and vaseline, clay, and sand. The substratum was imitated with an extremely plastic layer of modeling clay. Horizontally directed pressure was applied at one end of the

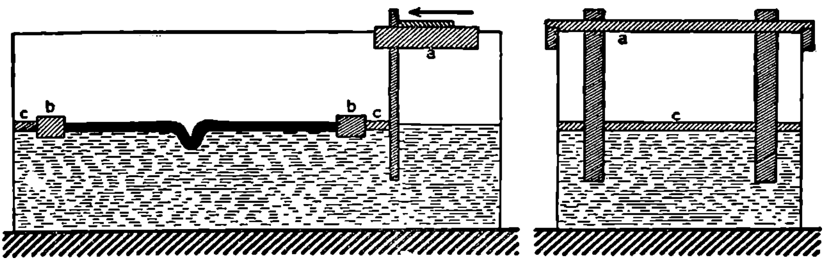
65. Cross-section of one of G. R. MacCarthy's experimental models, illustrating the compression theory of geosynclines.

model crust, which is the white band of Figure 65, the substratum being shown in black. We see, first, some crumpling of the crust at each end; second, the enforced development of two troughs separated by an arch; third, evidence that the substratum clay has flowed toward the arch and become thickened under it. As compared with the original state of the model, there is now excess of mass under the arch and deficiency of mass under each trough. Thus

[2] G. R. MacCarthy, *American Journal of Science,* vol. 16, 1928, p. 51. P. H. Kuenen, *Leidsche Geologische Mededeelingen,* Deel VIII, 1936, p. 193.

MacCarthy's results are in line with the favored explanation of geosynclines.

In more recently published experiments, Kuenen used the pressure-box pictured in Figure 66. The sides and ends were made of glass. The box was half filled with water, to represent the earth's substratum. In one series of experiments the crust was a thin layer of paraffine; in a second series, a mixture of paraffine, vaseline, and mineral oil. Throughout both series the water was kept at the temperature of about 40° C., or a few degrees below the melting-point of paraffine. At such temperature the crust was highly flexible and yet solid enough to bear shearing stresses. The water is indicated by shading; the crust by solid black. Horizontal compression of the crust was applied by the floating beam *b*, which was pushed in the direction of the arrow by the slider *a*, the pressure being communicated to *b* through a floating plank *c*.



66. Side view and cross-section of apparatus used by P. H. Kuenen in his experiments on mountain-building. The "crust" is shown in solid black; the "substratum" (water) is marked with horizontal shading.

When the lateral pressure was applied to a crust of pure paraffine, a series of open folds, downwarps and upwarps, synclines and anticlines, was formed (Figure 67). Because of some irregularity in thickness or strength of the paraffine crust, one of the troughs became the deepest of all, and, as the pressure increased, the deformation naturally became concentrated there. This particular fold became narrower and deeper, as shown in section D.

In other experiments the location of the master downfold or syncline was not left to chance, but was determined by the weight of a thin, narrow strip of crust material, which was laid across the pressure-box on an otherwise uniformly thick crust (Figure 68).

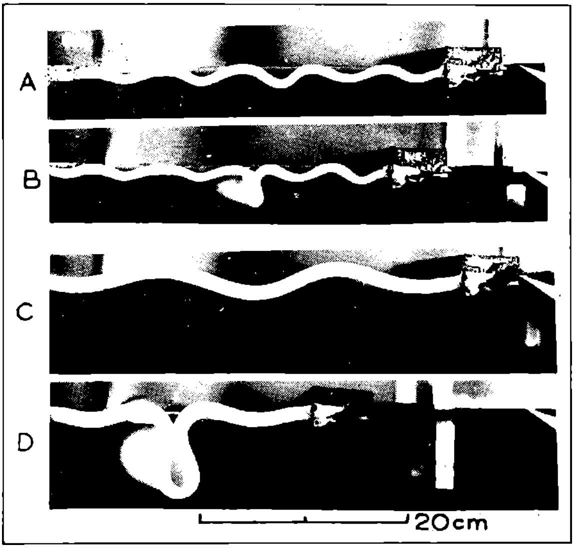
The added strip would thus correspond to some ribbon of sediment deposited along the flood-plain of a master river or along the bottom of a shallow sea.

With the paraffine-vaseline-oil crust an open syncline, flanked by two low arches or anticlines, was formed as in section B, Figure 69. Continued pressure deepened and closed the syncline; see sections C, D, and E. We note that at all stages the depth of the trough, measured from the original level of the surface of the crust, is greater than the height of either anticline, similarly measured. This was to be expected, in view of the fact that the super-elevation of an anticline is resisted by the full weight of mass above the level of equilibrium, while, on the other hand, downwarping meets little or no resistance of the same origin. The same principle applies in Nature; each open geosyncline has depth greater than the height of its flanking arch or anticline.

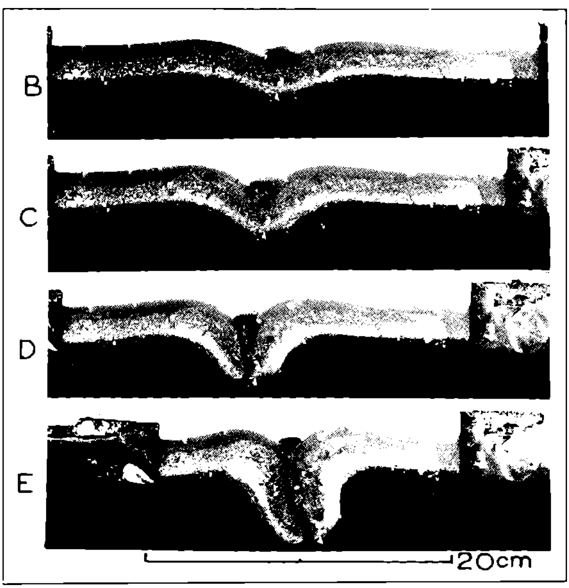
Both groups of experiments support the idea that open geosynclines have been developed by the horizontal compression of a crust with some strength, resting on a substratum which has little or no strength. The conception is made all the easier if, as our main hypothesis has it, the earth's substratum is basalt in the glassy state and therefore slightly less dense than the crust. In such an earth downwarping or buckling of the crust is facilitated by the particular arrangement of densities.

Geosynclinal Prisms

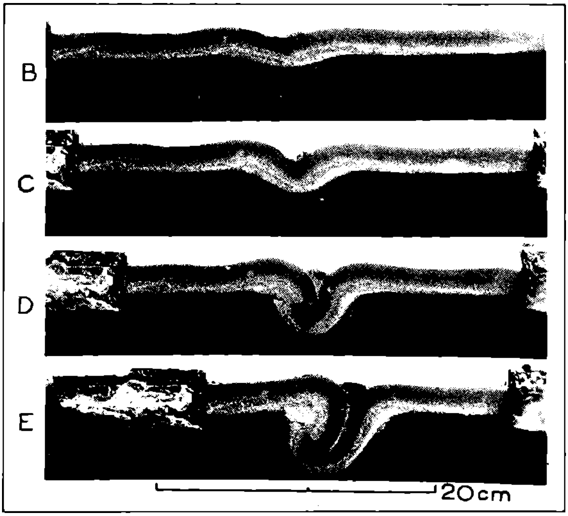
The foregoing discussion has already pointed a way to understand the geosynclinal prisms. We saw that each geosyncline, if due to horizontal compression, should be flanked by at least one broad arch of rock lifted above the average level of the crust. Compare the lowermost section in Figure 63. That such super-elevated belts were actually developed alongside old geosynclines is strongly suggested by observed facts. The geologist has discovered that as a rule at least one flanking belt was high enough to breed rapidly flowing rivers, which swept coarse gravels as well as sand and silt into the downwarps. Evidently the weight of the sedimentary material helped to deepen the initial downwarp. In truth this aid to horizontal compression has been so powerful that the floors of many ancient prisms were depressed much more deeply than any open



67. Successive stages of crust-warping in one of Kuenen's experiments.



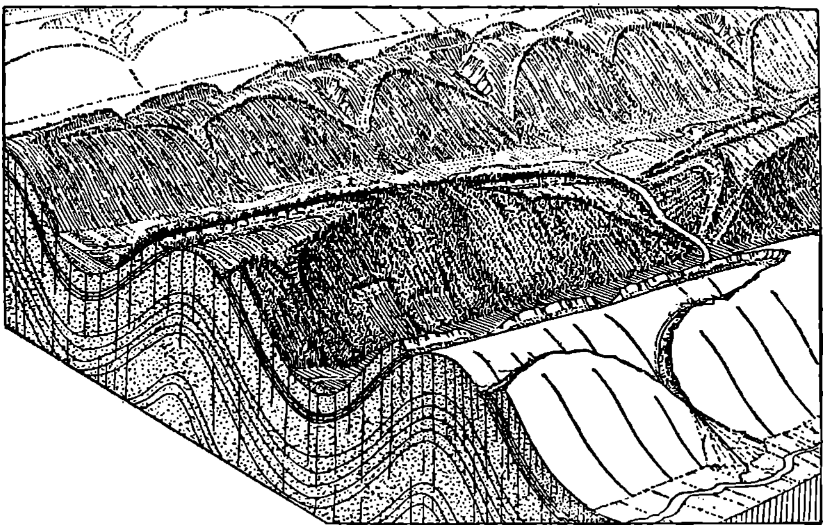
68. Downwarping of crust, determined by local load; Kuenen experiment.



69. Development of geosyncline and adjacent arches; Kuenen experiment.

geosyncline could be depressed. So great a downwarp, unfilled with sediments, is impossible because the crust is not strong enough to bear the great stresses involved.

The rock layers of a prism have densities between 80 and 95 per cent of that characterizing the vitreous substratum; hence there is a limit to the sinking of the original crust by the local load. After this limit is reached, the downwarp may, however, grow still deeper because of continued horizontal compression of the crust beneath. Under such circumstances the geosynclinal belt would not be in hydrostatic equilibrium with the rest of the earth, but should show

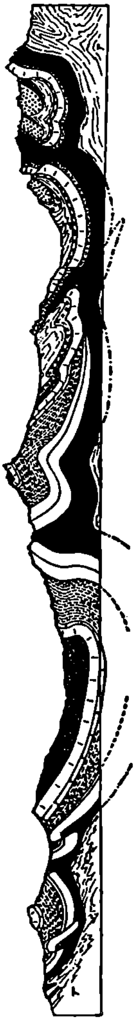


70. The Jura Mountains in diagram. After W. M. Davis. Courtesy of Ginn and Company.

deficiency of mass. This has been proved, for example, at the Punjab geosyncline under the plains of northern India, where the growing weight of sediments which are being continually washed down from the Himalayas helps to depress the old crust in that region. See Figure 19.

Experiments on Mountain-making

A second major problem in crustal deformation is that represented by the multiple foldings of the Jura Mountains (Figure 70) and by the more intense crumpling and thrusting in the adjacent

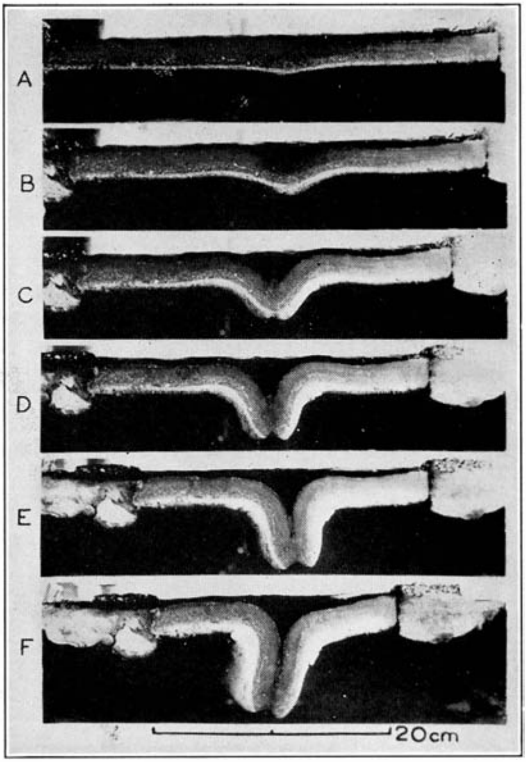


71. Cross-section illustrating complex structures in the Romande Prealps. After H. Schardt and L. W. Collet.

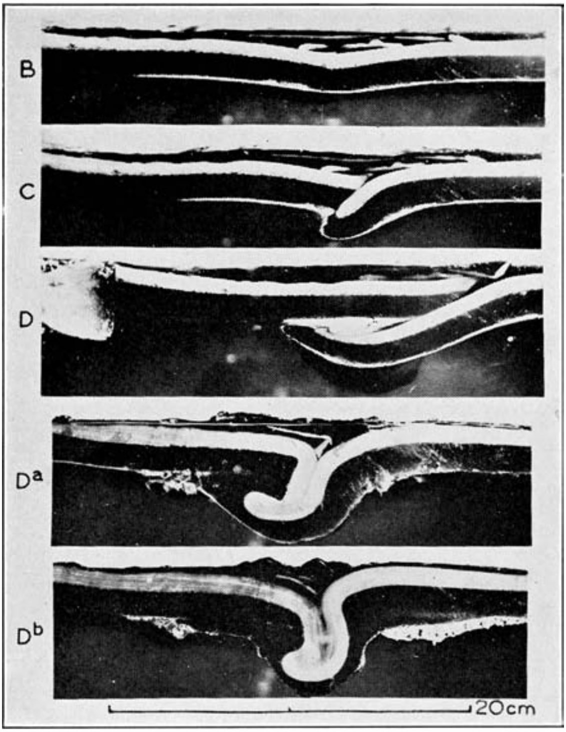
Alps (Figure 71), or by the mere upending of beds of sedimentary rock (Figure 57).

Because the effects of horizontal compression are concentrated along geosynclinal prisms, we must believe that a belt of crust harboring one of these thick prisms is weaker than the crust elsewhere. There are three reasons for this belief. First, laboratory tests show that sedimentary rocks in general have crushing strength lower than that of the crystalline rocks, which dominate outside of geosynclines. Second, an important source of weakness in a geosynclinal prism is found in its thin-bedded character, for here, under horizontal compression, slipping along the contacts of the different beds makes folding much easier than in massive, crystalline rocks, for these characteristically lack planes of bedding. The third reason is perhaps the weightiest of all. After burial under the geosynclinal prism, the initially strong, crystalline crust is warmed by the internal heat of the planet and by the now blanketed heat of radioactivity in the earth-shells and is thereby made specially plastic. Thus the geosynclinal belt is a zone of relatively low strength, and here at its weakest place the crust will collapse under sufficient horizontal compression.

Moreover, we note the principle of engineering, that stresses in a collapsing system are greatly concentrated at each successive point of rupture. So it is with a steel bridge. One of its plates yields under the weight of the bridge, and at that place the stresses quickly increase. With complete failure there, the breaking stress then rushes to other points, one after another, until the wrecking of the bridge becomes total. This law of enormous accumulation of breaking stress at dif-



72. Kuenen's experiment on the deformation of crust and overlying geosynclinal prism of homogeneous composition.



73. Kuenen's experiment with a heterogeneous geosynclinal.

ferent points in succession is of great importance for a real understanding of mountain chains. The average intensity of the horizontal compression of a geosynclinal prism may not be extremely high, but by concentration of the force at a point, the force ultimately can surpass the strength of any rock. It is by yielding at many such points, one after another, that a mountain-structure is developed.

Here too geologists have attempted to hold the mirror up to Nature, by carrying through imitative experiments in the laboratory. Each has added evidence that we are on the right track in our thinking. However, most emphasis will be given to the work of Kuenen, partly because he chose materials and dimensions of apparatus most nearly matching to scale the materials and dimensions of the earth's outer shells.

Kuenen's cross-sections, Figure 72, illustrate his results for a homogeneous geosynclinal prism resting on a uniform crust. At top is the prism, tinted black. It was initially a symmetrical lens. At Stage A this and the underlying part of the crust have already been downwarped a little by horizontal pressure from the traveling beam of the apparatus. See Figure 66. The beam, shown in white on the right side, moved from right to left. With growing pressure the downwarp deepened, and the material of the lens was thickened at the axis of the downwarp. There must have been much shearing and irregular flow in the material of the lens, but, because of its homogeneity, the complex structure could not be made evident in the photograph.

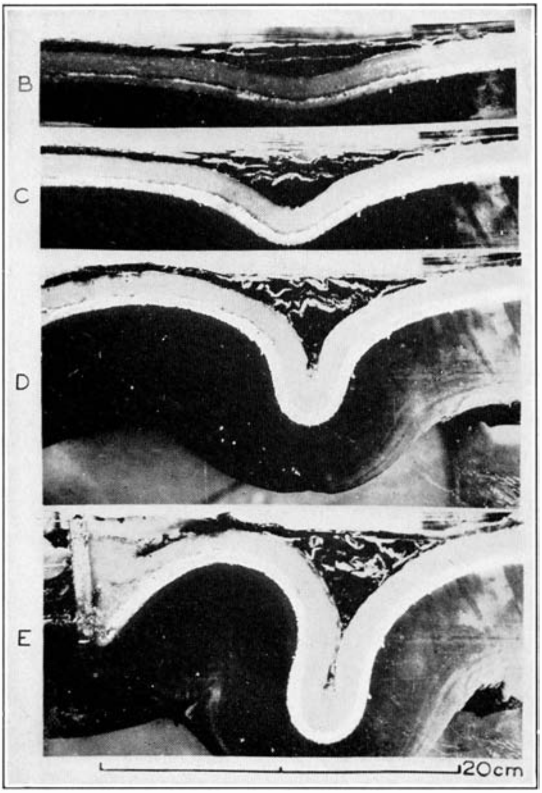
A second experiment was made with a crust, colored light above and dark below and covered with a lens of alternating soft and hard beds (Figure 73). The softer beds have the darker tint in this photograph. Successive stages of the deformation are portrayed in the cross-sections. The white line at the bottom of the crust is due to froth, made when the crustal material was poured on the water of the tank, the water itself representing the substratum. We note that the double, lower layer, which was stiffer than the overlying prism, yielded by both rupture-thrusting and downfolding. The thrusts were developed near the glass walls of the tank (sections C and D). The downfolding occurred farther in from the walls. See sections Da and Db. Here again, as the downfolding went on, the lens or "geosynclinal prism" was thickened by the drag of the stronger crust beneath. We see also that there was some breaking, bending, and upturning of the light-tinted beds of the lens. Sections Da and Db have profiles suggestively like that of a mountain range and its environment, and both sections, like section D, show a deep "root" under the thickened geosynclinal prism.

Analogous results were obtained when four harder, white beds had been interleaved with the black material of the prism. Some of the structural turmoil in the deformed prism is apparent in sections D and E, Figure 74. The enlarged photographs of Figure 75 show more details for Stage E. The white beds are seen to have been open-folded and close-folded, and here and there bent into overturned folds—all in principle copying the vastly greater crumplings in Nature's geosynclinal prisms.

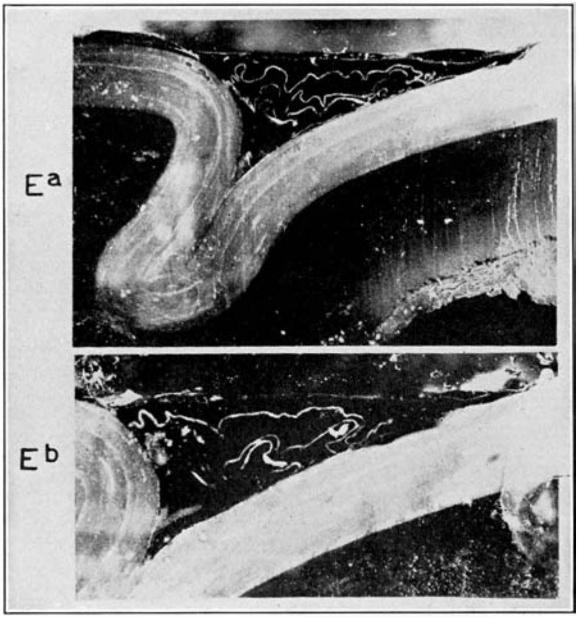
Thus the best designed of all the imitative experiments made by geologists emphasize the idea that the visible crumplings of an Alpine belt are largely the product of the downwarping and diving of the lower, stronger part of the earth's crust. As this deep sublayer buckles downward and dives, the two sides of the geosynclinal prism approach each other, and the beds of the prism are dragged into folds and thrusted blocks. These drag-folds are added to any folds which may have been produced by direct, end-on, horizontal compression of the crust as a whole.

Cause of the Horizontal Compression

When rocks are set writhing into a mountain-structure a colossal work is done. Potential energy is converted into kinetic energy, energy of motion. Whence comes the potential energy? On this subject geologists are now debating three different suggestions, embodied in what may be called the contraction theory, the convection theory, and the crust-sliding theory. The three theories are not mutually exclusive, and in fact each may well embody some of the truth about the making of mountain-structures.



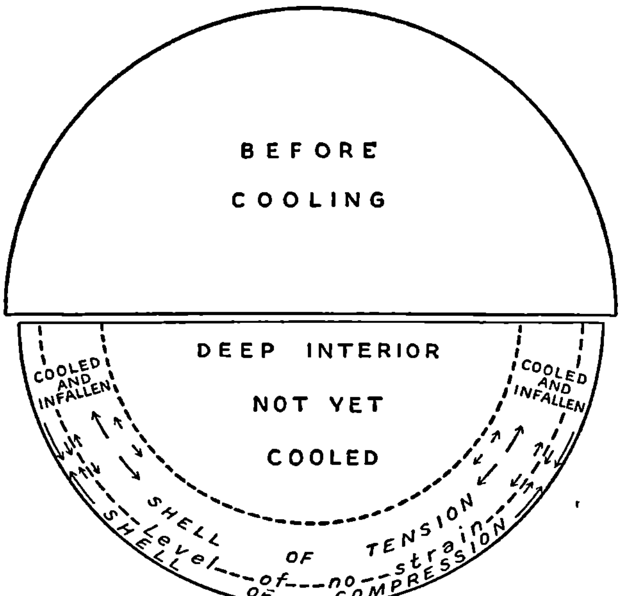
74. Another of Kuenen's experiments with a layered geosynclinal.



75. Detail of result of an experiment in the crumpling of a geosynclinal prism; after Kuenen.

The oldest and deservedly celebrated contraction theory is based on the postulate that the earth steadily cools. Analysis shows that a comparatively thin, superficial shell of rock early attained nearly its present temperature, the cooling thereafter being significant only in the underlying shells of the globe. With the resulting contraction and radial retreat of the interior, the superficial shell has to follow down, that is, fall. As it falls, nearly its full weight is felt by the shrinking interior. The superficial shell has to adapt itself to a globe with a diminished radius. This the shell can do to a certain extent without becoming warped, for the rock of the shell is somewhat compressible.

As the outer part of the earth's skin slowly falls, it is everywhere condensed in the horizontal direction. It becomes a "Shell of Compression" (Figure 76). Theory shows that below it is a "Shell of Tension," the two shells being separated by a "level of no strain."



76. Cross-sections of the earth illustrating the Contraction Theory of mountain-building. The lower section represents conditions after considerable cooling of a thick outer shell.

By falling a little toward the earth's center of gravity, the rock of the Shell of Compression has lost some energy of position, and has gained within itself elastic energy. This new elastic energy is analogous to that of a compressed coil-spring made of steel.

The stress in the Shell of Compression grows until it passes the limit of strength of the rock. Then the Shell ruptures. It ruptures where it is weakest, that is, along a geosynclinal prism. There the bedded, sedimentary rocks are crumpled into a mountain-structure by the elastic expansion of the now ruptured crust. During that forceful expansion, the whole Shell of Compression, all the way to the antipodes of the geosyncline, slips horizontally over the rest of the earth's body.

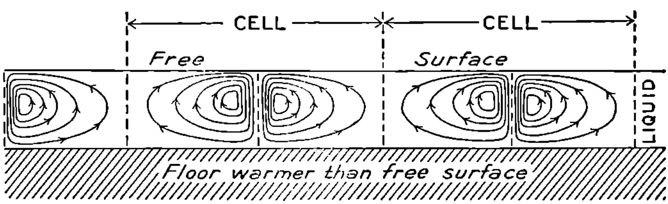
So runs the contraction theory. With assumed premises regarding the duration and rate of cooling, H. Jeffreys has calculated that the Shell of Compression long ago reached a thickness of the order of 60 kilometers. His figure is comparable with the thickness of the whole crust, assumed in our fundamental hypothesis.

Now it seems incredible that a 60-kilometer shell could slip horizontally over the rest of the earth's body, if the planet is crystallized, solidified in the true sense, to indefinitely great depth. In that case the slipping would be prevented by the considerable strength of countless crystals, distributed at all points in the earth's circumference. Strong solid would have to be sheared away from strong solid, horizontally and on a planetary scale. However, this difficulty disappears if we assume the 60-kilometer Shell of Compression to rest on a hot, vitreous substratum, for the hot glass would offer little or no permanent resistance to the shearing motion of the crust.

But the contraction theory needs supplementing. Unaided, it can not account for the total amount of horizontal compression suffered by the old geosynclinal prisms of the world. Hence geologists have begun to examine the possibilities of thermal convection in the earth's body. Every thunderstorm illustrates the principle. The thunder-cloud is due to the uprush of air that had been warmed at the surface of the ground and then pushed up to high levels by colder, denser air that was sinking alongside. The cross-section of

Figure 77, drawn to scale according to an experiment by H. Bénard,[3] shows what happens when a thin layer of liquid is stirred by convection. After the motion reaches the steady state, it has resolved itself into the form of up-and-down currents in each of many regularly bounded cells. The arrow-heads in the drawing indicate the directions followed by the convection currents.

And the atmosphere illustrates another type of convection. The cold air of the polar regions runs under the warmer, lighter air of low latitudes and enforces a return, poleward current at high levels. If the material of the earth's interior be assumed hot enough to behave like a viscous liquid, and if it be also assumed that one sector is cooler than a neighboring sector, then there is a tendency toward a convective overturn of the material. If the difference of



77. Illustrating convection cells. After H. Bénard.

density between the two sectors becomes great enough, a descending current is generated in the cooler sector and an ascending current is generated in the warmer sector. Between the centers of the two sectors compensating horizontal currents are also developed. The upper horizontal current flows toward the cooler region; the lower horizontal current flows toward the warmer region.

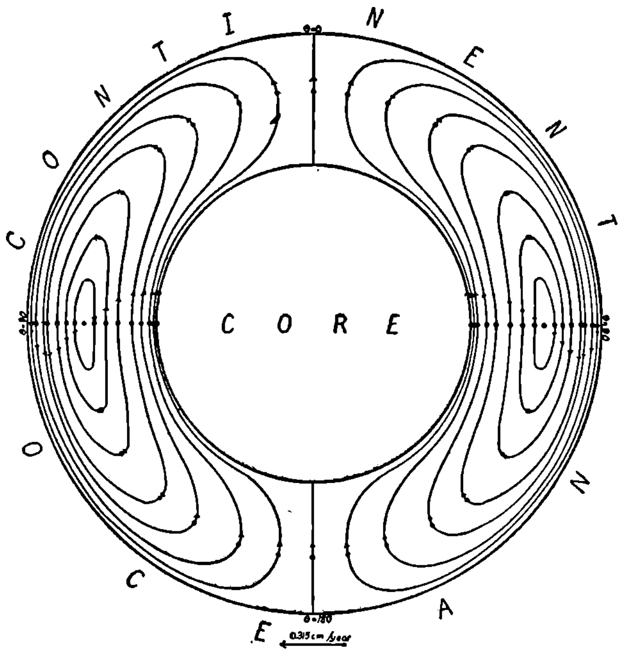
A. L. Hales finds by mathematical analysis that thermal convection is possible in a thick earth-shell even if the shell has a small degree of true strength.

C. L. Pekeris has applied the idea of differential cooling of the earth, and has discussed the subject mathematically.[4] He postulated a simple earth, with a hemispherical continent opposite to a hemispherical ocean, the former sector being the warmer of the two.

[3] H. Bénard, *Révue générale des Sciences,* vol. 11, 1900, pp. 1261 and 1309.

[4] C. Pekeris, *Monthly Notices Royal Astronomical Society, Geophysical Supplement,* vol. 3, 1936, p. 343.

This premise was adopted in accordance with prevailing opinion about the relative efficiency of the radioactive furnace beneath continent and deep sea. A solid crust, 30 kilometers thick and resting on a thick shell of homogeneous, highly viscous liquid and itself bottomed on the iron core of the earth, was assumed. Taking a moderate value for the difference of temperature between the two hemispherical sectors, and a reasonable value for the viscosity of

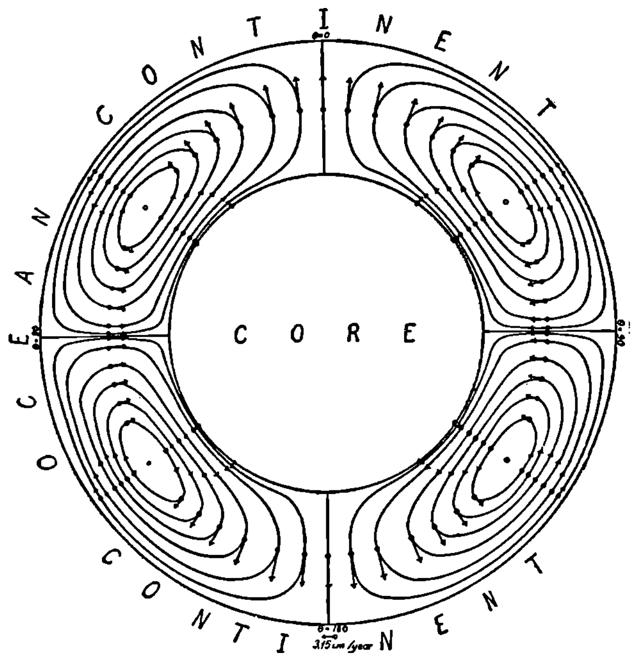


78. Convection currents in a hypothetical earth, according to the computations of C. L. Pekeris.

the thick, liquid earth-shell, Pekeris computed the directions and velocities of the convection currents developed by the difference of temperature. The result of the calculation is illustrated in Figure 78. There we see the location of continent and ocean; the 30-kilometer crust, drawn to scale, at the outer circle; the circular outer limit of the iron core; curved lines representing the currents; and many barbed arrows that show the directions and speeds of the convectional flow. Under the center of the continent there is an upward current.

To right and left, opposed, horizontally moving currents are rubbing against the bottom of the crust and tending to tear it apart at the center of the continent. In the oceanic sector, the conditions are reversed, and there the crust tends to sink, and at the same time feels horizontal compression by the rest of the crust from both the right side and the left side.

Another diagram (Figure 79) gives the analogous results when



79. Convection currents computed by Pekeris with assumptions differing from those for Fig. 78.

Pekeris assumed two polar continents and an equatorial ocean, again with differential cooling.

Pekeris knew well that his computations were based upon arbitrary premises, adopted for mathematical convenience, and that his results should not be taken as picturing actual movements in the earth. As a matter of fact the thick shell between crust and iron core is not likely to be chemically homogeneous. Much more probably this shell is composite, intrinsically less dense layers in succession overlying layers of greater intrinsic density. If this is true, convective overturn of the whole shell, even if vitreous from top to bottom, would have to be of the step-by-step kind. Let us suppose the uppermost, relatively homogeneous layer to be cooled above and then overturned. The layer next below becomes cooled by the sunken material of the first layer and is ultimately also overturned by convection. Still later the third layer feels, thus indirectly, the cold of outer space and it too is overturned. And so on. Thus the possible convection would be of the step-by-step or "tandem" variety. The process would have to be exceedingly slow, with periodic effects, at long intervals of geological time, on temperatures and densities of the upper layers of the earth. And it is further manifest that the convection cells in any layer would be much narrower than those deduced by Pekeris.

We note that convection would cause localized horizontal compression for a reason not connected with the viscous drag of the substratum on the crust. Pekeris shows that a rising current would have to push up the crust directly overhead; and that the crust would have to subside where the cooler material sinks. Thus warping or tilting of the crust would inevitably accompany thermal convection. A tilted segment of the crust tends to slide down bodily, over the plastic substratum, toward the zone of sinking currents. Hence at the lower edge of the tilted block there would be new horizontal compression.

Suppose, now, that the crust is actually torn apart by the friction of the opposing currents beneath. In this case each half of the continental crust is dragged oceanward on the back of its share of one current. Urged by that dragging current, the huge continental block exerts horizontal compression on the sub-oceanic crust downstream. The continental block itself is also compressed in the same sense, and increasingly in the downstream direction. If, then, the continental crust had been weakened by the development of a geosynclinal prism at or near the coast, the horizontally directed pressure might crumple the prism into a mountain-structure.

Before arriving at any conclusion as to the efficiency of convection in mountain-building, let us pause for a brief comparison. Like the contraction theory, the convection theory draws on the bank of potential energy; but the drafts are on two different accounts in that bank. The contraction theory finds the needed energy of position in the unstable crust. The convection theory finds it in a thick layer of liquid or quasi-liquid material, below the crust and differentially heated. According to the contraction theory, the horizontal compression responsible for mountain-making was exerted by the whole of the earth's crust, as the whole crust fell toward the earth's center. In contrast, the convection theory has the horizontal pressure applied by limited blocks of the crust, namely those torn loose from the rest of the crust by the friction of the horizontal current beneath.

But our earth-model implies that there may have been convectional displacements in the planet, due to conditions not discussed by Pekeris. The model permits overturn of material for a reason not directly attributable to the earth's cooling or to differential radioactivity. More than once we have observed that the crust is potentially in danger because its density is a little greater than that of the substratum. If a block of the crust were immersed in the substratum, that block would have to founder, sink away, to some deep level, where the block would stop in a layer of its own density. The place of each foundering block would be taken by material risen from the substratum.

Moreover, it should be noted that added pressure tends to freeze a rock-melt. Hence, if for any reason the upper, cooler part of the substratum begins to dive to levels of greater pressure, that part crystallizes and, by the consequent increase of its density (about 5 per cent), dives all the faster.

Hence we have two kinds of what may be called "solid-liquid convection." This type of overturning would be much more rapid than that represented in pure thermal convection. Naturally solid-liquid convection would be limited by the thickness of the subcrustal layer with density low enough to permit the sinking of the solid blocks.

