ART. XI.—*Volcanic Action;* by JAMES D. DANA.

THE new facts with regard to the recent eruption and subsequent movements at Kilauea, make this a favorable time for a review of volcanic action and phenomena; and especially so because the Hawaian volcano and its great craters illustrate more fully and simply than any others that have been particularly described the ordinary principles and methods of volcanic activity; and also because, although long since reported on, they have not yet their true place in most treatises on volcanoes. Vesuvius has been more accessible. The account of the phenomena observed by me at Kilauea in 1841, given in my Exploring Expedition Report,* needs no modification. But the conclusions after so many years of progress in science may well have a reconsideration. On the chief point, however—the essential identity in forces and laws of action between Kilauea and Vesuvius as well as other volcanoes---I find no reason for change. In my Manual of Geology (1863) I present, as the causes of eruptions:

The hydrostatic pressure of the column of lava; the pressure of vapors escaping in underground regions from the lavas, or produced by contact with them, acting either quietly or catastrophically; and the pressure of the subsiding crust of the earth, forcing upward the lavas in the conduit. I also state as sources of movements preceding an eruption: the enlarging of the mass of liquid rock in its higher portions through the vaporizable material contained in it and imbibed on the ascent; and, for aerially projectile effects, the elastic force of the vapors that escape by the forming and bursting of bubbles at the surface of the viscid lavas.

In the following pages the sufficiency or not of these causes of activity for all volcanoes, is considered.

* Geology of the Wilkes Exploring Expedition of 1838–1842, published in 1849. 225 pages (4to) are devoted to the Hawaian and other volcanic islands of the Pacific, apart from the subject of the bordering coral reefs. The time of my visit to Hawaii and examination of the Kilauea crater was particularly opportune because of the great eruption that had so recently preceded it, and which left behind, besides features of more ordinary character, also those rarely presented. I find no facts in Capt. Dutton's report to lead me to modify my conclusions as to the mode of action in Kilauea, or as to the relations of the crater to those of other volcanoes. My tour to Kilauea commenced on the western shore at Kealakekua bay, and led me by the south side of the island and the southern slope, to Kilauea: and thence, after a study of the interior of the crater and its surroundings, eastward to the outflow of the great eruption of 1840 at Nanawale where it entered the sea.

1. *General.*

1. *The more prominent phenomena of volcanoes.*—In the upward movement of liquid lavas, two operations apparently distinct, are concerned: (1) the ascending movement of the liquid rock in the subterranean conduit of the volcano from the deep-seated crustal or sub-crustal region of fusion; (2) the projection of the lava aerially upward from the surface of liquid lava in the vent. Outflows accompany the upward movement whenever the height reached by the lavas is such that they have an outlet either over the walls of the crater or through an opened fissure. Each of these operations, the upthrow and outflow, involves an expulsion of material from subterranean regions; and a usual consequence (3) is a subsidence, or, *Anglicè*, a down-plunge, of the overlying rock, or the material of portions of the cone especially the more central. The upthrow, the outthrow, and the down-plunge are the three most universal and most marked of volcanic phenomena. Connected with these operations there are: (4) The escape of vapors from the crater, and (5) displacements and the opening of fissures.

2. *The ascensive action.*—The actual ascension of lavas to a height, in many volcanos, of more than 10,000 feet above the sea-level is evidence of (1) the great power of the agency concerned. In Mt. Loa, a volcanic mountain of frequent extensive summit eruptions, the height is 13,000 feet (or six miles reckoned to the sea-bottom on the east.) The observations of Mr. G. K. Gilbert on the laccoliths of the Henry mountains, proving that strata 10,000 feet thick were arched upward to a height of three to five thousand feet, by the ascending and *intrusive* lavas indicate that the ascensive force at work (2) is deep-seated as well as of great power. This inference is sustained also by the long continuance of the heat in the lava-conduit of many volcanoes, as shown by centuries of activity, in spite of the various cooling influences to which the upper part is subjected.

