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EARTH MOVEMENTS ACCOMPANYING THE KATMAI ERUPTION. II

CLARENCE N. FENNER
Geophysical Laboratory, Carnegie Institution of Washington

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PART II. FRACTURING IN THE VALLEY OF TEN THOUSAND SMOKES

CHARACTERISTICS OF THE FRACTURES

Reference has been made several times in this paper to the formation of fractures in the Valley of Ten Thousand Smokes at the time of the eruption. Their formation was undoubtedly accompanied by earth movements of some importance. We shall now describe the more important features of the fractures, inquire into their causes, and see if their formation can be correlated with the tectonic earthquakes that have been described.

Some of the features of the fissures, especially their relation to the hot sand-flow and to the fumaroles, have been described in previous articles.[1]

For the purposes of the present paper, a brief recapitulation of the pertinent data of previous articles will be given, supplemented with other information, much of which was gathered in the second visit to the region in 1923.

During the period of the eruption a broad, Y-shaped valley, bounded by abrupt mountains, and extending several miles northwestward with gentle slope from the foot of Mount Katmai and its neighbor, Mount Trident, opened in numerous fissures. These are believed to have been the source from which a great volume of hot pumice and fragmental glass (the sand-flow) was poured out, forming a phase of eruption similar in some respects to the *nueés ardentes*, or "glowing clouds," of the West Indian eruptions of 1902, and since then recognized as a not unusual volcanic manifestation. This valley in its transformed character is now known as the Valley of Ten Thousand Smokes.

The extruded material forms a tuff deposit covering the valley floor to a great depth—100 feet and possibly much more in places. The location of some of the fractures[2] is demonstrated with certainty by fault scarps, visible especially around the margin of the valley, and very prominent on Broken Mountain, near the head of the valley, immediately adjacent to the new volcano Novarupta (see Fig. 11). The presence of many other fractures and fissures has been inferred from the manner in which fumaroles are disposed in long, definite lines, the whole length of which may serve as a vent for

[1] E. T. Allen and E. G. Zies, *A Chemical Study of the Fumaroles of the Katmai Region*, "National Geographic Society, Contributed Technical Papers, Katmai Series," No. 2. Washington, 1923.

R. F. Griggs, *The Valley of Ten Thousand Smokes*. Washington, 1922.

C. N. Fenner, *The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes*, "Katmai Series," No. 1. Washington, 1923.

[2] Where fractures are spoken of, a break is meant, with no implication as to whether there was or was not a significant amount of movement of the sides; fissuring is intended to imply some spreading apart of the walls; while faulting implies significant movement of the walls past each other.

vapors, or the exhalations may be concentrated at certain openings. This linear arrangement shows as a prominent feature in photographs taken by Griggs in his earlier explorations, and was still plainly evident in 1919. With the diminution of activity in 1923 it was not so perceptible, but was still visible in places (Fig. 5.). Frequently the orifices of continuous lines of fumaroles[1] are merely cracks in the tuff deposit a few inches in width, but they extend downward indefinitely, as is shown where deep stream gullies inter-

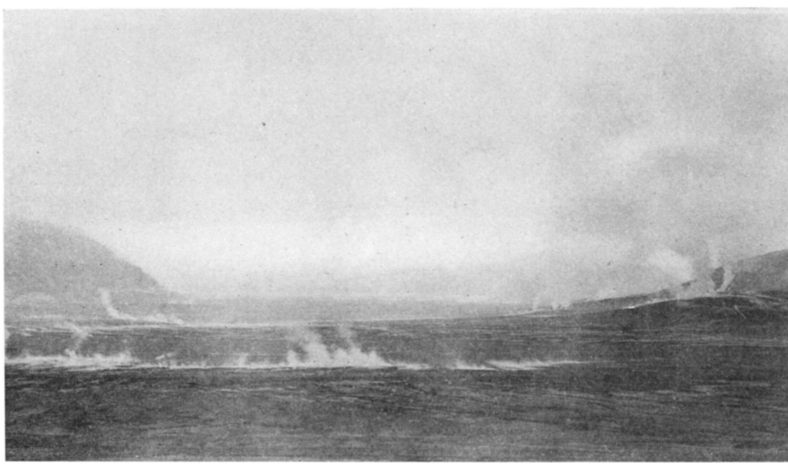

FIG. 5.—Looking northerly down the Valley of Ten Thousand Smokes from the base of Mount Cerberus. Linear distribution of fumaroles is evident. The photograph was taken on a damp day when visible condensation of steam from the fumaroles was a maximum. (Photo. by C. N. F., 1923.)

sect them. Occasionally, the orifices are open to a width of several feet, and one may look down to obscure depths. Fumarolic action was very vigorous when the valley was discovered by Griggs in 1916, and was still strong during the investigations of 1919. By 1923 activity had diminished very perceptibly.[2] Though the life of the fumaroles appears likely to be short in the valley as compared with

[1] For convenience, the description of the arrangement of fumaroles, on which inferences regarding fracturing are based, is given as if the activity visible in 1919 were still continuing in full force.

[2] Cf. Fig. 5 with the illustration on p. 234 of Griggs's book, *The Valley of Ten Thousand Smokes*. In the latter illustration observe also the alinement of fumaroles.

some other regions, the evolution of magmatic gases in quantity over a period of several years, and the many high temperatures found by Allen and Zies in 1919, point to a source for the emanations other than the superficial tuff deposit, and indicate a derivation from an underlying body of magma. The pumiceous character of the superficial tuff suggests that its supply of volatiles was practically exhausted during eruption. Emanations from it may have continued for a brief period after its emplacement, and may have

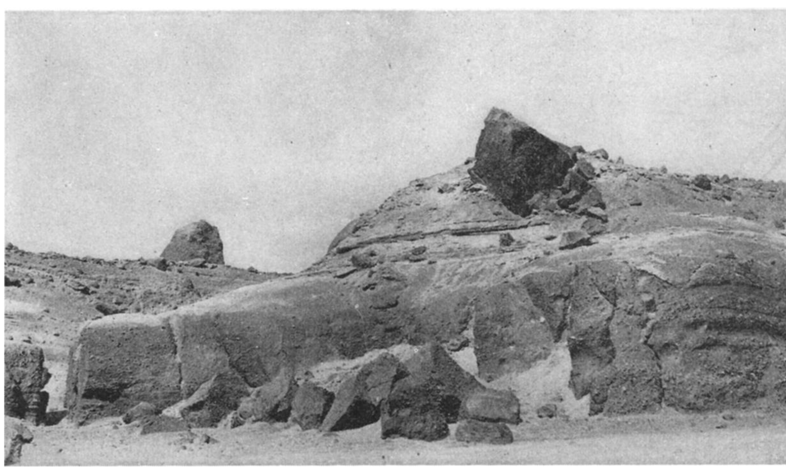

FIG. 6.—Portion of an east-west fault (along zone shown in Fig. 12) in the terraces at the southern head of Mageik Basin. In the photograph the lower deposits are indurated sand-flow tuff; above are irregularly stratified beds containing great blocks of sand-flow material thrown out by explosions. The camera faces the fault scarp. (Photo. by C. N. F., 1923.)

given rise to certain short-lived fumaroles of which evidences were visible in 1919, but which had already become inactive. It is very doubtful if any of those still vigorous at that time were of this derivation.

