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VOLCANOLOGY

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Division of Physical Sciences
with the Cooperation of
Division of Geology and Geography
and
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FOREWORD

It is generally agreed that more attention should be given to research in the middle ground between the Sciences. Geophysics—the study by physical methods of the planet on which we live—is a conspicuous instance of such a middle-ground science, since it shades off imperceptibly in one or another direction into the fields of physics, astronomy, geology, to say nothing of biology, with which the subject of oceanography is closely connected. Some branches of geophysics, such as meteorology, terrestrial magnetism, geodesy and oceanography have long had a more or less independent existence, but it has become increasingly clear that these subjects, and many others, are all parts of geophysics. For various reasons, among which may be mentioned the development of geophysical methods in prospecting for oil and minerals, there has lately been a considerable development of interest in geophysics, but this development has not been matched by the publication in English of systematic treatises on the subject. With these ideas in mind, Dr. J. S. Ames, during his term as Chairman of the Division of Physical Sciences of the National Research Council, was instrumental in organizing in 1926 a large committee to prepare a series of Bulletins on The Physics of the Earth, the purpose being "to give to the reader, presumably a scientist but not a specialist in the subject, an idea of its present status together with a forward-looking summary of its outstanding problems."

In due course sub-committees were formed to prepare reports on the following subjects:

- The Figure of the Earth
  - Gravity, Deflection of the Vertical and Isostasy
  - Tides, Ocean, and Earth
  - Variation of Latitude
- Seismology
- Terrestrial Magnetism
- The Age of the Earth
- Field Methods for Detecting Unhomogeneities in the Earth's Crust
- Internal Constitution of the Earth
- Meteorology
- Oceanography
- Volcanology

That this project, as ambitious as it is important, is now coming to fruition with the publication of these Bulletins is due partly to the skill and farsightedness with which Dr. Ames selected the committee and assisted in outlining its program; partly to the care and interest with which Dr. Ames' successor, Professor Dayton C. Miller, directed the committee's activities during his term as Chairman of the Division; and particularly to the devotion with which the Chairmen and members of the several sub-committees have carried out their respective assignments. The hearty thanks of the National Research Council and of the readers of these Bulletins is due to the several authors for their efforts.

The volumes will appear serially in the Bulletin Series of the National Research Council, with no particular regard as to sequence, each volume being issued when ready.

INTRODUCTORY

Volcanology has hardly yet attained independent recognition for itself as a separate branch of science, like meteorology or seismology, nor has it been formally welcomed into the family by physics or chemistry. The number of its votaries has always remained small and of somewhat diverse experience and view-point. This fact has had the effect of making the steps which have constituted its progress appear somewhat sporadic and isolated, sometimes directed from one quarter and sometimes from another, with little correlation and practically no evidence of organized effort.

An instance will perhaps illustrate the point in mind. It has been the habit, firmly established since the earliest mention of volcanoes began, to describe and to classify them according to the form or height or some other conspicuous feature of the great explosion cloud, which gives to volcanoes their distinguishing character among mountains and inspires every witness with awe, sometimes with fear, of them. When Perret, a few years ago, modestly called attention to the fact that the appearance of a steam cloud might depend quite as much upon the temperature and moisture content of the surrounding air as upon the chemical content of the emanation, it attracted little interest or attention. He even went so far as to give instances from his own observations at Stromboli, where the entire cloud was often and obviously due merely to a change in the weather which brought a moisture-laden wind into the stream of invisible dust particles above the crater and produced visible condensation. Nevertheless, so far as the present writer is aware, this observation is not quoted among the conclusions of dominating importance in volcanism and the "pillar of cloud" continues to guide the footsteps of the occasional volcanologist of today with as little question as in the days of the wandering Children of Israel. The reason of course is that few volcanologists attach significance to a background of meteorology in discussing the volcano cloud and so fail to recognize out of their own experience any tangible validity or importance in Perret's conclusion, although to students who have acquired this background it must at once appear vital to any appraisal of the gas phase of volcanic activity.

The writer has had a somewhat similar experience. In the long course of studies in the Geophysical Laboratory of the water found in solution in all rocks of igneous origin it has been abundantly demonstrated that these silicates *in the magma* can and do contain several per cent of water. It has also been clearly shown by Washington's Tables of Analyses that no such quantity of water (not more than one per cent) remains after the rock has crystallized from the magma. To the physical chemist, therefore, it is a perfectly natural and obvious conclusion, supported by many and varied laboratory illustrations, that this excess of water will presently be discharged from solution when crystallization takes place and also that it must reappear in some other appropriate place or relation. If the cooling magma is near the surface where the restraining pressure is not too great it will be obvious to him, where another may fail to find enlightenment therein, that in this discharge of water during the crystallization of such a silicate solution lies the long-sought source of the paroxysmal volcanic steam explosions which take their toll of human life and physical property. But if the closest students of volcanology happen not to be interested in these physico-chemical phases of volcanic activity then the suggestion is likely to pass into history without noteworthy reaction of any kind.

For this reason, namely, that there are so many directions of approach along all of which progress is necessarily slow and often fitful, there is not today any considerable body of well-correlated, substantive fact available and generally accepted which can be called the scientific background or foundation of volcanism. Most of the generalizations which are today applied in this field of activity still partake of the nature of individual opinion to which general consent has not yet been given.

For this reason, primarily, it has not seemed wise to offer a single review of the field of volcanism to be coordinated with other chapters, such as meteorology or seismology, which will together present the existing state of our knowledge of earth physics. If it be true that volcanology is not yet a science in the sense of having a well-correlated body of underlying observed fact, but if, on the contrary, it is still made up of individual "views" or hypotheses, then the student will attain to a better picture of this phase of earth physics if several representative modern views of volcanism can be arrayed before him.

With this purpose in mind, three distinguished students, members of this Committee, representing three different countries, have undertaken the task of formulating a modern and comprehensive answer to the fundamental question in volcanism, namely, "What is the mechanism of a volcano?"

It is appropriate for the Chairman to say at the outset that the three students whose presentation of the current views of volcanism form the body of this chapter are not only distinguished for preeminent investigations in this field, but they are among the few investigators who for many years have concentrated their entire attention and the resources of competent laboratories developed for the purpose, upon the continuous study of this subject *on the ground.* Two of these laboratories (those of Dr. Friedlaender and Dr. Jaggar) are located almost at the brink of two of the world's most famous volcanoes (Vesuvius and Kilauea). All the volcano world has been at different times the laboratory of the third (Dr. Sapper). The Committee therefore offers these discussions with unbounded confidence in their stimulating power in a field of activity which greatly needs and still awaits a powerful, well-ordered attack from the viewpoint of high-temperature, high-pressure physics and chemistry and which is, withal, one of the most interesting and important research fields in all geology.

ARTHUR L. DAY,
Chairman, Committee on Volcanology.

May 11, 1929.

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CHAPTER I

VOLCANOES, THEIR ACTIVITY AND THEIR CAUSES[*]

Karl Sapper

I. VOLCANIC ACTIVITY

Of all the natural phenomena which man has had opportunity to look upon, none equals the volcanic eruption in grandeur or in beauty. Whoever has had the good fortune to witness one of the great eruptions will recall that picture with wonder and amazement all his life and retain the deepest impression from it. Is it not the only spectacle which reveals the earth to man as a living organism discharging juvenile substances from its depths? All other great natural manifestations—be it earthquake, avalanche, hurricane or thunderstorm—consist in movement and reciprocal reaction between forms of matter which have been part of the substance of the earth's crust or atmosphere for a very long time.

Essentially a volcanic eruption consists in the sudden emission of magmatic substances (*i. e.*, lavas, scoriæ, gases) out of unknown depths of the earth upon its surface, in great quantities and with considerable heat development. It is important to emphasize especially the suddenness of the occurrence, as well as the movement of great quantities of matter and the considerable development of heat, in order to distinguish between a true eruption and the gradual emission of gas or the more moderate heat development of solfatara and fumarole activity in not yet extinct but quiescent volcanoes. Really no sharp distinction is possible, for often the fumarole activity so far revives that ejections of rocks, dust, sulphur smoke or clouds and similar phenomena, appear, where, because of inaccurate reports, there may be doubt whether a slight eruption has not occurred.

As forerunners and accompanying manifestations of eruptions there are at times volcanic phenomena which make a deep impression on the human feeling and occasionally do great damage. Frequently a terrific uproar is audible in the ground beneath the volcano or in its neighborhood, spreading terror far and near, but often dying away again without having come to an outbreak. In other instances the heat increases over wide areas to such an extent that fumaroles form, the vegetation is parched, or the snow melts, all finally returning after a few months or

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[*] Abstracted by the author from his book "Vulkankunde," Stuttgart, 1927. J. Engelhorn, Nachfolger. Translated into English by Arthur L. Day.

years to the previous condition. New springs may appear, the old ones meanwhile drying up, or great masses of carbonic acid may escape, without disturbing the volcano's repose. Once in a while, light or even heavy and disastrous earthquakes occur, sometimes as forerunners or accompaniments of eruptions, at other times unaccompanied. During the earthquakes, occasionally, systems of cracks form or whole mountain sides slide off, because of which, through the damming up of rivers and the bursting through that follows, serious floods may occur as in 1912 at Sarchí in Costa Rica. Also, elevations and depressions may take place.

It would probably not be erroneous to ascribe all the phenomena mentioned to movements of the underlying lava or to reactions within it, although the magma itself does not appear at the surface. If for any reason the subterranean magma forces its way through the surface, it almost always follows the old channels or others closely related to former ones in the volcano conduit and its branches. Seldom in history have eruptions occurred from newly-formed openings lying at considerable distance from existing volcanoes (Monte Nuovo, Methana) and never in non-volcanic territory. Most eruptions through new channels are confined to the slopes and to the immediate vicinity of volcanoes.

The eruptive manifestations occur in great variety, which may be explained partly through the varied nature of magma and partly through the different physical conditions under which the magma exists. They are doubtless affected also by the condition of the ground or atmosphere and, probably, by the water or ice covering the place of emergence.

We have no way of calculating the amount of energy set free by single eruptions. Only the output of lava and ash, possibly also the older rocks set in motion, can serve to a certain extent as a clue through which to measure the relative importance of single outbreaks or of series of eruptions. The liberated gaseous matter is impossible to measure in any way, or even to estimate.

We are most familiar with those eruptions which occur in the open air (*sub-aerial eruptions*) since they can be observed directly. *Eruptions discharging gaseous matter exclusively* are unknown to us, since wherever gases appear with great force they invariably carry along masses of surface material, rock or water, and even tear out fragments from the depths. The eruptions of Shiranesan (Kusatsu, Japan), August 6, 1882, or of the neighboring Bandaisan (July 15, 1888) are well-known examples of historic gas eruptions. Although in these eruptions the prevailing movement was of old rock material, gas eruptions near the surface not infrequently throw out masses of water encountered on the way. It is in this way that geyser-like outbreaks in crater lakes occur, like that of Poás in Costa Rica, or of Kelut in Java—often terribly disastrous.

The steam liberation at the foot of Lemongan in Java, February 4-5,1898, and the outbursts of salt water near Teguise and Tinguaton on Lanzarote in the Canary Islands (1824) have a similar origin. On the other hand, A. Wichmann has recently called attention to mud and water explosions on Ternate and other volcanoes, where one must assume that water formation took place within the conduit of the volcano.

Pure gas liberation out of the depths is apparently rare. Usually lava is thrown out with the gas, either in the form of finely divided magma particles (ash, sand, lapilli, possibly also bombs and blocks) or as a coherent lava stream. The first group always accompanies gas discharge, often with violent explosions; lava-flows more often emerge without any explosions worth mentioning but are frequently accompanied by considerable gas development, which one may recognize from the flames above the lava pools (*e. g.,* Matavanu on Sawaii, 1905-1906). In eruptions combining both types there are ejections of ash and scoriaceous material as well as fluent lava.

Scoriaceous matter may issue from the summit crater of a volcano as well as from its flanks, in the latter case often with formation of new cinder cones—“parasites.” Rarely, a new volcano of cinder-cone type may even be built up at a considerable distance from any other volcanoes, right under the eyes of the observer, as for instance Monte Nuovo near Pozzuoli, Italy, 1538; or a new lava cone may arise (Methana on the Ægean Sea in the north of Peloponessus, approximately in the third century, B. C.). In both cases, a swelling of the earth was reported before the eruption (because of lava pressure from beneath?) but in other cases no such observations were made (Chinyero on the Pico de Teyde, Tenerifa, Nov. 18, 1909).

From some volcanoes there are slight explosions at short intervals, which, by reason of the comparatively feeble force of the explosions, may be and have been closely studied at short range. Such eruptions break out directly from thinly fluid lava (Tanna in the New Hebrides); others become evident only after breaking through the crust formed by the cooling surface in the interim between two eruptions (Izalco in El Salvador). The lapse of time between single eruptions is at times astoundingly uniform (as with Izalco in December, 1902: 14 minutes) although as a rule it is irregular (Santorin, May, 1926, Stromboli and others).

If the explosions arise from deep down in the conduit lava of a volcano, the shattered slag fragments may, if powerfully blown upward, form a sharp-rimmed shaft kilometers high until strong winds bend it over, sometimes perpendicularly (St. Vincent, May 7, 1902), or until the explosive force gradually abates and the erupted mass is spread out in umbrella-form on all sides. Recently, F. A. Perret has been able to determine as a result of his careful observation of the final explosions of Vesuvius in April, 1906, that the spattering and ejection of scoriaceous matter, as well as the gradual clearing out and widening of conduits and craters (or calderas) in which they occur, is by no means due always to explosions, but rather that the mere gas discharge from magma, which takes place in crescendo and decrescendo, may, in heavy eruptions, through its enormous mechanical force and erosive energy, achieve the same result (*gas erosion*). When the eruptions issue from a lesser depth, the eruptive mass rises in wedge-formation or perhaps pear-shaped at first until it gradually disintegrates concentrically.

Often the cauliflower shape of the huge eruption cloud may develop near the mouth of the opening. When the propulsive force is small and the upward drive moderate, sharp winds may divert the mass of smoke and ash immediately after it leaves the conduit, and draw it out into a narrow smoke-streamer often many kilometers in length (Irazú in Costa Rica, Erebus in Victoria-land). But if the air is still or only slightly disturbed and the upward drive moderate, the masses of smoke may take on conspicuously distinct shapes (club shapes, rings, mushrooms, spirals) which K. Mack has explained, on the basis of experiments, as due to equalizing currents in liquids and gases, and attributed to vortex motions.

Whether the heavy rains and thunderstorms which often accompany greater eruptions are due in part to the precipitation of steam from the explosions, as former authorities believed, or whether they result solely from the drop in the temperature of the air due to screening off the sun's rays by smoke and ash masses, has not yet been adequately explained.

Ash precipitation during a strong rain may result in a mud-rain, and ball-shaped ash concretions of concentric-shell structure (pisolites) naturally and quite frequently result.

The expulsion of ash and scoriaceous matter during explosive eruptions is extraordinarily varied: Although the Tambora eruption in 1815 discharged about 150 cu. km. of loose material, less than 1,000 cu. m. are thrown up during some individual light eruptions; and it goes without saying that giant outbreaks (by which are meant eruptions of more than 1 cu. km. of scoriaceous ejecta) have a far greater physical, geological and anthropo-geographical effect upon the earth's surface than do light eruptions producing entirely insignificant deposits. But of course the extent of the effect depends largely upon the physical conditions in the surrounding territory, upon the concentration of colonization, the type of government, and so forth. Especially important in explosive outbreaks is the direction of the prevailing wind at the time, and it goes without saying that within the trade-wind belt there is one (in the monsoon belt, two) especially endangered regions—a fact with which the colonist must reckon.

If the eruptive conduit stands in oblique instead of vertical relation to the earth's surface, there is, naturally, again a particular region certain to be imperiled first of all (Vesuvius, 1906, etc.) and certain morphological consequences are to be expected also.

The height to which loose or plastic projectiles are carried upwards is extremely variable, depending upon the energy of the explosions and the size and shape of the individual fragments expelled, in which there is a decided sorting effect according to size and weight. Fine dust sometimes reaches tremendous heights (Krakatau, 1883: glowing nocturnal clouds at a height of 80 km.).

Sometimes, also, it happens that in spite of enormous explosive energy the weight and concentrated grouping of the ejected masses is so great that no scattering in the air occurs after the vertical explosive force has become exhausted. Thus there have been, during the eruptive period of Mont Pelée on Martinique in 1902-03, manifold instances, observed by Lacroix, in which the erupted matter climbed very high (2,000 m.) but fell heavily back upon the slopes of the mountain and flowed downward like an avalanche under gravitational forces. The downflow of the glowing cloud of May 7, 1902, on the Soufrière of St. Vincent may have come about in a similar manner, when an especially viscous mass of the magma was cast out. Usually, however, *descending eruption clouds* (Glutwolken, "nuées ardentes") will form whenever the cone of piled-up lava blocks the upward passage against the tightly compressed gases, so that they have to seek a side outlet or even discharge downward, with occasional disastrous results (destruction of St. Pierre, with 26,000 inhabitants, May 8, 1902). Aside from the enormous mechanical force, the destructive effect of the glowing clouds is due also to their great heat; we have reason to believe that the cloud which descended upon St. Pierre on May 8, 1902, reached approximately 800° C.

Glowing clouds can issue from cracks and crater-like openings and flow downwards, even when there is only a very slight inclination of the terrane (a little more than 1°), as was recently established by C. N. Fenner in his investigation of the Valley of Ten Thousand Smokes near Katmai, Alaska, which was active in 1912.

Expulsion of lava in many cases accompanies the discharge of loose fragments (mixed eruptions). The phenomena vary greatly with the point of lava outflow and the degree of fluidity of the lava mass. The lava outflow often issues from the summit crater, often also on the slopes or at the foot, and at times even at considerable distance from the central cone.

If the outflowing lava is viscous it remains over the place of outflow and grows there through injection of other fluid material to a steep *dome*. This has often happened right under the eyes of witnesses; at Mont Pelée, 1902-03; at the crater of Santa Maria (Guatemala) since 1922; on Tarumai (Japan) 1909, and on Santorin, repeatedly, as again 1925-26, etc. If the later injections are thinly fluid, little streams flow out at the surface again and again, and assist in enlarging the structure (overflow mounds, like the Colli Umberto and Margherita on Vesuvius).