3. *The deep-seated ascensive action not catastrophic.*—Dr. Gilbert's valuable observations illustrate another point of much interest: the *slow* action of the force concerned, for catastrophic violence would have opened large fissures to the surface, and produced a surface discharge. A quiet mode of ascent is probably the common fact also in the larger fissure eruptions. The movement appears to be very slow in the supply conduit of a volcano. For the epochs of high level in the lavas of a crater —flood level, we might say—are separated by years, years being required for a rise in level of a few hundred feet. Three great eruptions in Kilauea were eight years apart, and, in the interval, the lift in each case was about 400 feet. The last of the three referred to occurred in 1840; and the eruptions which

have happened since illustrate the same fact. Similar testimony comes from other volcanoes. If the ascent in the upper part of the volcanic conduit is aided by some additional upthrust force, then the facts just stated make the deep-seated action by so much the slower, since in that case it is accountable only for a part of the whole rise required for an eruption.

4. *Superficial ascensive action.*—The deep-seated ascensive force in a lava-conduit should raise the contained liquid rock to a common level for all its places of discharge in a crater. It was to me a strange fact that the lava-pools over the bottom of Kilauea underwent independent changes of level—a sinking of a hundred feet or more in one, unaccompanied by a like change or any change in another. But this admits of explanation on the ground of occasional discharge by local fissures opened beneath, and on the ground of much friction along the local conduits, and a depth to the common junction as great perhaps as the space between the pools (half a mile or so in the great pit crater). It was more of a marvel that while the pools were in their usual state of ebullition, lavas should be lifted at times to a level 500 feet or more above them in a fissure intersecting the walls of the crater. Here was an effect of ascensive force, but of a force of relatively superficial origin. A similar fact is mentioned by Prof. Alexander in his notes on the summit crater Mokuaweoweo, cited on page 235 of volume xxxii (1886) of this Journal, where the lift was 800 feet above the bottom of the crater, and the eruption a large one. Some superficial agency must be concerned in such eruptions; and the same may occasion local oscillations in associated lava-vents.

5. *Surface action in the lava; Projectile effects.*—In an active volcanic vent the feeblest action possible is the quiet escape of vapors. The second stage is the aerial projection of lava in portions, masses, or fragments; which fragments may fall back as cooled cinders or as liquid lava, according to the height of projection. The latter stage may be the final one before the return to a feeble or an inactive state in the crater. But the third may follow, namely: the outflow. As long as the liquid lavas are exposed in the bottom of the crater, aerial ejections are possible and probable; and if sunk below the bottom, they may continue provided there are cavities large enough to admit of the action. This projectile force is evidently distinct in origin from the supplying force.

2. *Kilauea.*

6. *Character of the lavas of projectile ejections and of those flowing from the open vents.*—The lavas of projectile ejections when cooled are usually scoriaceous and often semi-glassy, and the

brittle material may be shattered in the projection, under friction and sudden cooling, into the finest dust; those of the streams flowing from the vents or pools are cellular and in part scoriaceous; over the bottom of Kilauea in 1841, they had a scoria-crust of 2 to 4 inches, easily separable from the stony part below. They were *froth-covered* streams. On the contrary, the melted rock escaping from fissures in non-volcanic regions, and those of the remoter fissures about a volcano, are generally stony, without a scoriaceous aspect in any part. Even over the bottom of Kilauea, lava that had come up through fissures distant from the lava-vents was of the more solid, stony kind "either solid stone throughout, or so excepting a *compact*, glassy exterior half an inch thick."*

The making of scoria is dependent on the kind of action characterizing the open lava vent—that is the aerially exposed extremity, or extremities, of a lava-conduit. In a fissure-ejection, some one or more places in the fissure may be broad enough to remain open as lava-vents with the usual phenomena.

7. *Abundant discharge of vapors of water.*—The exposed extremity of a lava conduit discharges vapors in great volume, the amount of which increases with the increase of activity. When at Kilauea in 1841, an immense column of heated vapors stood over the great lava lake Halema'uma'u (1,500×1,000 feet by Wilkes's measurement) and the southern half of the crater—its base some hundreds of feet above the lake, owing to the intensity of the radiated heat. It had the appearance of a threatening storm-cloud as Wilkes observes (iv, 225).† Yet this was six months after a great eruption. At times of extreme activity the pit is sometimes so densely filled with the vapors as to "obscure all the glowing fires."

Many facts show that the vapors are chiefly those of water, as is generally believed. The features of the clouds were those of ordinary clouds, and the shrubbery and ferns about the margin of the crater derived luxuriant growth from the condensed moisture.

No direct experiments were made; but we have from Mr. Emerson on page 90 of this volume, the statement that he was half an hour at his station near Halema'uma'u W exposed to the vapors that came with the wind from over the pit, and suffered nothing from the sulphurous fumes present; a fact showing that they constitute a very small part of the vapors.