A feature of significance in its implication that the fracturing resulted in open fissures, which formed eruptive vents and supplied the material of the sand-flow, is shown in many places by explosive effects seen in direct association with them, as is illustrated in Figures 6, 7, and 8. In Figure 6 angular blocks of consolidated sand-flow material, many of them of great size and weighing many tons, have been thrown out of a fissure and now lie on the surface along the borders. A slightly different phase of explosive action along fissures is shown in other places by lines of large craters blown out of the tuff deposit and surrounded by mounds of *ejecta*. A crater of this kind appears in Figure 7. In places the craters are so close together that their arcs intersect. They frequently occur in situations where explosions due to the contact of hot tuff with water or marshy ground appears

FIG. 7.—A large explosion crater in the sand-flow tuff in the southeastern arm of the valley. The sand-flow is overlain by the stratified ash-fall from Katmai and Novarupta, but above this are strata of materials blown out of the adjacent crater, and containing blocks of sand-flow. In 1919 some of the craters in this area were still evolving clouds of steam, but in 1923 all were practically dead. (Photo. by C. N. F., 1923.)

very unlikely.[1] Figure 8 shows a portion of a line of craters close to the base of the falling cliff of Falling Mountain. The indication of explosive action here at just the place where a major fissure is inferred from the occurrence of the Falling Mountain landslide seems very significant. In explanation of these associations of explosive effects with fissuring it is inferred that after the violent extrusions of pyroclastic tuff that formed the sand-flow abated, feeble explosions continued at some of the orifices, and resulted in clearing out

[1] Explosive effects, probably due to the latter cause, are found in places, but may generally be differentiated.

again for a short time the material that choked the openings.[1] Subsequently, less violent evolution of gases and vapors continued for years in the form of fumaroles.

Near the head of the valley, in the area around Novarupta, fracturing was not confined to the valley floor, but affected the adjacent high country also. The prominent faults on Broken Moun-

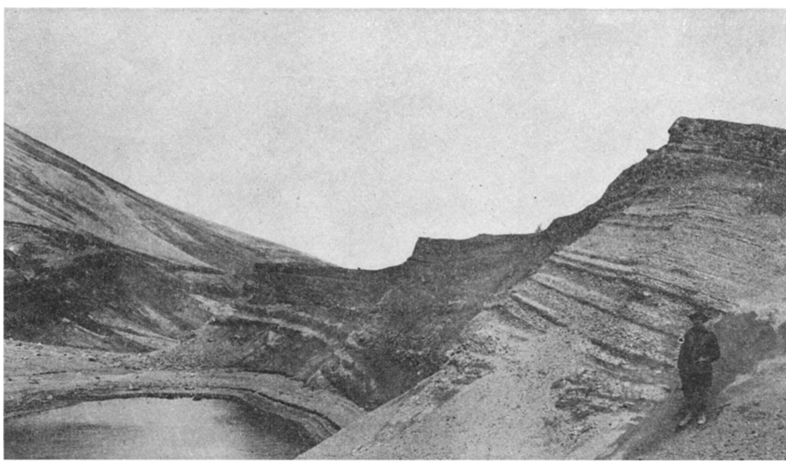

FIG. 8.—Explosion craters at foot of the northern cliff of Falling Mountain. The section of strata at the right shows regularly stratified ash-fall from Novarupta and Katmai, overlain by irregularly stratified beds of *ejecta* from the immediately adjacent craters. The broken cliff of Falling Mountain is to the left of the view. (Photo. by C. N. F., 1923.)

tain have been mentioned, and the adjacent lower slopes of Mount Trident also were faulted; and both of these localities became the scene of strong fumarolic activity. Undoubtedly, similar movements were responsible for the landslide from Falling Mountain. The

[1] A problem which is of interest, but will not be discussed in detail here, relates to the agencies that caused the fragmental material of the sand-flow to become cemented into the firm mass that we see in many places. This is its usual condition in the upper valley, and in places in the lowermost part of the deposit in the lower valley. This cementation apparently took place almost immediately after extrusion, for the *ejecta* of the waning phase of explosions contain angular blocks of indurated material. Possibly the induration was due to cohesion of the fragments of hot glass, such as is known to take place in commercial glasses at temperatures well below fluidity, or possibly chemical action of vapors may have been a factor. Among the masses of rhyolitic glass in Novarupta dome tightly welded crush breccias are found.

débris from this was covered by the sand-flow and is not visible, but a great scar has been left on the northern face of the mountain, from which small masses of rock continue to break away and plunge down, and cracks from which vapors issue are still active. An offshoot of the main area of fissuring is inferred to have followed the low divide of Katmai Pass also.

These last-mentioned occurrences comprise the only important areas outside of the valley floor in which recognizable fracturing has taken place, but several others of relative insignificance should be mentioned for completeness. On the westward-facing cliffs of Baked Mountain little seeps of steam were visible in 1919, and were still continuing in 1923. They issue high up on the cliffs, and examination shows that the orifices are merely joint cracks. There are indications that a similar leakage of vapors may at one time have been rather general on Baked Mountain. On the opposite side of the valley, on the lower slopes of Buttress Mountain (above the margin of the sand-flow), several small fumaroles were active in 1919, and were noted by some of the members of the expedition. I did not visit their site at that time, and in 1923 they had apparently ceased.

A certain amount of interest attaches to some of these minor vents, in that the vapors visibly rise from the bed rock. In the main areas of the valley there is no reasonable doubt that the fumaroles have a similar origin, but the superficial covering of tuff conceals it from actual vision.

With the exceptions noted, the fracturing is confined wholly to the valley. If a map were drawn on which were represented the fractures inferred from the alinement of fumaroles and from visible faults, a large area showing a network of cracks would be blocked out, which would practically coincide with the main part of the valley; and if the rather minor exceptions mentioned were disregarded, no fracture would be found outside of its boundaries. In the early years of exploration of the area fumaroles were numerous almost to the margin of the "high sand mark," and there stopped abruptly.

A feature believed to be of much significance is the fidelity with which fractures and faults follow the margins of the valley for long distances, even outlining projections and embayments, but do not pass into the adjacent hills. An instructive example is afforded by fissures along Baked Mountain. The western side of this eminence is marked by prominent fissures lying close to the mountain, some of which are open cracks and others are indicated by lines of fumaroles. At the southern end of the mountain, where the cliffs swing abruptly through more than a right angle to form the northerly side of Novarupta Basin, this set of fractures continues only a short distance out into the valley, and another set of prominent intersecting fractures, along which there is still fumarolic activity, starts at this point and follows the base of the cliffs eastward into the basin. In a similar manner the curving shore of Mageik Basin[1] is paralleled by fractures. These may be considered to begin with northeast and southwest fissures at the base of the northwestern face of Mount Cerberus. As the contours of Cerberus swing southward, the first fissures are succeeded by north and south fissures lying nearly parallel to the western face of the mountain and extending nearly to the base of Mount Mageik at the southern head of Mageik Basin. Along the foot of Mount Mageik, east and west faults with vertical throws of 30 or 40 feet are prominent, but they come to an end in the southwest angle of the basin, and another set, intersecting them at nearly a right angle, extends northward at the foot of the eastward-facing cliffs of Buttress Mountain. These last are marked by faulting at their southern end; northerly they are shown only by exudations of steam, but indications of them persist continuously for about 5 miles.