If the lava is very fluid as it emerges from the volcano conduit, it may occasionally fill the crater or a large part of it. In 1694 and 1733, the lava stood in the crater of Vesuvius with but little surface movement, whereas in 1876, 1877 and 1912 in Oshima crater (Japan) it undulated up and down. Sangay crater in Ecuador overflowed frequently in the eighteenth century, and there were similar occurrences repeatedly at Cotopaxi. Sometimes the crater walls can not withstand the pressure of the lava standing within. When the enclosing wall finally yields and affords a sudden outlet to great lava masses, these, together with the wreckage of the crater wall, devastate the surrounding country as at Asamayama (Japan) 1783, at Papandajan (Java) 1772, etc.

The overflow of temporary lava lakes in certain craters occasionally gives rise to lava streams, of which on steep mountain slopes (Cotopaxi) there remains no trace except lava bands at the rim, for until nearing level country the lava does not harden into a coherent stream. Most lavas flow from rifts or other openings on the mountain side or base, when the conduit walls can no longer withstand the pressure of the lava column, and radial cracks finally furnish an outlet to the earth's surface. The degree of lava fluidity differs according to the amount of silicic acid and stored-up heat contained in it. Viscous lavas pile up even on an inclined slope, forming knobs or domes, while the more fluid lavas follow the steepest grade, some flowing like water, while others, being thicker, roll forward slowly, sometimes only a few meters a day. Slow-moving flows seem by day to be dark and dead but at night they glow impressively in varied and widely extended forms.

The dimensions of lava streams are extraordinarily varied. Passing by the miniature streamlets of Papandajan (Java), described and photographed by W. Volz, some of which are only a few meters long and a few centimeters wide, it is noticeable that a few typical lava streams are uncommonly short (Lemongan in Java, 1885, 25m.) whereas others, as in Hawaii, reach a length of 50-70 kilometers and some (Laki, 1783, or the Eldgjá rift in the tenth century—both in Iceland) even flow out in broad lava fields hundreds of square kilometers in area. At times single lava streams empty into others flowing at the same time and together form a single flow; and in other instances the stronger stream on meeting will cut through the weaker (Aetna, 1865). Sometimes lava streams disintegrate into blocks and slag heaps (Soputan, 1908-13, and Lemongan, 1844), or even into thousands of fine splinters (Aetna, 1838, and San Miguel in El Salvador, 1844). Where lava streams flow over soggy ground they may even squeeze out the ground beneath until low elevations appear at the sides of the flows (Kamchatka, according to Erman). When lava streams flow into lakes or into the ocean, contact explosions often develop, with formation at the same time of great volumes of steam. Often in passing over small pools of water or patches of snow, explosions will also occur (Aetna, 1843, Sawaii, 1908). Occasionally, the flowing streams show the same peculiarities as the lava source at the point of issue (*e. g.*, horizontal explosions at Sakurajima, 1914; and knob formation on Santorin 1926).

An extraordinary characteristic of some eruptions is the uplifting of solid masses in the form of great *needles* (Mont Pelée, 1902-03, Santa Maria in Guatemala, 1924), also of lava plugs which after extrusion disintegrate into blocks which plunge down the mountain sides and sometimes inflict damage (Merapi in Java). Here and there in history the uplifting of a great volcanic mound has been observed (Usu on Hokkaido, Japan, 1910: a mound of 2,700 m. length and 600 m. width, raised to an elevation of 155 m.). Often there is a slight temporary rising and falling at the foot of the volcano before and during an eruption.

Although most eruptions are confined to a definite central zone, others issue from long fissures or rifts and are initiated by the bursting open of a deep fissure in the earth, often to the accompaniment of earthquakes, and are extended after the eruption is already in progress.

Fissure eruptions occur most frequently from radial cracks on the flanks of large volcanoes. These are often distinguished by parasitic cones and serve as points of release of lava streams. That separate radial fissure eruptions may be connected with each other was proved by A. Riccó in the eruptions from the flanks of Aetna in 1883 to 1910. He showed also that the lava solidified and closed the fissures formed each time, so that subsequent lavas found an easier outlet farther up: Flow of 1883, 1,050 m. above sea level; 1886 at 1,450 m., 1892 at 1,850 m., 1908 at 2,350 m., 1910 at 2,550 m. (later 2,050). Riccó deduced from this that mechanical obstructions determine the point of lava emergence, thereby coming to the same conclusion reached by me in 1905 and by H. Reck in 1907, in the study of the Laki fissure in Iceland. (Even the filling up of a fissure by loose material may lead to the displacement of a point of eruption, as was shown at Izalco in 1902).

Just as the opening of fissures on strato-volcanoes often leads to parasitical flank-eruptions, so is it often the source, on ring volcanoes, of great lava floods, wherein the deluge sometimes begins with huge lava fountains 120 to 240 m. in height, the heat from which occasionally gives rise to terrible whirlwinds (Mauna Loa in Hawaii, February 20, 1852).

Still more tremendous than fissure eruptions on steep slopes are such eruptions in the open country where the whole fissure becomes a volcano. The most marvelous example of such a fissure eruption in history is that of Skaptarjökull or Varmar-dalr (Laki) which gave birth to a line of volcanoes 24 km. long, and a lava outpouring of almost 13½ cu. km., to which should be added some 3 cu. km. of loose material, the lava covering an area of 565 sq. km. and the whole amounting to a national disaster for Iceland. One-fifth of the inhabitants, four-fifths of the sheep, three-fourths of the horses and more than one-half of the cattle were destroyed.

Certain peculiarities in the course of the eruptive manifestations of a volcano may be caused by a snow or glacial covering. A thin snow mantle can of course hardly bring to pass any essentially new phenomena, since the snow either melts away slowly, the water soaking away into the porous ground, or hot ash masses melt some of the snow away more quickly; but once cooled, this layer of ash acts thereafter as a powerful isolating medium (in cold regions such as Iceland, the ice and snow strata between tuff layers even form a permanent part of the volcano structure, *e. g.*, Askja).

When lava streams flow over great masses of snow, as often occurs in high mountains or in cold regions, they melt away the snow at once, setting free immense volumes of water which the subsoil cannot absorb. These great torrents of water tear down the mountain sides, carrying along great quantities of ash, sand, lapilli and blocks, and form mud flows of devastating proportions (Lodozales of Cotopaxi in Ecuador 1742, 1743, 1744, 1766, 1768, 1868, 1877, 1885).

On volcanoes whose craters and slopes are snow- and glacier-covered, as is often the case in high latitudes, explosive outbreaks may also cause disastrous floods (in Iceland "Jokulhlaup"—called *glacier-run*). The heat of the eruptions melts the snow and ice and the heated snow-water continues to melt the glacier and snow masses below. Thus the avalanches grow rapidly, carrying away great quantities of volcanic and glacial debris and gigantic blocks of ice until finally they rush into the lowlands leaving a hopeless waste in their wake.

Still other unusual phenomena occur when *volcanic eruptions* take place *under water.* If explosive outbreaks occur at the bottom of shallow lakes or parts of the sea, the mass of overlying water and mud is thrown geyser-like into the air. Smaller crater lakes, which are often found in regions of high atmospheric precipitation, may indeed be completely evaporated through prolonged heating (Boquerón in El Salvador, 1917). If the force in the explosions be great, enormous masses of water may be thrown out to flow valleywards as devastating *hot-water and mud streams* (St. Vincent, 1902). If the water be shallow on the other hand, it may be literally pushed aside to allow the passage of great columns of ash, sand and smoke as in ordinary subaerial outbreaks. In all submarine eruptions the water becomes heated, so that fish, turtles and other water animals are killed and often literally cooked.

Volcanic gases set free from the lava and rising as bubbles through the sea pass through the water less oxidized than the gases of subaerial eruptions when entering the atmosphere. The rise of the gases and consequent heating of the water often cause violent disturbances. Rising steam will generally condense in the water. Pumice fragments often rise quietly to the surface, though some blocks burst after reaching the surface of the water. Very flat cinder cones develop under water as a result of strong currents. Over the heated sea, slender pillars of steam or water-spouts are likely to develop with a whirling motion. When underwater eruptions take place in large inland lakes there may occur, through temporary elevation of the lake bottom, a serious flooding of the surrounding country (Ilopango lake in El Salvador, 1880). In inland lakes, and in the ocean, submarine eruptions not infrequently cause new islands to appear, which have, however, only a passing existence when they consist entirely of loose material, as this is easily carried away by the waves. Even islands formed of lava (*e. g.,* 3 miles from Minami—Iwôjima, in 1904-05) may quickly disappear again by sinking.

Having considered, up to this point, explosive and mixed eruptions, we must now turn to the rarer *purely effusive eruptions.* Their most characteristic form may be observed in the "*fire-lakes,*" of ring or other volcanoes. By fire-lakes we mean accumulations of thinly fluid lava masses which unlike the lava lakes occasionally to be observed in the craters of strato volcanoes, have not partially lost their gas content through previous explosive outbreaks, and therefore show various unusual phenomena such as were observed by the Spaniards in the west crater of the volcano Masaya in Nicaragua in the sixteenth century, and later (since 1823) became better known on Kilauea and Mauna Loa in Hawaii, and on Matavanu in the island of Sawaii (Samoa group) in 1905-1911.

Although the gas content of such lavas has not previously been partly lost by explosions or continuous discharge, it nevertheless seems to be comparatively small and escapes very easily. Portions of the thinly fluid lava often dome up and then discharge in *lava fountains.* Also, the lava surges up from the conduit source and forms a clearly defined *fire-stream* in the midst of the lava lake; in places depressions develop in the lava niveau into which the neighboring lava then pours like a cascade; the escaping gas often burns in small surface flames, or during violent eruptions even in flames hundreds of meters in length (Matavanu, 1905-06); and expelled drops of lava often are drawn out in long filaments by the wind (Pele's hair). *Lava islands* may form, for shorter or longer periods, or the whole surface may harden and then break up again into irregular masses which sink easily, giving place again to liquid, skin-covered lava, etc. Lava lakes often have no outlet, but Matavanu in 1905-1911 had a subterranean outlet which for several kilometers flowed in a tunnel to the sea, and made its path distinctly and impressively perceptible through fumes which rose from occasional openings in the tunnel roof.

Lava lakes also occasionally break out in explosive eruption (*e. g.*, Masaya before the coming of the Spaniards, Kilauea in 1790, 1924, 1927) which may take the form of a glowing cloud; but generally they maintain the characteristic quiet activity, whose manifestations and peculiarities have been and will continue to be made known to us through the observations of the American vulcanologists R. A. Daly, F. A. Perret, A. L. Day and E. S. Shepherd, and through the outstanding work at the permanent Kilauea observatory which since 1911 has been under the direction of T. A. Jaggar, Jr.

Observing the *diversity of activity* one may easily see that many kinds of volcanic action are literally the result of specific geographic conditions at the place of eruption. But there still remain phenomena in considerable variety after these geographically explained manifestations have been excluded which are immediately related to the more general principles of vulcanism; and it is no simple matter to condense these remaining types of activity into groups, as Mercalli, Lacroix and others have attempted to do. The attempt of Lacroix seems to me the most successful, wherefore, in the following, I wish briefly to refer to his classification. He bases it on the manner of release of the gases from the magma considered as a function of physical condition (degree of fluidity, viscosity) and distinguishes four types:

1. *Hawaiian type:* Magma of the greatest fluidity; violent paroxysms rare; expulsion of magma not always accompanied by explosion. The blistered slags are of black glass, sometimes drawn out into hair-like filaments.

2. *Strombolian type:* Basaltic magma of less fluidity than No. 1, but sufficient to permit it to exist freely in contact with the atmosphere. Gas development encounters greater resistance; violent explosions occur; magma splashes, pumice, cinders and pear-shaped bombs form.

3. *Vulcanian type:* Magma very viscous; between explosions, completely solidified at the surface; each explosion therefore tears with it many sharp fragments of the crust. The eruption clouds as a result are very dense, gray to black, and cauliflower shaped, rising slowly and appearing dark even by night. The lapilli are angular, the bombs bread-crusted; pumiceous within and glassy at the periphery.

4. *Peléean type:* Glowing clouds, even more dense than the Vulcanian clouds, formed in more or less solidified magma, expelled at low angles or first rising, then falling and flowing like avalanches, at the same time with intense upward expansion of the gases.

The types of explosion are usually associated with the chemical character of the magma, but not always, so that the knowledge of the chemical properties only permits a conclusion as to the probability of a certain type of eruption. The Hawaiian type, according to Lacroix, occurs only in basaltic magmas. The Vulcanian is possible with all volcanoes, especially in the early stages. The Peléean type is established for andesitic, labradoritic and basaltic volcanoes.

The four types of eruption differentiated by Lacroix suffice to distinguish the explosions which issue directly from the magma but it is plain that they do not cover all the kinds of eruptions which have been observed. Thus a number of gas explosions can not easily be traced to any one of these four types, for there is absolutely no magma expelled with them and the gases apparently do not explode until after leaving the magma and traveling a more or less extended path within the earth's crust. One has to come to such conclusions remembering, for instance, the close of the Bandaisan eruption, when loose masses were expelled almost horizontally at the last, indicating that the last explosions did not occur before reaching the top of the mountain, where no fresh lava was found.

In the same way with "*superficial eruptions*" generally there is no liquid lava to be found at the place of eruption, so that one must admit the explosion of ascending gases. The same conclusion applies to the explosion craters of some volcanoes, where it is often clear that the gases have sought escape from the magma in the deep interior through these channels. Sometimes *phreatic explosions* are suggested. Thus, according to K. v. Fritsch, shortly before April 24, 1866, a small explosive crater developed on Santorin, in the lava of 1707-1711. Its diameter was about 30 meters at the surface of the block-lava mass discharged in 1707; a smaller cavity measuring about 16 m. across extended shaft-like into the harder rock of the interior of the volcano for about 20 meters. The floor of this shaft was covered with light gray mud; similar mud and sand also lined the walls of the conduit, and covered the neighboring rocks to the depth of several centimeters. In the same way, the explosion shaft described by F. Plieninger, which was blown out in the crater of Nisyros at the end of September in 1888, threw out mud and masses of decomposed tuff, and may very well have been the result of a phreatic explosion.

When true eruptions have ceased one may still observe for some time in the ejecta and in the lava outflows various striking phenomena. Hot ejecta buried under an ash layer which acts as a very poor conductor of heat, often retain their heat for months, so that when drainage water occasionally comes in contact with these hot buried masses there may be *secondary steam explosions* in considerable number and violence (Mont Pelée, St. Vincent, Santa Maria 1902-03). The hot ejecta also quietly give off gases and volatile matter into the atmosphere for a long time, *surface fumaroles* (Mont Pelée) and *bituminous deposits* distilled from embedded logs and other organic matter (St. Vincent, 1902-03).

Lava streams retain their heat longer than do the loose ejecta, so that exhalations of gases and volatiles (such as ammonium chloride) from their surface may continue for several years.

The kind of gases discharged depends largely upon the temperature, and even though St. Claire Deville's rules are, according to Allen, not generally applicable, they still appear locally to correspond with the facts, so that at such places one may, according to temperature, find gaseous and volatile substances appropriate to the volcano magma in question. The gases and deposits from lavas originate in part directly from the lava, though some are formed by the reaction of such magmatic gases with water and air, and some would seem, according to A. Brun, to be formed secondarily through oxidation of components of the rocks (SO_2, CO_2, N.) to which are sometimes added substances derived from the burning of organic matter. If the gas exhalation at first appears as a general seepage, it concentrates later at certain cracks and local vents, "*fumaroles*," which at times even build up small cinder cones and lava funnels.

The gas content of bombs and blocks is seldom distinctly noticeable, as these small bodies usually cool down very rapidly. Nevertheless, they occasionally explode afterwards and may even cause conflagrations.

From the volcano conduit as well as from many of the fumarole vents, *gas exhalations* may be detected for a very long time after an eruption. Generally, the fumaroles are lower in temperature in proportion to their distance from the main conduit, since the path of the gases to them is longer and the cooling therefore more marked.

The exhalations from the volcano conduit following an explosive eruption apparently continue to come from the same magma which before supplied the eruption; they would therefore be likely still to contain the same gases and volatile substances, chiefly, which had been expelled in greater quantities during the eruption, although the possibility should be recognized that certain of the gases may have appeared only during the main outbreak. Lava fumaroles and volcano fumaroles are alike in their essential features.

The gas emanations of some volcanoes often remain homogeneous for long periods of time, from which one may conclude, either that these mobile substances come from great depths within the earth, or that they have remained over in the hot lava masses still contained in the volcano structure after the great mass of gases and volatile matter has been discharged during the paroxysmal eruptions. Wherever gas exhalations meet with ground water they may, according to v. Knebel, produce hot springs, mud-volcanoes and geysers; while, according to Ed. Suess, juvenile waters, that is, those rising from the virgin magma inside the earth, form the hot springs (or at least contribute to their formation).

When volcanoes are approaching the end of their activity, carbonic acid exhalations (*Mofettes*) form the chief feature of the gas emanations.

We are still at the threshold of our knowledge of the gaseous emanations of volcanoes. The most recent investigations (chiefly by American scientists) have increased our knowledge very considerably, but have also shown us that those volcanic gases which can be made available for analysis too often show decided alteration due to the influence of air, water and other substances—a fact which hampers us greatly in our further deductions. For not even concerning the amount of the original water content of the magma has the last word been said, in spite of the painstaking investigations of Arthur L. Day and E. S. Shepherd.

It is important to emphasize, however, that although many gases are common to all volcanoes, others, either individually or in their percentage composition, are characteristic of a certain few volcanoes or volcanic regions, so that it does not seem out of the question later, when investigations shall have advanced somewhat farther, to distinguish regions of particular gas emanation ("gas provinces") in the same way that *petrographic provinces* have been successfully distinguished. Even the latter, however, are not sufficiently well defined to permit fixing their boundaries cartographically; indeed, this goal is rendered difficult of attainment because of frequent overlapping of the regions.

II. THE VOLCANO AND ITS ROOTS

By a volcano we mean a place on the earth at which magma (*i. e.*, lava) or magmatic substances (according to K. Schneider's definition, "juvenile masses") come, or have come, from the interior of the earth to its surface. As these substances originate at great depths which are of course unknown to us, they show high temperatures at the moment of issue from the earth's crust, wherefore A. Brun frankly defines an active volcano as a place on the earth of much higher temperature than its surroundings. This definition is, to be sure, essentially correct, but the nature of the volcano will be better understood from the former explanation.