While vapors are so freely discharged from the craters, the amount from fissure eruptions, even those in a volcanic region,

* My Expl. Exped. Report, p. 180. † Narrative Expl. Exped.

are generally small unless open active vents exist along such fissures.*

8. *Projectile action.*—In Kilauea, in 1841, the projectile action of the lava-pools, consisted in the throw of jets of lava to a height of 30 to 60 feet over the whole liquid surface—many rising and falling simultaneously. I watched the process for some time while within four or five feet of one of the smaller lakes, and, also, but necessarily from a much greater distance, the more brilliant display over the great lake of Halema'uma'u.

This lake, owing to contact with the air above had usually a red-hot surface (except when blackened at times in part by incipient cooling); but in the play of jets over its wide surface, lines of white heat, or very nearly white, opened to view between them, which a companion in the expedition, Dr. C. Pickering, well compared to a net-work of lightning flashes.

The jets were ordinarily 30 to 60 feet high; in one of the small pools about 30 feet, but 50 to 60 at intervals. At times of lull they ceased or nearly so. The diameter, if I remember rightly, was three to six inches. With a mean of 4 inches and a height of 30 feet, each would have contained about 400 pounds of lava, making the force expended equivalent to that required to raise 400 pounds 10 or 12 feet. They were in form, in rise and fall, and apparently in mode of projection, like the little jets over a surface of boiling water; and the word *ebullition* seemed to all appearance to express what was going on. On other occasions jets have been seen of 100 to 200 feet, and also of five or six feet and less. In the higher jets the lava is usually broken into parts, and the lowest of two or three feet are sometimes broad and hemispherical.

The boiling movement has been recognized by all who have visited the crater. Rev. Wm. Ellis, of Kilauea, in August, 1823, describes a lake as a flood of fire in "terrific ebullition;" and Capt. John Shepherd, R. N., there in 1839, speaks of the "violent ebullition" as "caused by the escape of elastic fluids which threw up the spray [jets] in many parts 30 to 40 feet."

In the case of "blow-holes" the boiling process goes on beneath a small aperture in the solid lavas, and the liquid rock is thrown up in masses or driblets, with swashing sounds, and volumes of vapor at each throw. Small, steep cones of lava are made around the hole; and one such, surmounted by a column consisting of adhering lava drops (each 4 to 5 inches across), the whole 40 feet high, is figured in my Report, and the

* Prof. J. Prestwich discusses the subject of the agency of water in volcanic action at much length in a valuable memoir read before the Royal Society, in 1886. He makes no use of the facts afforded by Kilauea or of the bearing of the phenomena there observed on the great subject of volcanic action. As the views here given on the agency of water, and the special methods of its action are those of 1849, I have no occasion to make further mention of Prof. Prestwich's paper.

figure has been copied into several text-books. The hole may be what is left of a small lava pool after contraction from cooling. It varies greatly in size, from that of the open lava-pool to a diminutive hole through which drops of lava only a fourth of an inch in diameter are thrown out. One of the specimens which I obtained at the crater was a group of three slender columns, two to three inches apart, and about seven inches high, each made of lava drops of the small size mentioned—a fourth of an inch. Often the blow-hole emits intermittently only steam, whose rush out sustains the appropriateness of the name. Prof. Van Slyke describes one in action and ejecting lava, on page 96, and Mr. Dodge speaks of others, emitting steam only, on page 100.

Rev. C. S. Stewart, at his second visit, in 1829, saw, as he states, four cones from a few feet to twenty in height projecting flames [lava-jet] under a "laborious action of steam," one of which, tapering almost to a point, had "been formed by successive slight overflowings of lavas which, as it rolled down, cooled into irregular flutings ornamented with rude drops and pendants"—a good example of blow-hole action and result.

9. *Source of the vapors.*—While part of the vapors, as is well understood, are from the same deep source as the lavas or from their constituents, and some water may be here included, far the larger part have a more superficial source. The vapors from the deep-seated source of a conduit should vary little in amount except through variation in the area of liquid rock exposed; and the same would be true if the lava were a fused sedimentary rock of the depths below. But in fact, the variation between a time of quiet and of approaching eruption is often immense; the amount may increase rapidly as the height of the lava in the vent increases, proving that, as usually conceded, other more superficial sources of water-vapor exist.