A number of authorities are sympathetic with the idea of a possible relation between convection and mountain-making. Among them was A. J. Bull,[5] one of whose experiments helps one to picture

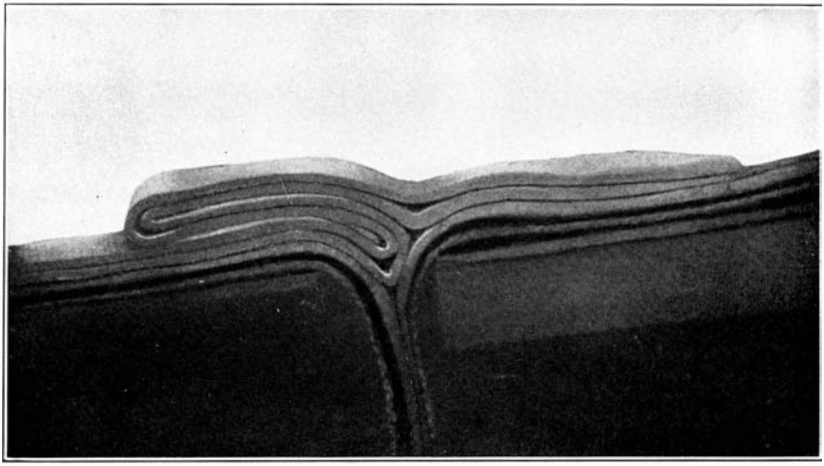
[5] A. J. Bull, *Proceedings Geological Association,* vol. 40, 1929, p. 105.

that relation through analogy. The experiment is represented in Figure 80. Layers of plastic material were piled on a board with a slot cut in the middle. On each half of the board a piece of webbing separated the board from the pile of layers, the ends of the webbing allowed to hang down in the slot. The whole assemblage was tilted and weights were hung on the pendent ends of the webbing. As these weights slowly pulled the webbing through the slot, the lowest layers were dragged down with it, while the upper layers formed arches which, because of their own weight, fell over in the direction of the tilt given to the apparatus. In this experiment Bull was attempting to explain the marked asymmetry in the structure of the Swiss Alps, but the result portrays analogy to two processes expected if convection below the earth's crust has coöperated in the making of mountain-structures. For the folding of the flexible layers in the experiment was accomplished by frictional drag, as demanded by the convection hypothesis; and, secondly, the experiment illustrates one way in which a mountain chain becomes provided with a root.

The third or crust-sliding theory of mountain-making may be grasped through the homely analogy of a ladder. Placed against a wall, the ladder presses its own foot, and this pressure has a horizontal component directed away from the wall. If the wall and floor were frictionless, the horizontal pressure would be equal to the weight of the ladder, multiplied by the sine of the angle of inclination of the ladder to the vertical wall.

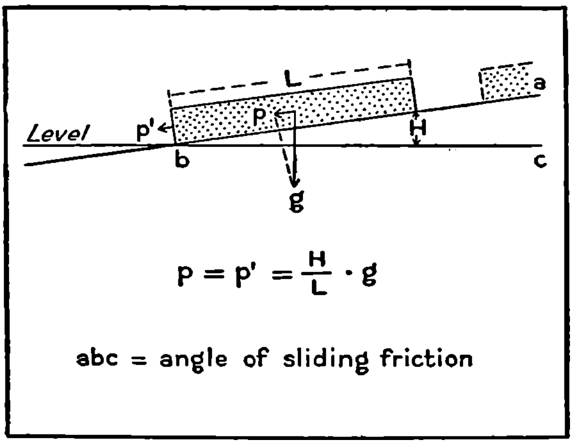
The principle involved may be further illustrated by Figure 81. Let the stippled rectangle represent a block of the crust out of level. The length of the block is L; the height of the upper end above the level is H. Then, as we see, the pressure (p′) is equal to H divided by L and multiplied by g, the force of gravity. As a matter of fact the section was made to correspond with the case where the friction at the bottom of the block was assumed to be just sufficient to prevent sliding. Sliding would begin if the angle *abc* were a little larger. In this case the block would exert horizontal pressure at its lower end.

So it would be with a segment of the earth's crust, resting on a quasi-liquid substratum and tilted enough. Suppose that at the foot



80. Illustrating the experiment of A. J. Bull on the possible relation of convection to mountain-making.

of the tilted segment there is a thick geosynclinal prism, a weak place in the crust. If, along the weak belt, the crust ruptures under the localized pressure, the tilted segment begins to slide. At the lower edge of the block the rocks are under new horizontal pressure. The horizontal thrust is propagated chiefly through the deeper and stronger part of the crust, which, as in Kuenen's experiments (Figure 73), is ruptured, buckled downward, and forced to dive into the substratum. The less dense and unsinkable sediments of the geosynclinal prism thus receive an increasing proportion of the squeezing pressure. At least one lip of the ruptured crust is shoved



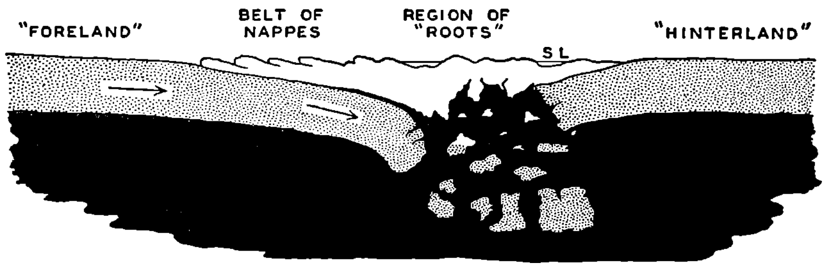
81. Section illustrating the principle of crust-sliding.

down and begins to feel the pull of solid-liquid convection. Meantime, liquid basalt from the substratum, shown in black on the diagram of Figure 82, rises along the planes of fracture. That liquid acts as a lubricant and still further lowers the resistance to sliding and diving. The resistance is also diminished as great blocks in the zone of rupturing founder in the substratum itself, for by so much is the stubborn, solid rock removed in front of the sliding segment of the crust. The final result is intense crumpling of the weak geosynclinal rocks into a mountain-structure.

The question whether the earth's crust has been disleveled sufficiently for the making of mountain chains is a difficult one. An affirmative answer seems possible, in view of four deductions from theory.

One of these deductions roots in the contraction theory. We remember that the earth's contraction puts the crust in a state of horizontal compression. It is easy to conceive that the strain would develop low but broad downwarps and upwarps of the crust. Just such warping took place in the imitative crust of MacCarthy's experiments and in that of Kuenen's experiments (Figures 65 to 69). We recall also that alongside the typical geosyncline in Nature there is at least one super-elevated belt; and that two adjacent displacements of the crust, one upward and the other downward, mean a total disleveling greater than either.

Secondly, we have learned that, if thermal convection takes place



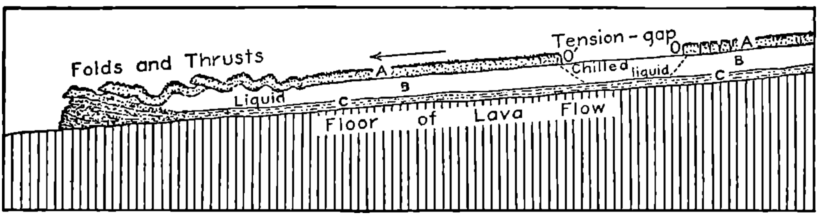
82. Diagrammatic section to represent diving of the crust, major stoping, and mountain-making.

in a thick subcrustal layer, the crust is thrown out of level over wide areas. Conceivably this secondary effect may have given pure thermal convection its greatest importance as a cause of mountain-making.

A third cause to be considered is differential radioactivity. An earth sector that is poorer in radioactive elements cools and contracts vertically at faster rates than a neighboring sector richer in those elements. The crust in the two sectors must ultimately stand at different levels. Have the circum-Pacific chains of mountains been there developed partly because the rocks of the Pacific sector are less radioactive than the rocks of the surrounding, Sialic sectors?

Finally, consider the situation when for any reason the lower, denser part of the crust is bent down into the substratum without losing solid, elastic connection with the rest of the crust. See Figure 82. That downwardly projecting part is at least 3 per cent denser than the substratum. Because of this difference of density a downward pull is exerted on the downfold, with an additional tendency toward local tilting of the crust.

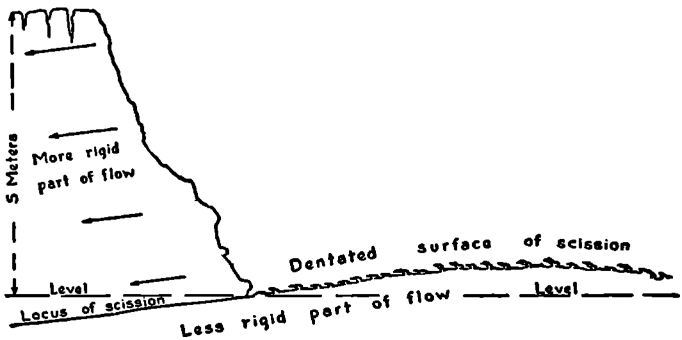
The foregoing discussion of the ways in which the earth's crust may have become warped enough to produce sliding of large segments has led us far into the treacherous field of speculation. In the present state of earth science it is out of the question to decide the merits of the crust-sliding explanation of mountain chains. However, neither geology nor geophysics seems to offer as yet any fatal objection to the hypothesis. Where speculation has so far out-



83. Longitudinal section of a basaltic flow in Ascension Island, illustrating the possibility of crust-sliding.

stripped the accumulation of decisive facts, it may not be amiss to record one relevant observation in Nature.

The idea that blocks of the crust may have slid, with crumpling pressure at their bows and tensional phenomena at their sterns will become perhaps less repellent when one studies an analogy from Ascension Island (Figure 83). There the chilled, superficial layer in a basaltic lava-flow actually slid on the hotter, much weaker material of the middle part of the flow. Upstream the sliding left a tension-gap with vertical walls. Downstream the superficial layer, solid though still hot and plastic to a degree, was folded, broken, and thrusted, giving a lively imitation of a mountain-structure. Within the tension-gap the glassy surface of the middle, glassy layer is marked with deep, parallel scratches and grooves, directed straight downstream and eloquent of the friction between the sliding layer and the glass beneath. The grooving completely proves the reality of the sliding. It may be added that the lower layer, though marked "liquid," was already cooled enough to have some of the properties of a plastic solid. As the weight of the slowly sliding, upper layer was removed, the glass in the tension-gap was gently arched. Once exposed to the air, the glass was rapidly chilled to brittleness, and, as the arching proceeded, the glass at the surface snapped up, giving the dentated profile shown in Figure 84.



84. Dentated floor of the tension-gap shown in Fig. 83.

Is this analogy from Ascension Island a will-o'-the-wisp, leading one into a bog of error? Perhaps so, but the case is worth remembering when judgment is passed on the hypothesis of crust-sliding.

A word in summary. This third theory, like the contraction and convection theories, demands relative thinness for the earth's crust and also vanishingly small strength for the earth-shell immediately beneath it. Hence each of the three most promising suggestions about the origin of mountain chains has little significance unless it is based on an earth-model which, in general, resembles the model described in this book. And it may well be that contraction, convection, and crust-sliding are all involved in the Herculean work of mountain-making.

Mountain Height

We have now sketched the problems relating to the location, internal anatomy, and origin of mountain-structures. Some of these questions will be considered again, in later chapters, but one other principal topic requires immediate attention. It is suggested by the very characteristic from which the word "mountain" is derived—the exceptional height of the younger ranges. Here we have a general problem, for the much older ranges, now of comparatively small elevation, were lofty before relentless erosion wore them down to the lowly stubs of the existing maps.

Twenty years ago most geologists assumed that each mountain chain grew to maximum elevation at the time when the folding and thrusting there registered was just completed. Closer study has proved a different relation. As already noted, the great heights of Rockies, Alps, Andes, and Himalayas were attained millions of years after the respective crumplings seated these kings on the thrones of the world (Figure 85). Why? An answer is at hand if the earth has a constitution like that of our mental model. For four reasons the model can account for the long delays in uplift.

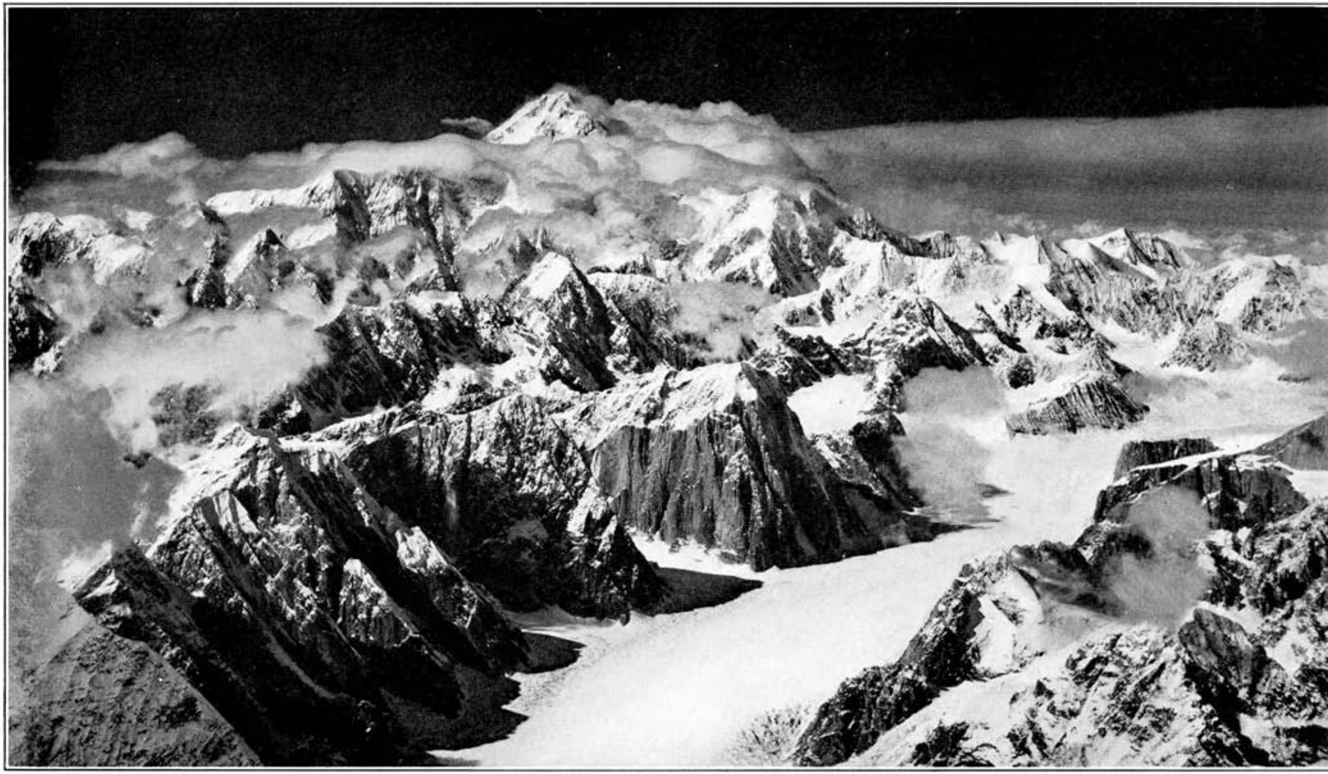
First, let us weigh a consequence of the weakness of the substratum. In general the high and steep slopes of individual mountains are not parts of the original topography, but are due to erosion by river and glacier. This erosion has removed vast quantities of rock along the valleys, the divides between the valleys losing much less substance and height, per square mile. Because the rock and corresponding load were removed from the valleys, the earth's crust under the mountain belt was thrown out of balance with the rest of the crust. However, the balance has been restored by lateral inflow of the material in the weak substratum. Thus the mountain range as a whole has been forced up, the interstream ridges and peaks rising higher than they had ever been before.

But that is not the whole story. Wide areas of the North American Cordillera are not greatly dissected by canyons and yet show evidence of strong uplift long after the structural revolution there was completed. In other words, the Cordillera and other mountain chains have felt the delayed uplift in amount decidedly greater than that occasioned by erosion and balancing movement. It is this excess of uplift, super-elevation of the chain as a whole, which we are now to consider. Here other causes can be deduced from the earth-model.

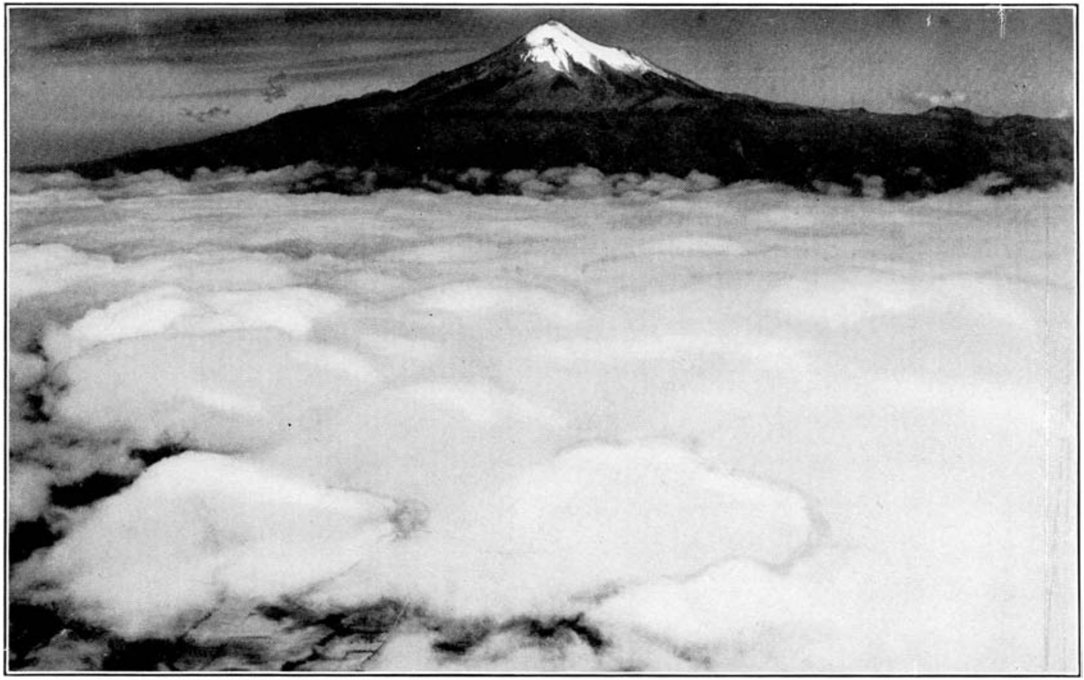
The second is found in the very essence of the mountain-making process. As we now visualize it, the process involves the diving of the cool crust-rocks into the substratum. The diving is of two kinds. Urged by the horizontally directed pressure, the crust bends down and makes coherent, deep roots for the mountain-structures. Moreover, large fragments of the crust are likely to be broken off, to become bodily engulfed in the substratum (Figure 82). Downthrust of the coherent roots and also foundering of large pieces of the crust have an effect in common. In both cases the depressed rock is cool. Contact with it chills the vitreous substratum to great depth. Solid-liquid convection and possibly other types of convection add to the chilling of the sector under the mountain-structure. We remember, too, that the top part of the substratum is at the temperature of melting and is ready to freeze with but moderate chilling. It is even conceivable that, by the time the turmoil of mountain-making ends, enough solidified basalt has been added to the base of the new mountain-structure to make the crust here thicker than it is outside the belt of crumpling. However this may be, we may rest assured that mountain-making is accompanied by rapid, specially deep chilling of the corresponding sector of the earth.

With equal clearness we can reason that this chilled condition is but temporary. Into the chilled part of the sector heat must be conducted upward from the still deeper part which has not been penetrated either by mountain root or by foundered blocks of the crust. But the conduction of heat through rock is extremely slow, and calculation shows that the warming up of the root and the restoration of thermal equilibrium in the planet must take millions of years. With the warming of the mountain root and of the substratum just beneath it, both of these masses of rock expand vertically, with corresponding rise of the surface of the recently deformed structure.

The third reason for delayed elevation will become better understood after we have covered the subject of the fifth chapter. Then we shall think in some detail about the fate of the crust-blocks that founder in the substratum. In the hot substratum the blocks are both melted and dissolved. Great volumes of such secondary melts, characteristically with density somewhat lower than that of the crust



85. Mount McKinley, Alaska (alt. 20.270 feet), seen from the south over Ruth Glacier. Airplane photograph by Bradford Washburn at 14,000 feet and about 15 miles from the summit.



86. Orizaba Volcano from an airplane at the height of 11,000 feet, looking west. Photograph by D. H. McLaughlin.

or the substratum, rise high into the mountain roots. Because of the contrast of density, the melts exert buoyant, upward pressure on the wounded crust, which therefore rises. Here again there is delay, for it takes much time for the meltings and dissolvings to take place. In fact there is definite field proof that the secondary melts do invade the mountain roots on a large scale after the main folding and thrusting have been completed.

The fourth condition for delay in uplift is the distribution of the radioactive elements in rocks. The light rocks, or Sial, of the earth's crust are about twice as radioactive as the heavier rocks beneath or the basalt of the substratum. We saw that the lighter crust-rocks are thickened in the mountain roots (Figure 82). Hence there the furnace action of the radioactive elements has maximum effect, and its new heat is developed with exceeding slowness. Millions of years are needed to allow any considerable heating of the mountain root by reason of the excessive radioactivity. Yet in the course of time the effect is brought about, and there is ultimate, slow, upward expansion of the earth sector bearing each new mountain-structure. The expansion means a much delayed uplift of the surface of the structure.

The reasons for the prolonged delay have been described in qualitative terms. Until they can be treated quantitatively it is impossible to declare which has been dominant during the earth's long story, but at present it seems that none of the causes suggested can be ruled out as of small importance.

Summary

In this chapter we have been picturing Nature in a paradoxical mood. We have studied the making of mountain-structures, a gigantic expenditure of planetary energy, and have found gravity to be the chief laborer. The earth's crust had to fall under the pull of gravity, if mountain chains were to rise. We have watched the planet cool and contract, the crust as a whole falling toward the center of gravity. The infall has not been uniform but largely concentrated in relatively narrow belts. Toward those belts we have imagined segments of the crust to be dragged by deep currents or to slip under a fraction of the segment's own weight, and we have come to the fundamental idea that, after each mountain-making segment reaches the belt of deformation, the downstream border of the moving block dives into the substratum. With the diving have come folding and thrusting of the more superficial rocks, geosynclinal rocks, to form the complex mountain-structures. We have seen how the diving and consequent formation of mountain roots is easier to understand if the earth has a true, crystalline crust, which is slightly heavier, per unit volume, than the vitreous basalt below it. And, lastly, we have found that both the structure and the height of a mountain chain are products of the downward invasion of the substratum by solid crust-rocks.

CHAPTER IV

THE ASCENT OF LAVA

"Vulcan the Heat-bringer"

Introduction

THE problem of the mountain chain becomes less formidable if the earth be supposed to have crust and vitreous substratum. On that assumption we have been led to picture each chain as the ultimate result of the diving of crust-rocks into the substratum. But any volcano shows that there has been invasion in the reverse sense, and we must examine our earth-model to see if it can account for the rise of molten rock into and through the crust, as at Orizaba, which is 18,000 feet high and the loftiest volcano in North America (Figure 86).

This chapter will be concerned with volcanic action. The next chapter will cover two related topics: the conditions that cause once-molten rocks to vary in composition among themselves; and the mechanism by which such melts came to invade mountain roots on a scale unmatched elsewhere.

In the interest of clear thinking a few definitions may be considered. When geologists designate as "igneous" those rocks that have solidified from a molten state, they use the word figuratively, not according to the root meaning, which is "made by fire" or "heated by combustion." In reality the molten condition is in part an inheritance from the earth's beginning, this heat being a cosmogonic mystery; in other part it is the product of radioactivity, another mystery. An example of the rock-melts of Nature is the river of incandescent basalt, which, at the rate of ten miles an hour, rushed down the gentle slope of the world's premier volcano, Mauna Loa, in the Island of Hawaii. See Figure 87.

The high temperature required for the molten state is first reached in the earth at an average depth somewhat exceeding 40 miles or

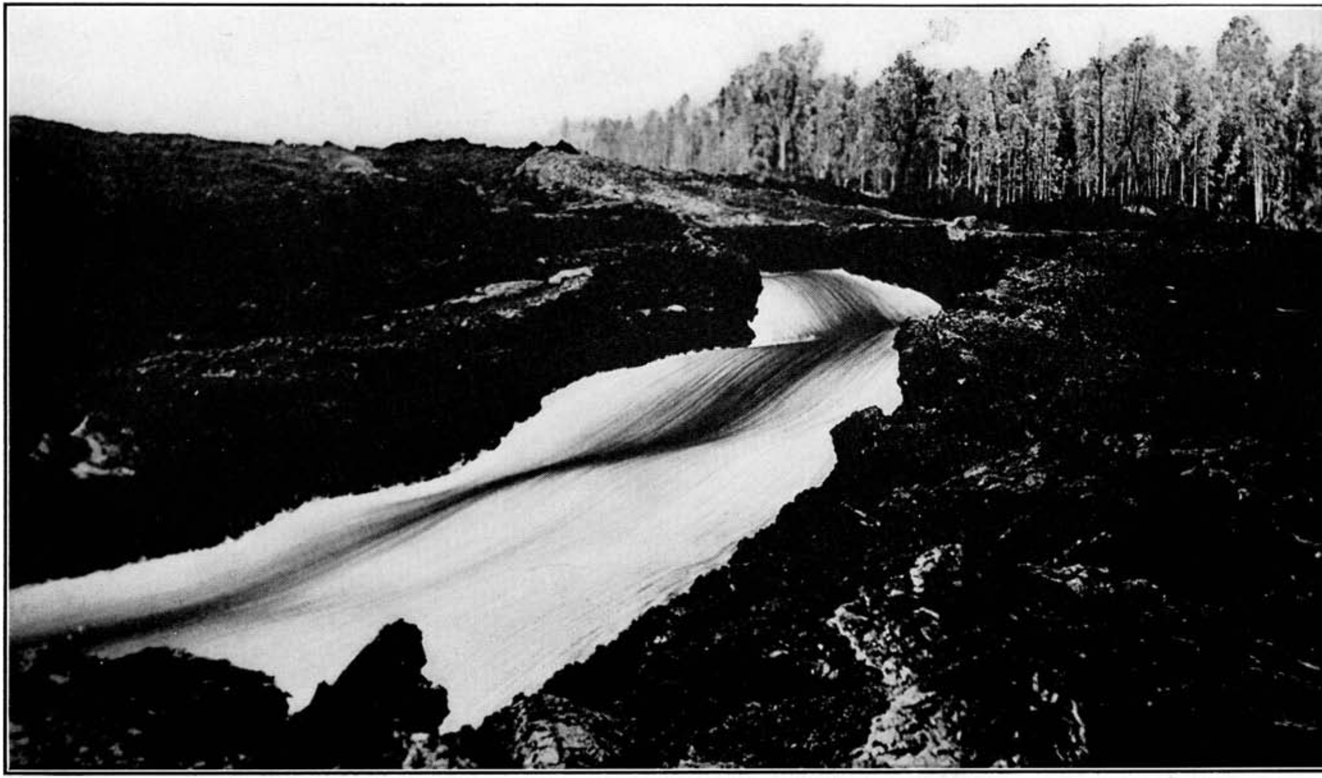
64 kilometers. Hence we may be sure that all visible igneous masses, younger than the Basement Complex, were pushed up through vertical distances of the same order. Therefore igneous rocks are called also "eruptive" rocks, meaning literally that they have broken their way out of the depths of the planet. It is appropriate to distinguish igneous material poured out on the earth's surface as "extrusive," and that erupted into the crust, but not reaching the surface, as "intrusive." Observation shows that basalt is the dominant extrusive material, while granite is the dominant intrusive material. Why this should be true is another principal question to be faced as we proceed to test our earth-model.

The Melting of Rock

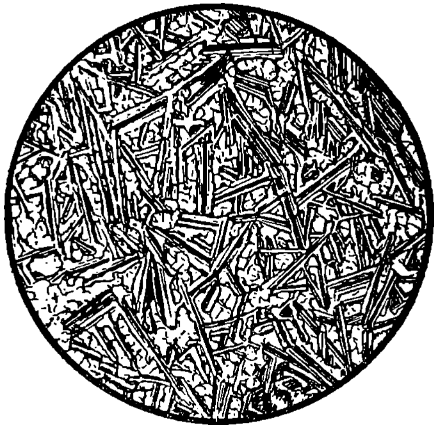
Intelligent testing demands some knowledge of the general processes involved in the melting of rocks. Hence a preliminary analysis of this subject will make easier the grasp of the vital queries associated with the extrusion and intrusion of igneous material.

Most rocks are composed of more or less interlocking crystals. The illustration, Figure 88, shows, by a drawing made with the aid of a camera lucida, a thin slice of well crystallized basalt viewed under the microscope by transmitted light. The rock is essentially composed of feldspar (white), pyroxene (marked with narrow, parallel cracks), and olivine (marked with apparently wider, more irregular cracks). The three kinds of crystals or minerals differ in chemical composition. In general there is also a wide chemical range among constituents of the different rock species.

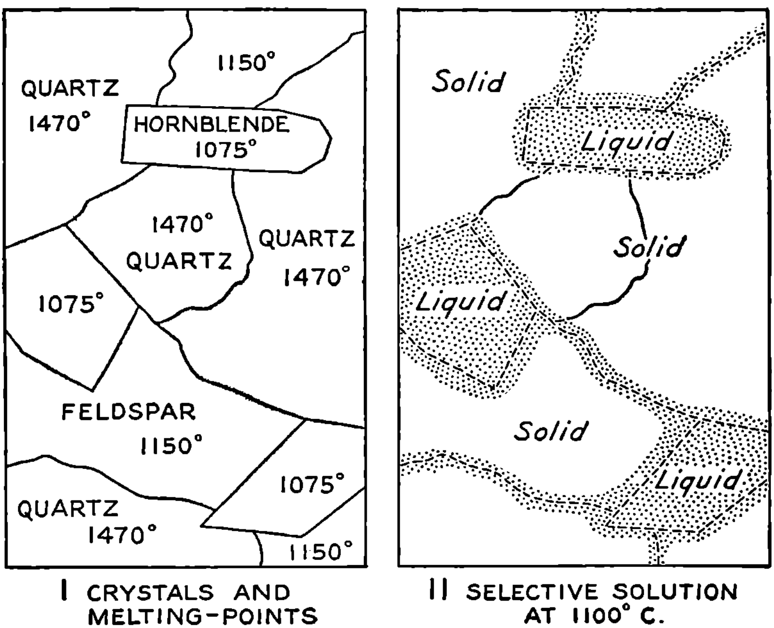
If a piece of rock is heated enough, its minerals of contrasted composition begin to dissolve one another. The left half of the drawing in Figure 89 is a diagrammatic cross-section of a granite, made up of three minerals: quartz, feldspar, and hornblende, the melting-points of which are given in the Centigrade scale. After sufficient heating of the specimen the hornblende, with a relatively low melting-point, becomes liquid, as suggested by the stipple pattern at the right. And the more refractory quartz and feldspar have begun to melt each other at their mutual contact. The resulting liquid, also indicated by stippling, makes up layers between the two



87. Alika lava flow, South Kona, Hawaii. Photograph by T. A. Jaggar.



88. Camera lucida drawing of a thin section of crystallized basalt, magnified. After A. Osann. Courtesy of Die Schweizerbartsche Verlagsbuchhandlung, Stuttgart.



89. Diagrammatic sections illustrating partial melting and mutual solution of crystals in a granite.

kinds of crystalline material. If this specimen had been heated still more, the whole mass would have become liquid. If it were then well stirred, a homogeneous, glassy liquid would result. A rock-melt is thus a liquid solution, just as truly as a brine is a solution of salt and water.

We shall first glance at a comparatively simple case, the melting of quartz (Figure 90). Although quartz melts sluggishly, it has a definite melting-point close to 1470 degrees Centigrade, corresponding to white heat. To raise the temperature to that point heat must be poured into the crystal. The quantity of energy needed to raise the temperature one degree is called the "specific heat," and this quantity increases with the temperature, nearly doubling itself between room temperature and the melting-point. In diagram A, temperature is shown as increasing in the horizontal dimension, the total heat in the crystal increasing in the vertical dimension. The increase of the specific heat with the heating is represented by the curvature of the thick line.

The furnace continues to heat the crystal after the melting-point is reached, but the temperature of the crystal does not rise so long as any remnant has not yet been converted into liquid. This heat, required for melting but having no effect on the thermometer, is called "latent heat." In diagram A the latent heat is accordingly represented by a straight, perfectly vertical part of the thick line.

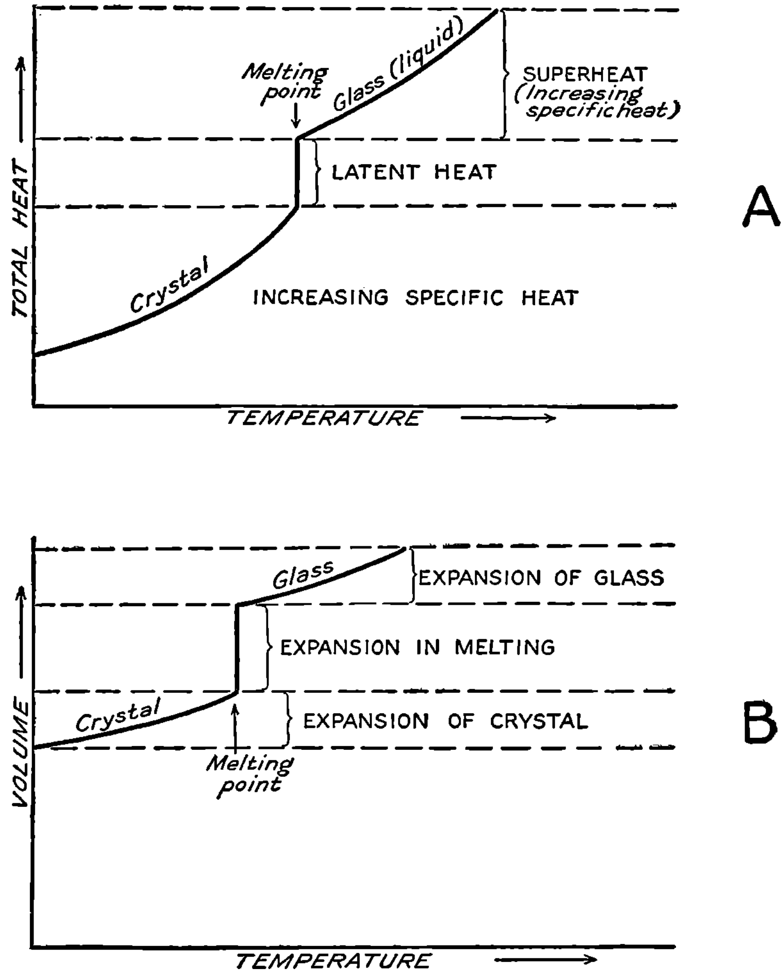
If the liquid is heated above the temperature of melting, the curve of total heat is once more inclined from the vertical, as shown, new values for the specific heat being reached.