The general restriction of fractures to the floor of the valley, and the intimate relationship that fracturing bears to this topographic depression, seem to indicate that the forces which caused the fracturing were local, and were situated at a comparatively shallow depth.[2] In previous papers I have ventured the hypothesis that the effects were due to the intrusion of a sill of magma, pre-

[1] Mageik Basin is the area at the head of the southern arm of the valley, just below Mount Mageik.

[2] It is interesting to contrast the relations here with those of certain regions in Iceland, so well described by Thoroddsen (*Island: Grundriss der Geographie und Geologie*, Gotha, 1905), where the fractures are undoubtedly fundamental. For instance: "The fissures always run in a straight direction without regard to the relations of the terrain, and in spite of small bends and curves always maintain the principal direction" (p. 118).

sumably derived from the same body that caused the eruption in Katmai crater, driven between the horizontal sedimentary strata underlying the valley. Where the roof above the intrusion was comparatively thin it was uplifted and fractured, but where the heavily loaded mountain areas at the sides of the valley were encountered an obstacle was met which opposed an effective resistance to further advance of the intrusion. For this reason, the fracturing was in most places restricted to the floor of the valley. The upheaval and fracturing of the roof allowed the escape of a portion of the magma, probably in a succession of outbursts lasting for a few hours. This was the hot sand-flow.

It is naturally inferred that the intruded body was derived from a source lying beneath the sharply defined volcanic zone along which Katmai, Trident, Mageik, and other volcanoes are situated. The form of the channel through which the magma rose from the subcrustal reservoir to the upper lithosphere can only be surmised. It need not necessarily have been the same conduit that supplied the material for the immediately succeeding eruption at Katmai crater; in fact, the thorough manner in which a limited area of the lower slopes of Trident was fractured gives a hint that it was at this point that the magma, which had probably risen through some steeply inclined fissure, found an escape to the side, beneath the strata of the valley. It may be for this reason that the immediately adjacent portion of the valley was so greatly disturbed. Here not only was the floor shattered, but considerable portions of Broken Mountain and Falling Mountain were greatly fractured, and the vent of Novarupta was established. The great amount of disturbance of this area seems to point to a greater impelling power acting upon the magma here than was later shown when intrusion had carried it under the wider spaces of the valley proper. In this later movement resistance to spreading beneath the floor seems to have been comparatively small and the adjacent mountains were hardly affected. They were disturbed only to the extent of opening up joint cracks to a slight amount in a few places.

This picture of the process need not necessarily be accepted in all its details. The essential feature to which attention should be directed is the disturbed condition of the valley floor in contrast with the relatively undisturbed condition of the surrounding mountains, and in explanation of this the hypothesis of the intrusion of a sill-like body has been formulated.

Novarupta seems to have been a vent essentially similar to the many other orifices of extrusion of sand-flow tuff, but in this case the opening became so enlarged that great quantities of pumice and ash were ejected, followed by the welling up of a mass of viscous lava to form the dome. In its neighborhood fissures are very prom-

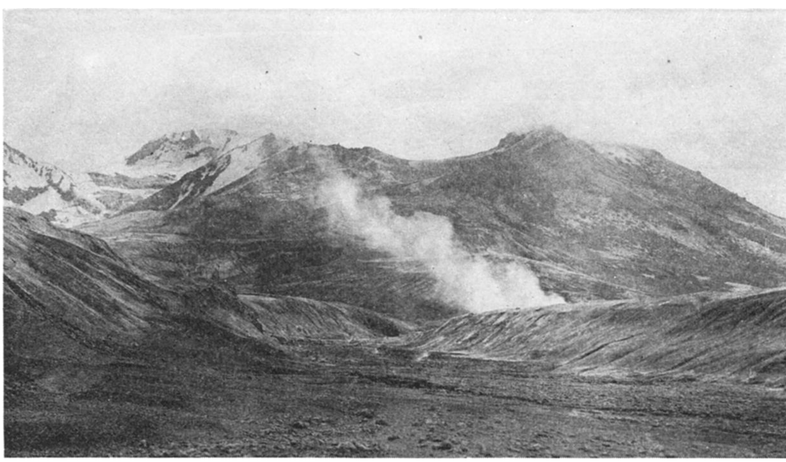

FIG. 9.—Fault graben in the area east of Broken Mountain. Mount Trident in background. (Photo. by C. N. F., 1923.)

inent, and fumarolic action has continued to the present time in more activity than elsewhere.

The movements along the faults in the valley appear ordinarily to have been simple vertical throws, but may take other forms. In the area to the northeast of Novarupta sunken blocks or gräben occur. One of these is shown in Figure 9. It forms a trough, probably 10–15 feet deep, running diagonally down a smooth slope of moderate inclination. Other faults in this vicinity are steplike. They run in various directions. The upper part of Broken Mountain, just to the north of Novarupta, is broken by numerous large faults. A sketch of one of these is given in Figure 10. It has the form of a sunken wedge with stepped faults at the sides. A photographic view of the northeast wall of the same fault appears in Figure 17. The general appearance of a portion of Broken Mountain, showing some of the prominent faults, may be gained from Figure 11.

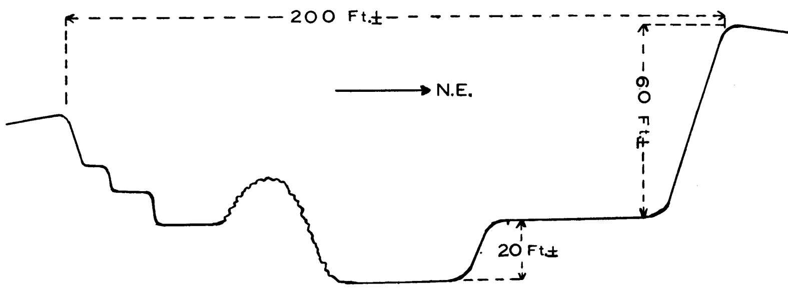

FIG. 10.—Diagrammatic sketch of faulting on Broken Mountain. The height and width of the benches vary along the fault.