The more superficial source may be either, as is generally admitted, the sea, or the fresh water of the land. Marine products like chlorides abundantly deposited about steaming fissures in the crater and outside, as at Vesuvius, have been accepted by most writers as evidence of the access of marine waters; and the absence nearly of such products at Kilauea, I regarded as evidence of the access there of terrestrial waters mainly. The latter are as likely to be concerned as the former, and the more so in most volcanic regions on account of the distance from the sea.

The very abundant rains over eastern Hawaii, the bare cavernous lavas of the mountains, arranged partly in layers or streams, and partly in vertical dikes often radiate to the crater, and the freedom from water-courses over a large part of the eastern and southern slopes of Mt. Loa, led me to regard the waters from rains as the chief supply; and Mr. Coan, who lived for years at the foot of Mt. Loa and watched the volcanic movements, was the first to suggest that seasons of abundant rain, besides multiplying steaming holes, increased activity and favored eruptions.

10. The introduction of outside waters, whether marine or fresh, into the lava conduit has often been thought an impossibility; and still it must be a fact, as this is the only means of getting the required water. The waters of the land, especially those of great rains, becoming subterranean, would descend deeply along the various vertical fissures, and the spaces by the sides of dikes, it may be to thousands of feet, since the bottom of Kilauea is between three and four thousand feet above the sea level, (and the summit of Mt. Loa over thirteen thousand); and if the copious waters filling the narrow passage ways below over a large area, anywhere reached the hot region along the conduit, they would encounter the action of the heat under great hydrostatic pressure, and be forced by the steam pressure generated into the conduit of ascending lavas as the easiest and only way of escape. Once within the conduit, they would follow the course of the hotter, more liquid, and upward-moving central portion, and expand into vapor toward the surface, there to make cellular and scoriaceous lavas, and escape as they could. The lavas from fissures that tapped the conduit below the level where the chief part of the waters were received should be feebly cellular, or not at all so; but froth-covered streams might be expected from the vents or pools of the crater; and cellular or scoriaceous from tapping near the top. The facts at Kilauea correspond precisely with this view of the operations, and give the explanation full support. The play of jets over the surface may serve to entangle some air and add to the volume of the confined vapors. But air alone has very feeble expanding power when heated, and could not make cells in the heavy liquid and much less make a scoria.*

11. *Projectile force at Kilauea.*—The vapors within the viscid lava struggling for escape are the obvious and the only possible source of the projectile results. The elastic force of the vapors would depend on the resistance to escape, and the resistance on the viscidity, as in the ordinary boiling process. The ascending spheres of vapors in the upper or more superficial part of the conduit would become bubbles at the surface; and the bubbles would continue to enlarge there until the elastic force within was sufficient to break the upper or weaker part, when a verti-

* The facts observed by Prof. J. W. Judd with regard to the waters present (sometimes over 8 per cent.) in an obsidian, (Geol. Mag. for June, 1886), have interest here. See also the important paper by J. P. Iddings on Lithophysæ, at page 36 of this volume.

cal or nearly vertical projection of the materials of the broken bubble would follow. A partial cooling of the lavas tends to increase viscidity, and this may account for the higher jets. The mechanism exists in Kilauea for making cinder ejections; but in the case of so low jets—30 to 60 feet—the liquid material descends before it has had time to cool and the dropping masses that fall outside the lava pool plaster themselves to its sides. The only cinder cones are found on the slopes outside of the crater where greater viscidity, due to partial cooling, may have existed.*

Kilauea continues this easy, quiet throw of jets even in the covered chambers of the now-existing cone. Mr. Van Slyke speaks of the puffing up and throw of the lavas, and the swashing sounds. The work going on, producing these sounds and the throw, is the same as has been described—the breaking of bubbles of the viscid lava by the elastic vapors or gases within them.

12. *Fundamental forces at work in Kilauea.*—In review: the two chief sources of upward movements are (1) the slow-acting ascensive force carrying the lavas to the surface, where they become exposed to earth-surface agencies. (2) The elastic force of the vapors escaping in bubbles from the exposed surface of liquid lava, producing projectile effects; these vapors partly of ascensive origin, but chiefly from external waters that become subterranean and were forced into the conduit. In addition to the above: (3) Subterranean vapors in confined spaces (α) derived from the surface of the underground liquid lavas (those of the top of the conduit), or (β) made, gradually or catastrophically, from the approach or access of waters to the sides of the conduit, may, by pressure, produce:

(*a*) Disruptive effects, opening fissures within the crater and in the mountain's sides.