Table VIII names other important rock-forming minerals with definite temperatures of melting.

Table VIII

Mineral	*Melting-point*
Albite (an alumino-silicate of sodium)	1100° C.
Anorthite (an alumino-silicate of calcium)	1550
Acmite (a silicate of sodium and iron)	975
Diopside (artificial, silicate of calcium and magnesium)	1391
Wollastonite (silicate of calcium)	1190
Magnetite (an oxide of iron)	1580

However, most of the rock-forming minerals do not melt at sharply defined temperatures. Each mineral of this kind begins to melt at a certain temperature, but does not become completely liquid



90. Diagrams illustrating thermal properties and changes of volume with heating of rocks.

until a considerably higher temperature is reached. Here, then, the melting-point is replaced by a melting-interval. The change of state occurs in successive steps, different parts of the crystal melting at different temperatures, and the delay in complete melting is due to differences of chemical composition among those parts. The liquid fractions tend to diffuse into one another, but the diffusion is a slow process, so that as a rule the final melt becomes chemically homogeneous only after the liquid has been thoroughly stirred by mixing currents.

Table IX lists examples of the second group of minerals—those characterized by melting-intervals.

TABLE IX

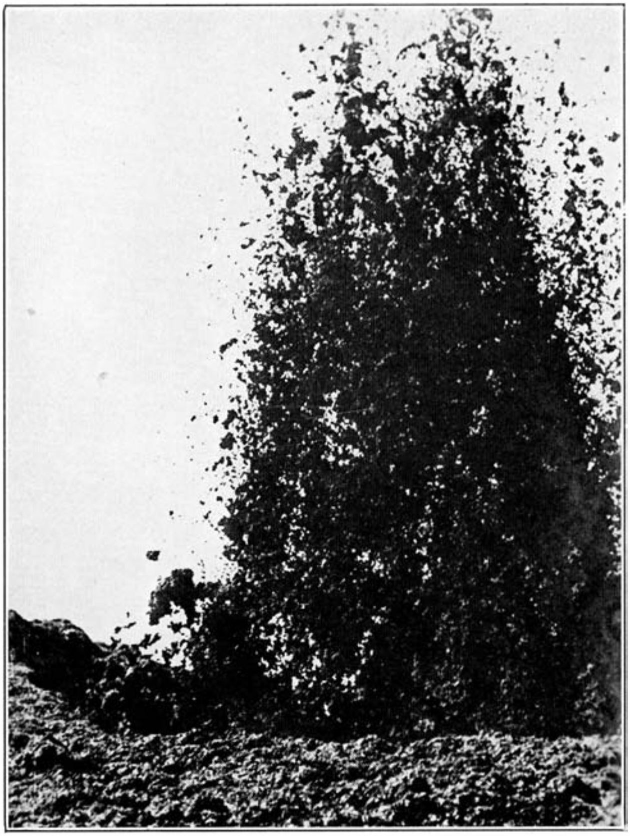
Mineral	*Melting-interval*
Andesine-labradorite (a mixture of albite and anorthite)	1287-1450° C.
Hornblende (a complex silicate)	1060-1200
Augite (a complex silicate)	1185-1200
Olivine (silicate of magnesium and iron)	1360-1410

Nearly all rocks carry minerals of both groups, and, as expected, have melting-intervals and not melting-points. The lower limit of each interval can be rather closely determined by experiment with the laboratory furnace, but for practical reasons the upper limit is less easy to find. For some common kinds of rock, Table X gives the temperatures where melting begins and also the temperatures where melting is advanced enough to permit ready flow of the material.

TABLE X

Type of Rock	*Temperature Where Fusion Begins*	*Temperature Where Ready Flow Begins*
Diabase (Palisades, New Jersey)	1150° C.	1225° C.
Basalt (Mount Etna)	1260	....
Basalt (Stromboli Volcano)	1207	....
Andesite (Santorin Island)	1098	....
Andesite (New Zealand)	1095	....
Granite (dry, Stone Mountain, Georgia)	Below 700	? (completely liquid at about 1050°)

Diabase is a crystallized form of basaltic liquid. The Table shows that the temperature-interval becomes lower in passing from basalt through andesite (a rock chemically intermediate between basalt and granite) to granite. All three examples illustrate the rule: the melting of nearly every rock is progressive.



91. Lava fountain in Hawaii. Photograph by T. A. Jaggar.

No less significant for an understanding of the evolution of rock types is the fact that the reverse process, the crystallizing of a rock-melt, is also progressive. In general the crystals begin to develop in an order just opposite to that found when the same material, previously completely crystallized, is liquefied by heat.

The next chapter will show how these two rules control largely the behavior and origin of the rocks that are most abundant in the earth's crust.

So far we have been noting the temperatures of melting for rock matter containing no volatile substances. Yet every important kind of lava contains gaseous water and other gases, which, weight for weight, act as powerful fluxes. The gas may have enough pressure to explode the liquid lava, as it did, for example, at the source of the 1919 outflow at Mauna Loa, Hawaii, where the red-hot fountains of fluid rock were 200 feet high (Figure 91). The effect of dissolved water on the fusion of granite has been studied by R. W. Goranson, whose difficult experiment is destined to be a classic among those bearing on the physics of rock at high temperature. He has shown that dry granite becomes completely molten at 1100° C., but also that a mixture of 94 per cent granite and 6 per cent water becomes completely molten at about 750°. At this lower temperature the pressure of the steam is 1000 atmospheres or that due to the weight of nearly four kilometers of crust-rock.

There is no reason to believe that, in recent geological time, the gas of any large mass of molten rock much exceeded two per cent by weight, or that the substratum is charged with any higher percentage of gas. In fact the temperature of melting is probably lowered, on average, no more than a few tens of degrees by dissolved gas. On the other hand, in volcanic pipes, where the gas becomes specially concentrated, it has fluxing power of decided importance.

High pressure prevents the escape of gas from an underground melt and therefore tends indirectly to lower the temperatures of crystallization and melting of the material. On the other hand, pressure has a direct and opposite effect on a gas-free or "dry" melt. For example, the melting temperature of "dry" basalt is raised about three degrees Centigrade for each kilometer of crust-rock resting upon it. The effect is greater, perhaps twice as great, in the case of granite. If the substratum glass is just above the temperature of incipient crystallization, and if some of it should be brought up to the earth's surface without any cooling, this erupted material would have a "superheat" of about 180° C.; that is, its temperature would be about 180° above that at which the same melt would begin to crystallize when at the surface. Such an amount of superheat would be nearly one eighth of the total content of heat above the zero of the Centigrade scale, and hence represents an extra supply of thermal energy, available for warming up and even dissolving a limited quantity of the invaded crust-rock.

Having reviewed the conditions for the melting of solid rock, we may now consider the change of density that goes with the change of state. Every rock, as it is heated, expands at a characteristic rate. In diagram B of Figure 90, again referring to a crystal with a definite melting-point, temperature increases from left to right and volume increases from below upward. We note that there is an increasing rate of expansion both above and below the melting-point, and a constant rate of expansion while latent heat is being passed into the crystal. The word "glass" on the diagrams is used as a synonym for liquid.

Experiments show that crystalline rocks melt with a six per cent to ten per cent increase of volume, at the melting-point and at the pressure of one atmosphere. There is a corresponding contraction of rock glass when it crystallizes. These rates of change are nearly the same for rock at depths reaching as much as 100 kilometers.

Finally, it is expedient to get some idea of the viscosity of the natural melts, that is, the rate of flow under a standard shearing stress. That of basalt is of special interest. By experiments in the laboratory K. Kani[1] of Japan has measured the viscosity of molten olivine basalt as it cools from the superheated condition at 1400° C. The results are shown in Table XI, which also gives the figures for an andesitic basalt. The unit of viscosity is that of water.

[1] K. Kani, *Proceedings Imperial Academy of Sciences, Tokyo,* vol. 10, No. 2, 1934, p. 82.

TABLE XI

Temperature	*Viscosity of Olivine Basalt*	*Viscosity of Andesitic Basalt*
1400° C.	137	139
1300	297	259
1250	656	541
1200	3,181	31,168
1150	37,897	79,470

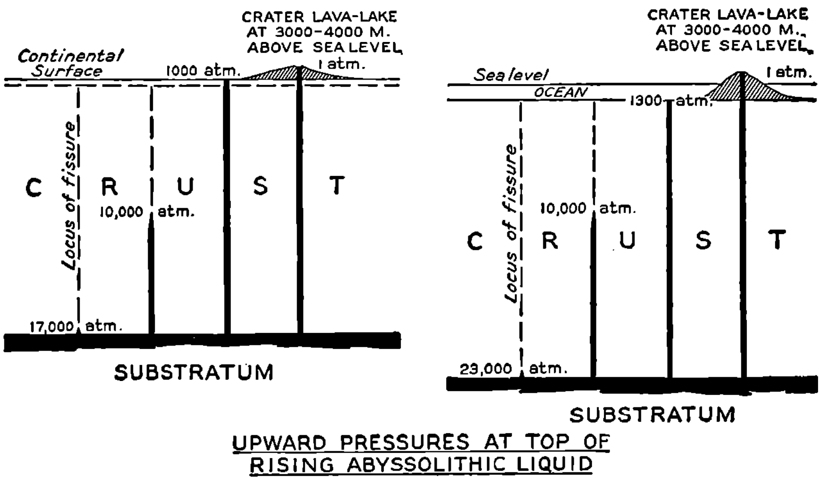
Just below 1150°, a temperature at which as yet relatively few crystals had formed in each melt, the viscosity was too great to permit measurement with Kani's apparatus. It should be noted, too, that he was working with "dry" melts. Dissolved gas lowers the viscosity somewhat, and gas in the form of thickly disseminated bubbles in a lava lowers it still more remarkably. The basalt issuing from the fissures of Hawaii, like that making the wonderful fountains and whirlpools of Halemaumau and Mokuaweoweo craters in the same island, is fluent to a spectacular degree, largely because it is highly vesicular, crowded with bubbles of hot gas.

Basaltic Invasion of the Crust

Our detour among the experimental laboratories brings us back to the main line of thought. The excursion has left us better prepared to discuss the origin of the igneous rocks and their methods of eruption. First let us ask the question: Do the facts concerning volcanic action agree with the expected behavior of a globe constituted after the preferred model?

The general hypothesis implies that the undisturbed crust is too cool to harbor any pocket or sub-layer of permanently molten rock; and that, after the crust approached its present thickness, the high temperature of all eruptive melts was derived chiefly from the heat of the substratum. The substratum is the heat-bringer par excellence. But transfer of heat on the scale represented in actual eruptive bodies requires the upward transfer of some of the substratum basalt itself, and specifically its ascent along more or less vertical fissures through the crust. Thus the first step in volcanic action is fissuring and abyssal injection of the crust, the word "abyssal" here being used in its original Greek sense of "bottomless"; for the liquid basalt occupying each fissure passes down directly into the substratum and initially has no floor of crystalline, solid rock.

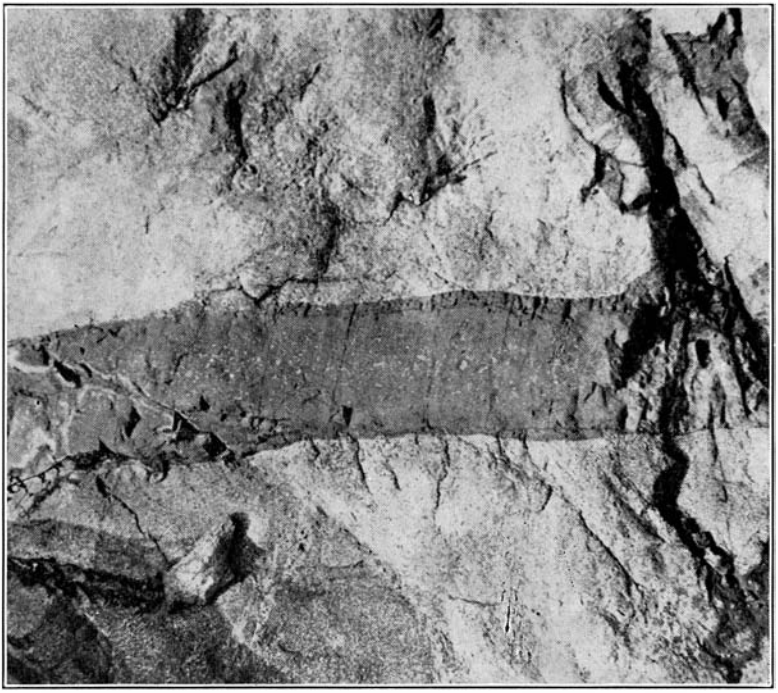
Such a mass of eruptive material, passing up without a break from the substratum itself, may be called an "abyssolith," meaning literally a bottomless body of rock material, initially molten. The idea of abyssolithic injection is illustrated by the cross-sections of Figure 92. On the left the broken line represents a potential crack



92. Diagrammatic sections of the crust of the earth, illustrating abyssoliths (left, continental sector; right, oceanic sector).

in the crust. Next to that line we imagine a similar crack, partly filled with hot, basaltic glass which has risen from the substratum as an intrusive abyssolith. The actual fissures, in Nature, are not so uniformly vertical nor of such uniformity of thickness as those drafted, but the diagrams will illustrate the principle. If the crust continues to exert its full weight at the foot of the glassy melt, regarded as a liquid, the pressure at the top of the liquid is here of the order of 10,000 atmospheres. Still farther to the right are sections of abyssoliths reaching all the way to the surface. As we shall see later, an extruding abyssolith can build volcanic cones projecting several kilometers above sealevel. See Figure 92.

At the earth's surface geologists have mapped multitudes of cracks into which basaltic lava has risen and there solidified. The



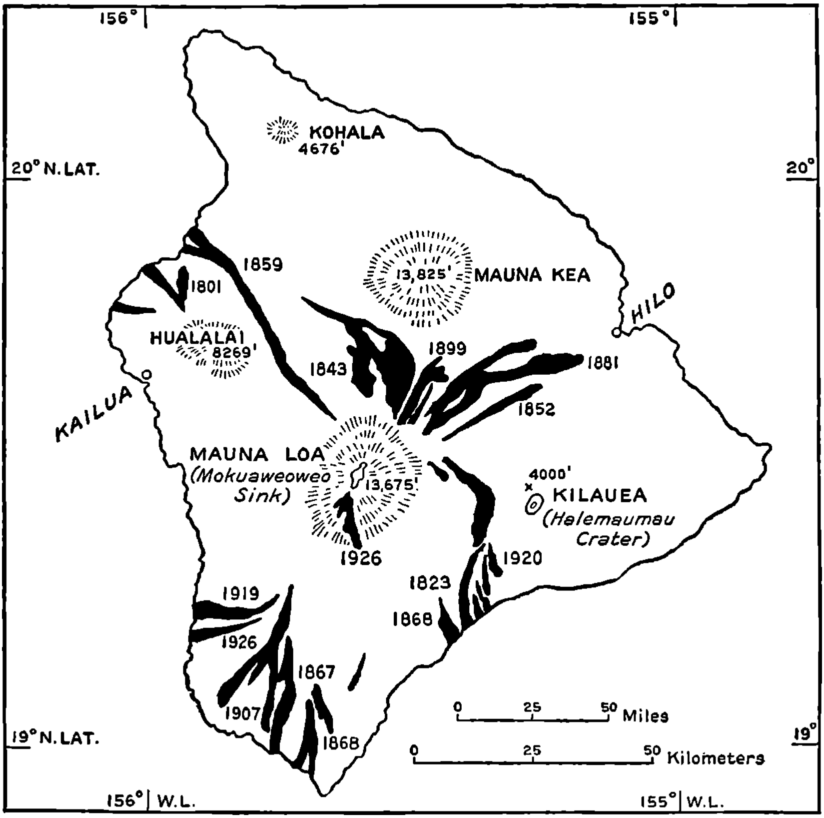
93. Diabase (basaltic) dike at Beach Bluff, Massachusetts.

resulting sheet-like bodies are called (basaltic, diabasic, or gabbroic) dikes. See Figure 94. Were any of these filled fissures truly abyssal, reaching all the way down to the substratum?

If the earth steadily cools and contracts, and if the crust were of uniform thickness and strength as well as uniformly stressed, through-going, abyssal fissures would be impossible. But the crust is now, and apparently always has been, highly heterogeneous, and the forces acting horizontally upon it have, at every epoch of the earth's history, varied greatly in direction and intensity. Under these circumstances local breaking-tensions were inevitable, and may be assumed even when the crust was under general horizontal compression.

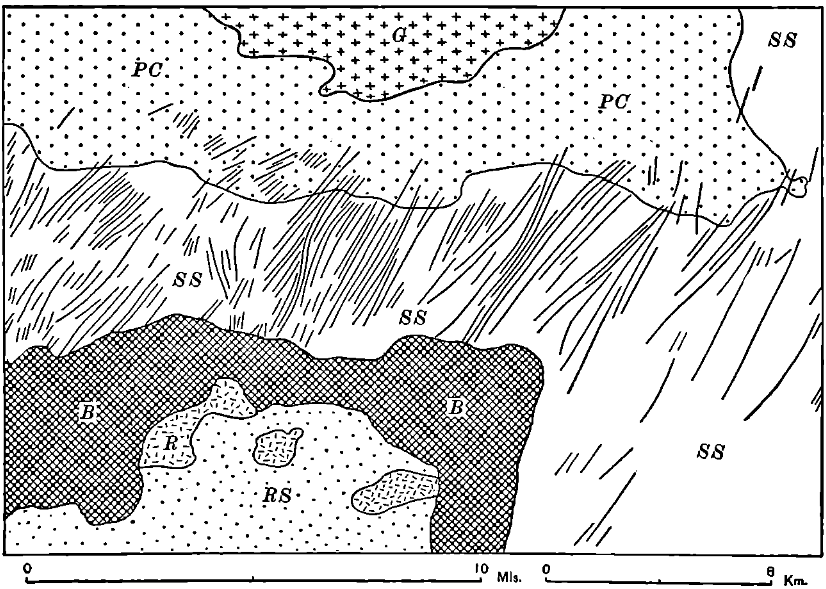
Still clearer is the theoretical case for abyssal fissuring, if segments of the crust were dragged apart horizontally by convection currents or, when tilted out of level, were pulled by gravity so as to slide over the weak substratum. In this connection we should note A. Wegener's startling idea that at certain epochs the continents have slipped their anchors and have migrated over the body of the earth. Wegener thought he had evidence for the horizontal separation of the Old and New Worlds by nearly the full width of the Atlantic Ocean. He concluded that about 200,000,000 years ago there was only one continent; that 150,000,000 years later the Atlantic basin was already of some width, because of the migration of the Old and New Worlds from each other; and that at the beginning of the geologically recent Glacial Period, some million years ago, the Atlantic had reached nearly its present width. Without doubt Wegener exaggerated this relative motion; yet able geologists think there is good reason to postulate some movement of the kind. How extended may have been the migrations of continental blocks is an unsolved problem, but even if none was for more than a few miles, each migration had to be accompanied, on the upstream side of each moving block, by tension and by fracturing clear through the crust.

By our theory of the earth, the tensional cracks should now be filled with substratum basalt, giving dikes like the one that cuts up through older granite at Beach Bluff, Massachusetts (Figure 93). According to the migration idea the British Isles must have been the fame of the flow of 1881 may be noted. It headed straight for Hilo, the chief town of Hawaii, which, however, was not obliterated. The native townsmen transferred their prayers from the Christian God to Pele, the goddess in charge of volcanoes, and sacrificed pigs to her. By a curious coincidence the sacrificing had



95. Map of Hawaii showing location of some recent flows of basalt (black). The dates of the flows are indicated. After map by the National Park Service.

brilliant success and the flow soon came to a full stop outside the suburbs. As such flows, interleaved with the debris of occasional explosions, pile up on each side of the abyssal fissure, they form a cone. See Figure 92. Inside the cone is a pipe filled with the liquid basalt, and the walls of the pipe form on all sides a retaining dam. Because the liquid column is a little lighter than the surrounding solid crust, volume for volume, the liquid rises to the summit crater and overflows. Each overflow freezes and adds to the height of the dam. Evidently there is a limit to the upward growth of the cone. Computation shows that when the liquid of a molten abyssolith, penetrating a continental segment of the crust, rises to a level three to four kilometers above sealevel, the weight of the liquid column balances that of the adjacent crust. Then



96. Dike feeders of fissure eruptions (plateau-basalts) near Mount Stuart, Washington State.

there is no force compelling additional overflow at the summit crater, and the cone has reached maximum possible height.

A limiting height of the same order should characterize a basaltic cone that rises from the floor of the deep ocean, and may be actually represented by the impressive dome of Mauna Loa, Hawaii. Its height, somewhat more than four kilometers, is comparable with that of Etna as measured from the shoreline of continental Sicily. Studies with the gravity pendulum suggest that the crust alongside the lava pipes of both Etna and Mauna Loa presses with full weight on the substratum.

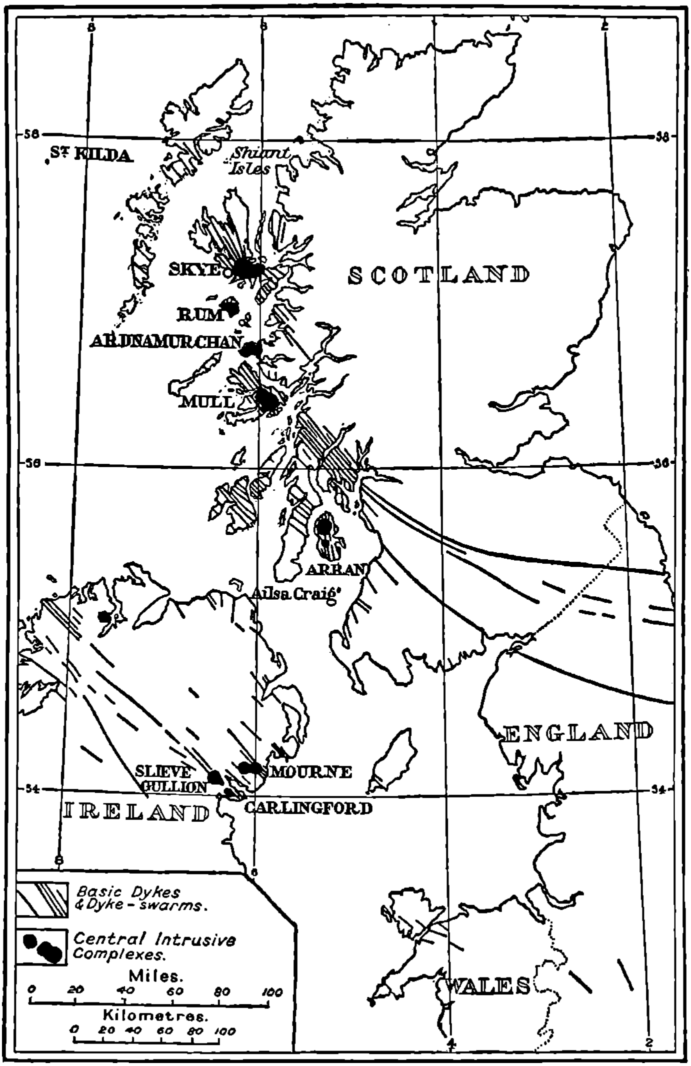
When we consider all the facts of the case, it does not seem extravagant to hold that the crust-substratum hypothesis adequately meets this test of prophecy.

As we learned in the first chapter, plateau-basalts represent volcanoes with linear vents: their lavas emanated through long fissures. On the map of Figure 96 are many black lines, each portraying the eroded top of a basaltic dike or fissure-filling. Through these fissures or their hidden equivalents, flows of plateau-basalt in great total thickness were poured out on the sandstone formation marked "SS." A large remnant of the plateau-basalts exists in the area most heavily shaded on the map and bearing the letter "B." All these eruptions took place so long ago that the edges of the basaltic flows have been eroded back many miles, thus exposing the dikes or feeding fissures shown.

Volcanoes with Cone and Crater

In contrast, Mount Etna, Mauna Loa, and the like are distinguished as volcanoes of the central type, because the lavas of each flowed out in all directions from a center, a point on the map. Each flow completed its upward journey through a narrow pipe. Yet fissure eruption and pipe eruption have often been intimately associated. For examples we go again to northern Britain. The black lines of Figure 97 indicate basaltic dikes, basalt-filled fissures, running in a general northwest-southeast direction. We also note spots of solid black which interrupt those lines of fissuring. Each spot represents an old major volcano of the central type. The association is analogous to that illustrated by Figure 98, the map of a row of cones, little volcanoes of the central type, which were built along an Icelandic fissure, where, in mid-summer of the year 1783, a flood of basaltic lava had gushed out upon the surface.

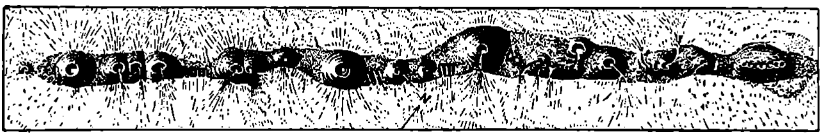
Whereas in the British case, prolonged erosion has laid bare the central pipe and feeding dike-system, the same relation is not easily discerned for the great active volcanoes, which hide the evidence under their own piles of lava and ash. Many examples are found



97. Map showing relation of great, deeply eroded volcanoes of the central type to systems of crust fissures; in Scotland and Ireland.

among the magnificent cones of Java, which smother nearly the whole of the older island terrain. Yet even there the genetic connection of fissure and central vent is strongly suggested by the marked alinement of the Javanese cones. Much the same failure of visual evidence is found among the scores of local vents in central France, but the French geologists believe that there also master fissures have controlled the volcanism in that classic land of geological study. The water of the ocean also prevents access to the deep-seated mechanisms; yet the existence of feeding fissures under the island chains of Hawaii and Samoa is made highly probable by the alinement of the giant cones and domes of each group. See Figures 32 and 33.

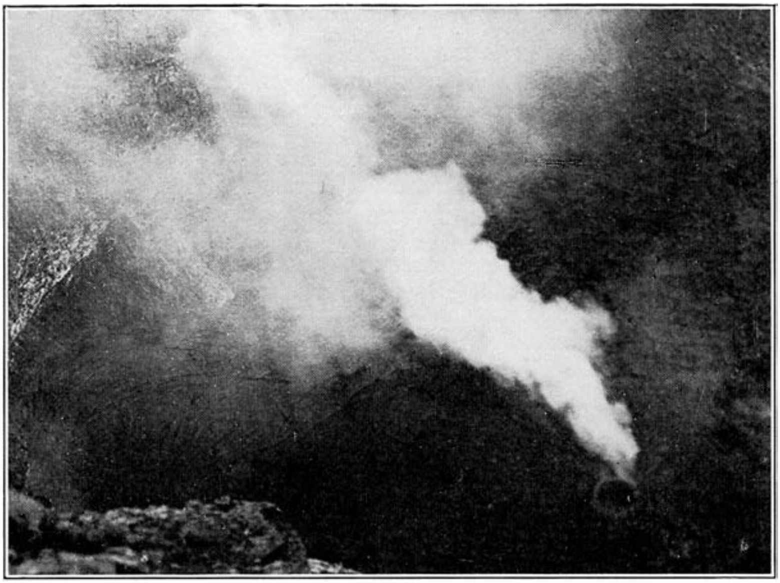
Can we be still bolder and assume that the fissure-filling, which has supplied the lava and heat to each central vent, was initially bottomed in the substratum? In other words, can our earth-model



98. Map of small volcanoes of the central type, originating along a fissure in Iceland. Courtesy of A. Colin Company, Paris.

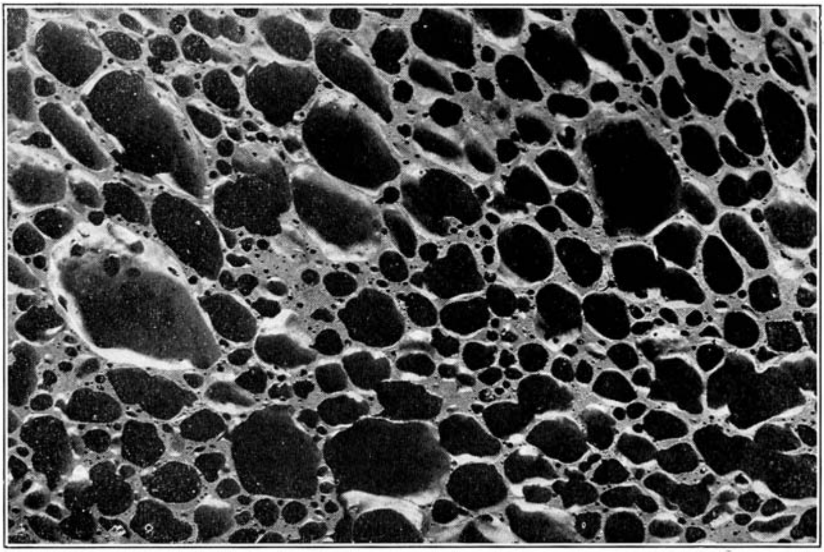
explain volcanoes of the central type as well as the basaltic plateau? The answer to this question is impossible until we solve several mysteries about volcanoes having cone and crater. Why have some volcanoes long lives, others exceedingly short lives? Why are there periods of dormancy? What causes the final extinction of activity?

We attack first the problem embodied in the prolongation of activity at every great basaltic cone. The upbuilding of each of the bulkier cones and domes in Italian land, the British Isles, Hawaii, and Samoa took many thousands of years and in some cases more than a million years. These facts intrigue us when we remember that lava in contact with the upper, cooler part of the earth's crust freezes with comparative speed and so tends to plug, seal up, its own feeding fissure or pipe. Volcanoes of the central type do plug themselves, but only temporarily, as illustrated by Figure 99, a view



99. Looking down into the crater of Halemaumau (Kilauea) when dormant.

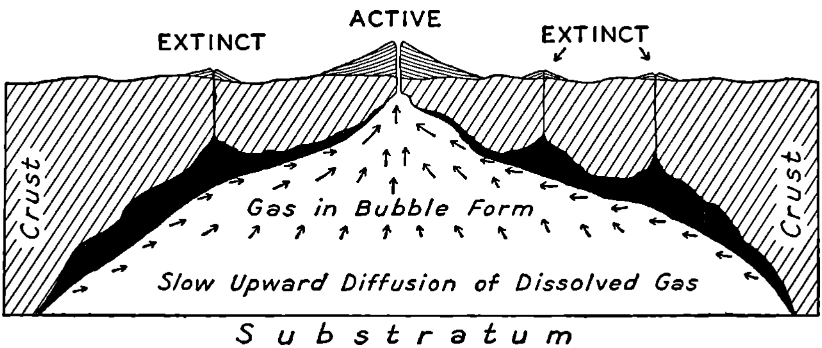
100. Lava fountain in Halemaumau, February, 1918. Photograph by T. A. Jaggar.



101. Surface of a sawed block of vesicular, basaltic lava. Four fifths of natural size.

of Kilauea's crater when almost completely dormant. There the only sign that Pele was sleeping below the frozen lava lake flooring a crater was the lazy cloud of vapor that rose from a hole in the temporarily solidified lake. Yet at each major vent heat is brought up in quantity sufficient to remove the successive plugs, so that final extinction is delayed for scores or hundreds of millennia. How is the heat transferred from depth?

All basaltic liquid carries some dissolved gas. The higher the all-sided pressure on the liquid, the more gas it can hold in homogeneous solution. With sufficient lessening of the pressure the gas separates as bubbles, just as soda water froths when the cork is removed. Lava fountains are caused chiefly by the forceful expan-



102. Longitudinal section of an abyssolith, illustrating the rôle of emanating gas in the lives of central volcanoes.

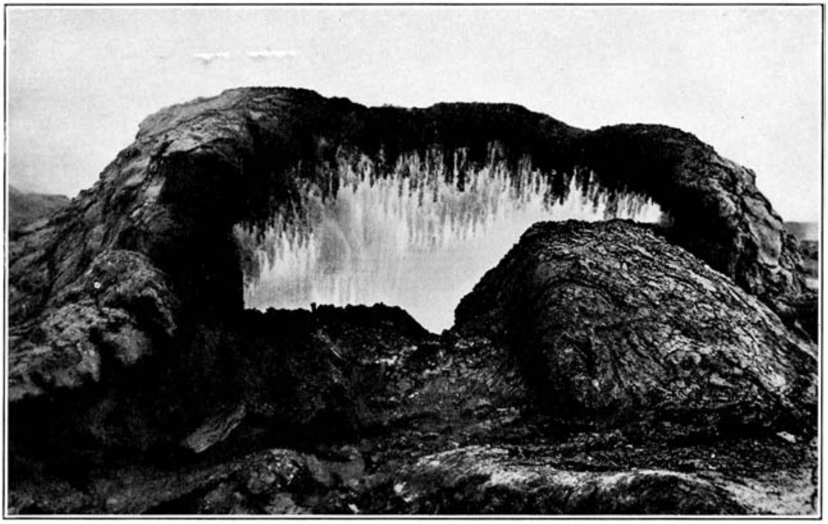
sion of many bubbles as these approach the open air. See Figure 100. It is not known whether vitreous basalt at the depth of 60 to 75 kilometers is saturated with gas, that is, holding all the gas it can hold in solution at the high pressure concerned; but, when basaltic liquid approaches the earth's surface, with diminution of pressure, bubbles do form in the liquid. Hence basaltic flows, more or less like the specimen represented by Figure 101, are markedly vesicular.

There is a second reason why gas comes out of natural rock-melts and forms bubbles. A subterranean body of liquid lava feels the coolness of its walls, where therefore the liquid begins to crystallize, as represented by the area of solid black in Figure 102, a diagrammatic section through a partly frozen abyssolith. As that peripheral sheath slowly crystallizes, little volatile matter goes into the new crystals and the proportion of gas within the residual liquid increases. When the gas has become concentrated enough, the liquid is saturated with it. Any additional gas, ejected from the thickening sheath, can not now be held in solution by the residual liquid, but forms bubbles.