Of first importance in a volcano structure is the connecting channel between the interior of the earth in which the magma moves, and the earth's surface. Of much less importance is the outward form of the volcano, which is determined chiefly by the type of activity: it may be an excavation due to the explosive eruption of juvenile gas, or to gas-stream erosion. Usually, however, masses of magmatic material either solid or in process of solidification, or else older masses of rock and earth torn loose from below, pile up about the volcano conduit, forming an enclosing wall or a volcanic mountain of varying shape. Sometimes, outpouring and accumulating lava, or overlapping lava flows, develop lava cones of various types.

From the surface edifice the connecting channel leads downward to the *roots* of the volcano, the subterranean continuation of the superficial structure and the original formation conduit within the earth. The possibility of reawakening volcanic activity, depends upon whether or not the volcano still contains active magma.

As we have no sure way of determining whether or not magma masses still capable of eruption exist anywhere beneath the volcano, we have no possibility of indicating with absolute certainty whether or not a volcano has already become extinct. Still, one may assume that in all probability volcanoes and volcanic regions which have not been active since the Tertiary, or even since the Diluvium, are now extinct.

Those volcanoes are called *active volcanoes* which have shown activity within historic times. But as history, in different parts of the world, has been of widely varied duration, and as many volcanic regions have only very rarely been visited by Europeans or other cultured peoples, the degree of probability that a volcano might still be active differs greatly for different regions. One may determine the number of volcanoes of whose eruptions there are records, but not the number of those which may become active in the future.

Unfortunately, geophysicists are not yet able to determine with certainty the structure of the earth's crust, and even though many, on the basis of studies of isostasy and of numerous gravity measurements, assume the level of isostatic equilibrium to be about 120 km. in depth, there is no agreement of opinion on these questions. Investigations by Love and Schweydar, for example, led to the conclusion that there can be no continuous layer beneath the earth's outer crust of the nature of a viscous liquid, certainly none that could be compared to molten magma. (To be sure, Love wished to admit the possibility of regions of molten magma of continental size.)

Alfred Wegener, who accepted Ed. Suess' division of the earth's crust into a lower, magnesia-rich stratum of Sima (R. A. Daly's basaltic substratum) and an upper, lighter one of Sal (or " Sial ") containing more alumina, assumes the continents to be swimming on a simic foundation, where he believes that " Sial masses of some 100 km. thickness rise to about 4.8 km. above the deep sea floor " (where, according to him, the Sima constitutes absolutely the boundary of the solid terrestrial body)— " that is to say immersed to a depth of 95.2 km."

The heat of those portions of the earth's crust which are accessible to us increases steadily with increasing depth. Besides the initial heat passed down from antiquity, the heat developed through mechanical and chemical processes, especially through radium decay, requires consideration, so that it is impossible to make reliable estimates of the distribution of heat within the earth.

If one accepts the mean geothermic rate of change with depth of about 33 m. per 1° C. as valid also for lower levels, one arrives at 1,000° C. for about 30 km. depth; 2,000° for 60 km., and thus at temperatures where in spite of the raising of the freezing point with increasing pressure, the magma must be accepted as molten or at least as potentially plastic. The magma may, therefore, be supposed to have its origin at the depth where the temperatures are found at which lava reaches the surface,— usually 1,000—1,200° C.

It is difficult to understand how the magma can break through the outer shell of the earth which weighs down upon it. Doubtless weak spots in the earth's crust, especially in the shell of compression, facilitate the ascent, hence the appearance of volcanoes and eruptive rocks on the surface is an indication of faults and disruptions in the interior. According to F. v. Wolff, such weak spots occur at the back of folded mountain chains; over ancient cordilleras, pushed together a second time but not capable of folding again; in areas of depression; and at points of tensional dislocation.

If the geophysicist, after most careful consideration, can give no reliable information about the structure of the earth and the ascent of magma, the geologist, in certain cases, even where the levelling down was already very far advanced, has been able to determine that modern volcanoes and recent overlying lavas are connected by conduits and passages (which are filled up with tuffs or massive eruptive rocks) with greater intrusive bodies of crystallized plutonic rocks, that they therefore have their roots and their origin from within these, whether they be batholiths, stocks, laccoliths, or sills.

If these formations stand in causal relationship to tectonic disturbances, explosion channels will also be found elsewhere, which break through undisturbed formations and apparently have no close connection with normal tectonic forces. Such upheavals originate at the particular spot in question, purely through the energy developed in the magma itself.

The relationship of the different eruptive masses to the neighboring rocks, whether underlying, overlying or breaking through, taken in connection with appropriate investigation of the rock structure—give reliable clues to the relative age. Likewise, the appearance of apophysae in the neighboring rocks, heat effects, and metamorphic changes of composition have led to the formation of valuable ore deposits. Why some eruptive rocks, older as well as younger, have a rich sequence of ore-deposits, yet others of the same mineralogical and chemical character leave none, is unknown to us. (According to A. Bergeat the formation might be a result of original inhomogeneity in the underlying magma.)

The most common deep-seated rocks are the granites, which we may regard as the prevailing magma of the earth's outer crust.

In spite of the fact that our knowledge of intrusives in the outer crust has increased considerably, we do not yet know enough about the relation between the superstructure of a volcano and the intruding masses under ground. It is true that in places the connecting channels between the two are partially exposed by erosion (Swabian Alb) or opened by mining operations (Blueground pipes, South Africa) but nowhere are they exposed down to the interior hearth. The same applies to the passages which fed the great lava expanses of the Columbia. The suggestion has been made that volcano conduits open out below into larger passages, but the direct proof that such a combination actually occurs is for the most part still lacking. It has many times been accepted as a fact that laccoliths, batholiths, and sills constitute the interior hearth of volcanoes; but nowhere is this connection absolutely clear, and there is much about which we are still in the dark. One can quite easily imagine that great bodies of plutonic rock which are now exposed by erosion may once have fed surface volcanoes; but that, in most cases, must remain a supposition. Observation indicates that a great many intrusive masses have remained fast in the earth's crust and never reached its surface.

Since geological field studies can neither give an adequate explanation of the connecting passages between surface and deep-seated structure of volcanoes, nor determine the depth or the form of the magma hearth which feeds volcanic eruptions, we must for the time being give up the hope of satisfactory information until new and hitherto undiscovered methods of research have been found.

Occasional information concerning the extent and the relative level of original magma hearths is furnished by a combination of petrographic and geographic methods of research. Modern petrography has indicated the probability that the Pacific magmas have their origin in a zone nearer the surface than the zone of Atlantic magmas, for they are richer in elements of low atomic weight. When the earth was young and a gravitational sifting of its materials according to the weight of the gases was still possible, these would have taken a place nearer the periphery. The investigation of petrographic provinces shows clearly that beneath certain regions a corresponding magma mixture, substantially uniform in composition, must have existed. And if, in individual volcanoes or in volcanic regions, the petrographic character of the ejecta changed frequently during the period of their activity, these changes were usually such as would permit the conclusion that magmatic differentiation within the original magma caused the changes, or in the other instances the assimilation of adjacent rocks subsequently picked up furnishes the necessary explanation. In still other instances, one must bear in mind the fact that schlieren of quite varied character may have found their way underneath the region in question. Adherents of Wegener's continental flotation hypothesis might, however, assume the contrary, namely, that part of the earth's crust might have been brought by passive drift over a magma region of corresponding character.

If we compare the number and energy of the volcanoes active at the present time with those of the Tertiary period we realize that present-day active volcanism is but a small remainder of that of the Tertiary period, just as the active volcanic terrane has dwindled in size to an extraordinary degree since that time. From such facts we may perhaps draw the conclusion that the magma hearth, originally far more extended, is now substantially diminished in size through crystallization of the magma.

III. THE EXPLANATION OF VOLCANIC PHENOMENA

We have seen something of the nature of volcanic phenomena and how they have their ultimate origin at great depths in the earth's crust, but even modern methods of investigation have not yet succeeded in solving the many riddles which rest like a veil over the causes, the seat and the internal mechanism of volcanoes.

Even the most ancient peoples have wondered about the origin of volcanic eruptions, but usually they have taken refuge in mythical explanations. The ancient Greeks, who imagined the earth to be traversed by caves and canals in the manner of their own country, first attempted scientific explanations. Plato conceived a subterranean river of fire (Pyriphlegethon) to be the source of the lava streams, and thought the driving power of the eruptions to be due to air imprisoned under great pressure. Aristotle also considered pent-up " winds "—but supposed these to come from the outside with power sufficient to arch even the earth itself into a dome. In much the same way thought Posidonius and Strabo, who supposed the rock to be set on fire by the friction of intensely compressed air in very narrow places; the fuel of the volcanoes was then imagined to be sulphur, alum, mineral tar and lava. Philo Judaeus, on the other hand, turned again to the Platonic ideas.

In the middle ages, the Bible views prevailed alongside those of Aristotle, which, however, were modified in essential particulars by Albertus Magnus and others. Astrological beliefs concerning the effect of sun and stars (especially Saturn) upon the kindling of the inner fire, must also have been widespread toward the close of the middle ages, for the excellent Agricola at the beginning of the new era turned vigorously against them and (1546) asserted the opinion that the subterranean fire was fanned by the Fire-spirit (" Spiritus Ignitus "). He believed that the latter became active either when the cold pressed out the fire, as the clouds create the lightning, or when vapors compressed in a narrow space become heated by the friction until they finally take fire. Even in the seventeenth century medieval opinions still prevailed generally and found brilliant expression in the work of Athanasius Kircher, " Mundus Subterraneus," which first appeared in 1664, and which accepted not only the great central fiery furnace, but many peripheral hearths besides, and even compared the volcanic explosions to powder explosions in a gun.

Before the appearance of this monumental work, however, entirely new thoughts had been expressed by Renatus Cartesius (Descartes) in 1643, which culminated in the theory that the earth had originally been a sun-like glowing body and that the formation and transformation of certain substances was possible, which if suddenly kindled within deep caves would break through to the outside and cause volcanic eruptions.

Although the second portion of the theory went back in part to older speculations, the first was absolutely new, and for a long time physical geography and volcanology profited by it.

Later the progress of the natural sciences continued to awaken new ideas in explanation of volcanic manifestations, until in most recent times the knowledge of radium decay has been called upon to explain the whole complicated volcanic problem in terms of this single natural agency just recognized. It is not possible here to go further into these interesting developments beyond pointing out the most important stages: The gradual development of *Chemistry* first suggested to L. de Capoa, in 1683, that volcanic heat originated in chemical processes. After Martin Lyster, in 1693, had called attention to the decomposition of pyrites, and Lemery in 1700 offered experimental proof (spontaneous combustion of a mixture of iron filings and sulphur buried in moist earth) of the possibility of explosions from chemical processes, this opinion prevailed for a long time. In the beginning of the 19th century the famous chemist Davy suggested a new explanation (addition of water to metallic alkali), which he himself soon abandoned again as incorrect.

In addition to chemical theories, electrical ones also came to the front after the middle of the eighteenth century (Stuckeley, Bina, Beccaria), while Count Buffon suggested a combination of the two. (Histoire naturelle, Deux Ponts 1785, T. IX.)

To these were added *mechanical theories,* already proposed by Descartes who attempted to trace melting processes to the friction of rock faulting, and further developed, after the Lisbon earthquake in 1755, by Joachim Franke; to be finally developed and more soundly established in the nineteenth century by Vogler (1857), Robert Mallet (1873) and Hans Reusch (1883).

The development of the heat hypothesis first influenced the younger Herschel (London and Edinburgh Philos. Mag. LXVI, p. 212) to offer a caloric volcano theory, while in 1837 Gustav Bischof (Wärmelehre p. 256, *et seq.*) expanded the theory further by very interesting, carefully considered reasoning.

The most important advances in volcanology, however, were made by *geologists,* who brought new life into the study of volcanoes, partly through accounts of their observations and partly through theoretical studies based on their own experiences. It is true their work did not always signify an advance, as for instance the famous Freiberg geologist Abraham Gottlob Werner, in 1788, on the basis of his investigation of the Scheibenberg basalt dome, ascribed an aqueous origin to the basalt and asserted in the course of the resulting controversy that volcanoes were formed by burning coal seams and that the basalt would melt if the coal-burning were to occur beneath it. If Werner, because of his limited geographic knowledge, was thus the victim of an error which was promptly set right by his contemporaries, his pupils Alexander von Humboldt and Leopold von Buch were able because of extended travels to gather new ideas which often proved fruitful. The former called attention especially to the similarity of volcanic activity occurring in all the zones of the earth, and concluded from this that there must exist a uniform and consistent source for all these individual manifestations. He found it in the reaction of a uniformly fluid interior upon the solid outer crust.

Leopold von Buch, however, in a lecture at the Berlin " Akademie " in 1818, concluded on the basis of his observations on the island of Palma in the Canary Islands, that besides volcanoes built up of solid ejecta, there existed, also, " Erhebungskrater " consisting of " layers which rise uniformly from the sea up to the greatest altitudes." The geologists of the European continent willingly accepted this doctrine, but their English colleagues, especially George Poullet-Scrope and Charles Lyell raised strenuous objection, in which they were later joined by W. Reiss (1861) and Georg Hartung (1862) with the result that for a considerable time afterward all idea of the active participation of magma disappeared. Following K. Gilbert's research into the conditions of stratification in the Henry Mountains, 1875, and the very careful investigations of W. Branca in the Urach volcanic domain, of A. Geikie in Great Britain, A. Bücking in the Rhön, and others, it reappeared again in new form and found such general approval, that H. Reck, on the basis of his observations in Iceland, 1907, literally returned to the idea of " Erhebungskrater." Emil Böse, too, emphasized the active rôle of the eruptive forces, following upon his Mexican observations.

In contrast to this, Eduard Suess (1883) conceived the idea of a *passive sinking of great blocks* pressing out the magma existing at a certain depth below. (Antlitz der Erde, 3rd ed., 1903, p. 20 ff.) Later, however, he gave way to the conviction (III, 2. p. 655 ff.) that at comparatively slight depth *phreatic explosions* could occur and (in 1893) that magma could ascend as a result of the *melting of the roof* (III, 2, p. 633 ff.).

New lines of reasoning were then opened through the gradual development of *physical chemistry,* and found an eloquent representative in Svante Arrhenius (1900), who pointed out the part played by water at high temperatures and its great possibilities as a powerful chemical agency. C. Doelter, in 1903, considered gas impregnation of the deep magma to be the most important feature of volcanic activity wherever the gases become explosive through lifting of the pressure. F. A. Perret was able to establish the fact, during the Vesuvius eruption of

1906, that after the conduit is open the gases may escape without explosions, with great force and powerful erosive action.

Besides tectonic release of pressure Doelter thinks (with Suess) of magma rising as a result of melting through the overlying strata. The primary magma hearth he removes to a depth of 100 to 120 km; from there, as he believes, the magma travels to peripheral hearths (lying at a depth of 10 to 20 km.) where it partly solidifies, gases are liberated through increase of vapor pressure, and new eruptions may occur.

An entirely different direction had been taken by C. F. Naumann in 1851. He assumed that the magma, during the process of solidification, underwent expansion, and his pupil Alphons Stübel returned to this hypothesis (1897) building upon it a carefully thought out theoretical structure upon broad and consistent lines. This theory included and expanded Athanasius Kircher's idea of peripheral hearths, and found in its time many followers; but it falls short in that the volume increase of the magma during solidification, upon which all of Stübel's final conclusions rest, has not been established.

While the conflict of opinions about Stübel's theory was still in progress, entirely new methods were again introduced by distinguished *chemists:* Armand Gautier, in the Comptes rendus de l'Academie des Sciences in Paris, 1900 to 1906, published numerous communications regarding his highly interesting laboratory experiments and built upon these a new volcano theory, whereby the lava becomes pressed upward through gas expansion and through the pressure of the solid crust along great faults. According to Gautier, the water which is discharged during eruptions is not vadose water infiltrated from above, but the constitutional water of crystalline rocks distilled out by the mounting column of magma. The liberated water is supposed then to react with the various components of the rocks to generate the remaining gases composing the volcanic exhalations. The older rocks when raised to red heat become explosive, and so explain the vast mass of liberated gases, which account for the splendor and the violence of volcanic eruptions. Under this supposition the magma provides little more than a heating mechanism; but Gautier admitted that mechanically developed heat, due to internal collapse, could also occur.

While the prevailing majority of geologists and chemists (with the exception of W. L. Green, 1877) gave to steam a very important part among the volcanic exhalations, the Genevese scientist Albert Brun (Recherches sur l'exhalaison volcanique, Geneva and Paris 1911), arrived at the conviction, on the strength of numerous laboratory experiments and field observations, that steam is entirely lacking in volcanic eruptions. According to Brun "active" rocks, such as lavas and obsidians, boil at high temperatures; that is, expand suddenly under intense gas development, behaving like explosives. The pressure attained during the gas development is represented as causing the ascension of lava in the volcano conduit as well as the bursting of its walls. The intensive heating of active rocks in the earth's interior is therefore sufficient, according to Brun, to cause volcanic eruptions. But unfortunately Brun does not indicate in what way he imagines this heating to take place, and so leaves his ingenious structure without a key-stone. The eruptions which Brun had in mind are (to take B. G. Escher's expression) of an *indirect* sort and can occur only in volcanoes whose conduit is already filled with obsidian; Brun's explanations in other words do not recognize *direct* eruptions, *i. e.,* those in which new magma is ejected.

These revolutionary conceptions of Brun called forth much approval, but also aroused much antagonism; they have had an extraordinarily stimulating effect and brought into the field a number of questions which are now being investigated with great enthusiasm. In the first place a far more vigorous interest has been aroused in volcanic exhalations and their volatile components, and numerous significant investigations have been made both in the laboratory and in the field. Taking part in the latter were first of all the American geologists, geophysicists and chemists, especially in the investigations of the phenomena at the lava lake of Kilauea, and the gas exhalations of the "Valley of Ten Thousand Smokes" near Katmai (Alaska). Although the investigations are still in progress, a considerable advancement of our knowledge has already been achieved because of them, especially through the studies of R. A. Daly (1909), F. A. Perret (1911), Arthur L. Day and E. S. Shepherd, as well as T. A. Jaggar, Jr., since 1912; E. T. Allen and E. G. Zies 1918, C. N. Fenner 1919. Of especial value was the discovery of the occurrence of steam in considerable quantities among the exhalations of Kilauea, 1912; nevertheless it must be mentioned that A. Brun does not admit this discovery.