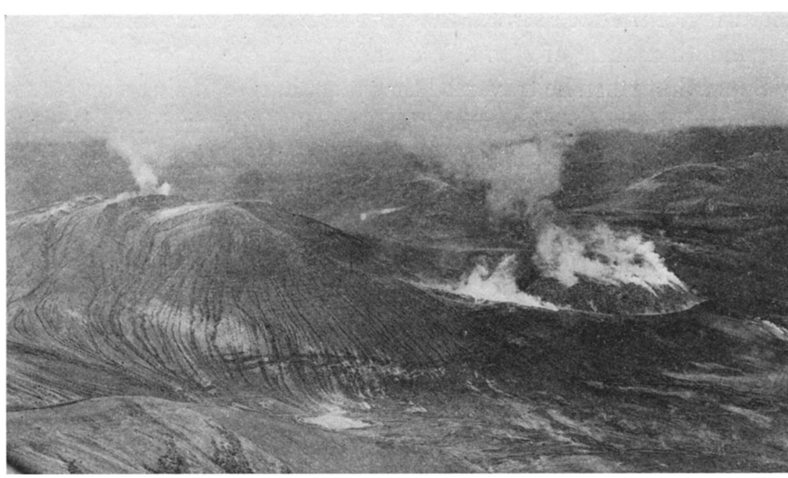

FIG. 11.—Looking downward from Baked Mountain upon Novarupta and the southern portion of Broken Mountain. Several of the large faults of Broken Mountain, which have throws of as much as 60 or 80 feet, are visible. (Photo. by C. N. F., 1923.)

With the exception of a few places previously noted, all of the areas of fumarolic activity and fracturing that we have been considering are heavily overlain with tuff, and the visible portions of the fractures are in these deposits of fragmental *ejecta*. In the elevated areas near Novarupta the sand-flow deposit is absent, but there is a thick mantle of pumice and ash from that vent and from Katmai. The throw of the faults is not sufficient to bring up the underlying rock. In the main part of the valley a great thickness of sand-flow deposit covers the floor, and the fault scarps do not reveal what is beneath. It is beyond reasonable doubt, however, that faults of such large throw are more than superficial phenomena, and must penetrate the rock-strata below.

One important consequence arises from the presence of these thick layers of tuff, and should be noted: The visible record reveals only the movements that took place after the eruption was nearly or quite at an end. If, as we believe, the first important episode of the eruption was the upheaval of the valley area, this was followed almost immediately by the outpouring of the sand-flow, and shortly afterward by the heavy downfall of *ejecta* from Katmai and Novarupta. Whatever displacements may have accompanied the initial fracturing of the rock strata, they were almost at once concealed by the smooth mantle of *ejecta*. We know from the description given by Spurr that when he traversed the valley in 1898 it showed a somewhat varied topography, with "great walls of moraine, damming mountain gorges," but all this disappeared beneath the pyroclastic deposits. The great avalanche from Falling Mountain also was buried and completely concealed.

UPLIFT AND COLLAPSE OF THE VALLEY FLOOR

Because of these facts there is no direct evidence of the character of the initial displacements accompanying the formation of the fractures. One would infer that if a sill was intruded beneath the floor, the first movement was an upheaval, which was followed by partial subsidence as a portion of the intruded magma found escape through the fissures, and that only the subsidence is recorded in the fault scarps.

The remarkable feature to which the term "high sand-mark" has been applied may probably be explained as a result of the final faulting and settling. The high sand-mark is the top of a terrace or slope which follows the margin of the sand-flow in much of the valley area.[1] In the southern arm of the valley it is especially well developed, but occurs in many other parts of the valley also, and in places is practically continuous for many miles. This marginal bench is composed of the same material as the general body of sand-flow, but reaches 200 feet (locally even higher) above the flat areas of the adjacent floor, to which it descends by a slope of 10°–15°. This elevated margin shows that the sand-flow, at the time of extrusion, attained a level considerably above its present general surface, and an explanation is required as to the manner by which its surface became depressed.

Griggs, in his early papers, regarding the sand-flow as an extrusion of mud, supposed the "high mud-mark" to indicate the height which the fluid reached at first, and at which a marginal portion was left after the level of the major portion had been reduced by draining away.[2]

Later, when the sand-flow had been more thoroughly studied and its origin as an outburst of incandescent material had been recognized, I suggested that the high sand-mark indicated the level of the deposit while in loose form, and that the process of settling together of the loose particles had reduced the general level.[3]

Further investigation in 1923 made this explanation seem inadequate and brought anomalies to light. Especially noteworthy was the evidence that the sand-flow tuff had become well indurated prior to the fracturing that accompanied the downward movements. It had assumed such firmness that neither flowage nor shrinkage would be likely to affect it. Moreover, certain phenomena were found which pointed strongly to another explanation.

Around the margin of Mageik Basin the high sand-mark is everywhere a prominent feature, and the marginal faulting of the basin that has been described occurs near the edges or part way down

[1] The characteristic appearance of the high sand-mark may be seen in the photograph on p. 262 of *The Valley of Ten Thousand Smokes.*

[2] R. F. Griggs, "The Great Hot Mud Flow of the Valley of Ten Thousand Smokes," *Ohio Jour. Sci.*, Vol. XIX (1918), p. 121.

[3] C. N. Fenner, *The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes* (published by the National Geographic Society), p. 12.

the slopes of the terraces.[1] On the western side of the basin, at the foot of Buttress Mountain and very near the edge of the high sand-mark, a fault, having a throw of 30–35 feet and easily seen from a distance of 2 or 3 miles, lies parallel to the cliffs for about 1½ miles. Toward its northern end the throw diminishes, and the fault apparently passes into fractures or fissures, which continue along the terrace for several miles farther and are marked by exudations of steam. Along the part of the course where the walls of the fault are visibly spread apart, the structure is well shown, and the relations appear as in Figure 13. The strata of the sand-flow lie nearly horizontal for the short distance from the cliffs of the mountain (on the right) to the fault; there is then a gaping opening, and a drop of the block on the valley side, together with a down-tilting toward the valley. The relations suggest that the whole floor of the valley has collapsed, leaving a marginal rim to indicate the height at which the surface stood.[2]

The high sand-mark, accompanied by marginal fracturing, has been traced around the sand-flow in the whole southern arm of the valley, almost without interruption. In many places evidence of vertical movements in these fractures is apparent, and the down-throw of the faults on the eastern, southern, and western sides is always toward the middle of the valley (cf. Figs. 12, 13, 14, and 15). Elsewhere vertical throws are not evident, but lines of fracturing, frequently accompanied by fumarolic activity, appear in the marginal terraces, or traverse the slopes that connect the high sand-mark with the floor of the valley (see Fig. 16). Such is the case along the western side of Baked Mountain. Here no vertical throw is perceptible, but there are open fumarolic fissures, several feet wide, whose walls can be seen to spread apart slightly as they approach the surface. There is reason to suspect that these marginal fissures may exist in many places where their presence would be inferred but cannot be seen. The winds prevalent in the valley constantly shift the

[1] Griggs noted that "All around the margin of the Valley, just below the 'high water mark,' runs a series of gaping fissures, as though the surface had been stretched by subsidence after its formation." See "The Great Hot Mud Flow of the Valley of Ten Thousand Smokes," p. 123.