(*b*) Displacements or uplifts over large or small areas; and opening spaces for the intrusion of lavas.

(*c*) When acting on a surface of liquid lava, the thrusting of the lava into open spaces between layers and thus producing an elevation of the overlying bottom of the crater and of the sides of boiling lakes; or into fissures, and in the latter carrying the lavas to heights several hundred feet above the level of the active vents of a crater, as in cases above mentioned, just as mineral oil is often thrown to heights by the confined gases below.

(4) The hydrostatic pressure of the column of liquid lava in the crater is a common source, probably by itself, and cer-

* In former periods pumice-like cinder ejections took place from Kilauea or its vicinity; but they cover a wide surface south of the crater, instead of forming cones. See my Report, p. 183.

tainly in combined action with the preceding, of extensive fractures and outflows, and sometimes in the case of both the Mt. Loa summit crater and Kilauea, of large and lofty fountain-like throws of the extended lavas.

(5) The expansion of the moisture in the liquid lava into vapors as the lava approaches the surface, thereby expanding the lava in this upper part, making it cellular and raising the level of the surface. This effect is limited by the amount of moisture present, and by the degree of pressure that prevents moisture below from taking the form of vapor.

(6) Underminings, through the discharge of lavas, leading often to subsidences and engulfments, and chiefly of the central parts of the volcano about and within the crater.

In 1840, after a time of violent activity over the whole of Kilauea, the subsided area included a large part of the floor of the crater, it being nearly two miles long and about two-thirds of a mile in mean breadth, with the depth nearly 400 feet. It left the crater over the sunken floor nearly 1,000 feet deep and elsewhere over 600 feet.

In 1886, after more local activity the subsidence was mostly confined to Halema'uma'u and its vicinity (including New Lake) the area about half a mile square; the depth of the subsidence was small, the depressions that were left being due mainly to the escape of the lava and some sinking of the walls of the two pits. Owing to the overflowings and intrusions of lavas since 1840 without equivalent subsidences, the mean depth of Kilauea after this last eruption was about 400 feet. There may be great empty chambers beneath, and after a time of general activity and great discharge, another subsidence like that of 1840 in extent may occur.

The form of Kilauea and character of the operations now going on within it show that the activity (ebullition, etc.) was at some time in the past so general over the included area that the subsidences which followed the eruption affected the whole, nearly to the present outer walls; and that under such conditions Kilauea took its form and size.* The underminings that have since occurred have from time to time caused down-plunges of portions of the walls into the emptied spaces beneath and so increased somewhat its extent just as the walls of the pits in the crater emptied by an eruption continue to fall until the pits are filled again with lavas.

3. *Vesuvius and other Volcanoes.*

13. *Fundamental forces in Vesuvius and other Volcanoes.*—Vesuvius and the Hawaiian volcano differ much in externals, but not in forces, or in their mode of action.

* The plate in Ellis's Polynesian Researches represents the lower pit in 1823 (after a great eruption), as reaching at the time very nearly to the outer walls of Kilauea.

The *first* of the operations mentioned above is necessarily the same.

The *second* method of work and its consequences must also be the same; for vapors rise and escape from the crater in great abundance during periods of special activity, as attested to by many observers. For years the outside waters needed to afford the working steam gain access quietly; but at times there have been large incursions, as proved by the violence of the earthshakings, the vast amount and height of the cloud of vapors, and the lofty projection of cinders.

The recent eruption in the Tarawera Geyser district, New Zealand, affords an example in which only fresh waters were concerned, and one of much instruction. The Tarawera mountain, its height about 3,600 feet above the sea level, though made of volcanic rocks, had, previous to the eruption, as Mr. S. Percy Smith reports from observations in 1874, no distinct crater. On the morning of the 10th of last June, after some rumblings for an hour, the mountain (at 2.15 A. M.) was rent from north to south; three craters were seen to be in action; and soon after, as later observations have shown, there were seven craters in the course of $2\frac{1}{2}$ miles along the top of the fissured mountain, and other small craters on what was properly an extension of the fissure six miles to the southwest. Black clouds, lighted below by the fires, rose to a height of "10,000 to 12,000 feet," and red hot scoria and cinders were shot up a thousand feet or more. The rain fell with the falling cinders in torrents, accompanied with the thunderings and shifting winds of a tornado. By daylight the village of Wairoa, five miles distant, was covered a foot deep with mud, made from the ejected cinders or volcanic ashes, and the descending waters (rain).