Such bubbles, because of their low density, must rise through the liquid toward one or another re-entrant in the roof of the abyssolith; and any gas, so concentrated at the upper part of the chamber, brings its heat and fluxing power with it. A vivid example was given at a Hawaiian craterlet of 1919, a photograph of which is reproduced in Figure 103. The linear pattern there shown was made by dripping, red-hot, and thoroughly liquid rock which was being fluxed by the outrushing gas. Gas issuing at a crater tends to prevent freezing of the liquid beneath and plugging of the vent, in spite of the exceedingly rapid radiation of heat from the surface of the liquid column.

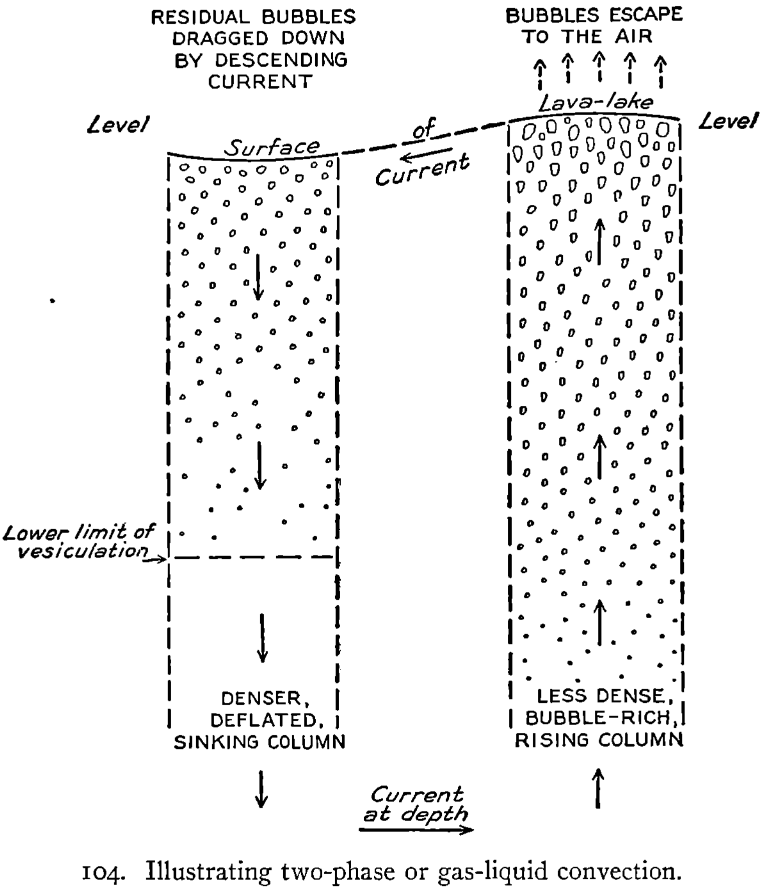
But activity is prolonged in still another way. Vesiculation of the lava column, however caused, can not be uniform at any level. Let us imagine a limited part of the liquid to be specially rich in bubbles. That particular mass, as a whole, has smaller density than the less vesicular liquid on all sides of it, and, as a whole, the more vesicular mass, liquid and gas-bubbles together, shears its way upward. See the right-hand section of Figure 104. With the rise of the emulsion-like mass to levels of smaller pressure, the bubbles expand and buoyancy increases. The speed of rise is correspondingly accelerated. The surface of the lava is locally raised, domed, as shown in the section.

A remarkable example of local differences in the vesiculation is illustrated by Figure 105. This is a view of the crater at Kilauea during a night in September, 1934. The scum-covered, fountaining lake of lava in the crater occupies the foreground. The visible wall of the crater is about 800 feet high. Four hundred feet above the lake level a strongly incandescent, basaltic froth kept pouring out of a long crack and cascading as shown. Since there can be little doubt that this froth rose along the same vent as that feeding the



103. Glowing mouth of a cone built above a rift in the floor of Kilauea, Hawaii. Photograph by T. A. Jaggar.

convectively stirred lake, the photograph seems to represent an extraordinary instance of differential vesiculation in a lava column.



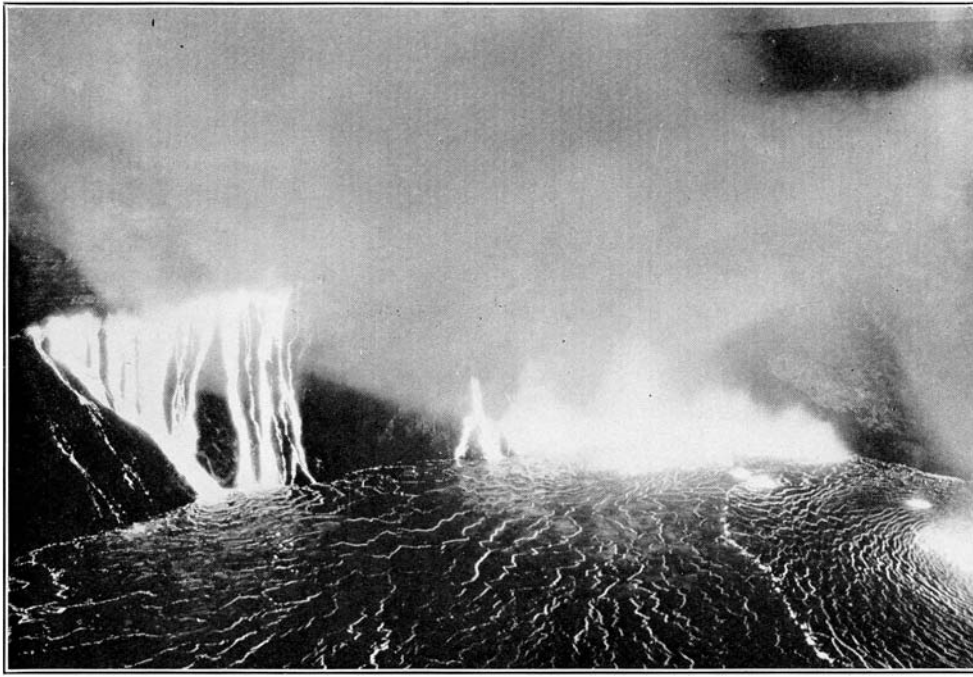
104. Illustrating two-phase or gas-liquid convection.

Arriving at the surface of the fluid column, much of the gas quickly escapes into the air, thus increasing the density of the more vesicular part of the superficial fluid. At the surface this part becomes denser than the fluid beneath and plunges downward. See the left-hand section of Figure 104, where the surface is lower than the surface at the right. We note also arrows indicating the nearly horizontal current enforced by the difference of level. With the sinking the residual bubbles, now fewer and initially smaller than those in the rising sub-column, are rapidly compressed and the sinking is accelerated. Thus the whole column of lava is kept stirred by a kind of convection—what may be called gas-liquid convection or, in technical language, two-phase convection.

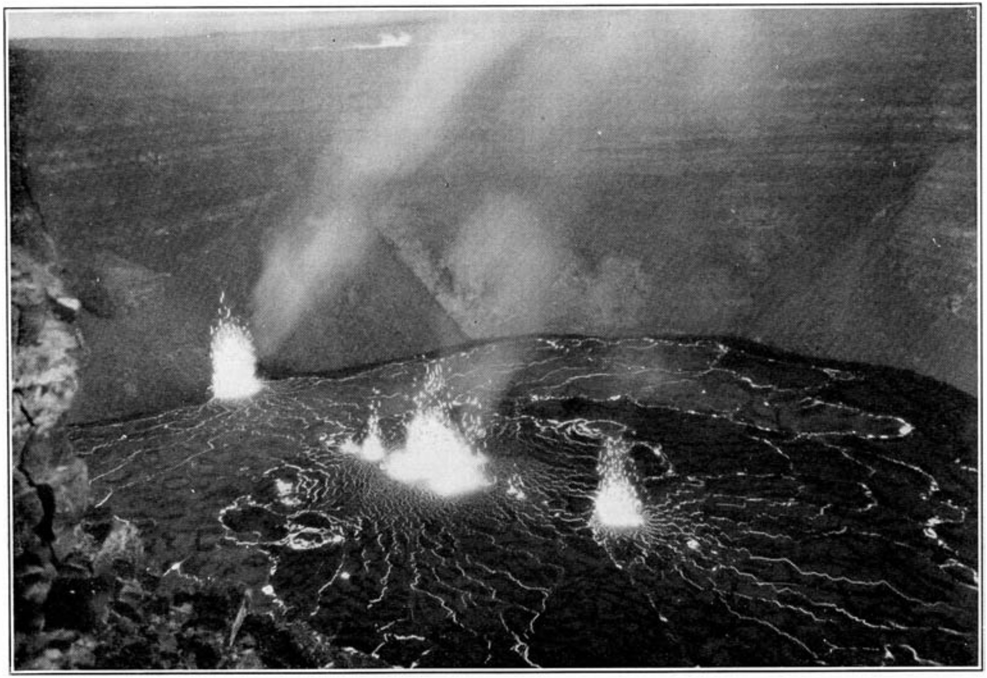
The overturning of the lava should not be at a uniform rate but rhythmical, according to a general law controlling the motion of one viscous fluid against another.

By two-phase convection the heat of liquid and also the heat of gas are carried up from depth to the crater, where the danger of freezing, plugging, and final extinction of the volcanic activity is at maximum. That the process described is actual in Nature is obvious to any one who has had the good fortune to look at Halemaumau, the Kilauean crater of Hawaii, when fully active. Then the supplies of gas and heat are so abundant that the amazingly fluent, foamy lava spreads out, lake-like, above the narrow feeding-pipe (Figure 105). On some occasions the lake at night has looked like a veritable witches' caldron, with its interwoven convection currents and with hundreds of fountains, caused by the sudden uprush and expansion of the more gas-rich, more vesicular, parts of the rising currents. The wonderful fountains, orange to blood-red by daylight and a peculiar gold-orange color at night, have on occasion been seen to reach heights of 300 feet. When the convection is not so lively, the fountains are less widely distributed over the lake, and then much of the lake, chilling rapidly, is coated with a thin scum of opaque, vesicular glass. Through that scum the fountains burst their way, and the carpet is torn to pieces also by the convection currents which drag the floe-like fragments apart. Through the cracks, with ever-changing pattern, the glowing liquid shines at night in unearthly, indescribable beauty. A photograph, such as that of Figure 106, can give but a feeble impression of this moving picture.

Similar lake-like, wave-tossed, and fountaining lava has at times been seen in the craters of the Samoan Matavanu and of Vesuvius. From published accounts it seems that Stromboli, "The Lighthouse of the Mediterranean," is occasionally active in the same way. But the grandest of all fountaining is seen when Mokuaweoweo, the



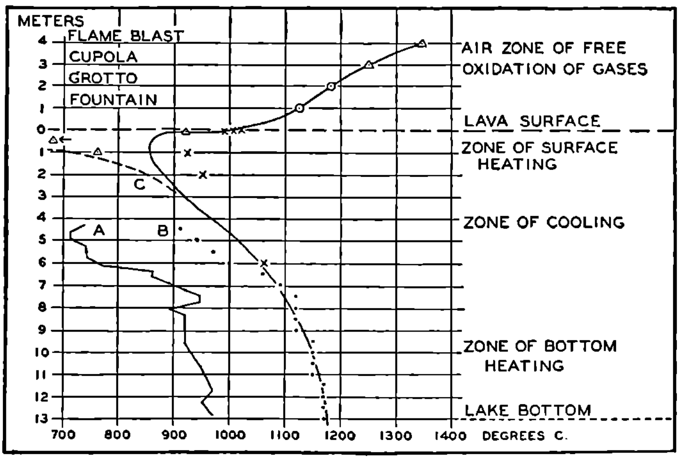
105. Brilliantly incandescent basalt cascading 400 feet down to lava lake of Halemaumau from fissure in the wall of the crater. Lava fountains in mid-ground, at right. Photograph by K. Maehara, taken at 4.30 A.M., September 6, 1934.



106. Lava lake in Halemaumau (Kilauea), showing incandescent lava fountains and cracks in the chilled scum on the lake. Photograph copyrighted by K. Maehara, Hilo, Hawaii.

main crater of Mauna Loa, is in full activity; there fountains 800 feet high have been reported.

There is a third reason why a volcano of the central type may have long life. The rising gas not only transfers heat from the depths but it also produces new heat as it approaches the earth's surface. The observer, standing on the shore of the tumultuous lake of lava at Kilauea, often sees blue flames dancing above the lake to heights of a few feet. Those flames are caused by actual burning of the emanating gas as it makes contact with the air. It is a case of combustion, a true furnace effect. T. A. Jaggar has shown that this burning in air produces specially high temperature at the surface



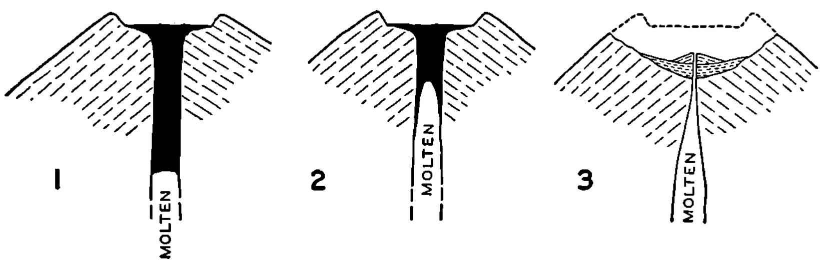
107. Temperatures in and above lava lake at Halemaumau. After T. A. Jaggar.

of the lake.[2] He measured the temperatures down to the bottom of the lake, by thrusting Seger cones into the lava. Figure 107 is a copy of his diagram showing the results. Temperature is indicated in the horizontal dimension; depth below the surface in the vertical. The curved line on the right gives the variation of temperature with depth, and we see that, by the burning of the issuing gas, the air above the lake was made much hotter than the lava itself. We see also that the uppermost two meters of the lake are hotter than they

[2] T. A. Jaggar, *Journal Washington Academy of Sciences,* vol. 7, 1917, p. 397.

would be if the combustion were absent. For in this case the line of temperature would have followed the curve above the letter "C."

The primary gases of a volcano are of many kinds, and the laws of physical chemistry suggest that at depth they are in a quite different state of combination from that which they ultimately reach near the crater, where pressure and temperature are smaller. It further appears that, when the gaseous elements change partners at the higher levels, much new heat is there generated. A complicated kind of combustion takes place among the primary gases. Hence there is furnace action within the lava column itself, quite independently of that due to the burning of the gases in air, whether this air be free, above the lake, or sucked down with the plunging convection currents.

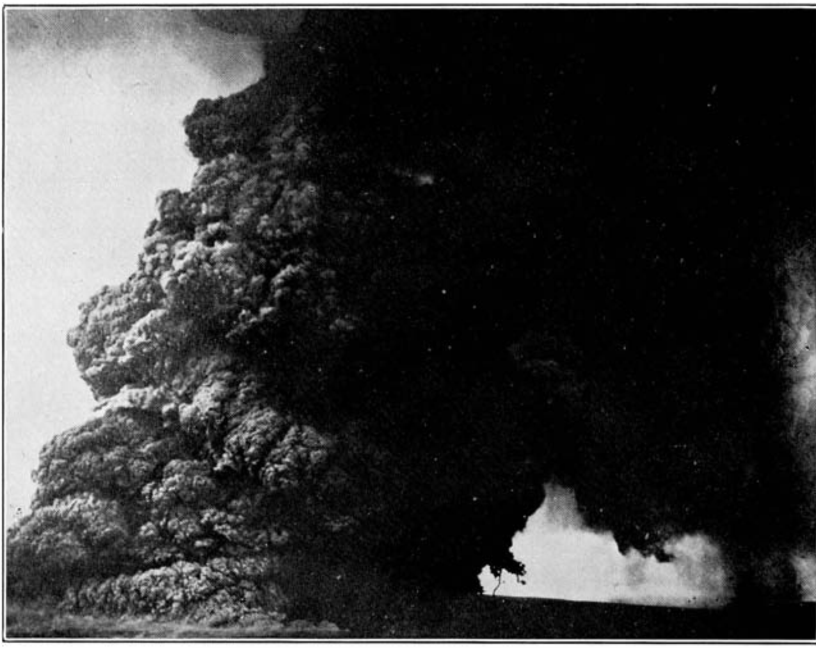


108. Diagrams showing gas-fluxing of, and ultimate explosive destruction of, lava plug (black) in a central vent.

Study by A. L. Day and E. S. Shepherd of the Geophysical Laboratory of Washington has proved that this third source of heat at the crater, the place of danger to the volcano's life, is highly important.[3]

In summary, the plugging of the volcanic vent by radiation at the crater is delayed for three reasons: first, by upward transfer of primary heat from the depths by a host of bubbles, each moving independently through the liquid and bringing heat with them; second, by the upward transfer of heat through gas-liquid or two-phase convection; and, third, by chemical reactions among the different kinds of gas present in the emulsion-like fluid. Since the volatile matter is essential in all three methods of carrying heat

[3] A. L. Day and E. S. Shepherd, *Bulletin Geological Society of America*, vol. 24, 1913, p. 573.



109. Explosion at Kilauea in May, 1924. Photograph copyrighted by K. Maehara.

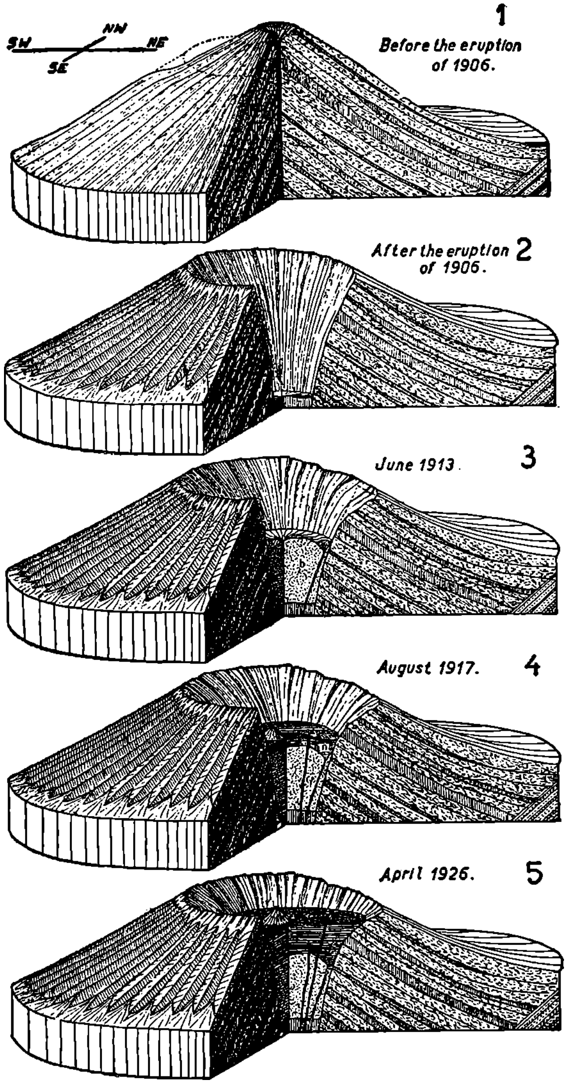
up to the crater, this explanation of prolonged activity for volcanoes of the central type is called the "gas-fluxing hypothesis."

We pass now to the second characteristic of every great volcano, its periodicity, its intermittent activity. For a period of months, years, or centuries the eruptive machine is in leash, and then for a time resumes the work of changing the face of the earth. Why should this be so? Can our earth-model account for dormancy as well as activity? If an essential condition for an open, active vent is gas-fluxing, it is logical to suspect that dormancy is caused by temporary lull in the rise of gas through the lava column.

Now the development of free gas, as bubbles in the depths of the column, is the result of diffusion, progressive crystallization, and reaction of the liquid with the wall rocks of the feeding abyssolith. All three processes are slow. It takes time for the generation of the many bubbles needed for a lively transfer of heat to the upper part of the lava column. And we have already seen that viscosity alone induces rhythm in the rise of the gas-rich lava and correlative sinking of that adjacent lava from which gas has escaped at the top of the column. Under the circumstances it is to be expected that at times the enormously rapid loss of heat at the crater should permit solidification, plugging, to some depth. This theoretical deduction seems to explain satisfactorily the temporary plugging and therefore dormancy of the volcanic vent.

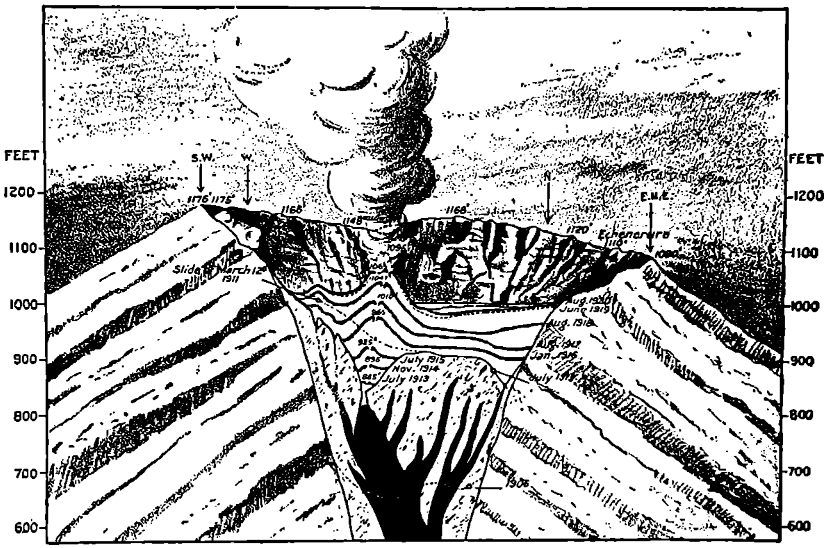
However, gas continues to rise slowly from the still deeper part of the abyssolith and collects under the new plug. There the hot gas begins to flux the base of the plug. In this way the material of the plug may become completely liquefied, and the volcano resumes quiet, normal activity, as at Kilauea and Mauna Loa. Or the plug, though still partly intact in spite of gas-fluxing at its base, becomes too weak to withstand the gas pressure. The plug is then destroyed by a major explosion, and for a time the volcano is again active (Figure 108).

This has happened only once in the last 148 years of the history of the Kilauean vent. In 1924 a plug at its top, the material of a temporarily frozen lava lake, and also much accumulated debris, that had fallen from the walls during a few years before 1924, were all blown high into the air. The photograph, Figure 109, shows the rain of fragments from the resulting cloud. The scale of operations may be gaged from the width of the cloud at its base, where the cloud fills the crater to the brim. This width was 1500 feet.



110. Stages in the recent history of the Vesuvian cone. After B. G. Escher.

The ending of dormancy by powerful explosions is usual for such volcanoes as Vesuvius. Before the year 1906 Vesuvius had a narrow pipe and a small crater, as shown by the uppermost diagram of Figure 110. In that year, following a time of relative calm, a tremendous explosion tore off the top of the cone, leaving a broad, deep crater, pictured as stage 2. Since then the lava has risen in the pipe and has built up a new, composite plug which, twenty years after the catastrophe, had reached the dimensions illustrated in the lowermost diagram. During the interval the plug was leaky and a



111. Progressive filling of Vesuvian crater from 1906 to 1920. After F. A. Perret and A. Malladra.

succession of conelets grew up on the main floor of the new crater. To represent the process acting between 1906 and 1920, F. A. Perret[4] drew the section-stereogram of Figure 111. At present Vesuvius is but mildly active, with a panache of gas-cloud which glows moderately at night.

Periodic action of the kind described accounts for the bedded

[4] F. A. Perret, "The Vesuvius Eruption of 1906," *Publication 339 of the Carnegie Institution of Washington,* 1924, p. 100.

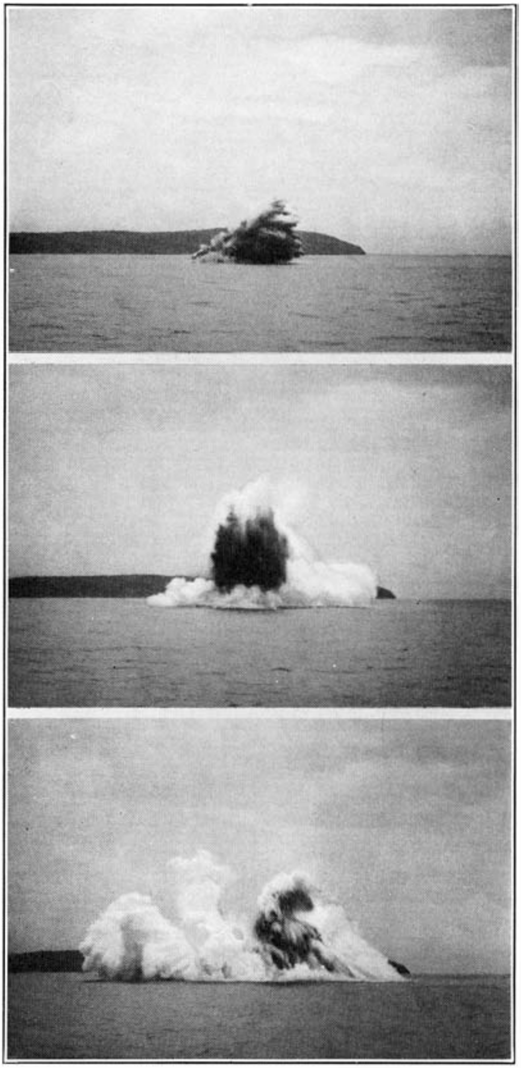
structure, the piling of ash-bed on ash-bed, flow on flow, as exemplified in the Island of Saint Helena (Figure 36).

In order to avoid misapprehension, it may be well to point out that volcanic explosion is not necessarily due to the tension of primary gas, that is, the gas originally contained in the abyssolithic liquid. The question here involved leaps to the mind when the facts about Krakatoa are considered. In the year 1883 this island blew up, the noise of this frightful disaster being heard in Rodriguez Island, 3000 miles away. The huge Krakatoa cone, including the visible island, was eviscerated over an area of sixteen square miles. The resulting hole reaches several thousands of feet below sealevel. It seems probable that a large part of the explosive energy was supplied by superheated sea-water which had been sealed in the ash-beds and porous flows of the cone as it was being built up from the deeply submerged floor of the ocean. Through centuries the heat of the central, lava-hot pipe was slowly conducted into the wet beds at depth. It is easy to assume that much of the trapped, non-volcanic water became superheated steam, the tension of which helped to tear the cone to pieces and fling rock fragments as much as twenty miles into the air.

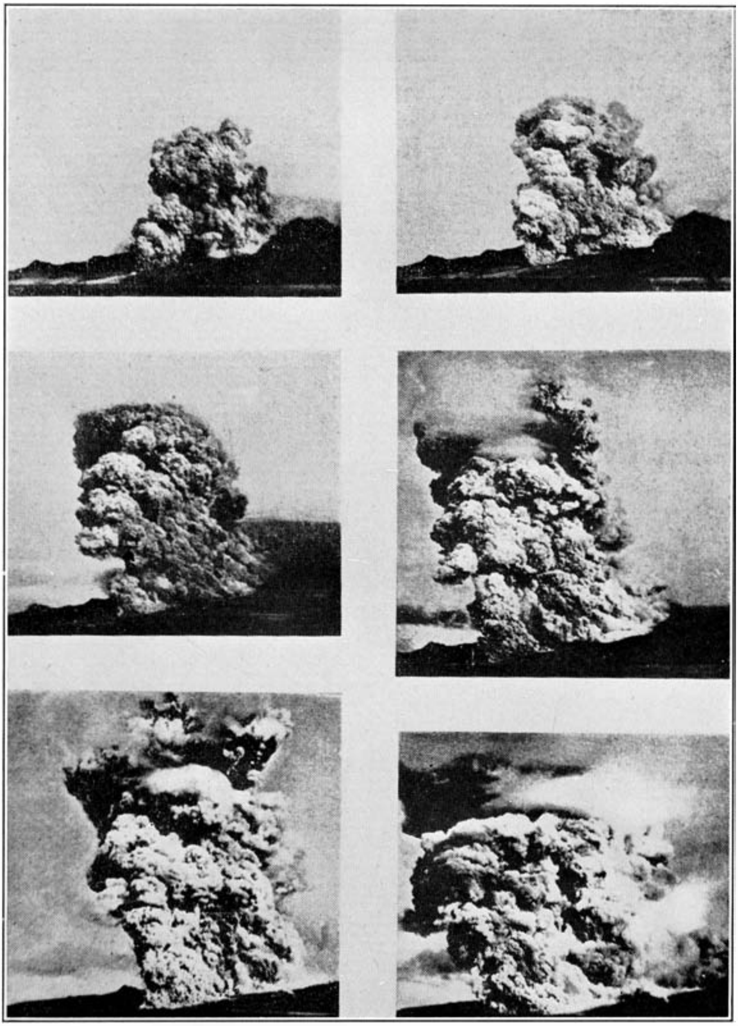
Incidentally Vulcan is still busy under the site of the former Krakatoa. In 1928 eruptions were resumed at the deep hole left by the explosion of 1883.[5] Figure 112 pictures three successive stages in the energetic rise of molten lava through the ocean water and on up into the air. The photographs were taken from the same spot. The dark fountain-like column is fragmented, incandescent lava which the Pacific Ocean could not hold down. The red-hot material fell back and boiled the sea. The white part of each cloud is the resulting steam. As yet no permanent island of debris has been formed, but we can see that repetition of even this moderate activity could build the submarine cone to notable height.

Another exceptional and particularly dangerous kind of explosion is typified by those of La Montagne Pelée, Martinique, during the year 1902 and again in 1929-1930. There the lava-gas was concentrated within the interstices of a plug which was being pushed up bodily above the lip of the crater (Figure 122). The side of the

[5] J. H. F. Umbgrove, *Leidsche Geologische Mededeelingen,* Deel II, 1928, p. 325.



112. Progress of a submarine eruption at Krakatoa in 1928. After J. H. F. Umbgrove.



113. Progress of a "nuée ardente" down the flank of La Montagne Pelée. After A. Lacroix.

plug again and again exploded, sending out, more or less horizontally, a mixture of rock fragments and exceedingly hot gas. The fragments and gas together formed a kind of emulsion with a net density much greater than the density of the air. Hence the emulsion, continuing to explode as it fell, rushed down the mountain slope and killed 30,000 persons in the town of Saint Pierre. These terrible downflows bear the French name "nuées ardentes," which may be translated "cloud-avalanches" or "exploding avalanches." The series of photographs in Figure 113 shows six stages by which one of these horrors traveled down the mountain side. The series should be taken in the order from left to right, the pairs of stages following one another in the order from top to bottom.

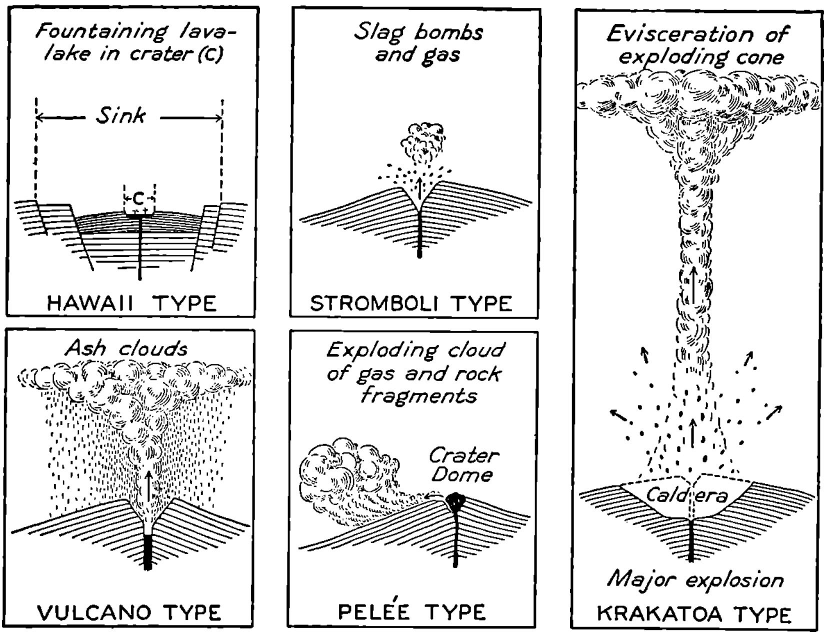
Figure 114, modified from one by B. G. Escher,[6] illustrates five types of gas emanation at central vents and also four kinds of topography there developed.

Quiet emanation has characterized the two active Hawaiian vents through most of their history. In each case the feeding pipe is run up through thousands of feet of old flows, among which some ash-beds are interleaved. From each pipe, heat was conducted into the layered rocks adjacent, and these became plastic. The upper part of the thick, composite cylinder of liquid and solid-plastic rock was for a time supported by the pressure of liquid lava at still greater depth. This pressure was lowered whenever the island cracked open and permitted the liquid of the pipe to flow out on the flanks of the island, whether under the air or under the sea. With the consequent withdrawal of support, the heated plastic rock surrounding the pipe subsided. This appears to have been one of the chief causes for the two great sinks at Kilauea and Mokuaweoweo. Cliffs reaching 600 or more feet in height now look down on the elliptical, sunken areas. Figure 115 is a copy of a photograph of Mokuaweoweo, taken by the Air Fleet service of the United States Navy. The floor of this summit sink of Mauna Loa is 13,000 feet above sea. In the distance we see the hot gas rising in its accustomed gentle manner.