Recently Arthur L. Day (1924) has advanced new and unusual views, supported chiefly by his own investigations on Kilauea and Lassen Peak. He points out that the temperatures of the lava lake of Kilauea undergo decided changes within a short space of time, and that the material in the lava basin is in part very fluid, but also in part almost, or even entirely, solid. Inasmuch as the temperature and the gas content of the magma undergo considerable local change it follows that the physical behavior of the lava is locally variable. At high temperature the number of lava fountains in Halemaumau was very great (on July 3, 1912, over 1,100!); at other times fountains only seldom appeared at all. The gases collected in 1912 differed widely in composition, thus proving that they could not be in equilibrium during their ascent in the lava basin, but were undergoing reactions whereby heat was transferred to the adjacent lava. As a result the heat is greatest at, or near, the surface, as T. A. Jaggar was able to corroborate by measurements. If the temperature in the deeper parts of the lava is lower than above, volcanoes can not (according to Day) serve as indication of a glowing liquid interior of the earth. Day accepts, therefore, a solid earth nucleus and believes that existing remnants of liquid lava may be considered merely a product of local conditions which must slowly come to an end. As long as the two neighboring volcanoes of Mauna Loa and Kilauea, but a short distance apart, show a difference of level in their lava lakes of over 3,000 m., one can not, according to Day, consider a liquid earth nucleus or a continuous liquid shell, still less so since the higher opening produces more lava than the lower. Eventual simultaneous eruptions Day considers a chance coincidence, and volcanoes themselves only local manifestations arising from uncommon local conditions.

A sharp contrast to Kilauea is given by Lassen Peak in California, which was explosively active from May, 1914, to May, 1917. Only during the height of its activity, May 19, 1915, at night, were red, glowing ejecta (of perhaps 750° C.) visible. Also at that time the lava plug of the crater floor was raised 90 m. high, and destructive horizontal explosions laid waste the surrounding country. Powerful steam explosions occurred, but no local heat development through chemical activity. Day regards Lassen Peak as a slowly cooling system maintained by the remaining heat from a locally hot zone beneath the surface.

The mechanism of the Lassen Peak eruption Day interprets as follows: a liquid silicate solution can absorb water in considerable quantity in solution; a solution of silica and potash is found to take up 12.5% water in solution, the more complicated silicate solution of a rock magma under favorable conditions at least 5 or 6%. The thousands of existing rock analyses, however, show only 1 to 1.5% water-content. Day concludes therefrom that most of the magmatic water was liberated during the process of crystallization, and believes that gigantic pressures and a powerful explosive activity must result when this liberation of water takes place in a closed space. The great eruptions of gases and dust-laden steam carried away the explosively liberated volatile components of the underlying magma.

If magma solidifies through sudden cooling without crystallization, the resulting glasses (pitchstones or obsidians) contain far more that 1½% of water, from which one may recognize the high water content of magma.

If then, as in the case of Lassen Peak, a magma body in the process of slow crystallization at comparatively low temperature exists beneath the mountain, and the liberated steam is held under pressure within closed walls, an earthquake might cause slight explosions, as was the case with Lassen Peak. Eruptions continued for months at short time-intervals with increasing force and magnitude. The melting snow in the crater penetrated, first as water and later as steam, into the heart of the volcano where the magma absorbed it, becoming more fluid in consequence, and so crystallized faster. During crystallization, however, water again becomes liberated, and continues as long as crystallizing magma exists within reach of the outlet passages.

At Lassen Peak the eruptions seem to have been made up of dust-laden steam, whereas with volcanoes of higher temperature and a greater proportion of chemically active gases such as chlorine, fluorine, sulphur and hydrogen, the magma may be expelled in liquid state, and then crystallize in the open air.

The chemically active gases liberated during crystallization are able, according to Day, to keep a lava lake such as that of Kilauea in liquid state. When, however, in 1924, the lava lake had been drained away through subterranean channels and the conduit, widened by explosions, stood open, there was no fresh obsidian or lava visible; on the contrary the ejecta were made up of fully crystallized material, quite fine-grained and free of bubbles. One had the impression of a central discharge tube with channels below leading to local chambers of crystallizing magma. On the inner conduit slopes small lava rivulets often ran out, quite high above the lava lake, and flowed into it. Day seemed to consider all this due to many sources of the magma and the gases. He came to the conclusion that volcanoes are local and superficial occurrences representing the last stages of crystallization in underlying magma, of which relatively little is any longer liquid, and this in pockets with greatly varied gas content, pressure and chemical equilibrium conditions. *The gas content of the crystallizing magma determines the nature of modern volcanism.* If chiefly steam becomes liberated in a closed chamber, as at Lassen Peak, then only steam explosions are to be expected; but with the addition of chemically active gases, also higher temperatures and lava flows.

These opinions of Day contain a number of assailable points. For example, it is not tenable to regard simultaneous eruptions of adjoining volcanoes as mere chance coincidences, for they have their origin, with greater probability, in a common source which, it is true, may be as likely to come from outside as from a magma hearth common to the two volcanoes. The statement that a liquid magma nucleus or a liquid spherical shell are out of the question in the face of the great difference in level between the lava lakes of Mauna Loa and Kilauea, is also assailable, for as early as 1877 W. L. Green, as I. Friedlaender emphasizes in the "Zeitschrift für Vulkanologie" III, p. 1, ff., gave an essentially correct explanation of this anomaly.

Like Day, W. H. Hobbs also is inclined to consider volcanic centres to be due to particular local causes. He believes (1921) that magma is formed at shallow depths (only about 10 km.) and that wherever through any local cause the vertical pressure of the overlying rocks of the Lithosphere is relieved a local pocket of molten rock (*i. e.*, magma) forms, provided only that the rock temperature is equal to or higher than that required to melt the rock at reduced pressure. If this hypothesis of a "latent magmatic state" were correct, volcanism would always be a result of magma formation caused by the relief of vertical pressure such as may occur during the elevation of anticlines and horsts.

B. G. Escher, who bases his conclusion upon Niggli's important investigations, suggested (1922) that the gases, dissolved under high pressure and high temperature in the magma, and escaping during an eruption, bear away with them finely pulverized magma. The explosions are caused by the expansibility of the gases which, under the changed conditions, can no longer remain dissolved in the magma. With *direct* eruptions, escaping gases furnish the motive power but the escape of the gas from the magma is not to be attributed to temperature increase from without, but rather to the sinking of the magma temperature. Niggli had pointed out that one of the most typical characteristics of magma lies in the fact that it is a system made up of volatile and non-volatile components, and that in such systems temperature-pressure relations occur in which the vapor pressure of saturated solutions increases with diminishing temperature, and retrograde distillation occurs. This increase in the vapor pressure may cause a volcanic eruption. If, in addition, reactions occur which proceed exothermally, the rapidity of reaction increases further and finally the magma explodes. The heat produced by exothermal reactions may cause *indirect* eruptions; if the heat thus generated is consumed fast enough, the paroxysm expires at once, but if there is a surplus of heat, a direct eruption must follow. As soon as equilibrium in the magma has been restored in place and time through these eruptions, the volcano again returns to a state of repose.

The loss of heat outward is, then, the cause of equilibrium disturbance in the magma. As soon as this heat is restored currents appear in the magma (which Escher imagines to be distributed in a spherical shell), causing waves in the overlying crust and mountain-folding, in appropriate places, due to the tangential pressure, while tangential expansion is found elsewhere in the lithosphere. Through these two tangential mass-movements weak zones are created in the earth's crust and the vertical pressure is relieved. As a result, the equilibrium in the magma becomes still more disturbed, reactions occur which in part proceed exothermally and give rise to magma intrusions into the earth's crust, and, in the weakest regions, to eruptions.

After radium decomposition became known, Dutton, as early as 1906, attempted to hold radioactive processes alone responsible for volcanic manifestations. John Joly repeated the attempt in 1926, in a new form and with better foundation. He assumes the universal distribution of a basalt-like substratum, which in the great zones of rupture of the earth's crust would occasionally come through to the surface as molten lava. The continents, according to Joly, swim in this viscous substratum like deeply immersed icebergs. Under the continents the heat, radioactively developed at greater depths, accumulates, whereas beneath the ocean floors where the prevailing temperature is near 0°, the heat developed in the upper regions of the substratum escapes along a steeper gradient.

Since the basalt in molten state occupies a larger volume than when solid, the isostatic equilibrium becomes disturbed at the moment of liquefaction and the continental crust sinks relatively into the now lighter substratum, while the earth's radius is extended as a result of the volume increase which has taken place. The tidal forces effect a slow shifting of the entire outer crust of the earth (the continents as well as the ocean floors with the seas above them) across the underlying liquid magma, as a result of the brake action of the magmatic tidal wave from east to west; because of that, the overheated areas underneath the continents are overrun by the crust, and exposed to the cooling effect of the oceans. Since, however, the earth's radius is now shortened again, the ocean floor becomes too large, the more flexible areas bordering the continental crust pile up and a corresponding growth downward occurs, mountain ranges form on the borders of the continents and in the geosynclines of the oceans. Convection currents of circulating magma are also set up, according to Joly, which are said to cause a more or less vertically directed magmatic movement (due to gravity and change of density) in the numerous cracks and passages beneath the oceans, while beneath the continents the movement would be more nearly horizontal because of the tides. Joly, in his ideas, touches to some extent those of Kreichgauer, who assumes a gliding of the earth's crust upon a magmatic substratum as a result of the earth's rotation. In the great arcs and loops of the great mountain chains Joly sees the effect of undercurrents which, chiefly through the influence of increased temperature and the earth's rotation, draw the earth's crust into their slow but unceasing motion.

Most recently Otto Maria Reis in a well thought out paper—from the geological standpoint (Geol. Archiv. 1926)—expressed a new idea suggesting a centrifugal upward motion of magmatic masses. He wrote to me regarding it as follows:

"The greatest changes of equilibrium in the structure of the earth's crust occur through the ascent of volcanic masses into the salic outer shell, particularly when the eruptions are basic ones, characterized by greater density and enriched by well disseminated ore minerals. It is, one may safely say, nowhere true that eruptive matter rises in absolutely untouched and still homogeneous parts of the earth's crust; on the contrary, portions of the earth shell everywhere lie separated, sometimes over one another and sometimes beside one another.

"Then, when magmas rise it will certainly happen frequently that they ascend comparatively quickly into the higher shell of the earth's sphere and accumulate outside in masses. Thus of course the weight of these regions is greatly increased. To this is added the circumstance that the magma comes from a zone of lesser velocity of rotation into one of greater. Thus it happens that in areas whose weight and velocity of rotation were formerly of a certain magnitude, and which possessed a certain equilibrium, a decided change must take place. A mass, now shot through with heavier intrusives can no longer move eastward with the revolving earth at the same velocity as its surroundings. It must tend to drag behind toward the west and it must exert pressure toward the west, if any opposition is offered from that direction to oppose its falling behind;—in other words it must, relative to neighboring areas to the south and north, apparently achieve a westerly motion. If, however, the intruded mass encounters sharp opposition from the west, or if it is in fact forcibly dragged eastward, it acquires, because of its increased weight and density, an increased kinetic energy of revolution so that it must move outward, that is, appear lifted, as well, and if, at the higher speed of revolution, it encounters less resistance it will then outdistance its neighborhood. It is assumed that there is a certain peripheral mobility of such masses wherever there is radial or tangential disruption."

In 1927 there appeared in Boletin XXX of the Academia Nacional de Cordoba—the "Festschrift" in celebration of Bodenbender's seventieth birthday—a paper by Paul Groeber entitled "Ensayo sobre Tectonica Teorica y Provincias Magmaticas."

The author sets out from the assumption that the observed conditions of equilibrium within the earth are approximately maintained, although in the great ocean basins a considerable deficiency exists in the solid earth. Following the teachings of geophysics he assumes further that the continental masses are made up of Sial (gneiss-granite) with a specific gravity of 2.75, and that the true ocean basins are of Sima (gabbro-basalt) of specific gravity 2.95. The latter assumption is based upon the observation that the only eruptive material found in the ocean basins is basalt or its differentiates. The continental masses can not extend down to great depths and continue to exist where the temperature is higher than the melting point of the Sial (1,250°) for it would then melt and diffuse through the heavier Sima along the base of the Sial. According to the geothermal temperature gradient the normal lower boundary of the Sial is assumed to be about 50 kilometers, which corresponds with the results obtained from the study of earthquake waves. It is further established by the fact that the Sima, which is poor in radioactive substances, must possess a steeper temperature gradient than the Sial, and its melting point of 1,050° will be reached in from 30 to 35 kilometers depth.

This assumes that a sharp boundary exists between Sial and Sima, which at the first glance will certainly prove disturbing to the prevailing views of geologists. It is customary to assume that the upper portions of the crust gradually become more basic downward with the increasing participation of the heavier simic components. This general relation is commonly attributed to the influence of gravity, which must necessarily bring about the sinking of the heavier molecules.

The author's view is that gravity clearly can not exert a determining influence upon the distribution of the atoms because the inter-atomic forces in chemical compounds are of a greater order of magnitude. He then proceeds to show that gravity must also be without a determining influence upon the distribution of the molecules.

First the molecular volumes of average granite and average gabbro are calculated, from which it appears that the granite is made up of about three-fourths lighter minerals and one-fourth heavy minerals, while gabbro on the other hand contains only two-thirds of the lighter minerals and one-third heavy minerals. He then calls attention to the fact that it is rather remarkable that the light and heavy minerals are thus found side by side. To explain this heterogeneous composition one might assume that gravity has not yet had sufficient time to produce the complete segregation of the components of gabbro or of simic magma. That this can not correspond with the facts, however, may be seen from the observation that simic rocks of like properties have been erupted ever since the early Proterozoic period. The time interval is so large that the segregation certainly ought to have occurred long ago. This becomes especially clear when its behavior is compared with that of the Mesosilicic rocks (diorite, etc.). The Sima has remained constant since the earliest time.

The author accordingly reaches the following conclusions: A separation of the Sima into lighter and heavier components is neither taking place now nor has it ever taken place. There must be an association of molecules here of great stability from which the author concludes that the Sima is a silicate solution whose components remain in a fixed quantitative relation, that is to say, in an extraordinarily stable chemical equilibrium. Without the maintenance of this equilibrium throughout the period immediately before solidification, and down to the beginning of crystallization itself, neither the silicates of the eruptive rocks nor the eruptive rocks themselves could come into existence in the form actually observed in nature.

Furthermore gabbro is not the only stable solution; granite is also such a one. It is not normally capable of differentiation. There is practically no acid rock with a greater proportion of free silica than granite such as certainly must exist according to the usual views of continuous segregation.

Although these varieties of magma can differentiate only under special extreme conditions the mesosilicate magma behaves in a wholly different way. The author cites many instructive examples of these in the Argentine. For example, the Patagonian basalt province stretches to the north as far as Diamante and from the earliest Tertiary down to post-glacial time has brought to light exclusively common plagioclase basalt with few differentiates. During the same interval from the lower Tertiary to post-glacial time the Andean magmatic province was active at least from 43 degrees south to 27 degrees and farther. In the Eocene it produced augite and hornblende-andesite; in the Miocene either in intruding masses or in separate zones, hornblende-andesite, dacite, trachy-andesite, trachyte and some liparite; in the Pliocene and Quaternary almost exclusively liparite. The original magma was a fairly basic diorite. During all this time the gabbroic or simic magma underwent no differentiation, while the mesosilicic magma was intensively differentiated. This same phenomenon of intensive differentiation of the mesosilicic magma has also been found by the author in the upper Triassic and upper Permian in the Argentine. It is indeed an altogether general phenomenon which can be followed over the whole earth and in the most widely different periods. This gradual increase in acidity is called an "eruptive cycle." Such a cycle begins each time with the eruption of a normal mesosilicic rock mixture; following this the rock series becomes increasingly acid (apart from local anomalies) in its surface indications; during the progress of segregation of the parent magma the eruptive material naturally represents the composition in which the upper portion of the magma is richest, *i. e.,* the lightest rocks, in other words the most acid. When all the zones of this mass have solidified down to the lowest, then basalt may be erupted as the last member of the series if tectonic conditions are favorable to its rise to the surface. The mesosilicic magma is therefore not a stable magma like gabbro and granite, upon which gravity has no influence. On the contrary it is continually in process of differentiation under the influence of gravitation. This process, however, does not take place in such a way that the individual heavier molecules sink to the bottom, but rather there are separated from the parent magma different silicate solutions appropriate to the temperature and other conditions then and there prevailing, which are in equilibrium under those conditions. But this equilibrium has little stability, as may be seen from the short duration of the occasional eruptions. It is rather a series of episodes or stages in the differentiation process in which the tendency is to re-establish the silicate solutions having the greater stability, namely Sial and Sima.

The magma masses of mesosilicic type may be very large, thousands of kilometers long perhaps, but they are comparatively narrow and confined to the geosynclines and to zones of mountain building. For these separations freedom from disturbance is necessary, that is to say, freedom from the irruption of new material.

The mesosilicic magmas, according to the author's view, are formed from superheated Sima coming by convection into contact with the base of the Sial. The continuous dilution of the Sial leads to its continual sinking, that is, to geosyncline formation. The Sial is thereby constrained to occupy more space in consequence of the formation of the downward curvature and suffers in consequence strain and rupture. In the course of the long life of a geosyncline the mesosilicic magma presses into the zones of rupture and forms batholiths. The invasion of mesosilicic magma can, under favorable conditions, as in the Andes in the Jurassic and Cretaceous, continue for long periods. The product is then almost continuously basic porphyry. When the reaction with the base of the Sial, that is to say the formation zone of the mesosilicic magma, is interrupted, differentiation of batholiths and an eruptive cycle begins; this happens if the convection currents during the growth of the geosyncline withdraw further into the interior or are diverted to one side, or if during mountain building a considerable thickening of the Sial occurs. The home of the mesosilicic magma is therefore confined to the geosynclines or their neighborhood and to the zones of mountain building.

The simic, gabbroic magma develops eruptive activity either in those regions where the Sial is wanting, as for instance in the true ocean basins, or it appears on the surface of the continental masses which have suffered no melting at their base, for under these inert or normal Sima must lie.

We see from this that volcanic activity can not be understood merely from a consideration of the individual rocks, but only by regarding it as one link in a chain of operations with a beginning and end which lie far apart in time.