[2] Other views of the same fault zone are shown in *The Valley of Ten Thousand Smokes*, opposite p. 225 and on p. 232.

surface sands, and tend to fill orifices in which the upward rush of steam is not strong. It is not unusual to find a well-developed fissure

FIG. 12.—Line of faulting, A–B, in the marginal terraces of the sand-flow, at the northern base of Mount Mageik. (Photo. by C. N. F., 1923.)

FIG. 13.—Looking southerly along the fault that follows the elevated margin of the sand-flow on the western side of Mageik Basin. Shows effect of collapse of the valley floor, with down-tilting of blocks on the left side of the fault, toward the middle of the basin. The vertical faces of sand-flow deposit in the foreground are about 30 feet high. Mount Mageik in the background. (Photo. by C. N. F., 1923.)

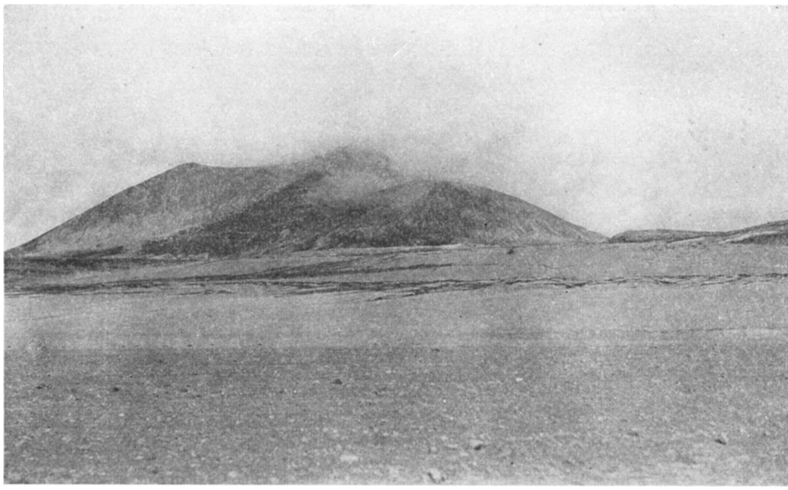

FIG. 14.—View easterly from the middle of Mageik Basin toward Mount Cerberus (about $1\frac{1}{2}$ miles distant), showing elevated margin of the Basin ("high sand-mark"). This elevated rim here has the form of two broad terraces, broken by longitudinal faults (see Fig. 15), and rises to more than 200 feet above the flat floor. (Photo. by C. N. F., 1923.)

FIG. 15.—Looking northerly along a fault in the elevated margin of the sand-flow, on the eastern side of Mageik Basin. (Photo. by C. N. F., 1923.)

with fumarolic openings only occasionally appearing, the spaces between being filled with pumice, and the surface leveled off. In the light of these inferred phenomena of collapse and marginal fracturing, we seem to see the significance of the fact mentioned on an earlier page that great fumarolic activity reaches nearly to the edge of the high sand-mark, and there abruptly ceases.

If the inferences drawn with regard to the significance of the high sand-mark and its structures be correct, a drop of the valley floor to the amount of about 200 feet after the first uplift is indicated.

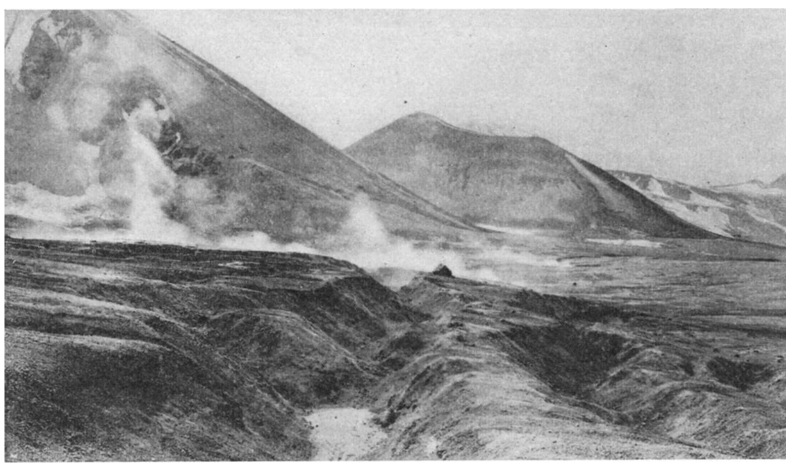

FIG. 16.—Small gullies, transverse to slope, and indicative of fissuring, in the northeastern marginal portion of Novarupta Basin. In the background, a part of Falling Mountain at the left, and Mount Cerberus in the center. (Photo. by C. N. F., 1923.)

This evidently occurred after the extrusion of the bulk of the sand-flow, though minor outbursts may have continued and served to smooth out small irregularities in the surface of the depressed floor.

The structure of the marginal terraces has been studied especially in the southern arm of the valley, but there is no reason to doubt that the same structure characterizes the terrace wherever it occurs. The terrace is found not only in the southern arm of the upper valley, but also in the main valley for several miles below the junction of the arms. In the lower valley the high sand-mark is a less prominent feature. In Knife Creek Valley (the southeastern arm of the upper valley) the high sand-mark is well developed at the lower end, but becomes obscure or disappears toward the upper end. Its constant association with the sand-flow over so much of the occupied area indicates its importance as an essential feature.

AN UNDERLYING BATHOLITH UNLIKELY

A collapse of the roof appears a likely consequence of the escape of magma from an underlying sill. Possibly it, by itself, is not out of accord with the idea that a larger body, such as a batholith, which had risen close to the surface, was the source of the extrusions. Such a hypothesis demands, however, that after the episode of eruption there was no further tendency for the material of the batholith to rise or be forced to the surface. It would seem that external pressures, or the internal tendency to expand from the presence of volatiles, would lead to a different result in the case of a practically inexhaustible batholith.

Griggs[1] has favored the idea that a batholith of regional extent and tens of thousands of feet thick had been intruded beneath the area. In order to account for the evident differences in amount of disturbance between the valley and the mountains, he supposes that the intrusion had approached the surface closely over a large area,[2] so that surface features exercised control over fracturing. One or two geologists in conversation have suggested a similar idea. For reasons more direct and less hypothetical than those mentioned above, I doubt if this explanation is tenable.

In discussing the question we shall have to discriminate between two forms which might be assigned to the batholith. In one, the upper surface may be supposed to have a widely extending horizontal form; in the other, there is an upward protrusion or stock which underlies an area not much greater than the valley, while beyond this the sides drop steeply.

If a widely extending batholith rose (by stoping or otherwise) so close to the surface as to cause the general fracturing of the roof that we see, the blocks thus separated from each other would be left with no effective support other than the body of magma below, and,

[1] *The Valley of Ten Thousand Smokes*, chapter beginning on p. 287.