Genetically quite contrasted with the volcanic sink, typified by

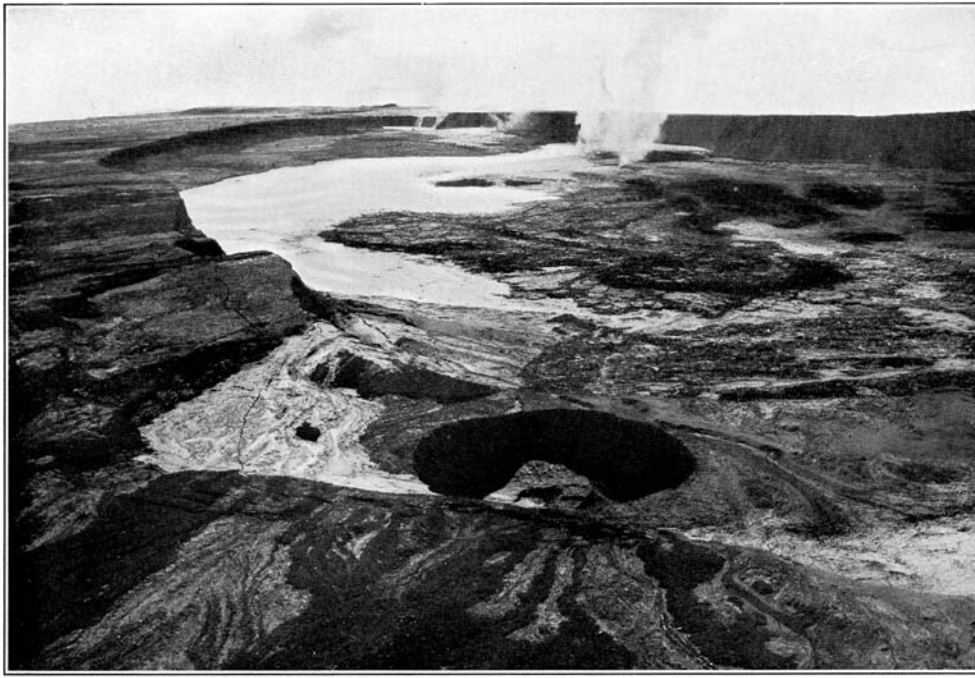
[6] B. G. Escher, *Leidsche Geologische Mededeelingen,* Deel VI, 1933, p. 45.

Kilauea, is the caldera, represented by the huge pit due to the 1883 explosion at Krakatoa. Topographically sink and caldera look much alike; in origin they are essentially different things. The gorgeously colored Crater Lake of Oregon occupies a basin which is 4000 feet deep and six miles in diameter. It is classed by some geologists as a sink; by others as a caldera. Probably it shares the nature of each of these physiographic types. A similar compound origin has



114. Types of volcanic emanation of gas and resulting kinds of topography.

been suggested for some great structural basins surrounding central vents in the East Indies. T. A. Jaggar has clearly shown that the actual crater, Halemaumau, which is nested inside the cliffs of the Kilauean sink, has doubled its diameter, its gaping mouth, since 1923, not merely because of the powerful explosions of 1924 but to a much greater degree because of subsidence of the floor of Halemaumau. It is also possible that the Krakatoan caldera was further deepened by subsidence of its floor.

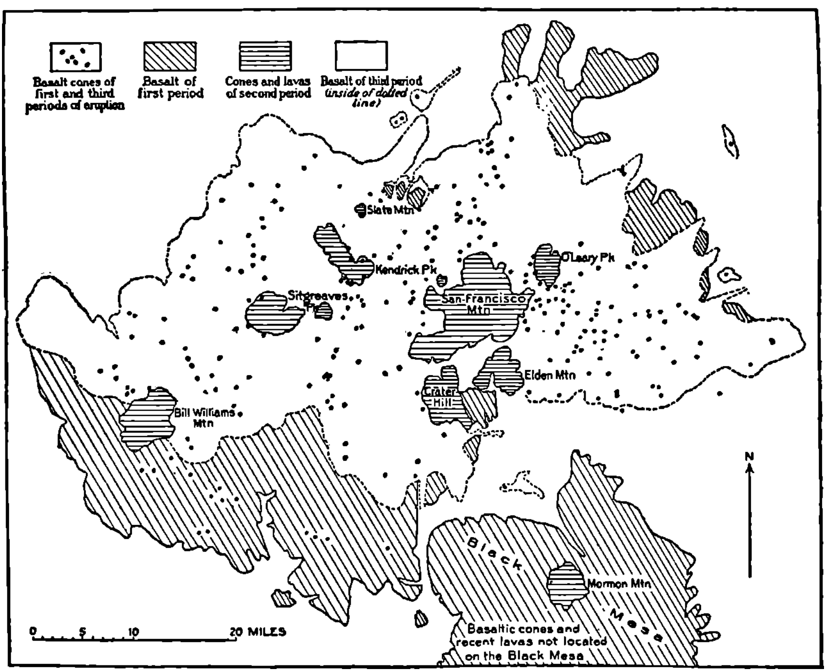


115. Looking south-southwest over the Mokuaweoweo sink from an airplane at about 15,000 feet above sea. Courtesy of Fleet Air Base, Pearl Harbor, Territory of Hawaii.

The periodic emission of lava, gas, and the associated heat at a central vent for hundreds of thousands of years implies a large feeding chamber within the earth's crust. We have visualized such a chamber as an abyssolith, at least 60 kilometers high and of considerable length and thickness. Whatever its volume, this great body of basaltic liquid must ultimately solidify, and by then its supply of fluxing gas has run out. Thus even an Etna or Mauna Loa will ultimately follow the universal rule for central volcanoes and become extinct.

Subordinate Volcanoes of the Central Type

But there are many vents of the central type with some characteristics unlike those of the huge cones we have been discussing. First, those other volcanoes are not alined, as if they were fed directly



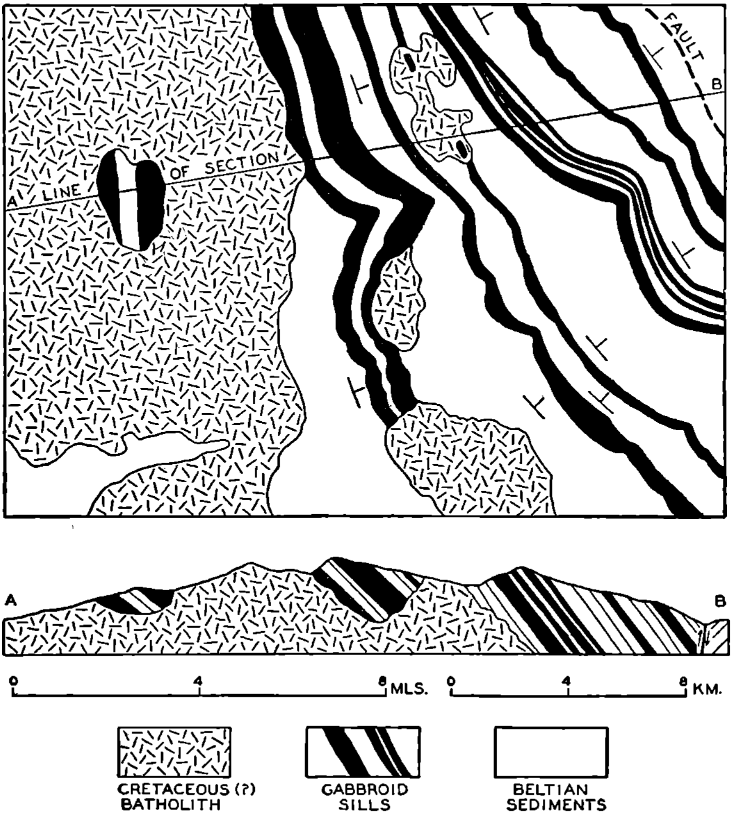
116. Two hundred volcanic vents of the San Francisco mountain region, Arizona. After H. H. Robinson.

from abyssal fissures. They are dotted about irregularly in groups, somewhat like the holes in a colander. Second, they had exceedingly short lives, and in some instances the eruptions were merely gaseous, with no outflow or explosion of liquid lava. The dots on the map of Figure 116, depicting part of Arizona, represent more than 200 such vents.

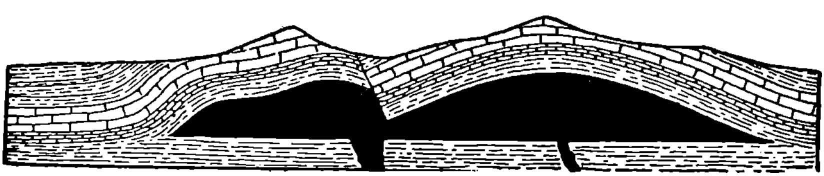
The relative feebleness of action suggests that these little volcanoes have been fed, not directly from abyssoliths, but from much less voluminous chambers of liquid wholly contained within the earth's crust, that is, chambers floored as well as walled and roofed by solid, comparatively cool rock. Thousands of floored injections of once-molten rock, exposed by erosion of their roofs, have been mapped. Many of them are of basaltic composition, and their emplacement high in the crust can be readily understood in the light of our general theory.

Look once more at Figure 92. If the crust exerts its full weight at the bottom of a liquid abyssolith in a continental sector, the pressure there is 17,000 atmospheres. In an oceanic sector the corresponding pressure is roughly estimated as 23,000 atmospheres. As the liquid rising along an abyssal fissure approaches the surface, it puts a pressure of more than 1000 atmospheres on the inclosing rock. This unbalanced pressure threatens the integrity of the crust. Sedimentary and other bedded formations are comparatively easy to split along their planes of bedding. If the abyssolithic liquid, under the unbalanced pressure, begins to force its way between two flat-lying beds, the splitting tends to continue, so that the injected liquid forms a sheet or pod. The resulting sheets are called sills. Idaho has magnificent examples (Figure 117). Many of the injected pods are known as laccoliths. Figure 118 shows a cross-section of two confluent Montana laccoliths, which characteristically domed the invaded sedimentary rocks. There are still other classes of floored eruptive bodies, but their description is not now necessary.

The essential point about all these intra-crustal masses of lava is that they were separated from their abyssolithic parents by the freezing of the connecting channels. Each of the new, floored bodies was hot and charged with gas, and was therefore capable of gas-fluxing here and there in its own roof, but the available energy

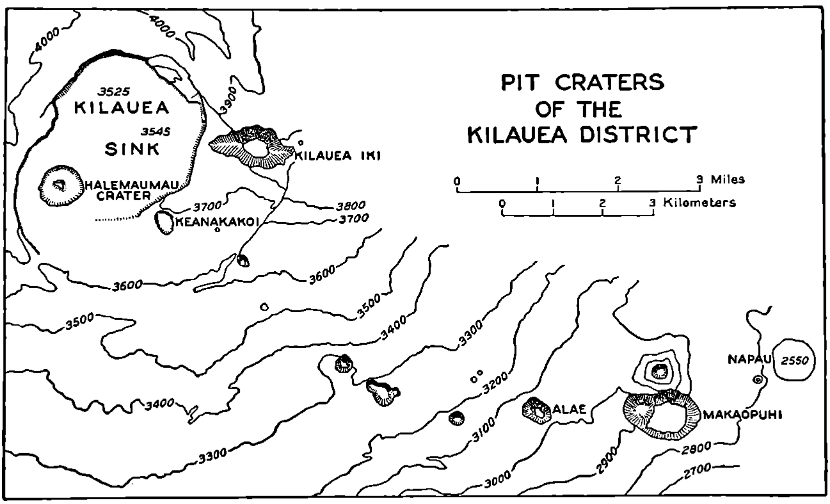


117. Map and section of layered, Beltian sediments, intruded by sills of gabbro and later by a large mass of granitic liquid, now rock. After V. R. D. Kirkham and E. W. Ellis.



118. Section of confluent laccoliths (black) of Montana.

was necessarily small and none of these vents could have long life. In general, too, they should not be alined. The re-entrants in each roof were irregularly, one might say accidentally, placed. Gas rose into those initial embayments. When there sufficiently segregated, the gas became able to flux or explode its way to the surface, opening a small crater through which gas alone or lava with gas was emitted. However, because each vent had a strictly localized supply of gas, it was soon plugged tight, with extinction of all activity. In general we should expect longest activity at the vent situated above the highest embayment in the roof of the isolated



119. Map of the pit-craters of the Kilauean region, Hawaii.

chamber. These deductions from theory seem to match well with two main facts about the Kilauean problem.

The first fact is the large number of small, clearly gas-fluxed, and apparently extinct craters—the so-called pit-craters—adjacent to the active Kilauean vent (Figure 119). The map shows the relative positions. We note the great sink, the active crater of Halemaumau; the extinct, smaller pits; and the nearly extinct pits called Kilauea Iki and Makaopuhi. These features can be accounted for, if we assume all the vents in the mapped area to have been fed with hot gas from an intra-crustal chamber of the laccolithic type. The pits outside the sink have become almost wholly extinct, because their gas-supplying re-entrants in the roof of the laccolith were closed by freezing, while the main re-entrant, presumably the highest one, still succeeds, at Kilauea itself, in attracting the gas as it streams up from the floored chamber of underground lava.

The second fact to be noted is particularly relevant to our main job of testing the crust-substratum hypothesis. We have seen reason to assume that the Mauna Loa crater, about 20 miles from the Kilauean vent, is kept active by the gas rising directly from an abyssolithic chamber. If the Kilauea vent, Halemaumau, is fed from a liquid-filled chamber which was opened centuries ago in the depths of the enormous, composite mass we know as Hawaii, a chamber completely cut off from the main abyssolith, the two vents should be quite independent in their activity. That the liquids of their respective pipes do not communicate hydrostatically is clear; for, when the two volcanoes are simultaneously active, the lava of the Mauna Loa crater does not drain out at the crater of Kilauea, about 9000 feet lower. See Figure 95.

The foregoing explanation of the independence of the two famous vents is in line with another apparent fact about Kilauea. From its history, recorded for the last century and a half, it seems probable that this vent is threatened with early extinction—perhaps at the end of another century or so. Here on the average the activity has greatly diminished since 1840, as if Kilauea is fed from a limited, laccolithic chamber.

Lavas of Non-basaltic Composition

Of the host of questions about the true nature of volcanic action only one more will be mentioned. Many lavas extruded at the earth's surface and many others intruded into the crust differ from basalt in chemical and mineralogical composition. Is our earth-model to be reconciled with this outstanding fact? The answer seems to be "yes." This opinion is based upon considerations which will be more fully set forth in the next chapter, but a brief statement is appropriate while we are concerned with volcanoes of the central type.

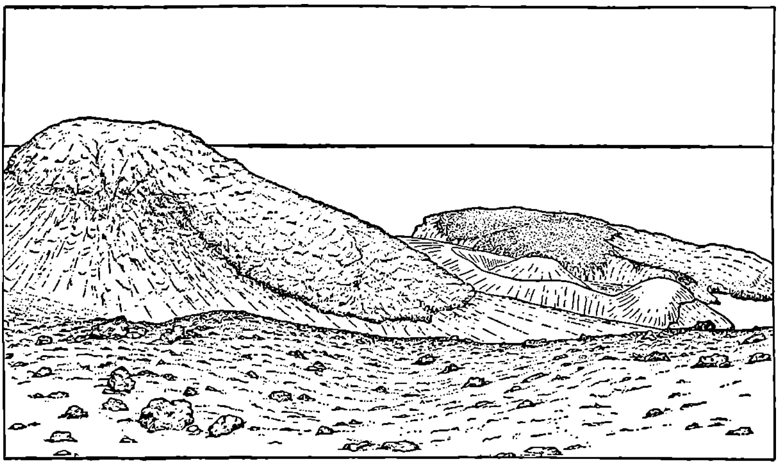
Laboratory experiments and field observations show that, so long as liquid basalt keeps above a certain temperature and is prevented from dissolving foreign material, the melt remains basaltic and practically homogeneous. However, with some lowering from that minimum temperature crystals begin to grow at separate points within the mass. Such early crystals are denser than the remaining liquid and sink in it. The mineral olivine is an example. The remaining liquid becomes chemically more and more unlike basalt, and is located near the top of the lava column, where it is subject to occasional extrusions at the earth's surface. Hence non-basaltic flows and ash-beds are built into the growing volcanic cone, as the volcano ages and the feeding pipe and chamber slowly cool. A whole series of chemically different lavas thus originate. One kind, specially contrasted with basalt both in appearance and mineralogical constitution, bears the name trachyte.

And there is another reason why volcanic pipes harbor non-basaltic melts. The primary basalt can and does dissolve the wall rocks of an abyssolith, either directly or by chemical reaction, that is, by interchange of elements. Some abundant lavas belonging to a group called andesite (named from the Andes Mountains where these species make up large volumes) seem best regarded as products of such contamination of primary basalt, though the gravitational separation of early crystals may coöperate or even dominate in the development of some of the andesitic lavas.

Because of their relatively low temperature when formed, and also because of their chemical character, trachytic and andesitic liquids are more viscous than thoroughly molten basalt. The viscosity is much increased when those derived liquids begin to freeze, as they are bound to do at the cool, high level where they accumulate. If the highly viscous trachyte or andesite, collected in the volcanic pipe, is driven up by renewal of the ascensive force, short, stubby flows issue from the crater, or else the crater becomes filled with a massive, dome-shaped body of ultimately congealed trachyte or andesite. The theory is again well supported by fact.

Figure 120 shows three recently erupted trachytic domes occupying older, basaltic craters in Ascension Island. A somewhat older and hence more eroded dome of trachyte looks down on the harbor of Pago Pago, Samoa (Figure 121).

In some cases the ascensive force has been so great that the monolithic crater-filling has been pushed up so as to become a gigantic, blunt needle, like the celebrated spine of La Montagne Pelée, Martinique. At the stage shown in Figure 122 the height of the spine was 840 feet, while at another time the height was 1500 feet. The rock of this upthrusted dome was too hot, and therefore too weak, to stand up permanently. It broke off in thousands of flakes which crashed down. When the spalling was finished, the spine resumed the shape of a rough, inconspicuous dome, but now surrounded with a thick ring made of the debris of collapse. During the months of its life the Pelée spine was one of the most awe-inspiring sights that any geologist has ever witnessed.



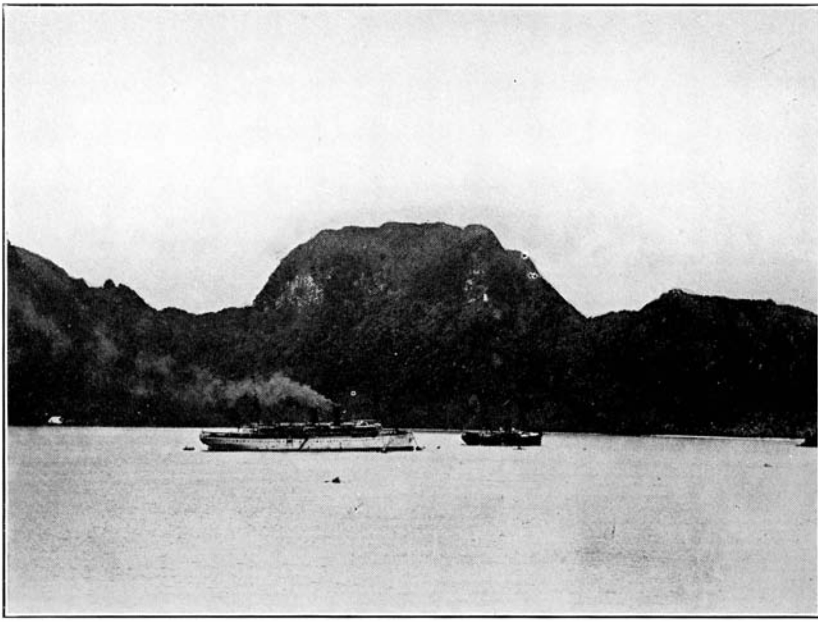
120. Trachytic domes, risen in basaltic craters, Ascension Island. The dome on the left formed a short, stubby flow. In the background are two other trachytic domes; the more distant one mantled with a thin, younger flow of lava, and the other (right, mid-ground) capped with a "wig" of dark basalt.

Summary

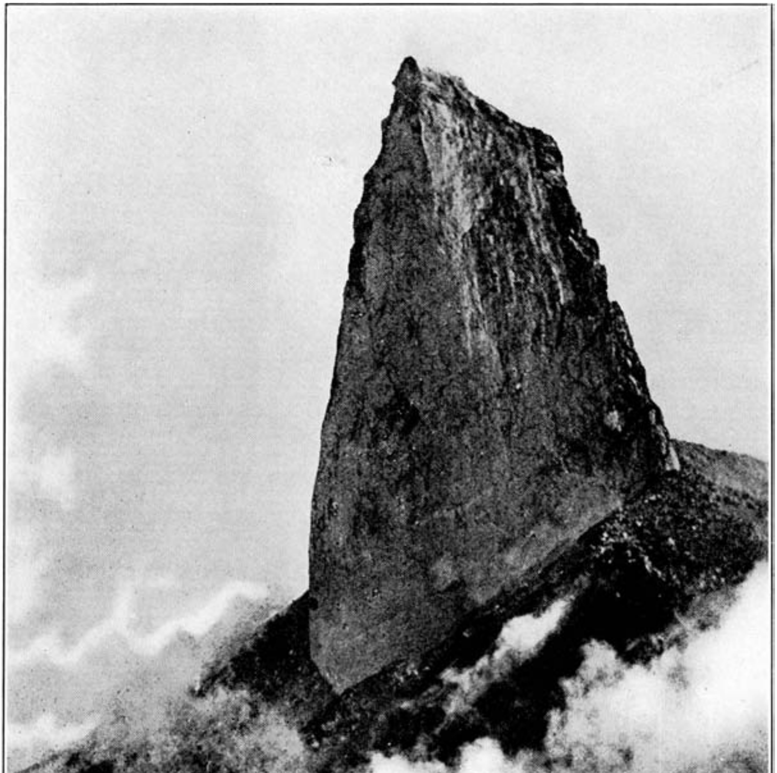
This chapter has begun a complex inquiry. The composition of the earth's crust has undergone, and is undergoing, countless changes through the eruption of molten rocks, some of which have reached the surface as extrusive masses. After their solidification they have become new component parts of the crust. Many other new components are represented by once-molten material which has been thrust into intra-crustal spaces, making up the intrusive masses. In this second case old crust-rock was displaced or replaced by temporarily molten rock that rose from the depths. The cause of this rising has been the main theme of the present chapter, and we have paid most attention to extrusion, volcanic action in the ordinary meaning of that expression. The aim has been not to present an exhaustive account of the protean changes by volcanic outbursts, but to see in a general way how the outdoor observations among the volcanic fields consort with our mental model of the earth.

In making the comparison we have specialized on basaltic eruption; the results are apparently satisfactory. The actual material and also the abundant heat of basaltic eruptions, whether of the plateau type or the central type, seem well accounted for. The density relations of the imagined crust and substratum supply a reason for the ascent of basaltic lava, even for its climbing far above sealevel.

But there are thousands of other volcanic masses which are not of basaltic composition, either in the chemical sense or with regard to the crystals developed in them. Can our earth-model take care of this principal truth also? Although a word or two of suggestion on the problem has been said, this specially drastic testing of the earth-model will be the theme of the next chapter.



121. Trachytic dome, risen through basaltic lavas, overlooking Pago Pago Harbor, Tutuila, Samoa.



122. Spine of La Montagne Pelée, Martinique.

CHAPTER V

INVASION OF THE MOUNTAIN ROOTS

"Pluto, Lord of the Depths."

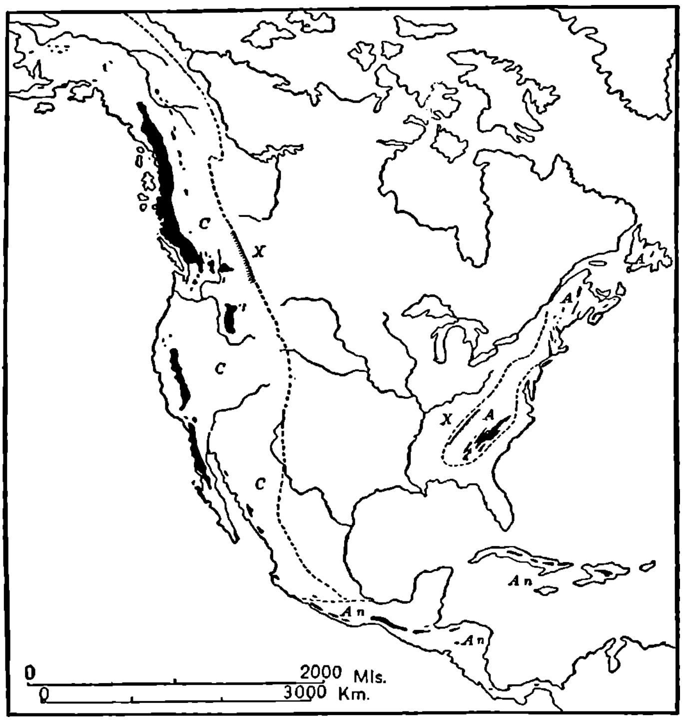
Introduction

OUR imaginative muscle has been stretched with the effort to relate a general theory of the earth with the varied phenomena of basaltic eruption. The strain becomes worse when we attack the problem of the other kinds of eruptive material. By far the largest part of the rock that has solidified from the molten state and is exposed at the surface of the globe is not basaltic, and comprises hundreds of different chemical species. Explanation of these facts is a complicated, technical matter. Here we shall focus thought chiefly on one class of the non-basaltic eruptives, namely those which have risen from the depths and invaded the roots of mountain chains. Bearing the name "batholiths" (literally "rocks of the depths"), they are the largest of all intrusive masses. How did they get where they are? How did they attain their chemical composition? Apparently satisfactory answers to both questions are to be found as we pass them on to our earth-model and ask it to account for these bulky components of the crust. In so doing we are to test still further the worth of the model.

After rising nearly to the surface of the earth the batholiths sent many tongues of their substance into the adjacent rock formations. Such offshoots evidently won their onward way by simply rushing into cracks in the invaded rocks. At first sight it would appear simplest to assume a similar mechanism for the emplacement of each of the parent bodies. Yet to this naïve hypothesis there are serious objections, among which is its failure to account for the variety of chemical types discovered within the individual batholiths, and this is the gist of the question before us. Another, and, it is believed, better explanation will be offered. A host of details regarding the chemistry and field relations of these monstrous invaders must be omitted. Also for brevity as well as clearness, the argument and conclusions are to be stated with a directness which should not be mistaken for dogmatism.

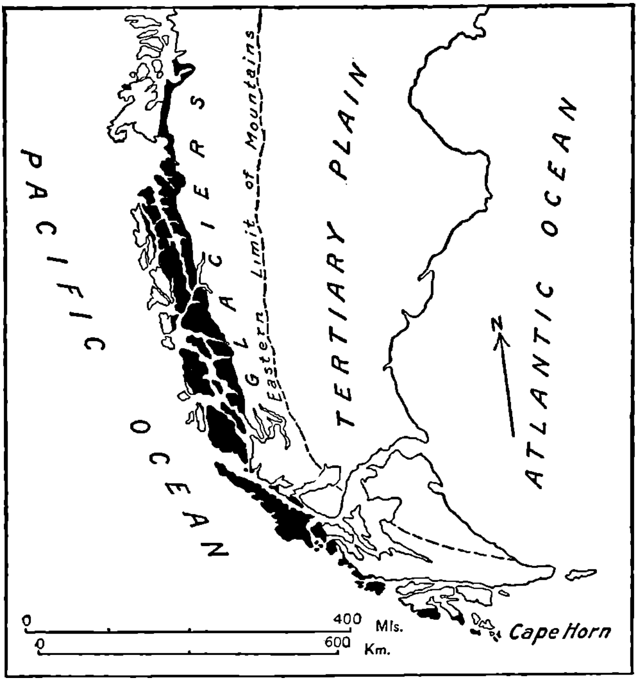
The Nature of Batholiths

Being intrusive into the earth's crust, batholiths were originally roofed and walled by older, solid rocks, including the crumpled

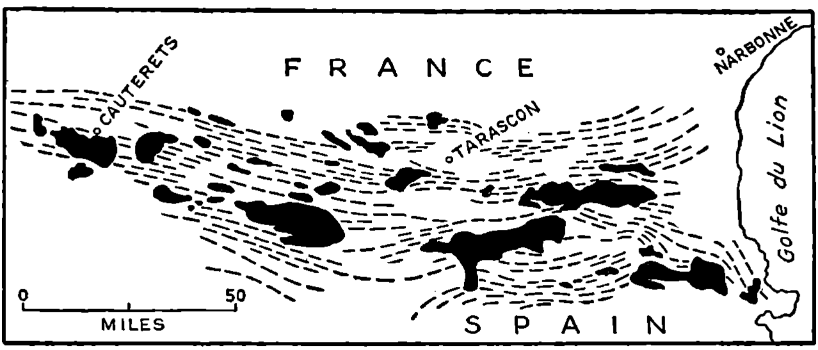


123. Map showing principal batholiths of North America.

and otherwise disordered formations of geosynclinal prisms. Hence the huge bodies could not become accessible to the geological hammer at all until prolonged erosion by running water had removed all or part of each roof. As a matter of fact, Nature has by erosion exposed the upper levels of the invading masses, and the fol-



124. Map of the Patagonian batholithic province.



125. Map of batholiths in the Pyrenees Mountains.

lowing statements refer to features there visible.[1] See Figure 135.

Typical batholiths:

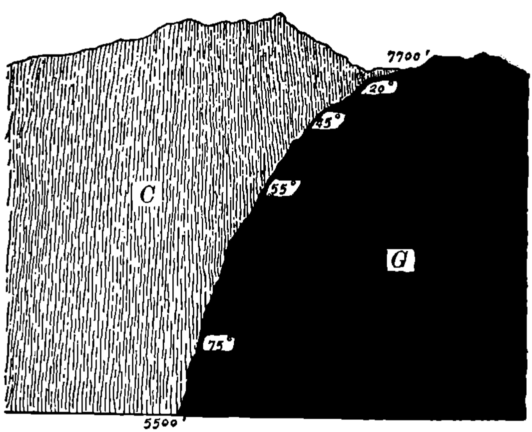
1. Have great area in horizontal cross-section;

[1] Many references to books and papers dealing with batholiths will be found in the author's technical work *Igneous Rocks and the Depths of the Earth,* McGraw-Hill Book Company, New York, 1933.

2. Are elongated parallel to mountain axes;
3. In general have the form of a dome, ornamented with roof-pendants and cupolas;
4. Have no visible floors;
5. Were emplaced after the chief paroxysms of the respective mountain-buildings;
6. Are in cross-cutting relation to the invaded beds of rock;
7. Have replaced the invaded formations in some volume;
8. Have recrystallized and otherwise altered the invaded rock;
9. Are of varied composition;
10. Have a general order of intrusion for the constituent, chemically differing rocks.

Figures 123 and 124 illustrate the bigger individual exposures or outcrops. We note the scales of the maps; the composite batholith of British Columbia-Alaska, 1500 miles long and more than 100 miles wide; the smaller but imposing bodies in California and the old Appalachian chain; and the 800-mile batholith of Patagonia.

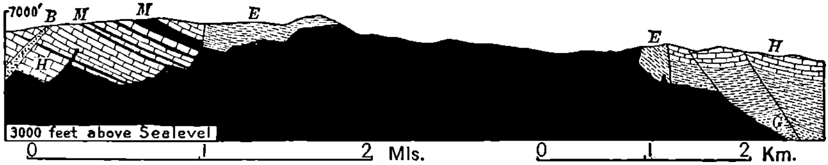
Both of those maps exemplify the second principal fact: batholiths are commonly elongated in the axial directions of the mountain chains which were respectively invaded by the emissaries of Pluto. Other cases are represented in the Pyrenees (Figure 125), where in general the outcrops of the intrusive masses (solid black) have major axes parallel to the trends of the older mountain-structures, indicated by lines.



126. Downward enlargement of Castle Peak "batholith," as shown in canyon wall.

127. Map of Marysville "batholith," cutting up through older, folded, and broken formations. After J. Barrell.

As already observed, the typical batholith can be well exposed to the air only after much of its roof has been worn off by the agents of erosion. The field geologist is therefore handicapped in his



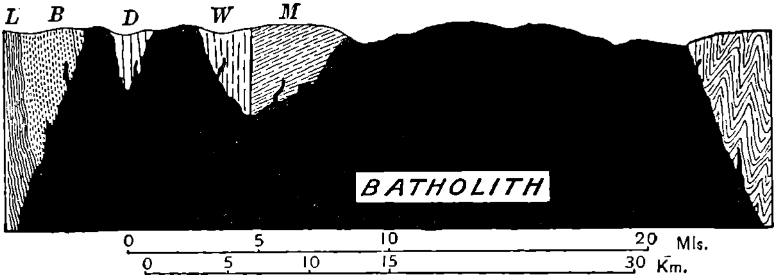
128. Section along the line X-Y in Fig. 127.

effort to visualize the roof as a whole. He has to build up the picture by studying the local relation between the invader and the invaded. If he is lucky, he may find a deep, stream-cut canyon or gulch, whose walls give direct information. This is the case with a small batholithic intrusive at the boundary between British Columbia and Washington State (Figure 126). On its northern side the wall of a canyon-like valley exposing the contact of the invading intrusive (black and marked with the letter "G") and the invaded, shaly, nearly vertical beds (shaded and marked with the letter "C") can be seen through a vertical range of 2200 feet. We see that the surface of contact plunges under the shales, first gently at an angle of about 20 degrees to the horizontal plane, and then, with increasing depth, more and more steeply. So far as it goes, such a cross-section implies that the roof contact of this invader had the general shape of a dome. More limited exposures on the southern, western, and eastern sides of the mass corroborate that impression.

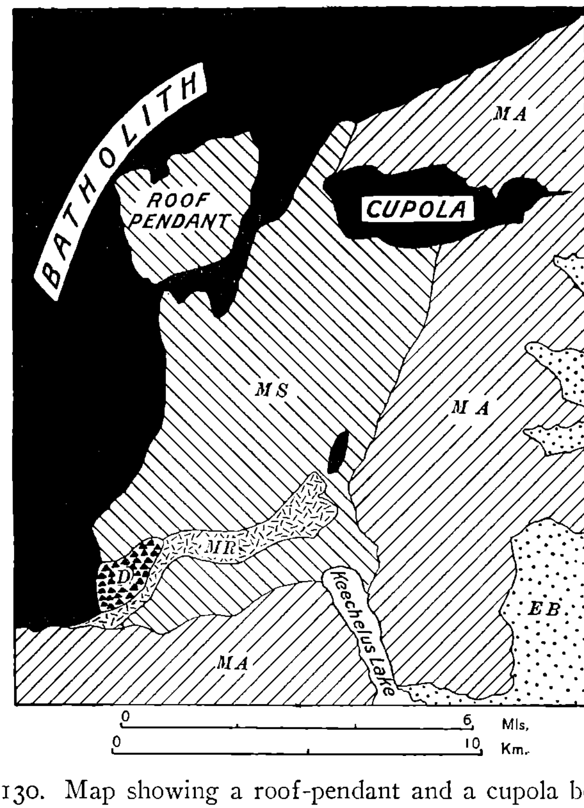
Mining operations have shown that a small batholithic body at Marysville, Montana, has a roughly domical surface of contact. See the map of Figure 127 and the cross-section of Figure 128. The intrusion is shown in black. The cross-section illustrates a quite common characteristic of the roof-contacts. Few are smooth. Here and there wedges of the roof rock hang down into the batholithic mass, below the general surface of contact. So it is at Marysville. Such wedges of the invaded rock, projecting downward, are called roof-pendants.