Three days later, the action in the mountains had mostly dwindled to steaming fissures, and on going to the region, it was found that the fissure, which was over two hundred yards wide, passed through Lake Rotomahana, $1 \times \frac{1}{4}$ m. in area; that the lake had lost its water; that the bottom was 250 feet below its former level, and in it there was a line of mud craters and geysers, one of the craters throwing the mud to a height of 600 to 800 feet. Evidence of the work of ejection and engulfment in the mountain existed in the great size of the fissure opened, and also in the depth and size of the mountain craters, one of them 900 feet deep, another 600, with five others of less depth, besides a great sunken area, 2000 feet long, 600 wide, and 250 to 800 deep in the southwestern slope of the Tarawera mountain facing Lake Rotomahana. There can be no doubt here that in this great outbreak, so sudden, so abundant in cinder ejections (but no flow of lavas), the lost waters gained access to the fires under the mountain. The waters were in so great abundance that they could not be driven back by the steam made at their approach to the fires; and they consequently entered,—the opened mountain having made upward escape for lavas and steam possible; and thence came the steam power for the grand occasion. And perhaps, the cooling action of so large a body of water may have put the surface-fires out, leaving the heat, however, in possession as before, at no great depth below.

Cinders are projected to a greater height at Vesuvius, and in most other volcanic regions, than at Kilauea; but this is proof simply of greater viscidity in the lavas; and the projected lavas fall in cooled masses or cinders because of the height of projection. Greater viscidity leads to the production of larger vapor-made bubbles before the explosion, and therefore fewer of them over a given surface of liquid lava; and, in times of moderate activity, the number may be only half a dozen or a single one at a time, while, on a like area, lavas with the Kilauea degree of viscidity would have scores. When at Naples, in May of 1834, there was at night an interval of seven to eight minutes between the explosions or the throw (some hundreds of feet in height) of fiery cinders; on the ascent, the following day, of four to five minutes; and on passing Stromboli, a fortnight later, June 16th, of fifteen to twenty minutes—the activity being less than usual, explosions every 2 or 3 minutes being common. As Spallanzani, Hofmann, and others have seen the rising bubble within Stromboli, the bursting, and, following this, the rush of vapor and the cinder projections, there is no reason to doubt that at Vesuvius, also, each throw of cinders has the same source. Mr. John Milne states that on his ascent of the Japan volcano, Oshima, in May, 1877, on approaching the top, successive explosions were heard every two seconds with occasional pauses, which explosions he found, on reaching the top, to be due to successive outbursts of steam, each projecting ashes and bombs to a height of nearly 6000 feet, that fell vertically unless wafted by the winds.*

At the eruption last June in New Zealand, above referred to, the "tremendous roar" of the craters that added to the terrors at Wairoa, five miles distant, was at Auckland, 120 miles away to the northwest, resolved into "a series of detonations, like the firing of a prolonged salute *at minute intervals*, with an occasional lull."† This fact signifies that only the heavier of the aerial vibrations reached that place. The roar heard at Wairoa was due to the simultaneous explosions in the several active craters and the storm and earthquakes; and

* Volcanoes of Japan, Trans. Seism. Soc. Japan, ix, part 2, 1886.

† Volcanic Eruption at Tarawera with an account of the Thermal Springs district of N. Zealand, by T. W. Leys.

the "minute" guns heard at Auckland were the larger explosions; and such a periodicity in the detonations, so rapid and continuous, shows that they were those of exploding vapor-made bubbles; for nothing else in the mechanism of a volcano can produce it.

The catastrophic effects of such an action, where the jets are single or few, are small, because the break of the vapor-enclosing shell takes place at the top, and the throw is nearly vertical; the energy is wasted in the throw of the fragments. Where many jets rise together in such lavas, as in a time of violent eruption, the explosive action is great; but it is still greatest at the center of activity, which is that of greatest liquidity and easiest movement. A cone of cinders about the vent might be destroyed by being added to the projections; but the more distant walls could suffer but little from the projectile action, except in the way of fissuring, and this might be all owing to subterranean shakings and the undermining; for the force from the accumulated elastic vapors in the rising and exploding bubbles is too much confined by the limits of the area of liquidity within the crater. Hence we have reason to doubt much that has been written about explosive eruptions projecting off the tops of mountains; or at least to question it, until the piles of great rocks from such projections have been described.*

The height of the aerial projections in some volcanoes is measured by thousands of feet; but how much of this height is owing to ascending currents of air is not stated. The fineness of the dust that goes to great heights makes it of easy transport.