Regarding the historical eruptions certain conclusions may be readily drawn. In those cases where the seat of mesosilicic effusion was formed in the Mesozoic, and where, in consequence of their separation from the zone of active magma formation, they have already given rise through mountain building to a Tertiary eruptive cycle, we can expect only feeble volcanic activity, and this chiefly of the acid end-members of a cycle, or else rocks of very heterogeneous character. But in those cases where the eruptive activity has begun at a later period the basic members of the eruptive mesosilicic cycle may be expected to appear and the province will be characterized by great homogeneity and very great activity. This difference will be indicated in the erupted material. In this sense Central America forms a young mesosilicic province. The eruptive activity does not begin until the middle of the Tertiary. Since the year 1500, on a stretch of 1,200 kilometers, 60 cubic kilometers and more of eruptive material have been discharged, while in the Cordillera of South America on a stretch of 8,000 kilometers only 10 cubic kilometers have been erupted, which only in part belongs in the mesosilicic group.

Of the basaltic group it may be said that with the exception of Iceland it is probably on the wane. The enormous province of the Pacific Ocean, which includes the basaltic islands from Samoa to Hawaii and thence to Juan Fernandez, to which, according to the author, the Patagonian basalts also belong, had its period of greatest activity in the Tertiary, as did also the mesosilicic Pacific province which surrounds the basin, the North American Cordillera, Kamchatka, Japan, Liukiu, New Guinea, the arc facing Australia, Fiji, Kermadeck, New Zealand, etc.

It would carry us too far to consider all the details, but the so-called Atlantic magmas must be rejected, according to Groeber, as an independent group.

CONCLUSION

Reviewing the efforts of the great number of scholars who since the earliest times have sought to solve the volcano problem, we realize that progress has been made in most manifold ways, and that with the continuing development of the different branches of science new approaches are constantly being sought in the effort to reach the desired goal. Of course it can not be denied that volcanological science has now and then retrogressed for a time; but aside from these periods of standstill one must recognize on the whole a very considerable advancement—so considerable that one may feel confidence that further patient work and more careful thinking will bring us gradually nearer the goal of better understanding. The attempts to solve the volcano problem from geographical or historical data, in spite of occasional and perhaps important partial successes, may be regarded as barren; for which the major fault certainly lies in the absolute inadequacy, for most regions, of statistical information.

Which path will eventually lead us to our goal we do not know. There are so many questions of detail that the work of scientists in the most varied branches and with every facility for mutual cooperation and support is necessary to achieve success.

One often returns to old ways of thought which for a time were entirely abandoned and even the most modern times do not scorn to work out further those thoughts which were expressed in the past, but could not then be sufficiently developed because of the state of science at the time. New ideas show themselves, sometimes timidly, sometimes with the claim of infallibility. All will share the credit for the continued stimulation of the search. But as the matter stands today we are still very far from the solution of the chief problem. Even on the basic questions there exists as yet no agreement. For example, very recently the question has again been raised whether volcanoes were not simply local manifestations,—a question which Alexander von Humboldt believed to have been definitely settled at the time when the fundamental similarity of volcanic manifestations everywhere was pointed out. It has certainly been shown that there is in fact far more local individuality in the phenomena than Humboldt once believed, and there is no doubt that chemical and physical reactions intervene much more decisively than was thought a century ago. But even though we admit all that, we must still insist that the petrographical facts speak most decidely against a local limitation; likewise the coincidence in time of several eruptions, which should not always be thought accidental, and, still more convincing, the alternating eruptions of individual volcanoes (Canary Islands; in Central America for a long time Fuego-Pacaya; in Japan, 1907-11, Asamayama-Iwôdake, and others.) To these must be added the phenomena of isostasy, which, in spite of the doubts of a number of geophysicists, point to the existence of a latently plastic zone, which may probably be considered the original seat of volcanic magma. But of course it is hardly conceivable that every small volcanic eruption is directly fed from this deep-seated zone, for the surface phenomena and the mass of the ejecta are often far too insignificant for that. So on the other hand it would be equally out of the question that some volcanoes should be able to react eruptively to sudden earthquake disturbance, if their hearth lay at the considerable depth of 100 to 120 km., or even 60 km., at which we suppose the potentially plastic spherical shell to be. It would be much more likely that the volcanoes are fed from magma pockets and hearths near the surface, as was once commonly believed. From such hearths the magma or its gases could easily and very quickly break through to the surface either through explosions and tectonic movements, or by melting away the rocks, surface tension, or other phenomena not yet well known to us—processes in which the erosive action of gas discharges may prove very effective.

Some of the assumed peripheral magma basins might be countrywide—as one would gather from the size of some petrographic provinces, others might be of more moderate size, and still others quite small. This isolation of the hearths whose magmas may at times undergo peculiar transformations, due to assimilation or to unusual physical conditions, may probably be held largely responsible for the locally varied behavior of certain volcanoes and volcanic regions. It may even go so far that single volcanoes or volcanic regions may come to possess a really high degree of individuality.

Whether the peripheral hearths, or some of them, occasionally receive a fresh supply of magma from the latent-plastic zone, or whether they are entirely severed from it and will in consequence exhaust themselves within limited periods of time, is unkown to us, just as we are still in the dark concerning the other basic questions of volcanism.

But if we steadfastly continue to gather new and dependable facts of observation we shall in time provide a solid foundation for more satisfactory theories than have hitherto been formulated. May the search be successful!

CHAPTER II

THE PRESENT CONDITION AND THE FUTURE OF VOLCANOLOGY

IMMANUEL FRIEDLAENDER

Volcanology is one of the most neglected domains of geology. The volcanologist can not expect immediate material rewards such as the student of oil-geology, of ore-deposits and of other practical applications of geology could easily obtain. Until recently no official position existed for the volcanologist, perhaps with the one exception of the directorship of the Royal Italian Observatory on Mount Vesuvius. Within the last two decenniums public opinion and scientific interest in volcanological studies have rather changed. Several new reviews and observatories have been founded and I am optimist enough to believe that conditions will continue to improve.

The study of the volcanoes, together with seismology and the other methods of physical exploration of the earth, is the very key to the understanding of the constitution of the one planet which certainly is the most interesting to us and also the most accessible for exploration. When we consider the amount of public and private money spent for astronomy it is quite discouraging to see how little is done for the physical study of our own planet.

Volcanology in some other ways is also the key which opens the way for geology at large. All geological deposits, whether sedimentary or not, drew their materials from eruptive or plutonic rocks. The only direct opportunity to observe the formation of such original rock material is offered by the volcanoes.

Volcanological phenomena have occurred in many, if not in all, geological periods. There is no doubt that such occurrences have been connected both in time and in space with the great geological changes and revolutions, and a good knowledge of the volcanological phenomena and their physical and chemical conditions will probably provide the key for the proper understanding of the great geological revolutions of the earth.

Although we are in possession of a few good books on general volcanology[1, 2, 3] and of many good descriptions of single volcanoes,[4, 17] the science of volcanology is still in its infancy and is not founded on exact knowledge and understanding of the phenomena. In astronomy predictions are easy and certain. In meteorology predictions are possible and in most cases correct. Also, in seismology predictions sometimes can be scientifically justified. In volcanology predictions are far less possible and even when they are possible, they are uncertain at least for the time of future events. As for the main questions—what a volcano really is, how it works, how different volcanoes are connected with each other and with the interior of the earth or whether they are connected at all with it—there does not exist any agreement of opinions. What I have to say in the following pages is based on a personal study within the last forty years of some hundreds of volcanoes; nevertheless, it does not claim to be more than a personal opinion of limited value. Real scientific progress can hardly be attained by the individual enthusiast working without well-organized cooperation and without ample means for instruments and laboratories.

In many places on the earth hot gases and silicates rise from unknown depth, the gases are dissipated often without leaving much trace near the place of their outbreak. The silicates remain near their sources and by their accumulation form more or less important deposits. Often, if the eruptions occur without much change in the position of their channel, a more or less elevated mountain with central structure results. In other cases the eruption moves along a fissure and builds up an elongated chain. If in one region many fissures exist and if the silicate magma is liquid enough, a plateau of igneous rock might be formed. All such eruptive regions and structures are called volcanoes.

The idea that such a volcano is no more than a phenomenon of small and local importance is certainly erroneous. On the borders and in the middle of the Pacific Ocean there exist long chains of volcanoes, such as the Fujiyama chain, the zone of the Hawaiian Islands, of the Aleutian Islands and the Andes volcanoes, each of them several thousand kilometers in length. Their great extent and the great similarity of their products proves that they can not be of superficial origin. They follow the lines of Tertiary and Pleistocene tectonic upheaval and are more or less parallel to the more recent mountain chains; so that their connection with tectonic movements is proved beyond doubt. The frequent observation that some volcano was active, while its immediate neighbor showed no sign of activity, has been used as an argument for the quite superficial origin of volcanic activity. But such independence can also be explained by the theory of Stuebel,[5] who believed that reservoirs of more or less liquid magma exist in the higher portions of the solid crust of our planet. Such reservoirs might have been, or might still be, connected with a deeper molten substratum. In many regions the distance from one volcano to its nearest neighbor in the same chain is nearly constant.[6] In Italy this distance is about 60 km. and in many other continental regions it is the same. In the Hawaiian Islands it is about 40 km. Lowthian Green [7] was perhaps the first to suspect that such a constant distance might be equivalent (or proportional) to the local thickness of the earth's crust. Certainly 60 km. in continental areas and 40 km. in the middle of the Pacific agree very well with the thickness of the earth's crust as calculated from seismological data. But there also exist regions in which the distances are smaller. In the group of the Lipari Islands and on the plateau of Ecuador the distance is about 22 km. One of the smallest distances between regularly distributed volcanoes is found in the Phlegræan Fields, near Naples, where it is only 2 km. In such cases we might suspect the existence of magma reservoirs or laccoliths as assumed by Stuebel. Their depths would be a little over 20 km. in Ecuador and in the Lipari Islands, and only 2 km. below the Phlegræan Fields.

Elie de Beaumont [8] and Lowthian Green [7] have already called attention to the fact that the fissures indicated by the distribution of the volcanoes show not only more or less regular spacing, but often form some regular network. Lately, Fujiwhara [9] by comparison with experimentally produced fissures noticed that some volcano-lines show the pattern of a system in echelon formation as though displaced by a vortical motion; doubtless this observation is of great importance, and further study in this direction might produce not only better understanding of the volcanological problems, but of tectonic geology in general.

VOLCANO TYPES

The rocks produced by the volcanoes vary within rather narrow limits and the fact that nearly identical types can be found in many and very distant localities is one more proof that volcanism is not a local but a universal phenomenon. The most obvious distinction between different volcanic rocks is founded on differences in acidity. The amount of SiO_2 contained in the rocks regulates also to a large degree the character of the volcanic activity. By consequence, the morphological aspect of a volcano is also dependent upon the acidity of the lava.

Volcanoes of purely basic type are not the most common among the recently active volcanoes, but they are the best known and have had a wider diffusion in earlier geological periods. The Hawaiian volcanoes Mauna Loa and Kilauea, the Samoan volcanoes, the volcanoes of Iceland, produce basaltic rocks; Etna and Stromboli are also basaltic; and the most famous of all, Vesuvius, although its rocks are not true basalts, is only a little more acid and is still of the basic type. The fact that these volcanoes are easily accessible and that the three Italian mountains mentioned above are located near to the very centre of the older civilization of our race is not the only reason that our ideas of volcanism are more or less determined by observations made on them. This class of volcanoes has been more thoroughly studied also because basic volcanoes have shorter intervals between eruptions and consequently more eruptions have been observed within the geologically very short period of scientific observation.

The rather regular cycle of the Vesuvian activity [4, 13] is the best known example: after the paroxysmal eruption which concluded the previous period of volcanic activity, there follows usually a period of repose and apparent inactivity. The newly-formed or modified crater enlarges its diameter and diminishes the height of its wall by a series of avalanches. The bottom of the crater fills up and newly-formed talus cones very soon permit the descent into the crater. There are many fumaroles, some only of water-vapor, but most carrying slightly muriatic or sulphurous gases and sublimations. Sometimes the center of the crater remains inactive and the fumaroles are restricted to a circle around the newly-formed plug which closed the eruption channel.

This solfataric action continues for some time and gradually increases. The part of the crater floor where the conduit has been buried begins to emit steam and becomes the locus of the strongest solfataric action, while the annular fumaroles disappear. The liquid lava is now very near the floor surface and soon works its way through, forming a small cone of scoria and covering the boulders, blocks and ashes of the crater bottom with small, fresh lava streams. By such activity in the course of several years the whole crater mostly becomes gradually filled up and the small, active, secondary internal cone eventually becomes the very top of Mount Vesuvius, and the old crater may be recognized only by some terrace on the outer slope of the big cone. Small streams of lava then issue from the very top or from fissures which open only a little below. During all this time the explosive activity of the cone continues, or even increases temporarily on occasions of lava emission. The glare of the liquid lava within the crater becomes brighter and it is obvious that the temperature of the internal lava is increasing. The fumaroles and the gases rising from the funnel have a strong smell of muriatic acid; and the sublimated chlorides, especially iron-chloride, color exposed parts of the cone with green, red and principally yellow tints. The scoriæ, which are emitted, are very soft, nearly liquid, and Pele's hair may be formed.

A catastrophic eruption is now near and will occur as soon as the increasing activity succeeds in opening, by the combination of melting and explosive blasting, a fissure at some lower level. A copious lava flow will follow and drain the upper levels of the reservoir within the mountain. The lower magma can rush up and will release its gases, before highly compressed, with tremendous velocity. Such explosions may continue for many hours or even several days and will form a steep funnel-shaped explosive crater. But very soon this crater will be modified by the subsidence of the bottom and also of the walls which, after the removal of so much material, no longer have strong foundations.

The explosive gases for some time continue to throw out boulders, blocks, scoriæ, sand and ashes, partly formed from the liquid magma, partly from debris of the walls. Finally, the channel is swept clean and the gases carry only fine rock dust and sublimation products.

Scientists have disagreed widely about the quantity and quality of the gases. For obvious reasons it has not been possible to collect the paroxysmal gases for analysis.[10, 29] Nevertheless for many reasons the author is convinced that water-vapor forms more than 90% of the volume of the gases.[13, 29, 34-37] Next to it very likely comes carbonic acid. Hydrogen and hydrocarbons are also certainly present, especially during the first part of an eruption and their presence probably limits the oxidizing power of the water-vapor on the ferric silicates in the ash.

Regarding the quantity of the gases there do not and can not exist any accurate measurements, but from an estimate of the size of the conduit and the velocity of emission, it appears that not only the volume, but also the weight of the gases must be many times greater than the total mass of the ash and lavas.[13]

The paroxysm here briefly described closes the cycle and thereafter a new eruption period begins.

If we consider the activity of Etna or of Stromboli the cycles are different, but of a similar type. Both of these volcanoes have nearly three times the height of Vesuvius (less than the third part of the cone of Stromboli is above sea-level). Of Etna the activity of the central cone is smaller than that of Vesuvius. Eruptions occur on a system of fissures and very often at pretty low levels. Stromboli generally shows an activity at its crater which is very similar to the activity of Vesuvius in the middle part of the cycle. Small terminal and subterminal lava streams are known to occur also on Stromboli and more copious ones very likely occur at deeper levels, but could not be observed.

The two ultrabasic volcanoes Mauna Loa and Kilauea are known for little more than a century.[1, 11, 12, 15, 16] Their activity is somewhat different from that described above, for explosive activity is almost entirely wanting. At Kilauea liquid lava is commonly present in the central crater and the gases are usually emitted in a very quiet way. Terminal lava outflows have frequently been observed, but here, as well as on the other volcanoes, the more copious lava flows which drain the crater occur at lower levels; often a part of the flow or even the whole flow is subterranean and does not appear on the surface. The bottom of the crater, after such lava emission, drops in and a deep funnel is formed. Also, the larger caldera which envelops the small crater of Halemaumau has been formed by subsidence and the progress of its formation has often been observed within the last hundred years. The terminal crater of Mauna Loa owing to its great elevation is not so well known. On the summit is a large caldera similar to the one of Kilauea, formed by subsidence and changing by new downbreaks. Eruptive activity is usually of short duration and interrupted by long periods of calm. It is also restricted to small areas of this caldera and is characterized by a little stronger gas emission and the formation of scoria cones. The great outpourings of lava, perhaps with those of Samoa and of Iceland, the greatest observed on our planet, very often in the upper zones are subterranean, but usually come to the surface on some part of the slope. The amount of gas emitted must be tremendous, for the roar and the hissing of the discharge at many eruptions could be heard for great distances[12] but never has any important explosion been reported from Mauna Loa.

The acid volcanoes, as we shall see, show rather different and far more explosive manifestations, although exceptionally strong explosions happen also on the basic volcanoes. Vesuvius has had three known catastrophic explosions.[13] One about 700 B. C., which covered a large part of the Campania with pumice and lapilli, the second in the year 79, famous because of the destruction of Herculaneum and Pompei, described by Pliny, and the last in December 1631. It is not known whether any liquid lava was erupted at the two first-named explosions. The amount of newly formed pumice on both occasions was prodigious and the magma, as shown by analyses of the pumice, was a little more acid than is usual in the Vesuvius lavas. Very likely during the repose interval of several centuries that preceded those eruptions a differentiation of the magma within the mountain had taken place, the heavier basic components settling down and the highly compressed gases (water-vapor) becoming occluded within the upper levels of the molten magma. The last and best observed of the three catastrophic eruptions in December 1631 produced smaller amounts of ash and of pumice. Nevertheless a very large area was covered by them and the total mass of cataclastic material was many times greater than the volume of the lava streams.

Several streams of lava came out in 1631. They are the largest lava flows known on Vesuvius and are of the usual basic type. Much damage was also done by streams of hot water and hot mud. Where did the hot water come from? The common explanation is that heavy rains fell on the mountains, and, mixing with the still hot ashes, formed the hot mud streams. But the contemporaneous observers were of a different opinion and some of them discussed this question. They did not attribute the water to rainfall and in addition to the hot mud streams described also a hot stream of clear water on the second day of the eruption.[14] Also, on other occasions the eruption of hot water has been often described and later has been denied by scientists. To me, such flows seem to be a fact, not easily to be explained, but well enough observed. Whether we have to conclude that the juvenile water of the magma had been condensed and accumulated somewhere within the mountain before the eruption, or that some phreatic water—either ground water or the sea itself—had access to the conduit of the volcano, is doubtful.