In many a case the roof is roughened in the reverse sense. The batholithic rock fills bays or cupolas in the general roof, making subordinate domes which are superposed geometrically on the main dome, much as bosses ornamented the curved shield of a Grecian warrior. One illustration is given by Figure 129, the cross-section of a large batholith in southern British Columbia. Although most of its roof has been worn off, two cupolas, separated by a roof-pendant (under the letter "D" in the section) appear, and the innermost cupola is separated from the main outcrop by the large roof-pendant (under the letters "W" and "M" in the section).

Figure 130 is the map of a relatively small part of a well ex-



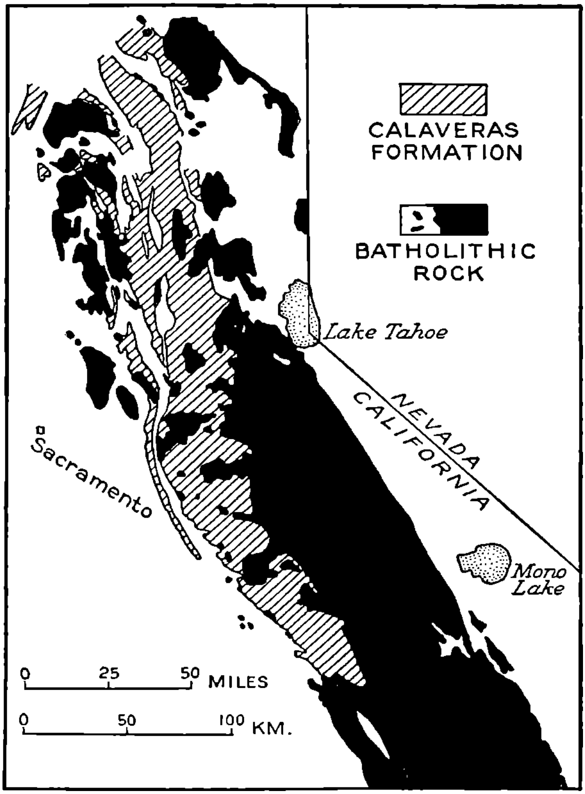
129. Section of a British Columbia (black) which invaded older, steeply uptilted, and folded formations of sedimentary rock.



130. Map showing a roof-pendant and a cupola belonging to a large batholith (black) cutting older deformed rocks indicated by shading; in Washington State.

posed batholith in Washington State. The main body and two outlying cupolas are shown in black, and again we note a roof-pendant.

The huge Sierra Nevada batholith of California has lost much of its roof by erosion. The unroofing is specially pronounced over the area covered by the black tint on the map of Figure 131.

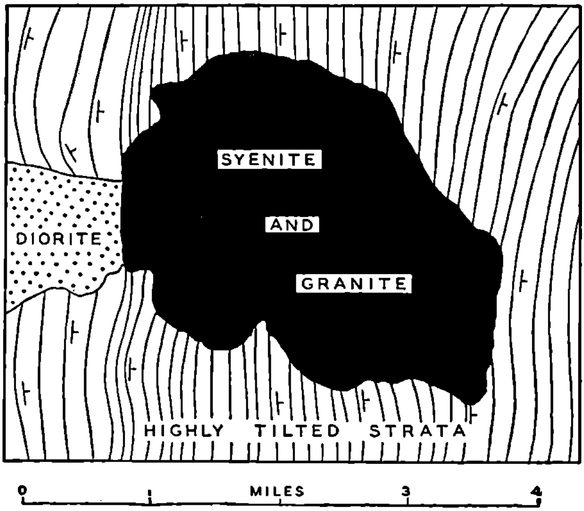


131. Map of the Sierra Nevada batholith, California. After R. Balk.

The map also shows with cross-lining the distribution of the famous Calaveras formation, which constitutes most of the remaining part of the roof. We see, peering out through the roof, many smaller masses of granitic rocks. These smaller bodies seem best regarded as cupolas on a single batholith, which still bears its roof in the western and northern part of the Sierra Nevada. Compare also the diagrams of Figure 135.

From these and hundreds of other examples a generalization can be made: the top of a typical batholith has the shape of a somewhat roughened dome.

Fact number four: A batholith has no visible floor composed of the invaded formations. Here we have a vital question. Is the lack of a visible floor due to insufficient erosion in each region, or does it mean that a batholith was never, at any time, floored with older, solid crust-rock? Deep canyons cut by running water show that the



132. Map of Mount Ascutney, Vermont, a composite, batholithic mass of granite and syenite, cutting up through steeply tilted, stratified sediments and a body of diorite which is older than the granite-syenite.

massive invader commonly retains the same composition to a depth of more than a mile, at the bottom of the deepest canyon.

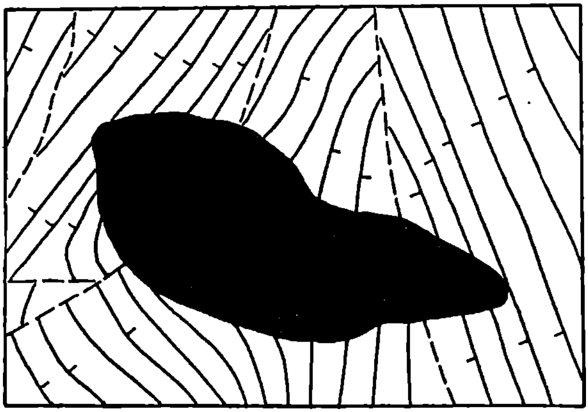
Again, most batholiths were intruded well after the respective main paroxysms of mountain-building. The rock formations of roof and wall were already crumpled and upended before the batholithic liquid rose to the levels now visible. This rule is manifest to the geologists who have worked among the mountains of the American Cordilleras (Figures 123, 124, 126-131 and 133), in the

Pyrenees (Figure 125), Brittany, Ireland, Germany, the Swiss Alps, Australia, and many other regions. The time relation is typified by a Vermont example on the small scale. Figure 132 is the map of syenite and granite, constituting an invader of the batholithic kind, at Mount Ascutney. This mass rose into the roots of the old Appalachian chain after the shales, sandstones, and limestones of that chain had here been folded and upturned, like so many packets of sheets of paper. That revolutionary bout of mountain-building led to a steep tilting of the ancient, bedded rocks, as indicated on the map. The local tilting was an incident of a torturing of the earth's crust comparable with that later suffered by the Alps of Europe. Yet the invading syenite and granite of Mount Ascutney escaped the torture. They were not squeezed, for they invaded the roots of the old Appalachians after the mountain-making turmoil was practically at an end.

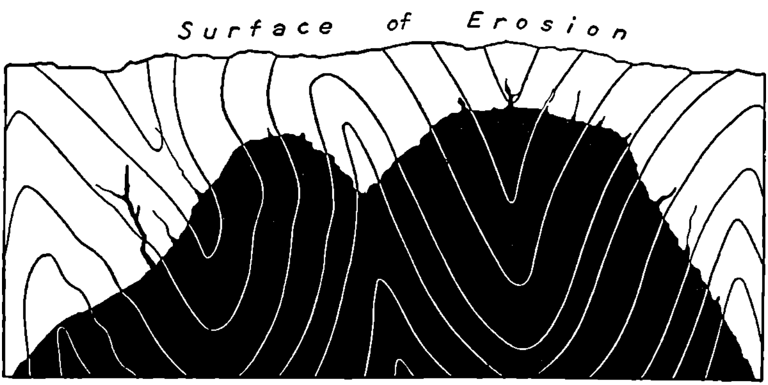
A similar time relation is just as clearly indicated in the regions illustrated by Figures 126 to 130 and 133.

The maps at which we have just glanced illustrate a closely connected feature of the mighty invaders. They refused to pay attention to the structure of the invaded formations. The interface of contact between the intrusive mass and the older rocks normally cuts across the deformed structures in roof and wall, only here and there paralleling the planes of bedding in the older rock. Hundreds of other examples of this might be cited, but only one more need here be used in illustration. Figure 133 is a map of the Castle Peak stock at the International Boundary between British Columbia and Washington State. The map shows a small batholithic mass, intruded into an extremely thick mass of shales and sandstones, after these beds had been highly tilted in the directions of the tooth-lines on the map. The batholithic liquid did not follow the bedding of the tilted sediments, the planes of easy splitting, but moved up in almost complete disregard of this easier way to advance. The behavior was like that so clearly manifest at Mount Ascutney.

Evidently the relations of contact can only mean that large volumes of crust-rock have disappeared. Rock of roof and wall have been removed, replaced, by batholithic liquid. The intriguing nature of this seventh leading fact may perhaps become more vivid after inspection of Figure 134, the diagrammatic cross-section of a batholith (solid black) which was intruded into the roots of a mountain chain when its strata had already been crumpled into folds. In roof and wall the warped interfaces between the beds are shown by black

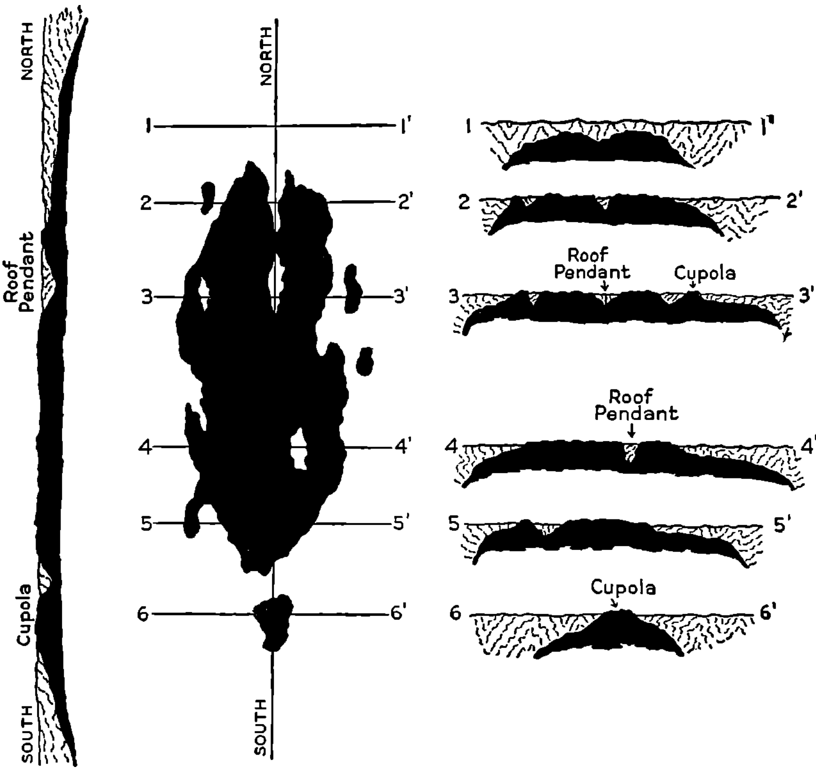


133. Map of Castle Peak "batholith" (black) at the boundary between Washington State and British Columbia.



134. Diagrammatic cross-section illustrating replacement of mountain-root rocks by invading batholith.

lines. The former continuations of the same interfaces into the volume now occupied by the batholith are shown by white lines, drawn on the black of the intrusive body. It is a case of replacement of the invaded formations by the melt. Further, according to plain evidence in the field, the replacement was not accomplished essentially through upthrust of the roof rock by pressure from the liquid. Hence the missing rock of the invaded formations must have

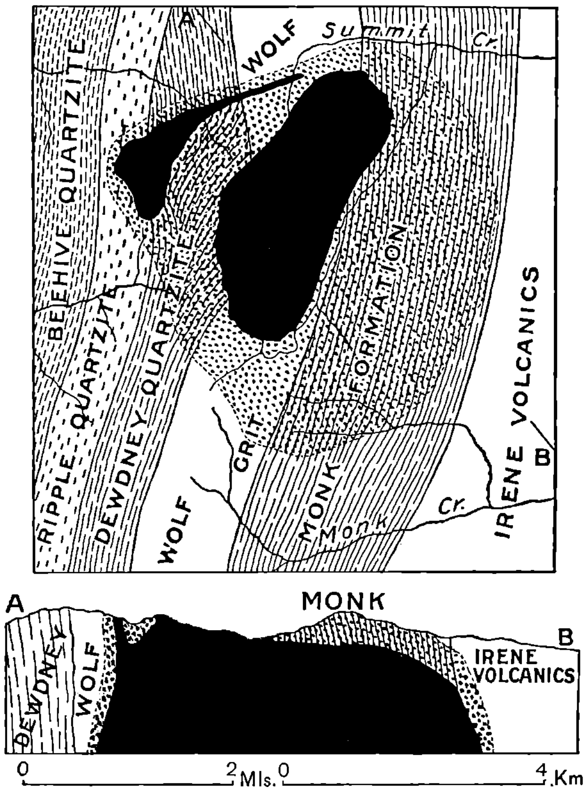


135. Diagrams summarizing the relations of a typical batholith to the invaded formations.

sunk down, at approximately equal pace with the rise of the liquid. This is a deduction of quite special significance.

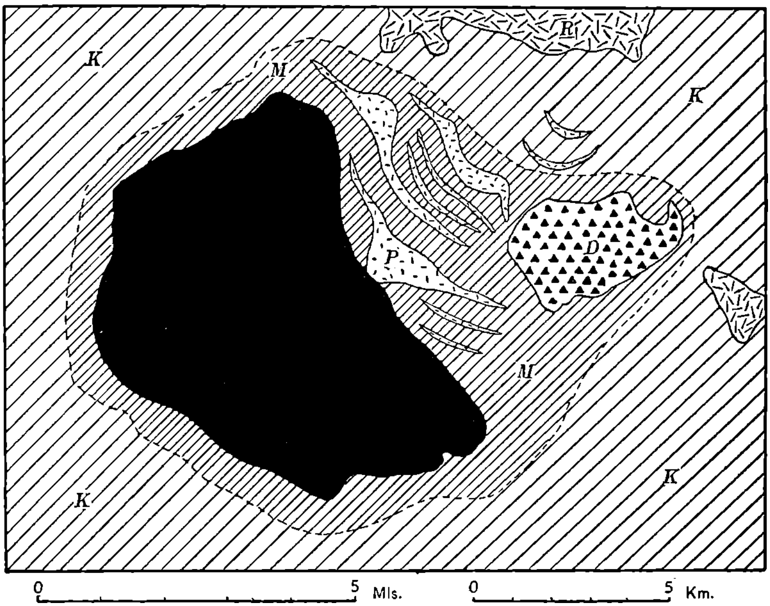
The seven rules governing the structural relations may be reviewed with the help of a set of diagrams, Figure 135. In the middle is a map showing in solid black the outcrops of a batholith, elongated within a mountain chain having a north-south axis. The invaded rock, left blank on the map, is indicated with diagrammatic folds in the longitudinal, north-south section on the left and also in the six tranverse sections on the right. We note the domical shape of the roof; its downward enlargement; three roof-pendants; and four cupolas.

The rock of roof and wall has naturally felt the heat of the molten mass. The result has been the recrystallization of the shell of older rock alongside the invader. This recrystallization (metamorphism) by conducted heat has been greatly aided also by the heat and chemical activity of the hot gases, sent out from the batholith as it slowly solidified. The shell of recrystallized rock is called a "metamorphic aureole." After sufficient erosion the aureole and batholith inside it are exposed. The outcrop of the aureole is naturally a belt adjacent to the invader.



136. Map and section of a small batholithic invader (black) of steeply upturned strata in southern British Columbia, illustrating an asymmetrical metamorphic aureole.

Figure 136 includes map and section of a spectacular aureole surrounding a small batholithic mass in southern British Columbia. The nearly vertical, sedimentary rocks invaded bear their formation names. The intrusive rock is shown in black, and the metamorphic aureole is distinguished by a dot pattern, superposed on the designs for the invaded beds. In this case we note the pronounced asymmetry of the aureole with respect to the outcrop of the batholith. The asymmetry seems best explained by assuming a rapid



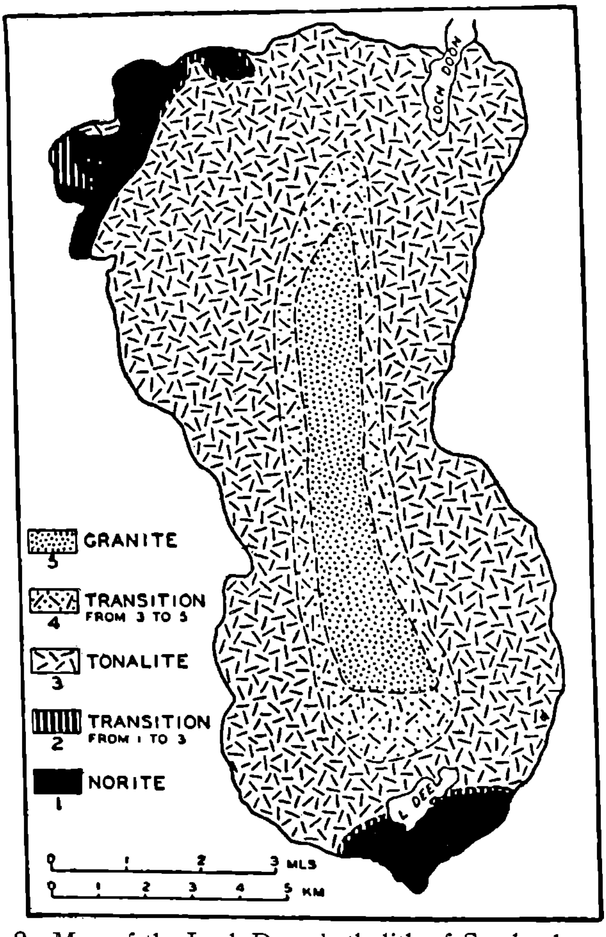
137. Map of a granitic invader (black) with an asymmetrical metamorphic aureole (stronger diagonal shading).

downward enlargement of the batholith on the side of the Monk formation, as portrayed in the cross-section.

A somewhat similar case is represented by Figure 137, the map of a batholith with an asymmetrical aureole (marked "M") in the Little Belt Mountains of Montana.

Although granite dominates among the batholiths, it is highly significant that the rocks of these giant bodies can be grouped in three classes, the granitic, intermediate, and gabbroic, corresponding to the three shells which we have found to constitute every part of the continental crust. See Figures 45 and 151.

And the tenth characteristic: Typical batholithic invasion of the crust begins with eruptions of basaltic liquid, continues with eruptions of intermediate types of liquid, and ends with granitic or chemically allied liquids. There is a strong tendency to a definite sequence in the chemical compositions of the liquids that rose from the depths during the long history of a batholithic invasion. An illustration is found in a large body that intruded the old mountains of southern Scotland, near Loch Doon. On its map, Figure 138,



138. Map of the Loch Doon batholith of Scotland.

the black area covers a rock called norite, which is chemically close to basalt. Early in the history this basalt-like material was chilled and crystallized. Soon thereafter a much larger volume of liquid rose and solidified as an intermediate type of rock bearing the technical name "tonalite." This is shown with a hachure pattern. A little later, molten granite, mapped with a stipple pattern, replaced the middle part of the tonalite, into which the visible granite is transitional.

Why Igneous Rocks Vary in Composition

Having grasped the essential features of batholiths, we are better prepared to reach our present objective. This may be re-stated. We want to know how to account for the wide variety of composition among igneous rocks in general, in spite of the fact that our earth-model contains, near the earth's surface, no primary, molten material other than basalt.

Apparently the answer is implicit in three principles described at the beginning of the last chapter. There we learned: first, that the crystallization of a rock-melt is progressive; second, that the melting of a rock is progressive; and, third, that granite and its allies melt at lower temperatures than basalt and its close allies.

During progressive crystallization, and also during progressive melting, there are two kinds of material present, crystals and liquid. With progressive crystallization the crystals, like the associated liquids, differ chemically from the original liquid. The partial liquids, formed during progressive melting, differ chemically from the remaining fraction of the rock and differ also from the original solid rock. If, then, in Nature crops of crystals are successively separated from a crystallizing melt, new, eruptible liquids result. And, if the successive partial liquids, formed during the melting of crust-rocks, are separated from the remaining solid parts, new, eruptible liquids, differing from one another in chemical composition, result.

There are two ways in which either separation can take place. The first method is by the gravitative settling of the solid parts, which are relatively dense, and the gravitative rise of the liquid parts, which are characteristically of lower density. The second method is by the squeezing of the interstitial liquid out from each composite of solid fractions. The gravitative effect is analogous to the settling of raisins or currants in a cake batter. The squeezing-out effect has an analogy in the wine-press.

How important the wine-press mechanism has been is not manifest. On the other hand, the principle of gravitative separation is abundantly illustrated by visible eruptive bodies, and will be specially emphasized, as the batholithic problem is pursued in its relation to the preferred earth-model.

The chief clue to the origin of batholiths and to the reason for the chemical diversity of their constituent rocks seems to be found in the local and temporary liquefaction of crust-rocks. The required heat is supplied by transfer from the basaltic substratum. The transfer of heat can take place only after preliminary displacements of the subterranean material. The displacements are effected, either by the injection of large volumes of the hot substratum basalt into the crust, or by the sinking of parts of the granitic and intermediate sub-layers of the crust down to lower, hotter levels.

The liquid basalt, thrust up and injected into the crust, passes some of its heat into the surrounding solid rocks, and melts a certain proportion of them. The other kind of preliminary displacement, namely, the subsidence of crust-rock to deeper levels, and especially if the sunken rock becomes actually immersed in the hot substratum, exposes the displaced solid material to a temperature at which it melts.

Both processes give secondary melts on a large scale, and the upper part of each major melt of the kind becomes, after freezing and after unroofing by erosion, a visible batholith. This is the theoretical conclusion, derived directly as we imagine our earth-model in action.

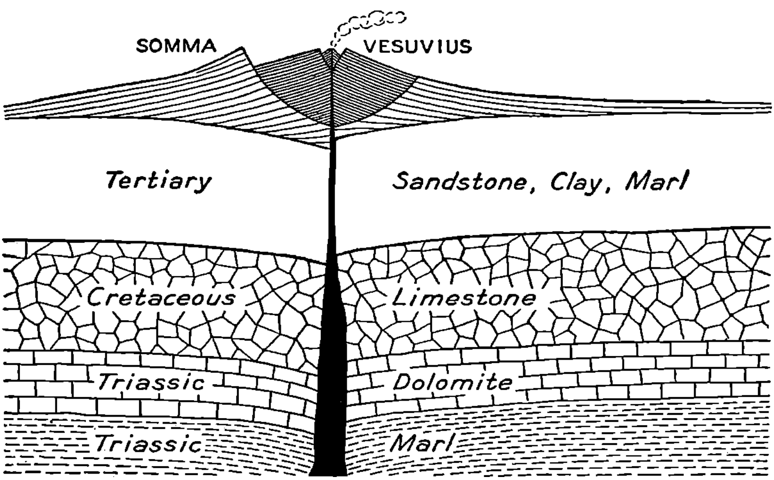
Neither mode of developing secondary melts can be valued through the most painstaking study of visible rocks. Most of the work has been done at deep, utterly inaccessible levels. Hence we can reason only at long range, comparing deductions from the basal premises with ascertained facts. Let us, then, imagine what ought to be the conditions for eruptivity under mountain belts, and afterwards see how our deductions match the results of observation.

Take, first, the case of a large body of substratum liquid, mechanically injected into the mountain roots, which include granitic and intermediate rocks of the old crust, as well as veneering, geosynclinal sediments. The injected liquid is competent to melt some of the granitic and intermediate sub-layers of the crust; for such materials melt at temperatures 100° to 300° Centigrade lower than the melting temperature of basalt.

But pure melting is not the only way in which the primary, basaltic liquid can convert crust-rock into secondary liquid. The conversion can take place also by solution of the solid in the primary liquid, a process known technically as "assimilation." On a minute scale it is illustrated by Figure 89. There, on the right-hand diagram, we see stippled areas representing cross-sections of three liquid masses, melted hornblende, surrounded by solid crystals of quartz and feldspar. Both quartz and feldspar are more refractory than hornblende, but each will slowly lose substance by molecular diffusion into the liquid. Thus diffusion produces a new liquid of composition intermediate between hornblende and quartz, or hornblende and feldspar. The liquid has assimilated some of the solid material.

The same process has clearly operated at many visible contacts of once-molten basalt and older rocks into which that primary liquid was injected. Nevertheless, hybrid rocks, that is, mixtures of basaltic and non-basaltic materials produced at visible levels in this fashion, must have insignificant volumes when compared with the huge massifs of granite and allied types which we have been discussing. At visible levels, necessarily high levels in the earth's crust, any rock-melt must lose heat with relative speed. There, the melt tends to freeze solid before it can heat up and dissolve much solid rock. Assimilation may, under certain circumstances, have results significant for the student of the chemistry and mineralogy of those eruptive rocks where gas-fluxing has prolonged the molten state at volcanic vents. For example, it is becoming increasingly probable that the peculiar minerals and chemical composition of the lavas of Mount Vesuvius are best explained by assimilation of limestone, dolomite, and marl along the walls of this volcanic pipe (see Figure 139). In general, however, assimilation has not affected any large fraction of the accessible basaltic injections. How is it at deep levels?

Pure melting depends on the diffusion of heat into rock—a slow process. Solution of foreign rock in a melt by simple diffusion of material is much slower still. Now, any mass of liquid basalt, thrust far up into the earth's crust, is chilled against roof and walls, and is thereby soon robbed of its dissolving power. Hence, if such injected basalt is to assimilate much foreign material, it must be kept vigorously stirred. For a similar reason the solution of sugar in a cup of tea is accelerated by stirring with a spoon. And we all know that loose crystals of the sugar dissolve faster than lump sugar dissolves, the reason being the much greater total area of surface exposed to



139. Section through Mount Vesuvius and the thick sedimentary rocks beneath the cone. Modified after A. Rittmann.

the liquid in the former case. Nature has acted on the same two familiar principles, when emplacing rock-melts of batholithic proportions near the earth's surface. At roof and wall of the invading liquid, the rock is shattered into separate fragments. These fragments, being denser than the liquid, sink in the liquid and stir it. Many shatterings of roof and wall rocks and many sinkings of the fragments and concomitant rise of the liquid mean much stirring and a greatly increased chance for assimilation.

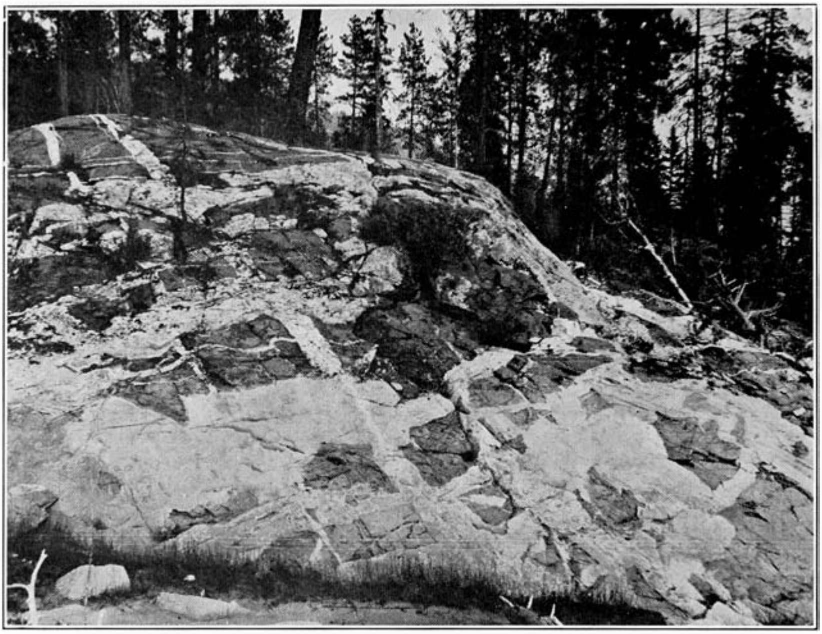
We note, too, an obviously related fact: the space in roof or wall, formerly occupied by each sinking block, is immediately filled with the liquid. By so much the liquid has succeeded with its task of penetrating the earth's crust. In other words, we have hit on a new, supplementary method by which batholithic invasion of the crust takes place.

These various considerations are so important that it is well to study illustrations in some detail.

The reality of the shattering at roof and wall is the first point to be discussed. That some shattering and engulfment of solid blocks took place is manifest at and near exposed batholithic walls and roofs. At a single exposure of a contact of the kind, scores or hundreds of blocks of the invaded solid rock can be seen inclosed in the intrusive (Figure 140). Mining operations have proved the same relation of included block and host rock many hundreds of feet below the surface. An example is found in the Tintic District of Utah, where deep mining has been going on within a small batholith or so-called stock. Figure 141 gives a cross-section of this body. The invader is indicated by the black tint. Scattered through this intrusive mass are large blocks of roof rock—quartz-rock shown with the stipple pattern (1), and limestone shown with the masonry pattern (2).

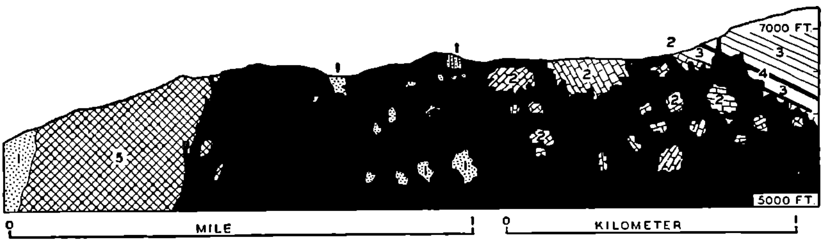
While we are at the mine, let us borrow from the miner a convenient name for the process that led to the shattering of any batholithic roof and engulfment of the fragments. The miner breaks the roof of his tunnel with dynamite. The shattered fragments drop to the floor of the tunnel, in shape to be carried away by the mining tram. To the act of so preparing the tram-loads the miner gives the name "overhand stoping." The analogous process, carried on by a batholithic invader, we shall call "stoping" or "overhead stoping." Since the blocks torn from roof and wall are small, it is further convenient to name this particular kind of Nature's quarrying "piecemeal stoping." A little later we shall recognize another kind of stoping which theoretically has worked on a vastly bigger scale.

The total volume of the visible blocks stoped off by any batholithic melt is minute when compared with the volume of the batholith itself. Hence, at first sight, one might be tempted to think that natural stoping has done little to heighten batholithic chambers, or to stir the batholithic melts, thus facilitating assimilation of foreign rock. Yet that conclusion would be unwarranted. For, the very fact



140. Shattering of the invaded formation by a British Columbia batholith (rock of lighter tint).

that the visible blocks are arrested in their downward journey, so close to the roof, proves the batholithic mass to have been frozen nearly solid when it engulfed these blocks. They were broken off from roof and wall at a time when the invader was at the very last gasp of its life as a liquid, energetic body. Yet even then, when cooling was so far advanced, the batholith was able to shatter and engulf the foreign rock. But its activity must have been enormously greater during the tens, yes, hundreds, of thousands of years during which the huge body of liquid had been cooling. During that long time, countless other blocks must have been stoped down to levels far below the levels occupied by the visible blocks. Thus we sense big



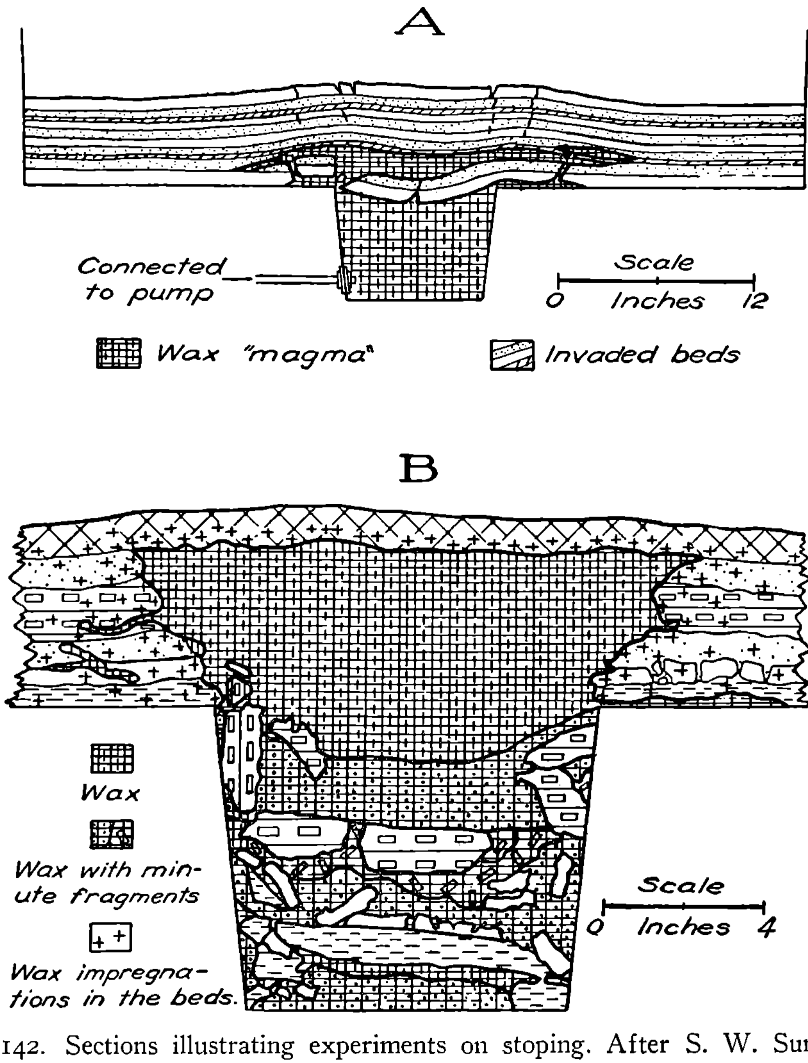
141. Blocks of crust-rock inclosed by a small batholithic invader, Tintic District, Utah.

total effects wrought by Nature's stoping: breaking of suite after suite of fragments from roof and wall; sinking of suite after suite of the blocks, most of them going to great depth; concomitant rise of the batholithic liquid, to take the place of the host of sunken blocks; and, of course, an equivalent advance of the molten mass upward, into the solid crust of the earth. It is as if the molten invaders were hungry monsters, biting off and swallowing piece after piece from the mountain roots.