[2] *Ibid.*, p. 301. See also his sketch of inferred conditions, shown on p. 263.

from ordinary laws of flotation, should sink into it until they displaced equivalent weights of liquid. Now the valley area is nearly surrounded by mountains, rising from 1,500 to 5,000 feet above the immediately adjacent floor, within distances varying from 1 mile to 3 or 4 miles. Moreover, if we pass outside of the area closely adjacent to the valley, and survey the surrounding country that would be underlain by such a batholithic body, we find a topography of great relief, in which high and rugged mountain blocks alternate with broad valleys similar to the Valley of Ten Thousand Smokes.

As long as the roof of the batholith was intact and no escape of the liquid body was possible, it would be able to support the superincumbent load, but as soon as fracturing occurred in the valley, this ability would disappear, and the condition would be that of mountain blocks rising from a shelf which projected horizontally over the batholith, presumably for several miles (depending upon the dimensions assigned to the body), and unsupported except for connection with the rock masses beyond the edges of the batholith. It seems only necessary to state these conditions to realize what a mechanically impossible situation is presented. Under such circumstances, rupture along joint planes, involving the whole region, should result. The mountain blocks should settle at least hundreds or more likely thousands of feet, and a corresponding amount of liquid would be forced up in the intervening low areas.

If the conception be modified so that only a stocklike protuberance of the batholith be supposed to extend upward to near the surface, undermining an area not much greater than that known to be fractured, the scale of necessary readjustment would be lessened, but would still be of great magnitude. Baked Mountain, Broken Mountain, Falling Mountain, and Mount Cerberus, lying practically within the valley area, rise approximately 1,500 feet above their immediate surroundings. Baked Mountain and Broken Mountain especially are completely surrounded by areas of fracturing, and Mount Cerberus is nearly surrounded. They should have settled deeply in the batholith. Buttress Mountain, also, a high, narrow ridge bounded by the main valley on the east and by the valley of Windy Creek on the west; and Falling Mountain, cut off from Mount Trident to the rear by a depression not much higher than the valley floor, might be expected to break off and settle in a similar manner. Instead of such great downward displacement of mountain masses, we find that in the latest movements (the only ones of visible record) the floor of the valley settled slightly, as might be expected with the outflow of a portion of a sill. In the section around the head of Novarupta Basin the movements involved slices of the adjacent eminences, but this does not affect the conclusions. With a batholith the whole of these mountain masses should have dropped to such a degree as to show an evident topographic unconformity with relation to their surroundings.

The sill explanation is not demonstrable, as the manner in which the various phenomena of igneous intrusion exposed by erosion around ancient volcanoes express themselves in surface effects is little known. It has seemed desirable, however, to make an attempt at interpretation of the surface effects, and the sill hypothesis has been favorably considered because the observed phenomena seem to accord with it. Indirectly, it has been strengthened by the difficulties that other hypotheses have to meet. Since it was first suggested in 1920 the probabilities in its favor appear to have been considerably strengthened with developments and with the acquisition of additional information. The waning of fumarolic activity in the period from 1919 to 1923 indicates that the mass of hot material is not of great dimensions. It is hardly possible to make a useful calculation of the rate at which heat would be transferred from a mass of hot rock, fractured to an unknown degree, to its surroundings and to penetrating meteoric water; but we know that in certain regions, such as Yellowstone Park, Iceland, New Zealand, the Mount Lassen region, or Tuscany, geysers or fumaroles have been active on a large scale for hundreds or thousands of years, and in such instances it is natural to infer that the bodies of hot rock from which they derive their energy are large. But in the Valley of Ten Thousand Smokes the diminution of activity from 1912 to 1923 is estimated (from the number of dead fumaroles and from the diminution of activity actually seen) to have been as much, at least, as two-thirds of its original magnitude, and this does not seem consistent with the presence of a great mass of hot rock.

LACK OF COMPARATIVE DATA ON ELEVATION OF THE VALLEY BEFORE AND AFTER THE ERUPTION

Considered in relation to the fracturing and faulting in the valley, the hypothesis of a sill probably implies that the floor was first uplifted and broken into blocks, that a portion of the magma escaped through the fissures in a succession of outbursts and formed the sand-flow, thus concealing the evidences of upheaval, and that as a consequence of the escape of material from below the floor subsided, but not to its original level.

In connection with these inferred movements of the floor some comment seems to be called for on arguments presented by Griggs in his *Valley of Ten Thousand Smokes*.[1] In arguing against the presence of a sill he says that the surface would be upheaved, and probably much broken, when the sill was squeezed in, and states, as a chief argument against a sill:

> No appreciable changes of altitude occurred at the time of the eruption. The precise triangulation of the Coast and Geodetic Survey gives us information as to the elevation of the high peaks in 1908. These altitudes have been checked against many observations by our surveyors and found to be unchanged within the limits of a few feet.

The inference that would be drawn from this statement is that data exist by which a comparison can be made between levels before and after the eruption, and that this comparison is sufficient to show that no significant change of level has occurred in the area that would be underlain by a sill. Unless this inference is intended the argument does not seem to be relevant.

I have taken pains to learn what data on elevations had been obtained by the Coast and Geodetic Survey prior to the eruption.[2] It was found that all the essential data of the Survey that have a bearing on the matter are shown on Chart 8555. This gives the position and elevation of several peaks visible from Shelikof Strait, as obtained by triangulation, namely, three peaks of Mount Mageik, two peaks of Trident, three peaks of Katmai, and Knife Peak. In

[1] Principally on p. 303.

[2] In this matter Colonel E. Lester Jones, director of the Survey, Major William Bowie, chief of the Division of Geodesy, and other members of the staff, gave me great assistance. The records were looked up, and sources of information ascertained.

addition, the general configuration of the neighboring topography is indicated approximately by dotted form lines, with no figures of elevation attached. These were intended merely to suggest the topography. In part, they were probably sketched from the deck of a vessel in Shelikof Strait; and, in part, are based on the sketch map made by Spurr's party in their journey through the valley in 1898.[1] No accurate mapping is attempted on the chart, except for the triangulated peaks mentioned, and no surveys had been made which would serve as a basis for this.

The several expeditions sent out by the National Geographic Society did a large amount of topographic work, and the results were published on a map accompanying Griggs's book. It is noted on this map that the triangulation and photography are based on United States Coast and Geodetic Survey stations. This implies that the position and elevation of previously determined peaks were accepted as correct, and the surveys continued on this basis. Accordingly, we find that the peaks of Mageik and Trident are shown with the same figures of elevation as on the chart of the Coast and Geodetic Survey. The peaks of Katmai disappeared in the eruption, and no comparison is possible. The elevation of Knife Peak is not given in figures, but contour lines represent it as 215 feet or more higher than on the chart. The discrepancy in the last case may be due to the fact that the determination by the Coast and Geodetic Survey was made by only one intersection, and the record with respect to it is annotated "no check." Necessarily an error in the altitude of Knife Peak was made either by the Coast and Geodetic Survey or by the topographers of the National Geographic Society, or else the elevation has changed. These data apparently cover everything on which Griggs's statement is based. Their consideration shows that the information does not support arguments in opposition to the injection of a sill. There are no comparative data relating to the valley floor or to those areas closely adjacent to it that might be supposed to have been uplifted by the intrusion of a sill.[2]

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska in 1898," *Twentieth Ann. Rept. U.S. Geol. Surv.*, Pt. VII, map inset between pp. 140 and 141.