Also, from Kilauea two strong explosions are known. The one in 1789 and the last one in 1924. In both of them the amount of water-vapor was extraordinary. In the case of the 1924 outbreak it has been suggested that the ground water had some access to the conduit of the volcano and originated the explosions.[15, 16]

The more acid volcanoes, the andesitic, trachitic or dacitic types, form the great majority on our planet, but rarely more than one or at most a very few eruptions have been witnessed on the same volcano. In Japan, in Mexico, in South America, and also in the Azores there are some acid volcanoes with a longer history. In the Mediterranean there are Santorin and Vulcano near Lipari. Acid lava does not form long streams like the basic lavas. A great part of the lava extrusion consolidates within the crater or above the fissure of eruption. Sometimes, after erosion has changed the configuration of the mountain, it is difficult or impossible to distinguish between the subaerial lava stream and the dyke in which it originated.

The thickness of such acid lava streams is often very considerable. The high viscosity of the magma favors the formation of domes and spines. The more violent gas emission may be caused in part by a higher content of gas, in part only by the more difficult and less continuous release from the dense magma. On Kilauea, Vesuvius and Etna, observers may go quite close to the lava lake or to the flowing lavas and even put walking sticks in the liquid mass. With an acid lava stream that would not be possible. Explosive gas emission at the front of Sakurashima lava flows threw down heavy trees.[81] The explosions within a still active acid lava dome shoot ashes and heavy debris to considerable distances. The rather weak explosions of Galeras volcano in 1926 threw incandescent blocks of several meters diameter to a distance of two kilometers.[82] On basic volcanoes the main craters nearly always, even during the strongest explosions, discharge their gases, ashes and ejecta in a vertical or slightly inclined direction (1906 Vesuvius to Ottajano), but the gases from acid volcanoes often are ejected in horizontal or even downward inclined directions and form what has been called by Lacroix "nuées ardentes."[17] This phenomenon has been described in connection with the 1902 eruption of Mont Pelée, but it certainly is not extraordinary, on the contrary, it is a quite usual manifestation of acid volcanoes. Pumice, volcanic sand and ash are more prevalent from the acid volcanoes and so also are the mud streams. Such mud streams might be occasioned by rain water, melting snow or melting ice mixing with clastic material, but local observers very often have insisted that mud or hot water was erupted by the volcano.[18]

I shall now close my very incomplete notes on active volcanoes. Inactive or extinct volcanoes are far more numerous and besides the evidence of former activity, of the character we have just considered, shows also the evolution of the activity from the beginning until the present time. These life histories of single volcanoes show many complications and many differences. Some facts are more or less often repeated. The quite recent volcanoes, whether still active or already extinct, in many regions of our planet constitute a second generation appearing after an interval above the ejecta of an older and larger volcanic formation. The recent cones of Vesuvius and the Phlegræan volcanoes are reposing on the yellow tufa strata and old trachitic lavas which also are of Pleistocene age. In the southern part of Kiushu, the volcanoes Kirishima, Sakurashima and Kaimon in a similar way are superposed upon an older volcanic formation of which the craters can no longer be easily identified.[19] Exactly the same thing has been observed by me in Mexico, in Ecuador and in many other places.

The lower part of most volcanic mountains is built up by very extensive lava masses. In a later period the production of ashes and tufa increases and the activity of the central vent mostly closes up with the formation of cinder and lapilli cones. So it happened in Hawaii with the Kohala mountains, Mauna Kea, Hualalai and Haleakala; although those last three very likely are not definitively extinct.

With the acid volcanoes, not only the production of lavas, but also the production of clastic ejectamenta seems to be decreasing as time goes on, and often they close their life with a production of some massive dome which plugs up definitively their conduit.

In many cases when a volcano is dying or already extinct some small new eruptions break out near the foot of the old volcano. Such epigonic small foot volcanoes are mostly of the basic type, even if the main volcano has been built up by acid lavas.

DEVELOPMENT OF VOLCANOLOGY

It would not be difficult to increase this enumeration of observed facts and make a longer and more complete description of volcanism, but it is better to use the remaining space to make a few suggestions for the development of volcanology.

The *geographical distribution of volcanoes* has been a subject of study by several of our best scientists. Mercalli,[2] Schneider,[20] Sapper,[21] Wägler,[22] and others have compiled lists of active volcanoes and constructed world maps of recent volcanism. The result of all these efforts is a very incomplete record and it is evident that something better ought to be accomplished. Several years ago I proposed the construction of a volcano map of the world and suggested using as a base the world and sea map of the Prince of Monaco. It would be necessary to divide the work and to have about half a dozen specialists work under one direction. The volcanological atlas that would result should not only show the exact position of every known volcano, but also the relation of recent volcanism to the tectonic lines of every region and its neighborhood.

The morphological type of every volcano should be shown by some conventional sign. In the same way the character of the later eruptions and the petrographical composition of their products should be distinguishable at the first glance by the use of other signs. For every sheet of the atlas some explanatory text should give all the most important facts and also some bibliographical notes.

The morphological descriptions of active and recent volcanoes constitute perhaps the best elaborated and most valuable part of recent volcanology. On some other occasions I have emphasized the fact that for real scientific progress something more is needed than the chronicle of volcanic events and corresponding morphological descriptions. Nevertheless even volcanic morphology is still very deficient. Morphology tells the whole history of a volcano, but usually only those features are described which relate to the different eruptions and the repose periods between them. Other features do exist which very often did not attract the attention of scientists. The volcano is not independent of the neighboring mountain chains and their tectonic lines. Very often it lies near the centre and in other cases near the border of a basin formed by faulting. Fault lines and scarps may be visible only about the rim of such basin, but sometimes they appear within the volcano itself. Such morphologic evidence of the larger tectonics of a volcanic region often has been neglected. The smaller tectonic features which properly belong to the volcano itself, such as the calderas and pit-craters with their terraces, their radial or tangential fissures, scarps, " Graben " and sectoral " Graben " very seldom have been well described in their most interesting details.[23, 24, 25] All these features are purely volcanic manifestations and if not originated by the eruptions, they surely are caused by movements of the magma.

Petrography certainly has developed within the last decades to be a very important science.[26, 27] Its progress is enormous and its importance for volcanology is evident. The distinction between the Atlantic and the Pacific rock families seems to be to some degree connected with the distribution and tectonic origin of the volcanoes. The long chains and fissures have generally produced volcanoes with Pacific magma, while the groups of volcanoes disseminated on large sunken areas often have lavas of Atlantic type. In many cases the lava composition of one and the same volcano has changed within its history. Very often, but not always, such changes did not transgress the limit of one magma type. The different analyses, if plotted on the Niggli diagram, usually accord very well with each other. It would be well worth while to prepare complete petrographical monographs, if not of all, at least of some of the most important and typical volcanoes, but up to the present time no such complete petrographical study has yet been made even of Vesuvius. There exist many inclusions and boulders among the rocks of Vesuvius which vary from the most basic to highly acid rocks. Splendid material is lying in the different public and private collections and on the mountain itself waiting to be studied by the petrographer.

Volcanic mineralogy is of the very highest interest. The conditions of the formation of the minerals can be better observed and studied about a volcano than in any other place and new minerals form with great rapidity. Perhaps there is no single locality in the world where so many different minerals have been found as on Vesuvius. Many other volcanoes are probably quite as rich, but have not been sufficiently studied. There exists a monumental treatise on the minerals of Vesuvius.[28] Similar studies ought to be made of the minerals of other volcanoes.

The *sublimates* form a distinct class of minerals. Their study is of special value, because they give evidence of some elements and chemical grouping within the volcanic gases, which hardly could be found by gas analysis.

The *gases* are, certainly by volume and, as we believe, also by weight, the principal product of volcanoes. Good gas analyses are very rare—if they exist at all.[10, 29] We hope that the time is not very far distant when the best gas analyses hitherto published will be regarded as quite insufficient. The varied appearance of the volcanic clouds, the changes in the sublimates and in the smell of the volcanic gases prove without doubt that very important changes of composition happen, often within an extremely short time. For that reason analyses of volcanic gases, even if the sample has been carefully collected and the analysis be perfect, can be only of very limited value. Samples of gas should be taken at short intervals, so that every important change can be detected. This has not yet been undertaken on any volcano! Of course no single scientist could perform this task. A local volcano observatory with a sufficient staff and laboratory appliances is needed.

OBSERVATORIES AND METHODS

Local observatories now exist at Vesuvius, at Kilauea, at Lassen Peak and at some of the Japanese and the Dutch Indian volcanoes. At present none of them is equipped to initiate regular gas examinations.

Local observatories on active volcanoes are of course the most effective means for real progress in volcanology. But they ought to be well equipped for their task and quite different from the present observatories. I do not doubt that the time will come when volcanological observatories will exist which can compete with the best astronomical observatories as to funds, instruments and staff. The working program of a volcanological observatory can not yet be fully determined. With the evolution of this science certainly the program must change and develop. The suggestions enumerated in the following lines form only a part of the program which can be traced for the present conditions and needs of volcanology. As the morphological features and the topography of an active volcano are liable to change more rapidly than anywhere else, the observatory ought to command instruments for making accurate and detailed maps and plans. The time that can be given for such work necessarily will often be much restricted and for that reason besides the usual transit compasses, theodolites and drawing outfit, the photographic camera will be of paramount value. Not only the ordinary camera, but also a stereo-photographic apparatus should be available for quick surveying.

The photographic camera has already been successfully used for documenting the chronicle of volcanic events on Kilauea and on Vesuvius, but up to the present time such records are scientifically very incomplete, because only seldom can they be corroborated by measurements. This defect is most obvious, especially for the gaseous emissions. The description of the form and of the appearance of Vesuvius clouds certainly is very interesting.[30] But, at present, observations can only be made during a few hours of the day and as the visible appearance of the clouds not only depends upon the gaseous emissions, but very largely also upon meteorological conditions, the form and size of the volcano orifices etc., such a description gives only a faint idea of what has been happening. The measurement of volume and of temperature, the sampling and analysis of the gases is doubtless a most difficult task and really efficient methods surely can be developed only in a volcanological observatory. But to attain this scope much time, ample means, a physical and chemical laboratory, which should also be able to construct quickly new types of apparatus, and a well-selected staff of scientific specialists are necessary.

A seismological station must be part of the observatory. Such a station is doing good work already at Kilauea. Besides the usual horizontal and vertical pendulums with medium or low magnifications, some very sensitive and short-period tromometers, such as the Japanese have already used, ought to be operated in every volcano observatory. Also, some very sensitive horizontal pendulums for measuring the tilt, with even more accuracy than it is done now at Kilauea, would give interesting results on every active volcano.

For measurements of the temperatures of gases and lavas, the Le Chatelier thermo-element has been used by Perret and others with good success. But such measurements hitherto have been sporadically made and continuous series are lacking. For the very highest temperatures optical pyrometers have been used, but only with small success. I proposed years ago to use the photographic camera and to compare the effects of the incandescent rocks and gases on the negative with those of incandescent materials of known temperatures. If the necessary care is taken to secure identical times of exposure and identical conditions of development, the results probably will not be inferior to those of the optical pyrometer and the camera will have the great advantage that we get certainly the brightest point on the picture, whereas the pyrometer might not always be directed exacty toward the brightest visible point.

The changes of the magnetic constants were observed on Vesuvius in the time of Palmieri.[33] I would suggest making magnetic observations with sensitive modern instruments.

Gravity observations with pendulums and with the Eötvös torsion balance will give interesting indications of underground movements of the magma, especially so if compared with magnetic measurements.

There is one phase of the subject which will chiefly interest the general public and the tax payers, who after all have to carry the burden of the government observatories. They all ask when the next eruption of a certain volcano will occur, if there is any danger, whether an earthquake is likely to happen. The one thing they ask is: *prediction.* We have already seen that such predictions in the present state of our science are difficult and uncertain.

For the basic volcanoes conditions are not quite so bad; the cycles are rather regular and one phase of activity follows the other with some certainty. Only the time occupied by each phase varies markedly and the violence of the final paroxysm can not be anticipated—except that after a long repose and a long preparation the outbreak is likely to be stronger than after a short period of calm. Accordingly, predictions on Vesuvius, Etna or Kilauea are more or less possible, although the most important item—the prevision of the time of the catastrophe—is impossible. Acid volcanoes have also their cycles, but they are far more irregular and deceive the best specialists. Premonitory earthquakes—important signs also for the outbreaks of basic volcanoes—are paramount as warnings with the acid volcanoes. But Ischia, which had its last outbreak in 1301, suffered no eruption after the earthquakes of 1881 and 1883. Of course there is doubt whether these two earthquakes were of volcanic origin. Likewise, on Vulcano (near Lipari) the rapidly increasing temperatures of the fumaroles have indicated the probability of a new eruption, which as yet has not appeared, and nobody would venture to offer any assurance whether it is soon to happen or not. The occurrence of muriatic acid in fumaroles, which previously produced only water-vapor, is also an indication of imminent eruption, and in the case of Usu led me to expect the eruption of 1910 about one year earlier. But all these premonitory signs are not reliable.

Observatories could do somewhat better than the casual observer. The regular observation of the number, force and direction of shocks permits us to judge of the importance of the earthquakes as indications of the imminence of eruption. It would also be valuable to observe the gradual increase of stresses in the rocks, which precede the release in earthquake shocks. The variation in distance between fixed and well-triangulated signals is already used for that purpose in California. Perhaps it would also be possible to observe the difference in the velocity of artificial earthquake waves caused by changes of elastic compression. I should propose to use the difference of the time of sound propagation within the rock between different stations for this purpose. The time required for the sound to arrive from an underground detonator at the depth of say 100 m. at a receiving microphone some kilometers away at a similar depth, can be very accurately measured by the apparatus now used for the echo sounder. A network of such stations would of course be expensive, but the expenses would be nothing in comparison with the values menaced by earthquakes—for instance in California. Every one of the boreholes near a volcano would be of such scientific interest that it would pay largely for its costs. The connection of magma movements with tectonic movements might be elucidated by the proposed method.

Many other scientific advantages could be realized, and also the practical exploitation of volcanic heat for generating power or for heating purposes would be facilitated by such installations.

There are many other tasks that can and will be accomplished within the near future by volcanologic research institutions and observatories. If scientific work is encouraged, not only scientific progress will result, but also practical advantages will be obtained. The safety of life and property within the regions exposed to volcanic catastrophes can be increased and to our two sources of energy—combustion of coal or oil, and waterpower—the third and greatest source, the internal heat of the earth, although not restricted to volcanic regions, can most easily be developed near volcanoes where high temperatures are reached near the surface.

Public interest in volcanology is rapidly increasing, and although America has already had her share in it (Dana, The Carnegie Institution, the Observatory on Kilauea, etc.) far greater accomplishments are to be hoped for.

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CHAPTER III

THE MECHANISM OF VOLCANOES

T. A. JAGGAR

FIELD EXPERIMENT

The study of volcanoes has been approached by means of occasional observations made by travelers, by study of specimens with microscope and chemical laboratory, by special expeditions in times of so-called eruptions, and by fixed stations. This is also the order followed in the development of volcanology as a science. The writer's experience began with expeditions under the United States Geological Survey to granite batholiths, laccolithic intrusives, and volcanic ejecta of such places as the Bradshaw Mountains of Arizona, the Black Hills of South Dakota, and the Yellowstone Park region of Wyoming, with much collecting of specimens and laboratory study of them during the winter months. He realized from these experiences great dissatisfaction with current methods of interpretation of the meaning of volcanism. His next experience was a visit, immediately after the disaster, to the volcanoes Pelée and Soufrière in 1902, in the Caribbee Islands, so exhaustively treated later in the large monograph by Lacroix. This experience led him to think that geologists will not know volcanism until they have data from numerous, selected, active vents, procured by fixed experiment stations, studying with instruments of precision the tremors, tiltings, changes of level, and changes of temperature and of chemical emanation, which are going on all the time over the intrusive magma that is always present beneath an active volcano. This conclusion was strengthened by experiences at the Vesuvian eruption of 1906, in the Aleutian Islands in 1907, in Japan and Hawaii in 1909, and in Central America in 1910.

In the year 1911 the Hawaiian Volcano Observatory was founded, and its work was based upon collaboration between the Department of Geology of the Massachusetts Institute of Technology, the Geophysical Laboratory of the Carnegie Institution, and the work of R. A. Daly, of Harvard University, who had just published his Nature of Volcanic Action, which was based on a field season at Kilauea in 1909. The examples that most influenced me in determining a line of action for the Hawaiian station were the work of Mercalli at the Vesuvian Observatory, the work of Lacroix's station at Pelée, the laboratories of Perret and of Friedlaender in Naples, and the big work of F. Omori on physical phenomena connected with the volcanoes of Japan. We were fortunate in getting

Perret to go to Hawaii in association with E. S. Shepherd of the Geophysical Laboratory in 1911, when much was learned concerning temperature measurement and gas action in direct relation to flowing lava.

The keeping of a record book at the Hawaiian station from that time to the present, and the field operation of experiments dealing with live magma and a bed rock seismically and thermally alive, have been the basis for the writer's entire point of view concerning the mechanism of volcanoes. His interest in theory extends only so far as hypothesis may be useful in guiding experiment.

The literature that is collectively a textbook for the Hawaiian station consists in the main of the following:

1) For volcanic seismicity, tremor, tilting, and changes of level, the work of Omori and his colleagues on such volcanoes as Asama and Sakurajima, and the correlated work of the investigators in America who determined geodetic changes after the San Francisco earthquake, and at Yakutat Bay and Katmai, in Alaska.

2) For mineralogy and petrography, the work of Lacroix, Washington, Cross on Hawaiian lavas, and that of many others, notably the workers of the Geophysical Laboratory, has created a complex laboratory science essential to the classification of volcanic products.

3) For measurements of temperature, the work of Brun, Daly, Perret, Shepherd, and Day in Hawaii was the foundation on which we built up our own field methods. There appears to be importance to Brun's determination that Kilauea lava is excessively hot when in action, as compared with the lava of other volcanoes.

4) Controversy, which was started by Brun's insistence on the nonaqueous quality of magmatic gases, led to the important work of Day and Shepherd in 1912 at Kilauea, that determined much water-vapor to be present in the gas actually boiling up from the molten lava. This work led to more studies of the composition and temperature of gases in several volcanoes, and fixed the habit of experimental attention to gas as prime mover in volcano mechanism.