The principle of piecemeal stoping has been illustrated experimentally by S. W. Sundeen.[2] He filled a pail with solid paraffin and then laid across the top of the pail a pile of layers made of wax, and also wax which was mixed with small bits of other material, as shown in Figure 142, Section A. The paraffine was then melted, reaching a density smaller than that of any of the overlying layers.

[2] S. W. Sundeen, *Appendix A, Report of Division of Geology and Geography for 1934-1935.* National Research Council, page 2.

Through a pipe connected with a pump the pressure of the liquid on its cover of layers was alternately increased and diminished, thus imitating the pulsatory movement of Nature's melts. The resulting strain caused the packet of layers to break to pieces. Because denser than the liquid, these fragments sank to the bottom of the pail. See Section B. Their place was taken by the liquid paraffine, which thus



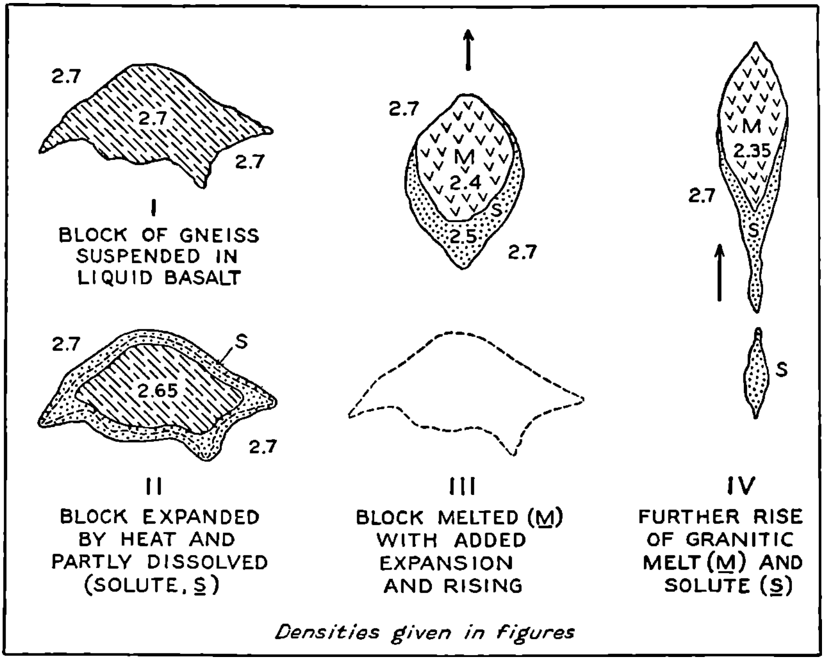
142. Sections illustrating experiments on stoping. After S. W. Sundeen and F. F. Grout.

attained an intrusive relation to the layers. If we imagine the layers to represent the solid rocks in the upper levels of the earth's crust, and the melted paraffine to represent a liquid abyssolith, we have a mechanism much like the one so cleverly designed by Sundeen. In the batholithic chamber of Nature the molten rock makes its own way upward, by piecemeal replacement of the solid rock of roof and wall.

The process comes to an end as soon as the inevitable conduction of heat into the surrounding crust makes the batholith too cool for such energetic work as shattering.

We now turn to our main problem—the cause for the diversity of composition shown by eruptive rocks. Apparently the best solution to the problem emerges when we ask a preliminary question: What will happen to the blocks of solid rock sunk by stoping? They go down to levels where the temperature exceeds that at roof and wall, and, being inherited from the abyssolithic basalt, long remains above the melting temperature of the average rock invaded. Hence many of the foundered blocks must melt, and many more will be dissolved or assimilated at great depth. But each liquid product of pure melting or of assimilation is less dense than the adjacent, primary, heat-bringing liquid, and has to rise through it. Moreover, we have seen that the melting is selective, giving secondary liquids of great variety in chemical composition. It is also logical to expect that solution or assimilation should give another set of secondary liquids, differing from one another and from basalt as well as from granite, the dominant rock of the Basement Complex. New solid rocks, developed by the freezing of all these secondary melts, shall in general have compositions intermediate between basalt and granite and yet have much variety of composition among themselves. Here we have what appears to be, in principle, the most promising solution of our main problem.

The imagined process is somewhat complex and may perhaps be clarified by inspection of the diagram of Figure 143. The series begins with a stoped-down block of gneiss, a metamorphosed form of granite and a leading constituent of the continental crust. The block, with density 2.7, is supposed to be poised in liquid basalt of the same density. After a lapse of time the block is heated and somewhat expanded, and also partly dissolved by the basalt (Stage II). The new mixture of material, or solute, is indicated by the letter "S." Later the block is heated enough to melt, its density falling still more, to 2.4, the solute having the density of about 2.5. Both are immersed in liquid basalt with density 2.7. Hence, as at Stage III, the block and its trailing solute have to move upward, in the direction of the arrowhead. The original location of the block is represented in Stage III by the broken lines. Stage IV shows a still later condition.



143. Diagrams illustrating stages in the melting and final solution of a block of foreign rock (gneiss) in molten basalt.

The gneiss, now heated to maximum, has a density of only 2.35, and tends to race ahead, upward, leaving the solute behind.

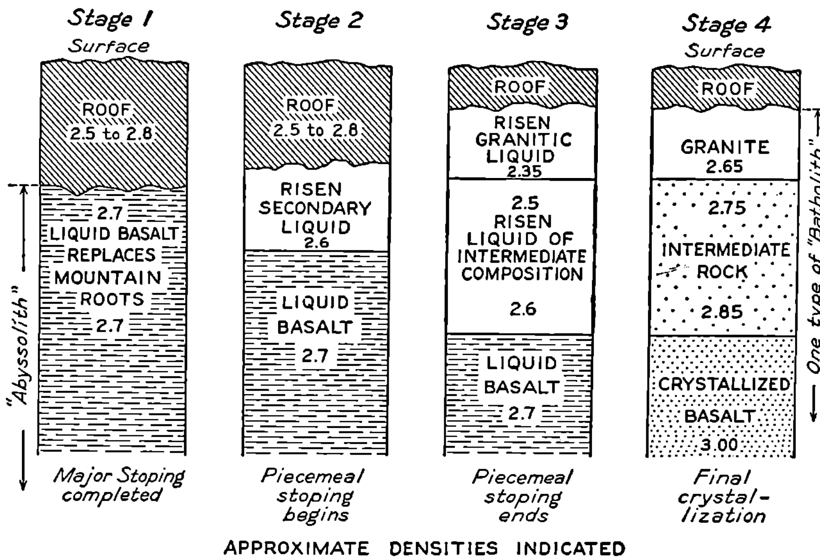
Thus, by a combination of stoping and deep-seated melting and assimilation, a kind of solid-liquid convection is established. The primary liquid is stirred as the solid blocks sink through it, and stirred again by the many streams of secondary liquid that shear their way up to, or toward, the roof of the great chamber. All this agitation of the liquid greatly accelerates the assimilation of the included blocks of foreign rock. We see that much more solutional work is done during the life of a major abyssolith than would have been possible if its roof and walls had been undamaged. We see also that those secondary liquids that have specially low densities tend to rise highest and so collect near the roof of the abyssolith. Molten granite has the lowest density among all the more bulky melts of Nature, and it is therefore significant that the overwhelming mass of batholithic rock, frozen at high levels and therefore visible today, is granite.

However, the crust-substratum hypothesis implies the development of secondary liquids in quantities still larger than those controlled by piecemeal stoping. We look once more at Figure 82, a diagrammatic cross-section of the earth's crust as we imagine it to have been torn asunder during the formation of a mountain chain. Here are: first, shattering of the crust on a Brobdingnagian scale; and, second, injection of a major basaltic abyssolith, flaring widely downward and continuous with the substratum over a wide area. The crust-blocks, with individual volumes reaching scores, hundreds, or thousands of cubic miles, are normally denser than the hot basaltic melt, through which, therefore, they sink. The blocks become engulfed in the substratum itself. Let us call this "major stoping," to distinguish the process from the quantitatively less important piecemeal stoping.

The substratum carries incomparably more thermal energy than even the widest abyssolith can carry, and in the substratum every crust-block can be ultimately liquefied. Here pure melting and assimilation are not limited by time, as they are in the case of an abyssolith, which must do such work before it freezes solid. Be the diffusion of heat or interdiffusion of solid and liquid ever so slow, there is ample time for the liquefaction of major crust-blocks engulfed in the substratum. Such secondary liquid, made of ancient granite and allied rocks, all less dense than crystallized basalt, is necessarily less dense than the primary basaltic melt. Hence the secondary liquids, generated in the substratum, do not remain there, but rise through it. Much of that lighter liquid will enter and rise through the abyssolithic chamber itself, and then proceed to stope the roof piecemeal.

The section of Figure 82 suggests a third condition for deep-seated liquefaction of crust-rock. While the more superficial rocks are crumpled, forming mountain-structures, the crust is bent down bodily into the substratum and is, therefore, in the same parlous state as the crust-blocks that have actually foundered in the vitreous layer. Thus the deeper parts of mountain roots also are threatened with pure melting and assimilation. Secondary liquid, so formed, should spread out horizontally, and some of it, impelled by differential density, may rise into the adjacent abyssolithic chamber, adding to the volume of derived liquid within that chamber.

The diagrammatic sections of Figure 144 may help us to picture



144. Diagrams summarizing a theory of batholiths.

the invasion of mountain roots by a major abyssolith. Each section represents a vertical column, like the core in a cheese-sampler. Stage 1 corresponds to a basaltic abyssolith, emplaced by major stoping. It is a case of replacement of crust-rock on a gigantic scale. The rock of the roof is shown relatively thick, and the contact of roof and primary liquid is arbitrarily drawn as nearly plane and horizontal. Stage 2 shows a later condition, after piecemeal stoping and deep-seated melting and assimilation have done two things: first, thinned the roof; and, second, developed, just below the crust, a layer of solute or secondary liquid with density of 2.6 and thus lower than that of the primary basalt, namely 2.7. This secondary melt would have the chemical composition of what we are calling intermediate rock. At Stage 3, still later, the solute embodies both intermediate material and also a layer of granitic liquid with density of 2.35. By this time the energy of the abyssolith is so much exhausted that stoping is no longer possible, and it is also supposed that the secondary liquids and primary liquids have attained final compositions and thicknesses. Stage 4 is reached when all three liquids have solidified. Theoretically the granite of Stage 4 represents the visible part of a typical batholith.

Let us now review the ground over which we have come, systematically considering the ten chief characteristics of batholiths.

First, we think back to the conclusions of the third chapter, which was concerned with the origin of mountains. Then we really found the reason why batholiths are located in mountain chains. Along those zones the crust was thoroughly sheared and broken. There also the edges of the ruptured crust dived into the substratum, and enormous blocks of the crust actually foundered. This is "major stoping." The space vacated by the down-bending crust and also by the foundered blocks was immediately filled with liquid basalt from the substratum. Thus in the initial stage of its evolution a typical batholith was a huge basaltic abyssolith, emplaced largely by major stoping. Then this highly energetic liquid continued its invading rise into the mountain roots by piecemeal stoping. But, because the major stoping was the more important, we can understand why batholiths are integral parts of mountain chains. Compare Figure 82.

Since the conditions of wholesale rupturing, diving, and major stoping existed all along the axis of each growing mountain-structure, we can also see why the outcrops of typical batholiths are elongated along such axes—characteristic number two of our list.

Because masses pendent from the roof of a liquid abyssolith were specially liable to break off and founder, an initially irregular roof tended, through piecemeal stoping, to become roughly domical—a deduction corresponding to characteristic number three.

And number four—the absence of any visible floor for a batholith—finds immediate explanation if a batholith is no other than the visible part of an abyssolith.

Because stoping continues long after the folding and thrusting of mountain-built formations has ceased, it follows that the principal uprise of batholithic liquid shall occur after the principal deformation of the earth's crust. This is the actual fact—characteristic number five.

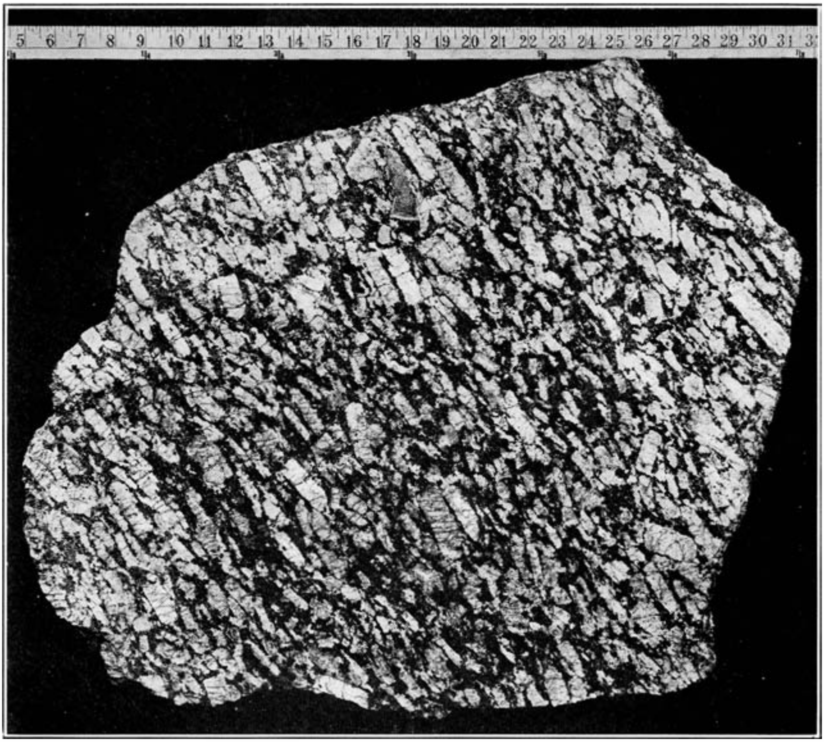
We now see why each batholithic mass cuts across the structures in the invaded formations. These rocks of the mountains had been crumpled. The new complex of strained rocks was under great stress, and was further stressed by the heat and pulsating movements of the invading liquid. The stresses leading to major and piecemeal stoping were so powerful and so directed that the crust-blocks were torn apart with little regard to the planes of bedding in the rocks of the mountain roots. Therefore the surface of contact between the batholith and the invaded rocks should, after exposure by erosion, be found to cut right across the grain of these older formations. It does just that, characteristically.

The principle of stoping supplies automatically a reason for fact number seven: molten batholiths replace the solid rocks of roof and wall. The liquid makes room for itself chiefly by engulfing the solid rock, rather than by thrusting the solid rock aside. Some mechanical displacement of this second kind has undoubtedly taken place, but is not of comparable importance. For an example see below.

Again, if the granitic invaders of mountain roots are the uppermost parts of abyssoliths, we can readily understand the recrystallization of roof and wall at these levels—characteristic number eight. For these great melts were not only hot but were charged with hot gas which rose from the deeper parts of the abyssoliths, much as we have seen gas rise in volcanic pipes.

The composition of batholiths, where exposed by erosion, should in general range from the basaltic to the granitic, and the series of rocks represented should exhibit what may be called family relationship. In fact the "consanguinity" of batholithic rocks is one of the best established facts of geology; it is characteristic number nine.

And, finally, the theory demands that in a given mountain chain there should be a fairly definite order of intrusion and freezing for



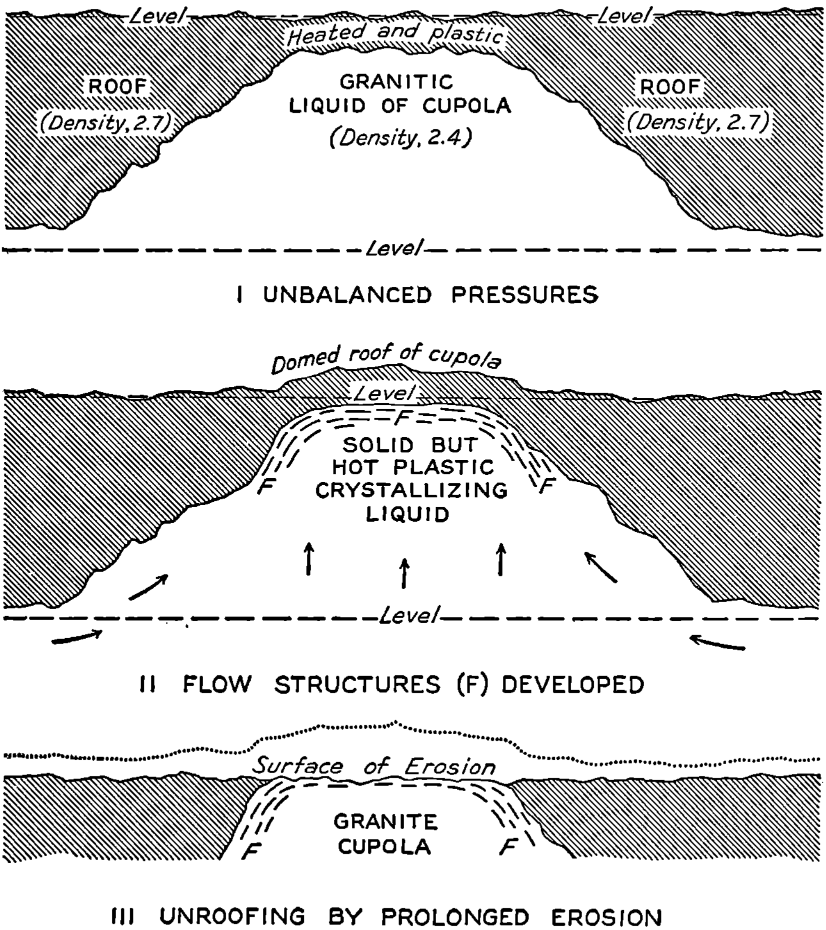
145. Polished surface of a New Hampshire granite, whose large crystals of feldspar have been pulled into roughly parallel positions; illustrating flow-texture in igneous rock.

the secondary liquids in batholithic chambers. The first invading bodies to freeze in the upper part of the earth's crust are the tongues or dikes of the abyssolithic basalt, injected along high-going fissures in the roof, before there has yet been time for the generation of secondary liquid. Or some of this primary basalt may be chilled and frozen early, forming local, thin sheaths of rock adjacent to roof and wall. Although themselves subject to later stoping, these newly consolidated rocks should now be represented by relics. A similar history should be run through by the derived, secondary melts that give rocks of intermediate composition. And we have seen that granite or granite-like rocks should be the last of the bulky rocks to crystallize in these underground caldrons. That the actual sequence of emplacement and solidification in batholiths is from basaltic to granitic is a characteristic fact—number ten of our list.

Some, but by not means all, of the batholiths have a structure which merits a supplementary word of explanation. These particular bodies have their constituent crystals and inclusions of foreign rock pulled out in lines and planes. In technical language, the masses show a flow-structure. See Figure 145. The arrangement of crystals and inclusions suggests that there was plastic flow of each mass after crystallization was well advanced. Then the rock had already attained a degree of solidity, but it was still hot, weak, and plastic. In many cases the flow-structure is accentuated at and near the wall. Doubtless there are several causes for this delayed flow of the freezing body, but on the present occasion only one of these causes will be described in detail.

While the granite filling a cupola or upper part of a main batholith is molten, its density is at least ten per cent less than the average rock alongside. For a long time after the complete crystallization of the granite, it remains expanded by heat and is from one to five per cent less dense than the rock which it has invaded. There is an evident tendency for the granite of a cupola, for example, to shear its way up, past the inclosing, cooler, and heavier rock.

Figure 146 illustrates the idea. The top section represents the roof and inclined walls of a granitic cupola or small batholith when liquid. We note the densities: 2.4 for the liquid and 2.7 for the solid crust-rock of roof and wall. The heavier crust-rock, to right and left of the melt, tends to sink, as it squeezes up the lighter mass of liquid. This shearing motion is resisted by the rigidity of the roof. However, in the course of many centuries the roof becomes heated by conduction



146. Diagrams explaining one cause for the development of flow-structure in a batholith.

from the hot liquid beneath, the upper part of the liquid being correspondingly somewhat cooled. Thus the roof is weakened by the heat and there is simultaneous crystallization of the upper part of the granite. With sufficient weakening of the roof it finally gives way.

The surrounding, heavy crust-rock drops a little and pushes up the slowly freezing granite. The arrows of Section II show the expected directions of flow in the granitic mass; the short lines indicate the resulting flow-structure. The upper part of the granite is, at this stage, more or less solid but remains hot and plastic. Deeper down, the granitic liquid is beginning to crystallize.

Ultimately the whole of the mass is solidified. Then follow many thousands of years, during which erosion sweeps away most of the roof—Section III. The geologist, roaming over the new exposure, sees the granite with its crystals and inclusions pulled out, as the differently colored grains of sugar are arranged after a candy-pull.

A close analogy to the described mechanism is provided in the salt domes of the oil fields. There, the relatively heavy rocks above thick, deeply buried beds of salt have squeezed the light salt upward locally, doming the rock-beds above and developing fluidal structure where the mass of salt is being so thickened.

Thus, some batholiths have been pushed up bodily for short distances after they were emplaced high in the earth's crust. But clearly the last upward movement, comparatively slight as it was, should not be taken as evidence concerning the nature of the vastly greater movements which have been engaging our principal attention. The moderate uprise represented by the doming of the roof is merely a late displacement, which is not essential in batholithic invasion of mountain roots.

Further, a batholithic melt, already partly crystallized in the roots, may be squeezed and pushed about in the last stage of the mountain-making paroxysm, or during the inevitable readjustments among the blocks of the shattered crust. In either case the frozen batholith could not fail to show fluidal structure, but here too the new structure could indicate little or nothing about the manner in which the great molten mass made its way up, tens of miles, from the depth where the mass won its initially high temperature.

Eruptive Rocks of Peculiar Composition

So far we have been concentrating attention on the physical and chemical reactions between the basalt of the substratum and the dominant rocks of the earth's crust. The dominant rocks are themselves of ancient, igneous origin. But quite different chemical reactions may be expected when the basaltic liquid or secondary liquid in abyssolith or substratum comes into contact with sedimentary rocks, for these are strongly contrasted with igneous rocks in chemical composition, as well as differing widely from one another. In particular, the sedimentary rocks, such as those constituting veneers on the Basement Complex, usually contain a much higher proportion of volatile substances than that ruling among the igneous species. Mudstone or shale includes five to twenty per cent of water by weight, while granite, diabase, gabbro, or intermediate igneous rock characteristically contain much less than five per cent. More than one third of a limestone, by weight, is carbon dioxide, a gas. Sandstones carry many times as much water as any of the standard varieties of igneous rocks.

Chemical reactions between the commoner rock-melts and the infinitely varied, gas-rich mixtures represented by sedimentary rocks could not fail to give secondary liquids of abnormal composition. Such derived liquids would differ greatly among themselves, and, for reasons too technical for present description, many of them should be specially charged with the alkaline oxides, soda and potash. Here, indeed, we seem to find the best explanation of many so-called "alkaline" species of eruptive rocks, that is, something like half of all the species named in the handbooks of geology. Again, since sediments constitute but a small part of the crust of the earth, the secondary melts and rocks now in question should not have large individual volumes. Such is the fact.

Origin of the Three Principal Layers in the Continental Part of the Crust

The study of batholiths suggests a possible way in which the "granitic," "intermediate," and "gabbroic" layers of the continental sectors were first developed. Assuming the chemical nature of batholiths, the largest eruptive masses, to have been established through progressive crystallizations and progressive re-meltings, it is natural to think of a similar control when our planet was originally organized. In principle this idea is favored by some leaders of geological and geophysical thought. Lord Kelvin made a lively picture of the youthful earth, with its successive crystallizations of crust-flakes, successive founderings of the flakes, and many consequent re-meltings at depth. In Kelvin's day the conception that both crystallization and melting of rock are progressive had not yet been thoroughly grasped. Now the well-established theories of physical chemistry and many special experiments with mineral melts permit reasonable speculation about the stabilizing of the earth's crust.

First we try to imagine the nature of the outer part of the planet when liquid at the surface. Whether or not the Moon was torn out of the earth soon after the solar system was evolved, it is not an entirely wild guess that a thick, relatively superficial shell of the infant earth had an average composition much like that of the Moon. Now, allowing for the self-compression of our satellite, the density of the Moon is the same as that of many stony meteorites, which themselves suggest a possible material for the outer part of the young earth.

Let us assume such material for the liquid shell, its thickness being a few hundreds of kilometers and the shell resting stably on material of still higher density. Suppose also that a coherent crust was ultimately formed by the Kelvin type of solid-liquid convection. This mechanism involves many crystallizations and re-meltings. Each crystallization and re-melting was progressive, with the separation of lighter and heavier fractions. Gravity would take charge of these fractions and move the lighter material upward and the heavier material downward. Possibly in this way the three principal sub-layers of the crust were developed from the original liquid shell. The process meant the chilling of the planet down to the bottom of that initially homogeneous shell. After its breakup into the three sub-layers, the lower part of the "gabbroic" layer would be expected to have become re-melted by the slow conduction of heat from the deep interior of the earth and by the slowly evolved heat of radioactivity. The result would be the vitreous, basaltic substratum of our earth-model. It is also reasonable to suppose that the upper part of the basaltic shell was never frozen in the way Kelvin imagined, for, after the granitic layer was separated by gravity and then frozen, this light rock could not founder in, and thus continue to chill, the heavier basalt.

But another portentous question looms up. Why are the granitic and intermediate layers nearly or quite lacking over most of each oceanic sector? This insistent problem, of supreme importance in a full-bodied philosophy of earth science, may yet be solved, if the geologists of the future succeed in explaining the structural turmoil of the Basement Complex. The distortion of its ancient granite, lava flows, and sedimentary formations is of the order expected, if an initially world-circling layer of these light rocks had been forcefully segregated in an area little greater than one hemisphere. Such segregation would demand force beyond imagining, force on a planetary scale. Students of the Complex are not agreed as to the cause of its intense foldings, thrustings, and upendings. They will continue to speculate, and perhaps they will seriously consider the possibilities represented in the idea of deep convection in the earth and also the idea of crust-sliding. For it now looks as if the distortions registered in the Basement Complex are of the same quality as those observed among the young mountain chains.

Whatever the cause for the concentration of the original granitic material in one hemisphere, that process meant thickening of the material within the area of concentration. So thickened, the relatively light mass still floats high on the earth's body. This is why we have dry land on the continental scale—a subject to be resumed in the next chapter.

Summary

We have tried to account for the eruption of a whole army of non-basaltic, liquid masses into and through the earth's crust. Both their emplacement and their varied composition appear explicable, as we apply the principle of reaction between crust and substratum. Reactions without number have taken place, and they have been of both physical and chemical nature. Those of physical character are recalled under the technical names: abyssolithic injection; major stoping, piecemeal stoping; and the pure melting of crust-rock by the hot basalt of the substratum. The chemical reactions concerned have been grouped under the general name "assimilation," crust-rock being dissolved in the basaltic melt of the substratum or in derived, secondary melts. Thus the pure melting and assimilation are conceived as taking place at the deep levels occupied by the substratum and also by the substratum basalt after it has been injected into the crust. Stoping may be likened to a man's mastication of food; pure melting, to his digestion of the food; and assimilation, to the absorption of the nutriment in the man's blood.

All three processes seem to have been most effectively at work when batholiths were developed. For this reason emphasis has been put on them, much less attention being given to the real, though subordinate, importance of assimilation in intra-crustal chambers of molten rock. Since no new principles are here involved, lack of adequate treatment of these definitely floored chambers is not significant for the present inquiry. But it was necessary to add a word about the peculiar results of reactions, when sedimentary rocks, like shale and limestone, have been more or less completely assimilated. The abnormal liquids and rocks so generated should be by theory, and actually are, always in small masses, no one of them rivaling the enormous abyssoliths under the mountains.

Finally, we used the experience gained from field work among the batholiths to launch speculations about the origin of the three sublayers in the continental part of the earth's crust, and about the reason why land life is possible on our planet.

CHAPTER VI

THE CRUST SUPPORTED

"Atlas the Endurer"

Introduction

THE conception of major stoping, that is, foundering of big blocks of the earth's crust along the localized belts of mountain-building, is an essential of the preferred theory of mountains. For the theory assumes the coarse fragmentation of the crust and simultaneous rise of thick tongues of molten basalt from the substratum. Any fragments, with density equal to or greater than that of the continental crust and wholly immersed in the basaltic melt, had to founder. The continental crust has an average density of about 2.80. If a complete block of it were sunk vertically by the amount of its own thickness, 60 kilometers, the block would be compressed, with increase of the density to about 2.85. It is now immersed in a weak substratum with a density of about 2.82, or one per cent less. The block would continue its way down in the substratum until it met a deep layer having the same density as the block.

A complete block of the heavier sub-oceanic crust would founder more rapidly and come to rest at a level still deeper in the earth.

Again logic raises a question. Does our mental model of the planet imply insecurity for the crust as a whole? Is the crust, as well as the organic life upon it, in danger of wholesale catastrophe?

That no such disaster has occurred for at least half a billion years is clear from the fossil evidence that organic life has been continuous since some epoch before the beginning of the Paleozoic Era. And there is no sign that the crust will be in danger for another half billion years. How to reconcile this fact of general stability with our basal hypothesis is the first problem to be attacked in the present chapter.

Afterwards we shall consider how the uneven relief of the rugged earth is supported. The unevenness of the crust may be illustrated by a few figures. The summit of Mount Everest stands twelve miles above the bottom of the ocean east of the Philippine Islands. A summit in Chile is about nine miles above the floor of an oceanic deep offshore. Mauna Kea, Hawaii, is topped at 13,800 feet above sealevel and 32,000 feet above the general floor of the Pacific in the same region. On the average the rocky surface of Asia stands 17,300 feet above the average level of the bottom of the Pacific. The corresponding figure for North America is 16,500 feet. In average the Pacific Ocean is about 1000 feet deeper than either the Atlantic or the Indian Ocean. Already we have found partial explanation for such contrasts of level (see page 73), but the ruggedness of the earth needs further attention. So our second main theme is to be a more detailed picturing of Atlas at work. Why are continental sectors of the globe dry and capable of harboring land life for a billion years on end? Why are mountains kept so high?

Stability of the Crust in General

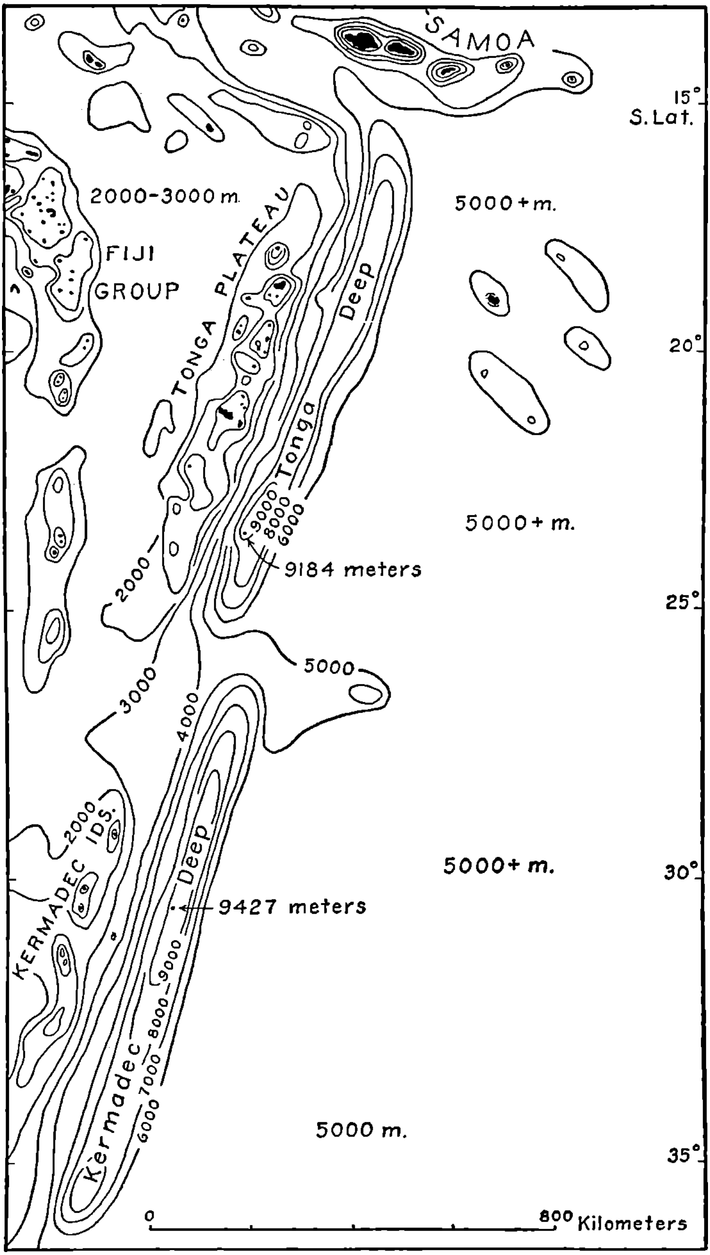
The threat of wholesale foundering of the crust would be serious if the crust were thin. For example, suppose the thickness to be only a few tens of meters. Because of the small pressure on the substratum, this melt, with a temperature of at least 1000° C., would be decidedly fluent. The hypothetical crust itself would have an average temperature approaching red heat, and therefore would be weaker and more plastic than the existing, much cooler crust. If these conditions prevailed over the whole globe, and if there were no disturbing forces at work, the thin crust might conceivably be stable. As a matter of fact, the crust of solidified paraffine on a dish of molten paraffine remains in place, even though the solid is denser than the liquid beneath.

But throughout geological time the earth's crust has been heterogeneous and it has been disturbed by tidal and other external forces. Still more important is the enormous area covered by the imagined thin crust, when compared with its thickness. This relation between area and thickness is a vital element in the mechanical problem, for the power of a very thin crust to resist down-bending and ultimate engulfment is small. Hence, as Lord Kelvin argued, wholesale foundering was inevitable during the first stage of the earth's refrigeration, when the crust was exceedingly thin, if not discontinuous. A stable crust could not be formed until the solid-liquid convection had chilled and crystallized the greater part of a thick, outer layer of the planet. Theoretically this change is dated long before the Basement Complex was developed.

For a crust 60 kilometers in thickness the situation is quite different. The existing crust is much too strong to bend down under the forces set up merely by the difference of density, and, unless it is bent down locally, there is no force to compel engulfment. Moreover, since, in the nature of the case, the down-bending is necessarily localized within a narrow belt, the size of the earth becomes of relatively little significance. It is a question of the bending strength of the crust, as measured by any local loads that may be placed upon it by outflow of the substratum lava.