[2] Other arguments used by Griggs in support of his batholithic hypothesis are not sufficiently related to the present subject to be discussed here, but will be taken up in a subsequent article.

TECTONIC EARTHQUAKES NOT DUE TO FRACTURING IN THE VALLEY

Whether or not the hypothesis of a sill offers the correct explanation of outbursts in the valley, it is evident that much fracturing and faulting of the rock floor occurred. In endeavoring to determine whether this was the cause of the earthquakes that affected distant seismological stations, it is important to consider the time at which the fissures opened, with respect to the sequence of events. From Table I (Part I) it is seen that for at least a month prior to the eruption there is no record at distant points of shocks originating in the region. The first shock of this kind, directly related to the eruption, of which there is indication, is that of June 6, at 12 hours, 41 minutes. The information regarding this is a press report that a shock was felt then at Seattle Observatory. Klotz's compilation does not refer to a shock at this time at the observatories listed by him. If the report is well founded, the shock was nearly coincident with the first great outburst of the volcano as seen from the Steamer "Dora." If the opening of fissures in the valley and the outburst of the sand-flow preceded the eruption of Mount Katmai, the accompanying shocks were not of a character to give a satisfactory record at far-distant stations. None are recorded in Klotz's compilation, and the records of the Harvard station are a blank between June 3, 3 hours. (unknown source), and June 6, 18 hours.[1]

The most convincing evidence that the fissures opened prior to the eruption of Katmai is that the layers of ash from Katmai that cover the adjacent region cover the sand-flow in the valley also. There is no difference of opinion on this matter among those who have studied the relations. This can only mean that the sand-flow preceded the main eruption, and that the fracturing associated with the extrusion of the sand-flow did not give rise to the well-defined seismic disturbances at distant observatories which later movements registered.

[1] Griggs mentions (*Valley of Ten Thousand Smokes*, p. 23) information received from the seismographic station at Victoria, B.C., to the effect that the Milne seismograph there recorded a large number of quakes on June 6 and 7, most of which appeared to have their origin in the Katmai district. This station is only 1,450 miles from Mount Katmai, and shocks might have been distinguishable there which were not recorded at more distant points. It would be interesting to know when these quakes began, but I have not yet been able to obtain information on this point.

Martin recorded that on June 5, late at night, observers at Cold Bay noted that the northern sky looked black and stormy, though the weather on the coast was fair. This may probably be referred to the outbreak in the Valley of Ten Thousand Smokes. The first outbreak of any importance from Mount Katmai seems to have been at 1:00 P.M. on the sixth.

During the summer of 1923 I obtained an interesting account from Mr. Bob Scott, a prospector who happened to have been at the native village of Savonoski, at the head of Naknek Lake, when the activity began. According to him, no one there had noticed earthquakes or heard noises or recognized any premonitory symptoms before the eruption began. The day before had been clear, and the people that night had gone to bed expecting nothing unusual. Early in the morning (hour unknown, but light had appeared) the outbreak came suddenly, with great noises and earthquakes, which were almost continuous. He said there seemed to be something different about these quakes from those in which an earthquake wave passes over an area, but could not define the difference. Almost at once the air became filled with dust, so that it became perfectly dark. No light from the eruption was visible, and in any case could not have been seen because of the dust. The natives were in panic, and started down the lake in boats immediately, leaving many of their possessions behind. They kept close to the shore so as not to become lost.

This brief account does not add much detail to our knowledge of the eruption, but it supports the view that the fissures of the valley opened in the early morning of June 6.

The lack of seismographic record at distant stations of the fracturing of the valley floor is probably what should have been expected. C. G. Knott, in his treatise on earthquakes, says:

> The destructive character of an earthquake as experienced at the epicenter depends directly on its intrinsic intensity and inversely on its depth. A deep-seated but powerful disturbance might have less destructive effect at the epicenter than a shallow but much less powerful disturbance. The former would be recorded on delicate seismographs all over the earth's surface, while the latter might affect delicate instruments only within a comparatively limited area.[1]

[1] C. G. Knott, *The Physics of Earthquake Phenomena* (Oxford, 1908), p. 98.

The lack of record confirms the view that it was essentially a superficial phenomenon.

If Mr. Scott's recollections are accurate, the fracturing came suddenly, and was not preceded by recognizable earth movements at Savonoski, only 10–15 miles from the valley and 21 miles from Mount Katmai. It appears from this that the earthquakes felt at Uyak, Kanatak, and Nushagak, 56–131 miles distant from Mount Katmai in various directions, on June 4–5, were not directly related to movements either in the valley or at the volcano. Minor tectonic disturbances seem a likely explanation. The connection of the explosions noted at Seldovia and Nushagak on the morning of June 6, with outbursts in the valley, seems more probable. Regarding the earthquakes occurring on the same day, some doubt is felt, but, on the whole, it does not seem that they are to be referred to outbreaks in the valley or at the volcano. This is the inference drawn from evidence presented on previous pages, relating to the occurrence of loosely hanging rocks in cliffs in this neighborhood, which seems to show that neither the outbursts at Mount Katmai nor the upheaval of the valley floor were of the character to give rise to distinct earthquakes at distant points. Undoubtedly, the explosions accompanying the eruption of Katmai were of very great violence, and the uplift of the valley floor produced violent shocks in the areas actually fractured, as is shown by the total disruption of the slice of Falling Mountain that was involved; but the violence was not exerted in such a manner or at such depth as to affect severely even the immediately contiguous territory. No displacements of such great masses of rock as are involved in tectonic earthquakes were caused by them. The tectonic earthquakes that actually occurred during the eruption, and to which the shocks felt at distant points are seemingly to be referred, should be ascribed to the operation of other processes.

COLLAPSE OF THE FLOOR APPARENTLY GRADUAL

A feature of the faulting not yet referred to is of significance. The great faults on Broken Mountain have throws of as much as 60 or 80 feet in some cases. An idea of their magnitude may be obtained by reference to Figures 11, 17, and 18. The southern portion of the mountain (the side toward Novarupta) has been broken to pieces by faults running in various directions, only a few of which are shown in the photographs. At the surface the fault scarps intersect beds of gravelly pumice of only slight coherence, but, in spite of this, relatively little of the material of the walls has been dislodged to form talus slopes. (See Figs. 17 and 18; also the photograph on p. 244 of Griggs's *Valley of Ten Thousand Smokes* and that on p. 46 of Fenner's *Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes.*) From our knowledge of the

FIG. 17.—Wall of a fault of large throw in strata of pumiceous *ejecta* on top of Broken Mountain. Height of wall is about 60 feet. (Photo. by C. N. F., 1923.)

great dislodgments that violent earthquake shocks cause, as contrasted with the comparatively little disaggregation of strata seen here, we are led to ascribe only moderate intensity to the shocks accompanying these movements. It has been pointed out that these scarps do not record the initial fracturing but only the movements after the pumice beds were deposited. The initial fracturing may have been rather violent, but the final readjustment seems to have been gradual.