5) The chemistry of the sublimates and incrustations, as well as that of the lavas themselves, has developed at great length during the last fifteen years, much of it being guided by the critical work of Zies, Allen, and Fenner on Katmai and Lassen deposits, chemistry, temperature, oxidation, and hydration proving an extremely difficult combination where the ultimate motive is to discover magmatic as distinguished from secondary processes. No department of field work in volcanology is more in need of simplification than collection of chemical products and definition of what is essential.

6) For theories about volcanism, the crust of the earth, and the volcanic substratum, the workers at the Hawaiian station are probably influenced most by the nineteenth century dicta of Green, Dana, Dutton, and Russell, and such controversy as the twentieth century has produced through the writings of Holmes, Jeffreys, Love, Daly, Adams, Washington, Bowie, E. W. Brown, Willis, and Joly. Few of these theorists make any attempt to suggest field experimental tests that will confirm or refute the implications. As theories in astronomy, for instance, are of use only to such extent as they are followed up by investigations at fixed observatories, it is unfortunate that the same policy can not be made to apply to geophysics.

7) For general volcanology, including distribution of volcanoes and the comparison of Tertiary and recent volcanic structures, the textbooks of von Wolff, Daly, Mercalli, Schneider, and Sieberg, and the geographic studies of Sapper, as well as the journals and bulletins published by Friedlaender, Malladra, and the volcanologic services of the United States, Java, Italy, and Japan, provide a growing literature that is being added to as new lands enter the field of volcano research.

It will be seen from the foregoing that the writer limits his conclusions to impressions drawn from experiment in the field. He does not pretend to understand the inner earth. He is working over the literature always in the hope of finding a suggestion for experiment. He is convinced that quantitative records are as yet inadequate, just as they would be in astronomy if the observers had been working from fixed stations for only half a century.

UNITY OF VOLCANISM

There was a tendency in the volcano geology of the nineteenth century to consider volcanism diversified. The textbooks classed under volcanism solfataras, great explosions, flowing lava, geysers and boiling springs, mud volcanoes, and submarine eruptions. They put in a separate class plutonic intrusions, dike intrusions, and laccolithic intrusions. They insisted on volcanic eruption being actuated by steam, and cautioned students against mentioning smoke or fume. They placed hot springs in a nonvolcanic category, connected in some way with tectonic or mountain-folding processes, and were careful to guard the student from the extreme views of the vulcanists of the time of Playfair, who conceived mountain-folding as affected by igneous intrusion.

These textbooks did not give the student the idea that volcanism might be a unity marked by an astrophysical sequence from the prominences on the sun through the pristine earth, as represented by the frozen surface of the moon preserved to us as a sample of primitive conditions, and on to a crusted earth, where the complications of sedimentation have largely masked the original volcanic surface. Moreover, the teachings of geology did not accent the intrusion mechanism as a process now going on. Even the volcanoes had little unity from this viewpoint, the flowing basalts of Hawaii and Iceland were considered exceptional, eruption was synonymous with explosion, and even on the moon reputable investigators insisted on finding the traces of explosion, impact, and violence. The lithological theories of the school of Iddings, before seismology, geodesy, and geology had found increasing experimental evidence of a density transition under the earth's crust, considered the igneous materials of the earth to be heterogeneous and pockety, and this made even magma an object without unity of origin.

Studies of a succession of events in Hawaii—a quiet, fuming pit, some years of fluid lava slowly rising in that pit, outbursts of flowing lava punctuating the rising, a grand climax of many flows from two neighbor volcanoes in a five-year culminating period, these events separated by pulsatory subsidences, and finally a grand subsidence with engulfment, accompanied by pure steam explosion—all this sequence for both Kilauea and Mauna Loa during a decade, checked perfectly with a conception of volcanic cycles, and the explosive engulfment corresponded perfectly with such eruptions as Bandaisan and Tarawera, which the older textbooks believed different from Hawaii. This implied that volcanism has unity, but that surface conditions in continental Japan and New Zealand prevent liquid outflow, whereas oceanic Hawaii still permits liquid outflow after a fashion that was prevalent on the continents in Tertiary time, but is now decadent or obstructed in those places.

I now conceive of volcanism as a process that is at work in and under the crust of the earth everywhere, a thermal remnant of a primitive thermal and gas-evolving process which began when the earth separated from the sun. This mechanism produced rhythmic orbital motions, rotations, and pulsations, and probably the principal pulsations for the earth itself were tidal and thermal. This would mean a rock shell cooling, a tidal mechanism establishing strain cycles in the solidifying crust, and a gas chemistry series of thermal cycles liquifying and frothing the material beneath the crust. The cycles are compound, and a volcanic belt of the present day is merely a cracked zone in the primitive crust, still exhibiting thermal recurrence in 1) age-long intervals of geologic revolution, 2) shorter epochs of alternate glaciation and volcanic outflow, 3) still shorter episodes of volcanic revival a few thousand years long, 4) historic records of big volcanic crises at intervals notably of about 130 years, and 5) in Hawaii for a single volcanic system, an observed short-term cycle of volcanic culmination and depression about eleven years long. Nothing is really known about the compound cycles of the intermediate group. Observatories may work effectively with the cycles of the present day, and even carry them down to semi-diurnal tides and semi-annual lunisolar crises. Theorists like Joly may find materials in the geologic record for cycles 25 million years long, which check with measurements of volcanic deposits that alternate with glacial deposits.

There appears to be no reason for considering the volcanoes of South America in any way different underground from the volcanoes of Hawaii. Stübel has shown that basaltic domes commonly underlie andesitic cones. In Tertiary time, Cotopaxi and Fujiyama were probably Mauna Loas in appearance and mechanism. Simple cooling, together with sedimentation, burial, and the complexities of intrusion and tectonic unlift, are amply sufficient to account for the difference between Cotopaxi and Mauna Loa today.

We conclude that terrestrial volcanism is a unit; that Iceland, South America, and New Zealand have the same volcanic mechanism. If the one gushes liquid flows while the other explodes and flings up ash, that is a matter of crustal obstruction. The primitive process would send out liquid flows. If the lava of the one is viscous while that of the other is fluid, that is a matter of crustal adulteration, degeneracy. The primitive lava would be liquid and basic.

THE FUNDAMENTAL GAS MECHANISM

The controversies over the "ascent of lava" which agitated the nineteenth century do not greatly worry anyone who has measured in the field the rising and falling of lava in the Hawaiian ducts. Gas is the impelling agent. Gas in solution in a silicate glass, is amply sufficient in exothermic heat, expanding power through formation of vesicles, mixture through heterogeneity, combustion through phase changes, to create a flaming furnace, a frothing slag pot, and a reasonable hydrostatic system.

The writer was greatly affected in his thinking by petrographic differentiation until he studied Hawaii by the method of continuous residence there. At other volcanoes a siliceous or hornblendic dacite, an obsidian, an alkaline andesite, an obscure diorite porphyry or gabbroid dyke had all seemed to indicate genetic differences of magma in different parts of the world, because the specimen and the synthetic furnace loomed large; vesiculation was avoided as vesicular rocks do not make good slides; while the proportions in volume and time for the place of origin vanished in distance, and facts of gases lost, gases that vesiculated, gases that stirred, gases that heated, gases that altered density under ground and above ground were simply unknown. Such critical monographs as Rollin D. Chamberlin's investigation of the gases in rocks were read, of course, but their interest was academic. The prime interest was the fascination of collections, mineral differences, and the optical microscope. The real geological interest is quantity of commonest types. The laboratory interest is quality of uncommon types.

Daly, Brun, Day, Perret, and Shepherd appear to have laid the foundation for twentieth century volcanology by clear exposition of gas fluxing, gas heating, gas oxidation, and gas-actuated convection. Magma consists partly of gaseous elements and partly of crystal-making elements. This is the sun-matter imprisoned in the sun-fathered earth. The "crust" is the prison wall. Volcanism at volcanoes is the feeble remnant of visible sun-process. It is enormously important and enormously precious for geophysics, just as visible gas-process on the sun is precious for astrophysics. The whole of astronomy thereby has altered its outlook. The spectroscope in a hundred forms has been the tool to work the change. As yet, the spectroscope has not been applied, beyond the barest reconnaissance, to the sun-magma vomited at terrestrial volcanoes. This earth remnant of sun-magma is gaseous, just as are the outer solar envelopes. The application of the spectroscope continuously to earth-magma effervescence, with theory, mechanism, and experiment all working in harmony and in sequence for as many years as astrophysics has used them, will give magma a new meaning to geologists.

That the application requires travel and field set-up of instruments is true. So does an eclipse. But that the globe does not furnish the opportunity is not true. Stromboli, Tanna, Pavlof, Oshima, Santorin, Ngauruhoe, Mauna Loa, Vesuvius, Reunion, Kilauea, and Izalco, to mention only a few, have been places of glow and burning gases within the last few years, and some of them are flaming now. When the method is perfected, the seeking of volcano spectrographs may well become a new branch of science, quite as alluring as big game hunting, and much more useful. Several of these volcanoes are so continuous in their magmatic flaming as to warrant fixed stations for spectrographic experiment.

The ascent of lava, then, is actuated by the release of pressure on magma when a fracture plane over the magma yields, and the dissolved gas starts vesiculation and consequent liquefaction. The fixed gases react with each other and with air. This heats the system and increases mobility. The heating and frothing find outlet through the fracture. The result is lava outflow. In Hawaii, this magma is olivine basalt.

On the higher and greater edifice Mauna Loa, the lava ejected is lighter, more vesicular, and hotter than on the lower and smaller edifice Kilauea. This appears to imply greater resistance overcome on the greater edifice, and greater pressure release.

The gases are hydrogen, carbon, and sulphur, quickly becoming oxides when observable, and minor quantities of chlorine, nitrogen, and argon. There are no clouds of steam over a hot Mauna Loa fountain, the column is blue-brown fume, and vanishes into a milky cirrus that hangs for hours above the normal rain clouds of the mountain. Collected with vacuum tubes, the gases are, of course, oxidized, and largely air: these collections are wholly imperfect, and are never made at the vents of grand paroxysm for obvious reasons. Here the spectroscope would have every advantage. But it should be a large, photographic apparatus of great speed and wide dispersion. The jets of flame and spume frequently rise 600 feet, continue for weeks, and may be approached with impunity to within 100 meters. In the last 15 years there have been four occasions of this quality for Mauna Loa, and Kilauea had 10 years of molten lava and flames.

The fractures are more or less permanent fissure zones. Everything observed proves the presence of permanent magma straining upward. If an extraneous force breaks the edifice, there is no seismic evidence to prove it. Wood has quoted the 1868 major earthquakes as possibly showing a "tectonic" release, that turned the magma loose. But this 1868 occasion broke open to effusion the south flank of Mauna Loa, a region previously quiet for more than half a century, and the Kilauea center suffered a major collapse. The seismic center was approximately between the two. Other Mauna Loa effusions have shown similar seismic accompaniments on a smaller scale, and the seismic events are synchronous with effusion. The implication appears to be a downbreak along subparallel fault planes on the east side of the whole combined edifice, begun by an upward tumefaction that accumulates for years prior to the crisis.

This was confirmed by the cycle 1913-1924, when measurement by leveling showed a meter of uplift at Kilauea summit for the effusion years, and three meters of depression for the three years of culminating engulfments. The effusions came on gradually, the collapsings were more rapid.

It may be asked, "If the magma is always straining upward, what is the force generatrix of that stress?" The two probabilities are 1) that the upper subterranean magma always has a restrained gas potential expanding it, and 2) that with gas in complete solution unvesiculated, the magma tends to rise by displacement at the crater centers because the outer segments of the dome edifice are heavier, and always increased in weight after an effusion by the amount of the last outpouring. The vent lavas are light and pumiceous. The flows are heavier and more crystalline.

As to the hydrostatic question, " How can 'liquid' lava emerge 3,000 meters higher than Kilauea, if Mauna Loa and Kilauea are connected? ", this is disposed of if we grant a gas potential always present. The underground magma will then be more or less vesiculated at all times, Mauna Loa lava is always light and frothy as compared with Kilauea lava, and the "ascensive force" at an effusion is a geyser effect superadded to a hydrostatic difference of level. This difference of level is determined by the heavy Kilauea column supporting the light and frothy Mauna Loa column.

Supposing a connection, and both craters open, we should then get a geyser-like foam release with increased expansion pressure on the hydrostatic system during Mauna Loa's outbreak, and a slower rising of the heavier Kilauea column. When, at the end, the geyser effect failed from gas exhaustion to the lower limit of pressure release within Mauna Loa, the Kilauea column might be expected to act as a cooler reservoir suddenly drained to restore the balance. Exactly these two things happened at Kilauea for the 1914, 1916, and 1919 effusions of Mauna Loa; a slow rise and a sudden fall.

On the other hand, supposing the Kilauea vent not open at the time of a Mauna Loa outbreak, but the lava column frozen in the pipe for some distance down, then the Mauna Loa column might achieve effusion without producing any visible effect on Kilauea. This would leave the columns in Mauna Loa and Kilauea after the eruption balanced for their respective vesiculate densities, but below the bottom of the Kilauea pit. Just this was the situation at the 1926 outbreak of Mauna Loa, which was short-lived, and apparently showed lower temperature than during the eruptions above mentioned.

OLIVINE BASALT AND HYDROGEN

Just as calcium and hydrogen are conspicuous spectroscopically on the outside of the sun, so olivine basalt and hydrogen appear to be conspicuous volcanologically on the surface of the earth, for the stage of volcanicity now present. Hydrogen in the form of a liquid oxide covers 72% of the surface, and still emerges gaseous at the hot vents. Olivine basalt forms most of the outer shell with transition to dunite approximately 60 km. down, and still emerges liquid with hydrogen in solution at the hot vents. Remains of the solar ancestry, perhaps, appear in concentrations of calcium, carbon, iron, and sodium in the form of carbonates, oxides, and chlorides. The domination of silica and oxygen on the surface shell of the earth probably differs from the sun merely because those elements were internal in the ultra-volcanic solar stages of terrestrial progress, and are so today on the sun, or because they do not lend themselves so readily to spectroscopic analysis in solar investigation.

That olivine basalt and its kindred make the fundamental magma on earth is indicated by its presence in the volcanic islands of the deep oceans, its recurrence in all geologic ages in the volcanic history of the earth, its presence on the continents in immense bodies of Tertiary outpouring, and the correspondence of its density to the computed density of the bottoms of the deep oceans. This last fact indicates its probable presence as the main rock under those oceans, and the occasional manifestations of submarine volcanic activity which are known suggest unknown activities of wide extent revealing this magma. That olivine increases 60 km. down is shown by the seismic wave-speed transition at that depth and the compressibility correspondences developed by Adams.

The implications of isostasy, and the evidence of engulfment as a large post-Tertiary volcanic process along primary earth-rift lines where volcanoes are now, as well as the density distribution of the inner earth shells, leads to the surmise that the continental magmatic volcanism on the earth in the present cold epoch may be very shallow.

Engulfment measured at Kilauea in 1924 corresponds to Daly's important observations on stoping as a plutonic process, and his deductions in agreement with Lacroix's work on inclusions to the effect that assimilation-differentiation is a widespread process. Daly's notion of a general highly siliceous or granitoid primitive earth-shell has never appealed to me, because of the absence of obsidian or granite (probably) over the ocean basins; that is, over seven tenths of the earth.

The gradation from basic rocks in the ocean, to intermediate rocks in the coast ranges, and thence to granitic shields in the continental core, appears to suggest:

1) A clean-cut outlining of oceanic seas where the primitive basic volcanism of the earth first declined most, and the crust thickened and lowered.

2) Where the thickest crust was, water accumulated, and the magma-effusion persisted up cracks from lower, more gaseous, hotter, and denser layers.

3) A thin-crust subaerial volcanism, with less pressure to restrain gas and with concentration of silica as a lighter element, persisted in the higher residuals between ocean depressions, making the continents.

4) The excess of silica and defect of gas of itself viscidified continental effusion and added relief by heaping and intrusion.

5) The border fractures between continental and oceanic crust blocks yielded intermediate magma.

6) Erosion and mediterranean seas produced concentrations of siliceous, aluminous, and calcareous rocks as sediments in the continental areas, which by assimilation yielded the complex differentiates of petrography.

7) Volcanism in the deep oceans remained fluent, primitive, and basic, while in the continental thin-shelled erosion areas there came about much local sinking under sedimentation, and local rising over intrusion. Engulfment, assimilation, and explosive eruption were common where tension developed, while mountain-folding was common where compression developed.

All of this was isostatically controlled by the larger primary isostasy of oceans and continents, and possibly by an intra-continental secondary isostasy involving crust thicknesses and anomalies of a different order. Such a condition can hardly be avoided if the original splitting up of oceans and continents really marked a great and critical earth adjustment. The geologic and volcanologic evidence indicates that it did, but the evidence will remain incomplete until the red ooze of the deep oceans has been probed by borings. Even a little powdered bedrock sample, could it be obtained in a hundred places, would suffice to settle the question. This to my thinking is the most important geophysical and astrophysical experiment needing fulfilment in the whole range of science.

THE SUBSIDIARY VOLCANIC PRODUCTS

By the foregoing conceptions, which recognize oceanic and continental hydrography, sedimentation, deformation, and volcanism as fundamentally different throughout the ages, the primary distinction between olivine basalt and granite is the distinction between deep and shallow volcanic process, between pure effusion and pure plutonism. This clarifies the definition of "pure" volcanism as basaltic, non-explosive, and effusive. It is quite capable of producing intrusion of gabbroid rocks wherever deep magma can rise from the under-crust. It becomes impure when it assimilates, and loses gas and creates voids for water to enter. It has probably existed for ages as an effluent process on the bottom of the deep oceans where it would make no man-studied record whatever if those water-covered depressions are permanent. Oozing forth today such flows under water at zero temperature and vast pressure would be merely sills between bottom and sea. It is worth computing what their form would be, and then testing the forms by sonic sounding.

The siliceous and alkaline lavas and laccolithic intrusives become thus subsidiary continental productions. Carbon, sulphur, and chlorine are probably largely secondary in present-day volcanism, assimilated from concentrations about ancient vents, and from percolations of concentrate waters like sea-water. Carbonic acid in the volcanic gas, or burning carbon monoxide, may be either primal or secondary according to how much charcoal or limestone is buried under the volcanic edifice.