One evidence that the crust is strong enough to resist considerable loads was presented (page 80), when we studied the deep-sea troughs and other open geosynclines, major downwarps, where the crust steadily resists powerful pressures tending to flatten out those downwarps. Compare Figure 64 and also Figure 147, a map of the remarkable Tonga and Kermadec Deeps, which for a length of 1400 miles interrupt the flat floor of the Pacific. From the contour-lines for depth we see that the plummet has to drop more than 8000 meters or five miles before touching the deeper parts of these troughs. At the Tonga Deep, apparatus designed to measure the force of gravity has proved just such deficiency of matter under the Deep as that expected if the earth's crust was here pressed down, and thereafter has been held down by the strength of that crust.

Further evidence comes from gravity measurements on the deep-sea islands. The gravity pendulum shows that these piles of lava are largely masses in excess, that is, extra rock placed on the crust where it was originally in equilibrium and not stressed by local weights. So it is, for example, with Bermuda, which is a volcanic cone, camouflaged by a thin coating of shell limestone. In the same way it has been shown that Saint Helena Island, Ascension Island,



147. Map of the Tonga and Kermadec Deeps. Depths in meters.

Hawaii Island, and Oahu Island represent huge loads of lava on the crust, which are supported largely by the strength of the crust. It should be noted that these more or less circular loads have wide spans, reaching as much as 400 kilometers in the case of Hawaii, the biggest of all the composite volcanic cones of the earth.

Many of the great atolls of the intertropical belt seem best regarded as shallow crowns of coral and associated organic growths, resting on volcanoes of the same order of size as those just mentioned, but old enough to have been completely truncated by stream erosion and wave erosion long ago. (See Figure 31.) Although these older piles of lava have lost much substance, they too probably represent heavy loads on the sub-oceanic crust. Yet the underwater topography of the atoll structures and especially the remarkable flatness of their lagoon floors show that the underlying cones have not subsided in any systematic way for at least a million years. There the crust has been able to resist plastic basining and important breaking-down under enormous weights.

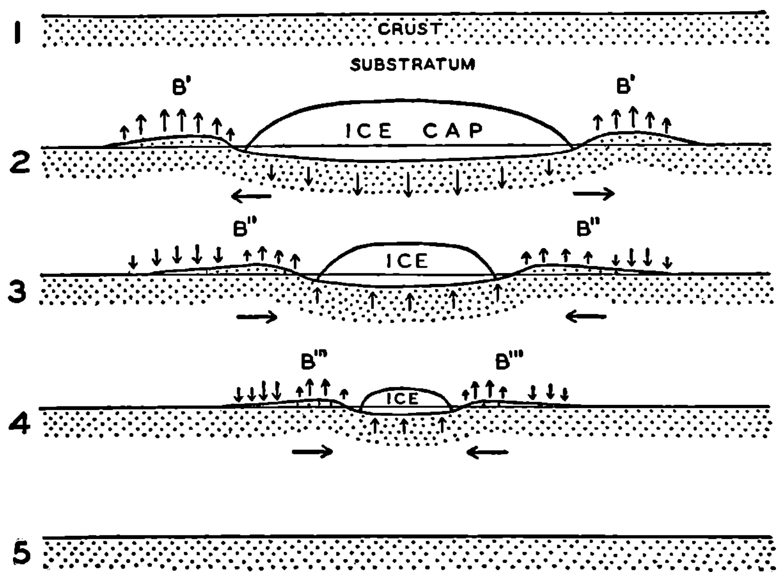
Other witnesses to considerable bending strength are some regions where, during the Glacial Period, ice-caps were wide, thick, and weighty. Those on the Faroe Islands of the Atlantic and Kerguelen Island of the Indian Ocean are illustrations. On the other hand, a dozen caps with larger diameters did bend down the crust plastically. From this difference of effect it is possible to get a rough idea of the relation between the limiting span of a surface load which can cause plastic, non-elastic basining of the crust. It is worth while to glance at a few details in these experiments made by Nature, experiments that throw light on the conditions for crustal stability.[1]

In every case where geologists have proved basining under the load of ice, the span of the load was more than 300 miles or 500 kilometers, and the thickness of the ice at the center of the cap exceeded 1000 meters or 3300 feet. For example, the nearly circular ice-cap on northwestern Europe had a minimum diameter of more than 1000 miles, and its central thickness was more than 7000 feet. Urged by this gigantic weight, the rocky floor was basined, sinking

[1] R. A. Daly, *The Changing World of the Ice Age,* New Haven, 1934, p. 112; The Strength of the Earth's Outer Shells, *American Journal of Science,* volume 35, 1938, page 406.

considerably more than 1000 feet at the center of the glaciated area. And, after the ice melted with removal of the load, the sluggish earth slowly responded; the crust was warped up, nearly to the position it had before the Ice Age.

The cross-sections of Figure 148 will in principle illustrate the course of events. At the top we see a horizontal line, representing the level surface of the ground before the load of ice was applied. The curvature of the earth is neglected. In Section 2 arrows are



148. Diagrams to illustrate basining of the earth's crust under an ice-cap, and also recoil of the crust after the ice has melted away.

drawn to show the downward displacement of the rocky surface under the ice-cap, and other arrows show, with great exaggeration, the much smaller upward displacements that made a low peripheral bulge around the cap. Section 3 portrays the immediate effect of the removal of the ice by melting; there was a prompt, elastic uplift of the whole region, including the peripheral bulge. Then follows stage 4, when much of the delayed, plastic uplift within the basined area had already taken place. A corresponding drop of the surface in the peripheral belt accompanied the central upwarp. After a long period of time the highly viscous earth has returned nearly to equilibrium. When the return shall have become complete, we have stage 5, where the surface has the original form of stage 1.

In reality Scandinavia has not yet quite reached equilibrium. The uprise in the basined regions still continues—at the center with a measured rate of about one meter or 3.3 feet per century.

Similar basining and recoil have affected most of the still larger area that was covered by the last ice sheet in North America.

The upheaval of Scandinavia is due to inflow of the material below the flexible crust, and it has been shown recently that this material has exceedingly small strength, if indeed it has any strength at all. Herein we have one of the most eloquent suggestions of a non-crystalline or vitreous state for the substratum.

The fact of plastic distortion of the crust under ice-caps of wide span does not conflict with the fact that there was no apparent basining under the Faroe Island and Kerguelen Island ice-caps. The difference of behavior becomes understood in the light of a law of physics: the maximum shearing stress in a loaded plate increases directly with the square of the radius of the plate. The two ice-caps just named had relatively small spans, and the crust beneath them was able to resist the moderate stresses involved. It is probable that the diameter limiting the size of the ice-caps of the great thickness characteristic of those in the Glacial Period, but ineffective in producing plastic deformation of the crust, is somewhat greater than the diameter of either the Faroe cap or the Kerguelen cap.

Combining the evidences from deep-sea troughs, gravity studies on master volcanoes, and the physical history of glaciated regions, we seem entitled to believe that the earth's crust can sustain a bending force measurable in scores of atmospheres, if the region subjected to the force is no more than 200 miles or 300 kilometers in diameter.

A mantel shelf furnishes an analogy; the shelf does not continue to bend down under the weight of a clock, placed near its edge.

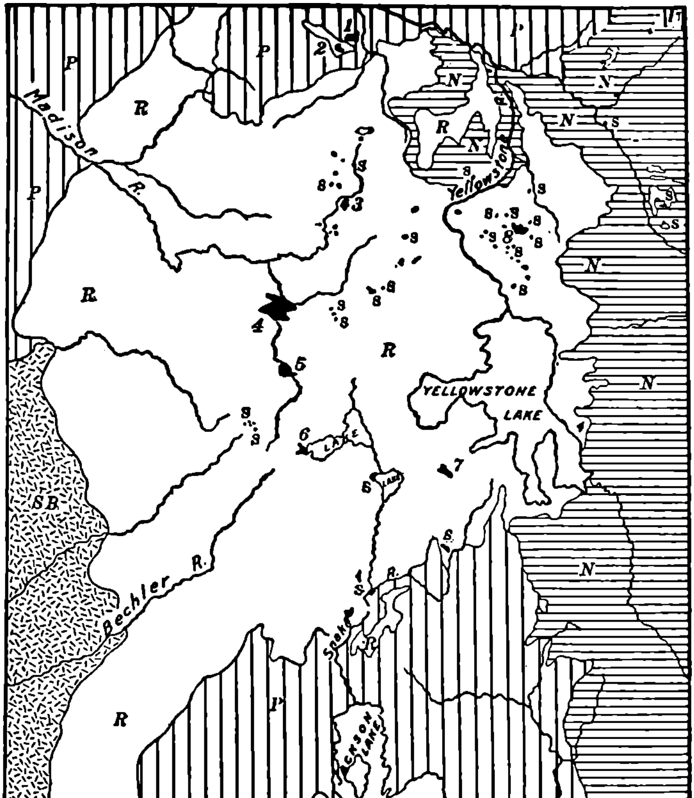
We now make specific application. The crust of the earth is quite secure, so long as its surface is not covered to the depth of many miles by a single flood of basaltic liquid, transferred from the substratum. The crust would sink because of that transfer, that is, because of the removal of so much underpinning, but the crust would not continue to bend down under the new load on its surface. As a matter of fact, dangerous flooding is resisted by the strength of the crust. Moreover, the normal flow of liquid basalt does not run more than a few tens of miles before freezing, so that the area actually covered by a flood of the lava, while the feeders are still liquid, is correspondingly limited. Even if local major stoping takes place, the crust around the wounded region is too strong to be pulled down by the difference of density between crust and substratum, with general foundering as a result.

And there are other guarantees of crustal stability. One of these is the self-healing property of the crust. Except along mountain belts, the through-going, liquid abyssoliths are comparatively narrow. See Figure 92. Because narrow, the dike-like abyssolith is chilled quickly and therefore solidifies quickly. Therewith the passage to the earth's surface is sealed, and the outflow of lava there comes to an end. Any unbalanced pressure tending to urge additional liquid to the surface—it can not be a great pressure—is counterbalanced by the strength of the frozen plug occupying the upper part of the fissure. We conclude that the crust is not in even theoretical jeopardy for more than the limited time needed to freeze part of an abyssolith. Here the demon of destruction has to race with time, and loses the race.

Suppose, however, that an abyssolith is locally so wide that it can continue to emit flows of substratum basalt for many thousands of years. In the fourth chapter we noted the result: the growth of a high cone or dome, threaded through with a central column of liquid lava. We found that, when the top of the liquid column reaches a height nearly that of Mount Etna, the weight of the column equals that of the crust alongside. Hence, if the column is still in hydrostatic communication with the substratum, the column must act like a hydraulic press and restore full supporting pressure to the crust.

Finally, belief in general stability for the crust of our earth-model is strengthened as we study an analogy. Bodies of liquid granite, which we have learned to call batholiths, have invaded the roots of mountain chains. Many batholiths, like that of the Sierra Nevada of California, have widths of tens of miles. See Figure 131. Although no floors are visible, the thicknesses of the liquid masses are known to have exceeded a mile. Their surfaces have the form of gently curved, almost flat-topped domes. Their roofs of solid rock varied in thickness from a few hundreds to a few thousands of feet, relatively small figures. Now the density of the molten granite was about 10 per cent smaller than the average density of the roof rock. This difference represented a potential menace to the roofs. Yet geologists agree that foundering of roofs has been exceedingly rare.

In fact, there is only one instance that is strongly suggested by direct observation. It is found in the Yellowstone National Park, represented by the map of Figure 149. There, the area left blank



149. Map of the Yellowstone Park, showing its 4000 square miles of rhyolite (originally extrusive granitic liquid).

(4000 square miles) was flooded with a lava called rhyolite, which was really molten granite. The famous geyser basins are situated at the places marked with numbers 3 to 7. At those marked with the letter "S" are some of the abundant hot springs of the more ordinary kind. For at least a quarter of a million years, geysers and hot springs have been playing on this marvelous plateau. The exploding steam is chiefly rain water and snow water, which sinks into cracks in the rhyolite, there to become heated far above the temperature of boiling. Thus the rhyolite has been steadily chilled for at least a quarter of a million years, and yet the heat conducted upward and the still more efficient heat brought up by gas emanating from moderate depth have sufficed to make steam from cold, imported water, and to superheat that steam. No other source for the heat except a mighty batholith, erupted in recent geological time, seems adequate. It seems further necessary to assume that, when liquid, the batholith tore its way open to the sky, the great central part of the mass being still exceedingly hot. In other words, we picture a case of actual, local foundering of the roof of a batholith. On the other hand, there is some field evidence that a large part of the roof did not founder.

However, even if part of the roof of the Yellowstone batholith did founder, we should here have merely an exception, proving the rule of stability for the roofs of batholiths.

The spread of any batholithic roof is small when compared with the area of the earth's crust, but this aid to stability in the former case is largely offset by the thinness of the roofs, and by the fact that the difference of density between roof and underlying liquid is much greater than the difference of density between crust and substratum. Moreover, the crust has a third advantage, since the great excess of average pressure on its rock gives this rock more than double the strength of the roof of a liquid batholith. Balancing all factors in the problem, it appears right to use this analogy from batholiths as an additional reason for assuming general security for the crust of our earth-model. On the other hand, the same principle of potential instability was, in the third chapter, used to explain mountain chains, where local collapse and foundering, major stoping, was postulated. Only within those narrow zones did the potential instability become actual, and each instance of this was merely another exceptional item, proving the rule of general stability for at least the last half billion years.

Maintenance of the Earth's Relief

We now pass to the second principal inquiry of this chapter. How is the topographic relief of the crust sustained? Part of the answer is obvious. A sky-scraper is kept upright by the strength of steel and concrete. The cliffs of the Yosemite National Park persist because their granite is strong and able to oppose the permanent tendency of the granite to flow down, under gravity, and fill the famous valley. Also because the rock is strong. Hawaii projects nearly 14,000 feet above sealevel and five miles above the bottom of the Pacific; the Alps continue to look down into Italy (Figure 150); and North America does not flow away to the floors of the Pacific and Atlantic oceans.

And yet this is far from being the whole story; for it can be shown that stable support for the parts of the crust represented by high mountain chains and by continents is given largely by flotation. Here the analogy of a raft in water is relevant.

We recall that, when a mountain chain is formed, the relatively light rocks of the geosynclinal prism and of the Basement Complex beneath were crumpled, thrusted, piled together, and thus thickened in the belt of paroxysmal movement. The mountain chain has a root, made of rock that is less dense than the average rock alongside. During the process of mountain-making the crust was thoroughly broken. It was further weakened by injection of liquid basalt from the substratum, and perhaps to a still greater degree by major stoping. Under such circumstances the light root could not fail to grow down to an abnormally deep level, that is, become lengthened in the vertical direction. On each side of the mountain chain, however, the crust retained its usual layering. And, again because of the local weakening of the crust, the deep mountain-structure soon reached approximate equilibrium with its environment. From the beginning the mountain-structure was not far from being in a state

150. The Matterhorn and Dent d'Hérens.

of true flotation. It was, and still is, floating in the crust, a positive buoyant pressure being supplied by heavy rock of the crust outside the mountain-built zone.

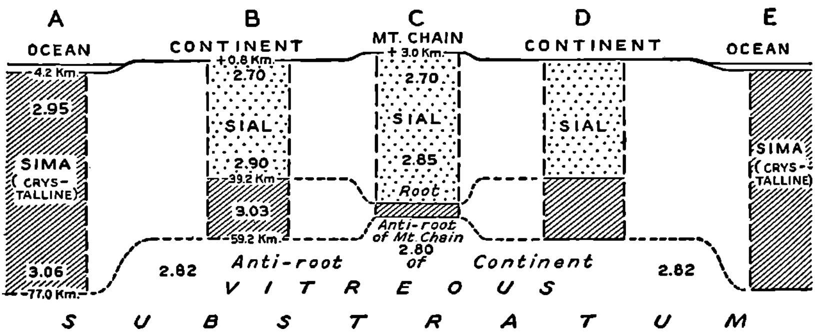
In like manner the continents are kept floating, high above the ocean floor. They float, partly because the continental sectors of the globe include, at top, about 40 kilometers of the light Sial, which is balanced by a thinner layer of crystallized, heavy Sima at top of each oceanic sector. See Figure 151. On the other hand, Nature's fundamental experiments with ice-caps show, of themselves alone, that no continent can be permanently held up many meters by the strength of the earth's body. Later on we shall note the proofs that rock material has little or no strength at depths greater than about 80 kilometers or 50 miles. This result of special investigation in the field is of interest, since it represents another test favoring the crust-substratum hypothesis, but for the moment we are concerned with a by-product of the investigation. Thereby it has been demonstrated that the buoyant support of each continent is largely supplied within the crust.

Thus we have found two reasons why the rocky surface of the earth has varied relief. One reason is the inherent strength of rock, and the other reason is the fact of flotation, lighter parts of the crust being positively buoyed up by the heavier parts of the crust.

There is a third reason implied by our earth-model. The thickness of the crust has been roughly estimated through an extension of the law of increase for temperature with increase of depth below the surface, as observed at deep borings. The rate of the increase has been measured only on dry land. The rate under the ocean is smaller, if geophysicists are right in their conclusion that the continental crust is more radioactive than the sub-oceanic crust. Allowing for such difference and also for the difference of conductivity of heat in Sial and Sima, we can make a crude estimate of the depths at which basalt should be vitreous, that is, too hot to crystallize. Such a computation has given about 60 kilometers for the thickness of the continental crust and about 80 kilometers for the thickness of the crust under the deeper part of the Pacific Ocean. Under the Atlantic the crust should be less than 80 kilometers thick; under the low continental plains, a little more than 60 kilometers thick;

and under the high, deep-rooted mountain chains, less than 60 kilometers thick.

In more detail the results of this attempt to take a mental look underground are represented by Figure 151. It is a diagrammatic cross-section of a continent containing an extensive mountain plateau of the Tibetan type, 2200 meters higher than the average surface of the continent and, like the continent, considered to be flat, without the accidents of valleys. Sections of the cheese-sampler kind are represented in the columns marked A to E. Sections A and E refer to the ocean where 4200 meters is average depth. Sections B and D typify those of the continent outside the plateau area, and section C that of the plateau itself. The Sima or crystallized "gab-



151. Section of the continental crust in balance with the suboceanic crust; approximate densities; roots and anti-roots.

broic" rock is indicated by inclined shading; the Sial by stippling. The vitreous basalt, Sima of the substratum, is left blank.

Although exact values can not be given, a set of reasonable densities is indicated with figures. With those densities all five columns have approximately the same weight at the depth of 77 kilometers below sealevel. Below that depth, then, the substratum is in almost perfect hydrostatic equilibrium, as expected if its strength is zero or close to zero.

The longer, continental columns of rock are nearly or quite balanced by the shorter, sub-oceanic columns of rock plus the cover of sea water. Similarly the three continental columns balance one another. The Sial of the plateau section extends downward 7800 meters deeper than the Sial of normal thickness. The mountain plateau is in part held up by the buoyancy of this root, but in part it is also held up by the buoyancy of the substratum glass immediately below that root. This lowest division of column C may be called an "anti-root," since it is an upward projection of the substratum material directly beneath the downward projection of the Sial of the root.

The same convenient name may be applied to the analogous upward projection of the substratum under the continental Sial in general.

Thus the earth's major reliefs are assumed to be compensated by two kinds of difference of density. A block of mountains is kept high by its root and anti-root. The visible part of a continent is supported by the Sialic root and by the anti-root of that continent. The sea floor is kept low because the crust is there thickest and densest.

Now we may conceive the buoyant support given by a root as concentrated at a single level; and that given by an anti-root as concentrated at a deeper, single level. The approximate position of each of the two levels can be calculated. From the result a level is found, where, if both kinds of buoyancy were concentrated, the relief of the crust would be fully supported. At that intermediate level is what we now regard as the "center of gravity" of the entire compensation of the relief.

Actual computation puts the center of gravity of compensation in all five columns at a depth not far from 40 kilometers below sealevel. We keep this figure, 40 kilometers, in mind, for we are going to compare it with the depth of compensation for the earth's relief, as derived from measurements of gravity by the geodesists. In fact, we have now arrived at a conclusion which suggests a new way of putting our earth-model on trial.

Both the plumb-line and the gravity pendulum are being used to indicate horizontal change of density in the earth's crust. Hence by each of these two geophysical methods the picture of Sial and Sima, just drawn, can be checked. Elaborate studies of the kind have already yielded results full of meaning.

At any point on the surface of the earth the plumb-line is a line at right angles to a level surface and passes through the zenith. At the same point the line makes a certain angle with the direction of a distant star. Suppose, now, that an extra mass of rock is placed alongside the point in question and centering in the vertical plane that passes through the star. The extra mass would attract the plumb-bob toward itself, so that the plumb-line would then make a small angle with the direction it had before the extra mass was placed on the earth. This small angle measures the so-called deflection of the plumb-line, due to the attraction of the extra mass. In principle, masses of abnormally dense rock just below the earth's surface similarly deflect the plumb-line. Abnormally light masses deflect it in the opposite sense. Hence we have an instrumental method of detecting irregularities in the distribution of density and mass within the earth's crust.

Again, since a pendulum swings at a rate depending on the force of gravity, it must in the course of a day make more vibrations over a specially dense part of the crust than it would if swung over an equal volume of lighter rock at the same level. At any locality the rate of swing, by taking the average of many vibrations, can be got with great accuracy. That rate enters a simple equation giving the operating force. When the values of the force, as it varies from point to point, are plotted on a map, it becomes possible to deduce the distribution of rock densities below, but relatively near, the earth's surface.

Both plumb-line and gravity pendulum have been used in the process of determining the shape and size of the earth, a complex investigation which has a whole science, geodesy, to itself. Among the results of such observations is proof that as a rule the relief of the globe is compensated by variation of rock density in the horizontal direction. Analysis of the observed facts has also shown that the horizontal variation of density is almost entirely restricted to a superficial earth-shell, no more than about 80 kilometers or 50 miles in thickness. Furthermore, geodesists have located the center of gravity of the compensation for the normal height of a continent above sealevel. The depth of that center of gravity, thus computed, is about 40 kilometers. How the geodesists have reached their results may be briefly indicated.

As far back as 1749, Pierre Bouguer had found that the Andes Mountains do not attract the bob of a plumb-line as much as their volume and density demand. Six years later R. J. Boscovich accounted for the fact by assuming a relatively low density for the rock beneath the mountains. For a century little attention was paid to his idea. In 1855 G. B. Airy, Astronomer Royal of Great Britain, made it specific by postulating roots of relatively light rocks under the mountains, and in 1859 Archdeacon Pratt offered the alternative suggestion that the comparatively low density under the Himalayas, a type for the high mountain ranges, is due to local expansion of the rock composing the earth's outer skin. He gave no reason for the expansion, which he called "attenuation." Although the explanations differed, both Pratt and Airy made finally clear the fact that each mountain range as a whole is held up by flotation in the denser, surrounding rock of the crust.[2]

It was natural to inquire whether the protuberance of continents above the floor of the ocean can be similarly understood. An adequate answer to this question had to await the twentieth century, when suitable apparatus for field observation was first perfected.

The detection of horizontal variation of density in the outer part of the solid earth, whether by the use of the plumb-line or by the swinging of the gravity pendulum, depends upon knowledge of the shape and size of the globe. Moreover, the shape and size must be definable by a simple mathematical expression. The so-called reference figure of the earth is, in fact, so described in the technical literature.

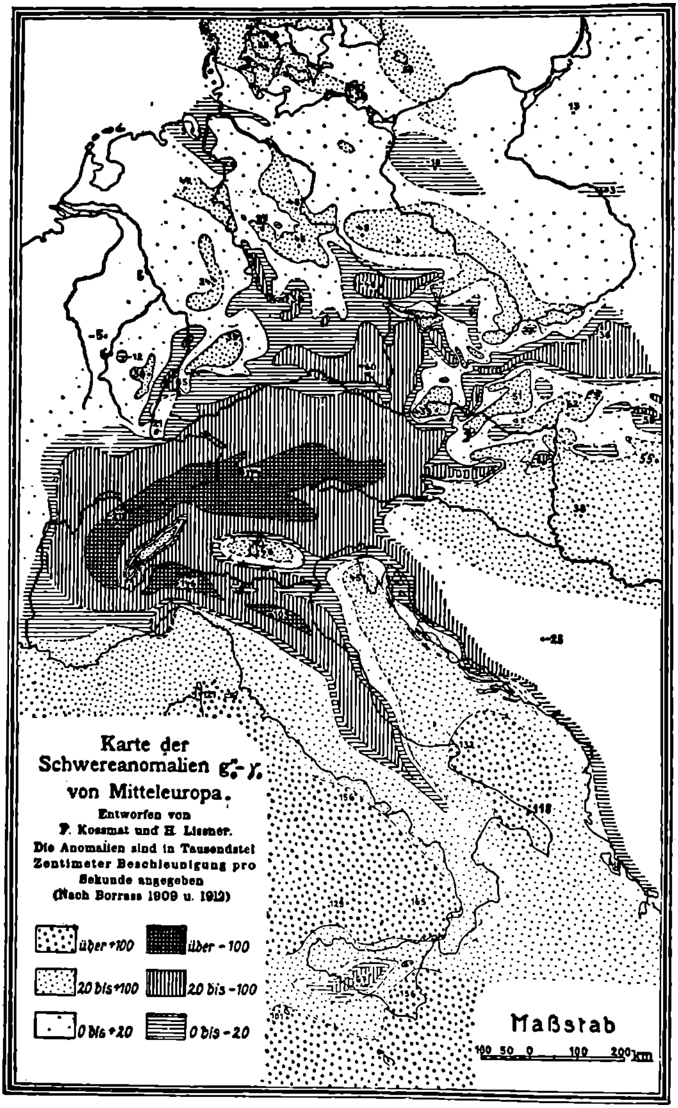
There is no such thing as a definite shape of the earth in a physical sense. This is obvious when we think merely of the eternal dance of the atmosphere and ocean water. The investigator of gravity is therefore compelled to be arbitrary. He seeks a mathematical formula that shall be wieldy for practical use, and yet shall fit closely the average dimensions that the planet would have at the surface of an undisturbed ocean. He must also devise a method of locating the same level, as it disappears under the rocky continents and islands.

[2] P. Bouguer, *La Figure de la Terre,* Paris, 1749, p. 391. R. J. Boscovich, *Voyage Astronomique et Géographique,* Paris, 1770, p. 463. G. B. Airy, *Philosophical Transactions Royal Society of London,* vol. 145, 1855, p. 101. J. H. Pratt, *ibid.,* vol. 149, 1859, p. 745.

On account of the earth's rotation on its axis, the shape of the sealevel can not be spherical, but must closely approach an ellipsoid of revolution, that is, the three-dimensional figure generated by the rotation of an ellipse about its minor or shorter axis. With their wonderfully accurate instruments geodesists have proved that the sealevel figure does nearly coincide with an exact ellipsoid of revolution. This so-called Standard Ellipsoid (Spheroid) can be used for measuring local deflections of plumb-line and also local abnormalities in the force of gravity at the surface. For our purposes it suffices to consider in any detail only the teaching of the vibrating pendulum.

Assume the pendulum to be swung at a point high in a mountain range, a point whose latitude and longitude are known. The height of the station above sealevel is assumed to have been determined by precise leveling. From the time taken by the pendulum to make one oscillation, what is called "observed gravity" at the station is calculated. Because the earth's gravitation varies inversely with distance from the center of gravity, the observed amount of the force would be increased if, while the attraction of the mass above sealevel is still included, we imagine the pendulum to have been swung at that level and directly below the station. We now compare the value of observed gravity, so arbitrarily increased, with the value which gravity should have at the same latitude and longitude on the Standard Ellipsoid (or Spheroid). The difference between the two values is the so-called "Free-air Anomaly."

Useful information regarding the distribution of densities is got when at each gravity station the attraction of the rugged topography above sealevel and below the station is subtracted from the value of gravity obtained by the arbitrary Free-air reduction. We then have a new reduced value which may also be compared with the value on the Standard Spheroid. The difference between these two values is called the Bouguer Anomaly, from the name of the celebrated French geodesist. In high mountains the Bouguer anomalies are systematically negative. This means that above a limited depth the rock of the crust has smaller attractive power and lower density than rock normally at the same range of levels. Figure 152 shows by shading the Bouguer anomalies under Alps and Apennines. The intensity of



152. Bouguer gravity anomalies in central Europe. After A. Born. Courtesy of Das Firma Julius Springer, Berlin.

the shading is proportional to the increase in the negative values for the anomalies. We see that the central and higher parts of the mountain ranges have the largest negative anomalies. Here, then, is direct evidence of roots of relatively light rocks under Alps and Apennines.

In principle and on a much grander scale the same result was found when many hundreds of Bouguer anomalies were plotted on a map of the United States, from Atlantic to Pacific and from Canada to Mexico.[3] It became at once clear that as a whole the country is underlain by rocks of smaller density than the rocks down to the same (moderate) depth under the oceans, the average density of this more superficial rock in the United States being at minimum under the Western Cordillera, where there is maximum height.

Thus the gravity pendulum corroborates a conclusion, won from both geological and seismological observations: the continents are floating in the denser crust-rock that surrounds them. In a sense, then, the continents also have roots.

But the Bouguer anomalies can not give us what we want, namely, the actual thickness of each root, whether of mountain range or continent. Here valuable data have been supplied by the geodesists, as an incidental result of their study of the figure of the earth. In order to understand the values of gravity at their thousands of stations, on land and at sea, they have tried several theories of the underground arrangement of densities. Particularly elaborate have been the discussions of the Pratt theory of "attenuation" and of various forms of the Airy "root" theory. No matter what theory was adopted, it was found that the center of gravity of compensation for the earth's relief averages 40 to 50 kilometers below sealevel. We remember, now, that the deduced center of compensation for continent or mountain range, when controlled by root and anti-root, is about 40 kilometers below sea. Since none of the geodesist's theories of the compensation can be quite correct, and in view of the merely approximate character of the values assigned to the densities of the rocks of the Sial and Sima, it appears that our

[3] W. Bowie, "Investigations of Gravity and Isostasy," *Special Publication No. 40, Coast and Geodetic Survey,* 1917, Plate 13.

earth-model meets fairly well this new geophysical test, that provided by the gravity pendulum.

Extensive and expensive studies of the deflections of the plumb-line, studies also founded on the Pratt and Airy theories, have yielded the same order of average depth for the center of compensation. And again the depth is not significantly different from that won when the compensation is attributed to root and anti-root.

Finally, all of the methods of diagnosis agree in discovering that for at least some distance below the depth of about 80 kilometers the material is practically in, or close to, the hydrostatic state.

In conclusion, it seems not too much to say that geodetic research supports the geological evidence that the earth has a heterogeneous crust resting on a nearly or quite homogeneous, hot, and therefore non-crystalline substratum.

GENERAL SUMMARY

A WORD in retrospect. At first we traveled over the earth, collecting facts, and we then tried to reduce those facts to system. In imagination we built an ideal earth and then proceeded with the long inquiry whether a planet so constructed should respond to forces as the real earth has actually responded. Our aim has therefore been double: on the one hand to summarize facts about the real earth; and, on the other, to attempt a matching of those facts with the reasoned or deduced behavior of our chosen earth-model through geological time.

One vast display of facts was glimpsed, when, as in the first chapter, we joined the gods above the blue sky and watched the earth as it spins. We saw water with volume enough to drown all lands two miles deep, if the rocky globe were smoothed. Yet out of the dazzling ocean we saw the green, gray, and brown continents and islands lift their heads from the smothering flood. We saw the upstanding continental bucklers, here and there mantled with shallow Seas of Transgression and more deeply penetrated by Seas of Ingression. On both continent and sea floor, plateaus, mountain chains, geosynclines, and geosynclinal prisms were identified. We could see a little below each continental surface and learned of the Basement Complex and its spotty cloak of sedimentary rocks, lavas, and ice-caps. We distinguished two kinds of deep-sea islands: one kind essentially basaltic and of volcanic origin; the other kind partly volcanic and basaltic, but harboring rocks characteristic of the continents. We learned that locally rocks of continental type exist also under the sea, far from any land.

From the lofty perch in space we sensed many mysteries. Of them we selected four problems for study: mountain-building, the eruption of lava, the diversification of lavas, and the stability of continents and island masses. And we have asked our earth-model to clarify these four mysteries.

The secret of each is in the depths of the earth. We plumbed those depths with human instruments, the seismograph and the thermometer. We read Nature's messages from below: lava flows, earthquake waves, and body waves of tidal origin. We watched Nature perform colossal experiments with ice-caps, piled on the continents. We added laboratory experiments on the strength and elasticity of rocks, on the mechanics of mountain-making, on the eruption of lava, on the origin of the non-basaltic lavas, and on the properties of glass. We returned to the open spaces, with plumb-line and gravity pendulum, to discover why continents look down on the sea floor, and why mountains look down on the plains. And we asked the astronomer for his contribution regarding the physical nature of the planet.

Qualitatively, by field observations, and quantitatively, by controlled experiments, we have tested the earth-model. From both sources seems to come evidence of a composite, solid crust, overlying a vitreous, basaltic substratum—with strength in the one and extreme weakness in the other. The substratum is ready to move under steady pressure, even small pressure. The crust stubbornly resists until the pressure grows strong. The crust can slip along the weak substratum and crumple itself into mountain-structures. The much more mobile substratum can send tongues of itself high up into the crust and make volcanoes and batholiths. The density of the crust varies from low plain to mountain and to ocean basin, and varies so that the crust is securely balanced on the earth's body.

Thus we created the earth, an ideal earth, and we too created it out of chaos. Our chaos is the welter of observations described by the field geologists. Many of the records of fact shine with the pure gold of clearly derived meaning for both philosophy and practical life, but the meaning of countless other records must continue to elude us until they are brought into relation with the earth as a whole. Clouds of uncertainty and mystery will lift and roll away if we can discern the essential nature of our evolving planet.

That vision is not assured by science in its present state, but it is no less true that trial of different conceptions of the earth's body is the best guide to Pisgah. One particular mental picture of the underground and its potentialities has been boldly drawn. It can hardly be correct in details; yet it seems to make a basis for correlating the chief facts and principles of geology. However, a clearer sanction for expending thought on one earth-model is found in its direct call for alternative models and for their systematic examination.

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