14. The other forces acting at Kilauea, must be alike active in all volcanic regions. The third is the one usually appealed to by writers in their explanations of eruptions, especially *3a*, *3b;* and that numbered *3c*, must have its effects also, although less easily detected where the crater is not broad and open, like Kilauea. The *fourth*, hydrostatic pressure, has, no doubt, far more common effects than has been recognized, especially in high-sloped mountains like Vesuvius. The quiet character of many of the fracturings at Vesuvius and of some of its large eruptions are strongly in favor of this conclusion. The sixth operation—subsidence or down-plunge of the undermined parts of the mountain—should be doubly more active at Vesuvius than at Kilauea, since the undermining in the latter is produced only by the outflow of lava, while at Vesuvius there is loss both by outflow and upthrow. I have alluded to

* According to some describers of the New Zealand eruption, the Tarawera mountain had its top blown off in the making of the great southwest chasm. The place affords an opportunity to ascertain whether the piles of masses of the solid rocks which in that case should exist, are to be found to the southwestward.

this point already in this Journal (xxxi, 396, 1886) and need not repeat here.

15. In external dress the crater of highly viscid lava is very unlike that of the feebly viscid. The cone in the former often rises with slopes of 30° to 35°; that in the latter, often of but 5° to 10°. The former commonly uses cinders largely in making its cone, or else has the less fusible orthoclase lavas to deal with; the latter is chiefly lava-made, cinder-deposits being subordinate to those of lava. The crater in one is lengthened upward at top by cinders; and has cinder cones about each vent of liquid lava within the crater; that in the other, is often a broad pit, with a floor of cooled lavas over which are large and small lava-vents, and low lava-made cones. The volcano of the former kind is more liable to catastrophic eruption with noisy earth-shocks, though often quiet in some discharges; those of the latter commonly work with comparative quiet, having their large outflows at times without announcements of any kind to those dwelling a few miles away. These are differences; but they are differences in some of the results of the action going on, not in causes or methods. The first of the two kinds of volcanoes prepares for a new eruption by the gradual filling of the emptied crater, doing this by means of one or more lava-vents in the bottom, which, besides throwing up cinders, have their little outflows (as well described by Scacchi for Vesuvius), and keep at the work until the crater is filled or nearly so; and then comes the break and the greater outflows. The second kind differ only as to the cinders; and in Kilauea, as to the height of the floor of the crater before the outbreak.

16. Both from Vesuvius and Kilauea we learn that, next to the lava-vent, the crater of a volcanic mountain is its prime or most fundamental element. It encloses the extremity of a lava-conduit of greater or less breadth that reaches down to the seat of fires; and this enclosure exists because of the ejections by outflows and upthrows and the consequent down-plunges, which superficial conditions in large part determine. The growing mountain-cone cannot be rid of its crater except by the gradual disappearance and healing over of the lava-vent; and commonly, when extinction happens, the crater is still of nearly full size. If half or wholly obliterated, it may be again restored; and is likely to be, if action is ever renewed in the region by new ascensive action below. If so renewed, it may go forward through refusions and new engulfments. But the first step may be the opening of the old fissure upon which the crater was originally made; in this way the lava conduit might secure for itself at once an open way to the surface.

It may be that the course of the old fissure has been a chief cause in determining the form of a crater; and it may lead, in after history, to changes in the locus of the chief vent, or an elongation of the crater in one direction rather than another. The form of the Kilauea crater, and the existence of those steaming fissures southwest of it and others on the northeast side, suggest some such determining cause of change. The elongated form of Haleakala, the great crater at the summit of Eastern Maui, may have this explanation.

17. *Quiet after an Eruption.*—A decline to a season of quiet follows an eruption because the preceding action had opened fissures, and so the crater and the upper part of the conduit had become emptied of lava, and, as a consequence, had also become chilled down to the new surface. Further, in the inactive or weakened condition thus occasioned, the cooling of the conduit-lavas might sometimes extend to a great depth because of the still-continued intrusion of subterranean waters. The completeness of the quiet and the length of the interval would naturally vary with the greater or less extent of the discharge and of the accompanying cooling influences. An empty caldron will not overflow before its cracks are mended and the steam apparatus at work has again filled it; and it may be so badly cracked and the supply of heat so cut off as to fail of further use.