In Hawaii some of the CO_2 may be juvenile, but whether it exists elemental as carbon in the deep solutions is unknown. There is an enormous quantity of charcoal unconsumed under every lava flow that traverses the Hawaiian jungle. Every engulfment where a fissure opens and collapses through these charcoal strata complicates the gas collections of the volcanologist. One wonders how much of the volcanic CO_2 oft-quoted as quantitative basis for climatal theories is reliable, with tropical volcanoes overlying charcoal, Vesuvius overlying limestone, and Katmai overlying coal.

THE WATER QUESTION

The conclusion that explosive eruption is secondary volcanism is drawn from the writer's observations at Yellowstone Park, the Caribbees, Vesuvius, Bogoslof, the Japanese volcanoes, Santa Maria in Guatemala, Lassen, Tarawera in New Zealand, and Kilauea in 1924; and his reading concerning Taal, Krakatau, Sumbawa, Katmai, and the volcanoes of the Dutch East Indies. He grants for the continents the possibility of such a mechanism as Day has suggested, but not for the oceanic volcanoes like Hawaii; that is, that some volcanoes are superficial developments of the last stages in crystallization of magma, with fluid magma remnants that are pockety. Such process appears to the writer to be secondary volcanism and is also mixed with water accession as Day has shown.

Explosive eruption in the main, however, appears by all accounts to be an engulfment phenomenon, actuated 1) by tensional opening of a rift by intrusion, 2) subsidence of magma in the opened void, 3) entrance of groundwater, 4) steam explosion stoping out the opening and engulfing rock, and 5) rise of magma until the released pressure is restored.

Both the beginning and the end of this sequence may be intrusive, or semi-intrusive as in the viscous lavas of the Soufrière, Pelée, Tarumai, Katmai, and Bogoslof eruptions: or they may be riotously liquid and frothy as at Kilauea in January and July of 1924, the intermediate time February to June showing engulfment and explosion, with graben sinking along thirty miles of rift, from sea-level to 1,200 meters elevation.

The explosive eruptions mark such graben collapse at the end of a high-pressure magmatic cycle. This high-pressure cycle was evident as overflow for years at Kilauea; at Santa Maria or Soufrière or Sakurajima it was not perceived, unless elevations or tilts or unusual earthquakes were recorded. An " eruption " in the colloquial parlance really generally means a downbreak at the end of intrusions or effusions. This was never so clearly shown as at Vesuvius in 1872 and 1906. The present upbuilding at Vesuvius is preparing for another crisis of downbreaking. The measured changes of level of the surrounding country at Sakurajima and Kilauea both showed uplift before collapse, and finished with subsidence greater than the previous tumefaction.

Where the magma goes when it retreats is problematical. In Hawaii there is a slope of 5,000 meters under the sea for outlet of flows unperceived. In other cases there may be actual tension breaks and openings in the deep crust into which the magma retreats, then the lessened pressure lets loose the magmatic gas, and the foaming up of lava mixes with the exploding of groundwater steam.

In all of this the writer does not envisage volcanic explosion as occasioned by magmatic water. Magmatic water he thinks of as oxidized hydrogen. In this he follows F. W. Clarke, " this reaction alone, this combustion of hydrogen in air, evidently plays a very large part in the thermodynamics of volcanism." * He believes hydrogen in volcanism can oxidize quietly.

ENGULFMENT

We conclude that explosive eruption is impure or mixed volcanism, and that such decadent volcanism is the rule in Quaternary time.

The subject of engulfment has already been outlined as a large process in present-day volcanism, and as coordinate with Daly's stoping, if volcanism be conceived to include intrusion, its dominant form in continental areas.

Quantitatively, gases collected at volcanoes are never alike in proportions and are mostly oxidized. Engulfment at Kilauea in 1924 accounted for 253 times as much broken rock as was thrown out. Rapid collapse and engulfment closes every short cycle of slow lava rising. Such engulfment down vertical chasms is a normal process for introducing in magma oxidized minerals, especially ferric oxide.

To quote Clarke (*loc. cit.*), " one gram of hydrogen, burning to form water, liberates a quantity of heat represented by 34,000 calories." The ferric oxide and hydrogen would yield ferrous oxide and water with

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* **Data of Geochemistry, Bull. 770, U. S. Geol. Surv. (1924).**

evolution of heat. Given hydrogen in the rising magma, and oxidized crater rock engulfed frequently, enough heat would be supplied to keep lava volcanoes going. This hypothesis has been suggested by E. S. Shepherd.

In 1924 Kilauea dropped from the walls of its pit a column of broken rock into the pipe equivalent to a cylinder 450 meters across and 1,000 meters high. The new lava that reappeared in the pit at the end of the eruption had frothed its way up through the crevices of this oxidized breccia. It took up oxygen and was heated as it rose, along with other oxygen from air in the pores.

By this mechanism hydrogen can burn quietly in a volcanic edifice with large evolution of heat. This theory perhaps accounts for the channels and tunnels of the lava-lake bottoms, and for the benches and crags in Halemaumau at Kilauea. The half-melted breccia is lifted or lowered as a paste by the gas-charged melt in its interstices, and convection through the crevices produces the varying supply wells and sink-holes of the lava lakes.

The breccia is renewed by every crateral subsidence. The crater edges that cave in to make the breccia are renewed and filled with sublimates such as sulphates, alums, chlorides, and sulphur by every period of crateral overflow. This makes a concentration mechanism for the less volatile gases, such as sulphur, while the acids oxidize the ferruginous basalt.

At a volcano like Kilauea or Vesuvius there is fed down the iron oxide fuel at every collapse, and there is worked over a lot of sulphur, chlorine, and probably selenium and fluorine. Hence the explanation of the chemical mystery, "Why so much sulphur at volcanoes, when there is so little in the rock?" This leads to speculation as to whether the sulphide ores, so often associated with igneous breccias, are not concentrated by some similar mechanism at dikes. Big engulfments will explain the replacements by igneous rock, of lost sedimentary belts in such places as the Sierra Nevada.

TERTIARY AND PRESENT-DAY VOLCANISM

Professor Joly's conclusion that once in many million years, perhaps twenty or more, the earth reverts to general increase of volcanism by storage and release of radioactivity from within, has much to recommend it from the standpoint of volcanology and geology, apart from the competency of the suggested cause. Like the sun's occasional or periodic increase of sun-spot eruptions, the cause may be unknown, and may be a complex of factors radiational, tidal, and gaseous. But the fact of such recurrence is strongly suggested by the geologic record of volcanic and orogenic revolutions, at least on the continents, and by the intervening cycles of cold and glaciation from the Precambrian to the Present.

The last of these world-wide times of intense volcanic effusion appears to have been about the Miocene, followed in due course by the glaciation of the Pleistocene. We are living probably in the closing thousands of years of that time of ice, with glaciers still in evidence, but diminished. Volcanism is decadent everywhere, and this is marked by its occurrence on the same fields where it was intensely effusive in the Tertiary. It should be marked with a negative or minus sign.

This conception of plus and minus volcanicity through the ages, or at different times and places, appears to me fruitful and is based directly on the notion of short and long cycles, and the experimental results from the short ones at Hawaii. We had for the Hawaiian system upward pressure, elevation, upward overflows from 1914 to 1920: downward release of pressure, downward depression, collapse dominant without outflow from the summer of 1921 to 1924, and a big engulfment finishing it. The 11-, 65-, 130-, and 260-year cycles have some appearance of verity in Hawaii or Japan, and possibly all are compounded into agelong cycles.

E. W. Brown's challenge to the geologists to explain the fluctuations in rate of the earth's rotation, by periodic expansion and contraction in the crust of one to seven meters of diameter, presents evidence from both solar and lunar time-keeping that crises occurred about 1785 and 1898, near the ends respectively of the eighteenth and nineteenth centuries. It is remarkable that volcanic effervescence of extraordinary magnitude took effect in the last decades of the eighteenth century, when Iceland poured out about a third of the world's historic lava flows, and Italy, Hawaii, and Japan record tremendous effusive eruptions. On the other hand, the end of the nineteenth century produced enormous engulfments and earthquakes, Krakatau, Tarawera, Bandaisan, and the Caribbean eruptions of 1902; the Charleston, Neo Valley, and great Indian earthquakes, the Tuscarora Deep earthquake wave of 1896, and the Yakutat Bay shocks. This would suggest crustal contraction and magma release about 1790, and crustal expansion, faulting, and engulfment a century later. Apparently the observed solar deviations and lunar fluctuations platted by Brown indicate in 1785 a crisis of terrestrial shrinkage, and 1898 earth swelling. The former agrees with the greatest lava eruption ever recorded in history, Laki in Iceland in 1783. On the other hand, the year 1899 produced the greatest earthquake uplift ever recorded, the shore-line elevation of 14 meters at Yakutat Bay in Alaska. The curve of eruption frequency in the eighteenth and nineteenth centuries (Sapper, Z. Vulk., 1917, Bd. III, Tafel XXIII) shows considerable agreement with Brown's curves of earth slowing and speeding. (Trans. Astron. Obs. Yale Univ., vol. 3, pt. 6, (1926), Fig. 4.)

The chief point I would make is that volcanism with cyclical recurrence is accordant with what the individual volcanic systems show, and an age-long minus phase marks the present epoch of geologic time. Down-faulting, so-called " calderas " or sinks, collapse with explosion greatly dominant over visible lava extrusion, earthquakes with settlement, and engulfments, at places where the recent geologic history shows continuity of volcanic eruption declining from the Miocene to the present, all mark the volcanic belts of the earth. There is nothing in geologic history to show that this is anything more than an epoch, and everything to show that volcanic effusion will return in a few million years, but that it does so now only in feeble spasms as at the end of the eighteenth century.

THE EARTH CRUST

In Hawaii the earth crust, supposed 60 kilometers thick, stands unduly high unless some volcanic mechanism will account for a defect of density along the medial line of the Hawaiian ridge. This ridge, 2,800 kilometers long and 6 to 10 kilometers high above the sea-floor, is all basaltic so far as known.

The explanation has been hinted at in what was said above about the hydrostatic relations of the Kilauea and Mauna Loa lava columns. These columns appear to be connected, but to show sympathy only when both are liquid in the craters. The liquidity is that of a gas-foam, and the greater gas-content is conceived to hold the Mauna Loa column higher than that of Kilauea.

Possibly the maximum gas efflux at the greater center has been maintained from the time when the edifice was begun on the sea-floor. It may be over the highest part of the batholithic cupola that supplies the magma. Whatever the cause, the structures erected by fountaining vents along the Mauna Loa craters are pumiceous, while those at Kilauea Crater are generally viscous and heavy. If structure on structure down the sections are the same, and the live column also of Mauna Loa is always less dense inside the mountain than the peripheral rocks, then it is isostatically reasonable that the big central volcanoes Mauna Loa and Mauna Kea should stand higher.

Probably this has been the mechanism for the uplift of the whole belt of large islands from Kauai to Hawaii, progressively higher and more effusive eastward. It seems likely that if effusive volcanism gradually ceased in any island, the internal magma would exclude its gas and crystallize as heavy gabbro. Such an island should subside. The gradation to lower drowned volcanoes and then coral islets west from Kauai, where probably the thermal gradients are progressively flatter, and the surface volcanism more ancient, points to such subsidence coordinate with replacement of effusion by intrusion. And a bowlder of very coarse gabbro has been found on Kauai, the westernmost of the large islands.

In this connection the following quotation[5] is of interest (from Dana's Manual of Geology, 4th ed., 1894, p. 290): "E. D. Preston has proved, by gravity determinations with the pendulum, that Haleakala below its crater is solid, the gravity found being 2. 7, and that Mauna Kea in its upper part, giving 2. 1, is hollow. The same evidence has indicated that the volcanic mountains of Ascension Island, St. Helena, and Fujiyama in Japan, are hollow—densities of 1.6, 1.9, and 2.1 having been found severally for the masses of these mountains; and by the deviation of the plumb-line of only 7 or 8 seconds by Chimborazo, it is believed to be indicated that this mountain also is hollow. Preston obtained for the lower part of Mauna Kea the extraordinary density of 3.7, for which volcanic science has as yet no explanation." Apparently vesicularity would answer for "hollowness." And isostatically an internally hot and vesicular portion of the earth's crust should stand higher than an internally cooled and crystallized belt of intrusive rock.

Accordant with this notion Daly found a transition increasingly femic and heavy from the top of Mauna Kea to the bottom, with trachydolerite and cinder cones at the top, andesitic basalt at 11,000 feet, and olivine basalt of the fluent type in the sea-cliffs of the basement. (Proc. Am. Acad. Arts Sci., vol. 47, no. 3, p. 104, 1911). Here again experiment is suggested: What would a properly sampled set of specimens show, with vesiculation allowed for in the weighing? And further: What would the bedrock of the sea-bottom off Hawaii show, down to 3,000 fathoms?

RELATION OF VOLCANOES AND EARTHQUAKES

On the facts developed from measurement of volcanism, its unity of magmatic process, its gas thermodynamics and tumefaction, its elevatory relation thereby to isostasy, the sub-crustal nature of magma over the oceanic segments, the development of tensions versus compressions in the crust from tidal or luni-solar controls—all of these matters heretofore touched upon indicate that volcanicity is an intrusive process in the present geologic age, and by Brown's hypothesis the decades about the year 1900 may be especially so by crustal extension inducing rotation-slowing.

Crustal extension and local volcanic minus movement go together; crustal contraction and local volcanic plus movement go together. The crust as Brown computes it may change earth radius only from five inches to 12 feet, but areally this effect may be great, and in thickness affect 60 km. of crust. Lambert (J. Wash. Acad. Sci., vol. 17, no. 6, 1927) would have non-uniform expansions and contractions, which would help to explain polar wandering. This would also help volcanology. Crustal extension, an increase of circumference *within the crust itself,* means intra-crustal tangential pressure but not due to internal shrinkage of the globe. This, for localized magma in crust fissures, means prevention of gas heating and of efflux, restraint of gas and of gas expansion of magma, crystallization shrinkage, and consequently a weighting down and isostatic negative in volcano localities. Thus crustal swelling in the Brown sense would be the opposite of volcanologic swelling or plus action.

On the other hand, crustal contraction, a decrease of circumference, means tension deep and large in the wide areas, affecting by trigger pull the gas expansion and gas heating of magma in local rift systems such as underlie a chain of volcanoes. Here again the crustal negative is a volcanic positive. The former is large, the latter small.

There has been much discussion of the relation of volcanoes and earthquakes. I have tried to show in the foregoing statements about volcanism that, first, from the time of earliest congealing to the present day there may have been a difference between the volcanism of the continents and volcanism of the oceans; and, secondly, that within the centuries of the present geologic epoch, for either continental or oceanic volcanism, there may be a difference between the surface eruptions of a time of compression as compared with a time of tension. In both the cases cited, namely, the geographic case of oceans and continents and the temporal case of compressions and tensions, the oceanic and tensional tend to go deep, while the continental and compressional tend to be shallow. The reason is that the oceanic areas are conceived to overlie the thickest primitive crust over magma which crystallized from below upward, and therefore also tends to fracture from below upward in emitting the basic magma of the substratum. It may well be that the geologic cause for the change toward contraction at the end of a century comes from the oceanic segments, whereas the counter effect, a change toward expansion more than a century later, may be volcanologically merely a slowing down of the more widespread processes of contraction to permit the combined continental segments to execute their normal function of expanding where the crust is thinner and isostatically the materials are lighter and tend to stand high. As the border fractures between the larger and heavier oceanic crust blocks and the smaller continental units are naturally the weakest places on the globe, it is in this region that the effects of tension should be strongest in producing graben faults. As the mediterranean bays or seas are the places of greatest blanketing by sediments and consequent rise of the isotherms, it is here that a directive weakness and guidance should be given to continental forces of expansion at those times when expansion is permitted to take effect.

This all means, in short, that the lack of uniformity in crustal expansions and contractions postulated by Lambert should manifest itself at such times as the 1785 crisis of contraction by opening the deep oceanic fissures near the borders of the great oceans; and at such times as the 1898 crisis of expansion by tending to fold the deeply buried sediments of synclinoria in mediterranean seas. This also means that the larger terrestrial process areally from the primitive times of the earth is contraction of the crust, because it affects the depressed great ocean basins that involve 72% of the surface. There should be, then, in the long and large, more contraction than expansion of the crust, but the expansional phenomena should be more evident to man, because he knows nothing about the geology of the deep-sea bedrock, and much about that of the continents and the sedimentary basins. According to this, Brown's curves of earth slowing and speeding, could they be prolonged beyond two and a half centuries, ought to exhibit more and greater contractional crises than expansional ones. This is pressing the matter, however, beyond the limits of existing scientific data, and furthermore we do not know to what extent the deeper solidification of the oceanic segments might compensate the contractile tendency of their larger area.

The point of this discussion is that volcanism thus conceived should have a very large effect in producing earthquakes. The deeper earthquakes should be at all times at the graben faults of the ocean borders. The shallower earthquakes of all times should be within the sedimentary basins. On the other hand, for the critical times of expansion the conspicuous earthquakes should be continental. And for the critical times of contraction they should be oceanic in excess of the usual quota of shocks.

Seismologists may judge to what extent the shakes of history bear out these deductions. The Yakutat Bay shocks of 1899 elevated the shoreline and appeared to be compressional. The earthquake best known to history in the last half of the eighteenth century was the Lisbon cataclysm, which was distincly oceanic. At all times the mapping of epicenters located by seismometry has clustered around the ocean deeps, and adjacent to these same deeps are great volcanic systems, mostly linear from piling of lava over elongate rifts. The deeps are probably graben depressions and hence tensional in origin.

THE STUDY OF VOLCANISM

It is useful in such a discussion as this to try to discover whither it leads and directs future experiment. It is obvious from what has been said that such experiment should be directed to the study of the bedrock of the sea-bottom, and to better mapping of changes induced by volcanic process, both on the sea-bottom and on the land. Along with this repeated mapping should go study of tilt measured with pendulums or level bubbles, and studies of changes of level of the surface of the earth correlated with the best available datum figure of reference. Apparently mean sea-level is the only datum figure yet discovered, but it is far from perfect for the purpose. Otherwise the experiments needed deal with spectroscopy applied to volcanic gases, studies in field and laboratory of viscosity of silicate melts when inflated by gas as in nature, and studies of temperature of rock, the gases and the lava flows themselves at volcanic places. There remains the study of tremor and earthquake in volcanic lands and at graded distances from volcanic centers.

It will be seen that to achieve rigorously the objects suggested by this list of possible volcanologic experiments, the only way is to establish experiment stations in volcanic lands equipped with all the refinements of the physical and chemical laboratories and with workers who are physically or chemically trained engineers.

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