On nearly all sides of Novarupta there are indications of a settling of the surface toward that vent. On the northern or Broken Mountain side, the total throw of the faults is probably 200 feet or more. On the east, there is a zone of complex faulting running for a considerable distance from the southeastern side of Broken Mountain in the direction of the western peak of Mount Trident, and the total movement here also has been large, though probably considerably less than on Broken Mountain. To the south of Novarupta, faults are visible on the lower slopes of Mount Trident, swinging around toward Falling Mountain. The throw of these appears to be less again than in the zone just mentioned. On the western side of Novarupta, there are steaming fissures, but it is only very close to

FIG. 18.—Pumiceous strata, chiefly from Novarupta, along a fault scarp on Broken Mountain. Height of wall is about 40 feet. Steam haze on right side. Note in Figs. 17 and 18 the comparatively small amount of talus thrown down by the fault movements. (Photo. by C. N. F., 1923.)

the dome that indications of fault movements may be seen, and the throw does not appear to be great. All this applies to faults in the pumiceous deposits, and therefore refers to movements which occurred near or after the close of eruptive activity. A great quantity of material was ejected from Novarupta, and here, as in the wider spaces of the valley, the settling around the vent seems referable to a collapse of the roof over the body of magma.

At the summit of Novarupta dome a wide and deep trough in the jagged lava may be due to the same cause. All these displacements probably occurred very soon after the eruption. There is evidence that at present and at least for a number of years a condition of repose has prevailed. In 1919 a highly unstable-looking cliff of lava was observed on the southern side. In 1923 it was still standing and its appearance was the same as before. Many other rock masses in the dome appear ready to crash down with the slightest shock. The blocks of talus are so easily set in motion that only in a few places does it seem safe to ascend to the summit, and in these places much caution must be used.

UNLIKELIHOOD THAT DISTURBANCES IN THE VALLEY WERE DUE TO OTHER CAUSES THAN THE INTRUSION OF A SILL

In the discussion of the eruptions in the valley and the fracturing and faulting associated with them, little consideration has so far been given in this article to the possibility of their having been caused in some other manner than by the intrusion of a sill or batholith. To one on the ground any explanation which does not assign an important rôle to a body of intruded magma at moderate depth appears very unlikely. The batholithic hypothesis has been discussed; a few words should be said with regard to other possibilities.

Any such alternative explanation encounters the great difficulty of accounting in a satisfactory manner for the very close relation of the fractures to the valley area: their abundant distribution within this area and their abrupt cessation at the sides. Perhaps the least unlikely expression of such an alternative explanation would be the supposition that the valley is an old fault block, which experienced renewed dislocation at this time, with uprise of lava from a deep-lying reservoir. No evidence that the valley originated in this way has been seen, and the hypothesis does not seem to account satisfactorily for the uniform settling that it experienced in 1912. Much more irregularity of dislocation might be expected from such causes. The greatest obstacle to accepting this explanation, however, is that a tectonic movement, reaching to great depths and involving great masses of material, is implied, and the seismographic evidence fails to support this.

It may be contended that our knowledge of volcanic phenomena and their causes is not yet sufficiently exact but that there is a possibility of processes of which we have little inkling. There is some basis for such a contention, but the idea should not be carried too far. For instance, it is difficult to picture in a wholly satisfactory manner the processes by which either a far-extending sill or dike is intruded, but there can be no question that such intrusions occur. Likewise, there is still much difference of opinion on fundamental points regarding the emplacement of batholiths, but there is no hesitation in accepting the reality of their intrusion. With reference to the valley, the sill hypothesis is not demonstrable, and a dogmatic attitude that would reject other possibilities would be unwise, but it seems to explain the phenomena more satisfactorily than any other hypothesis that has been suggested.

SUMMARY

At the time of the eruption of Mount Katmai, numerous earthquakes occurred in the surrounding region, some of which were felt as distinct shocks at points 100 miles or more from the volcano. In Part I of this article an inquiry is made as to the nature of the movements, especially as to whether they should be classed as volcanic earthquakes, due directly to the volcanic disturbances, or whether they had a deep-seated origin and should therefore be considered tectonic earthquakes.

The characteristics of the two classes are well known and are distinctive. Volcanic earthquakes are characterized especially by rapid diminution of intensity with distance from the focus; therefore a shock recognized as of considerable severity at a distance of 50 or 100 miles should have been of extreme violence in the region immediately adjacent to the epicenter, and should have produced effects recognizable several years later. During the two visits made to the region the terrain was studied for evidence relating to this matter, and the phenomena found seemed to be inconsistent with very violent movements. In many places cliffs were observed, with masses of loosely hanging rocks or insecurely supported columns, which should have been easily thrown down by movements of the severity apparently called for if the shocks felt at a distance were of volcanic origin with Katmai as the center of disturbance. On the other hand, the occurrence of a number of rock slides showed, as might have been expected, that movements of some severity, at least, were not lacking. On the whole, the evidence indicated that

disturbances occurred in the Katmai region, but they were not of extreme violence, and in order to account for all the phenomena tectonic quakes seemed to be demanded in addition to the volcanic quakes that doubtless occurred.

To confirm this tentative inference, a study of the records of seismographic stations has been made. These show, beyond doubt, that tectonic earthquakes were registered at stations over the whole Northern Hemisphere at the time of the eruption, with calculated epicenters falling as close to the Katmai region as calculations of epicentral positions usually give. The conclusion is well supported, therefore, that the eruption was accompanied by tectonic movements. It is only rarely that eruptions, either large or small, have this association, but instances are known.

In Part II, the fissures and faults produced by the outburst of the sand-flow in the Valley of Ten Thousand Smokes are described and discussed. Their most striking feature is their abundance over the valley floor and, generally speaking, their restriction to this depression. The inference is that the forces producing the fracturing were situated close enough to the surface so that surface features exercised control. Since the fissures formed vents for the extrusion of the body of pyroclastic tuff that formed the sand-flow, and later became fumarolic orifices, the presence of a body of magma at a rather shallow depth is inferred, and to this intrusion the forces of fracturing are ascribed. The question of the form and volume of the intruded body are considered, and evidence on the matter is supplied by the character of the faulting and by other phenomena.

Only two possibilities seem to require detailed consideration. One is that a sill-like body of not great thickness was intruded between the horizontal strata beneath the valley, and the other is that the valley is underlain by a batholith extending downward to a great depth.

Opposed to the hypothesis of a batholith are several considerations. The valley floor has been thoroughly fractured, and the areas of fracturing completely surround several eminences rising to considerable heights above the floor. If the whole area was underlain by a batholith close to the surface, the various blocks were left virtually unsupported except by flotation, and great readjustment of level should have taken place to conform to this condition. It is obvious from the topographic aspect that nothing of this sort has occurred.

With a sill, on the other hand, the intrusion is inferred to have advanced under the low areas, causing upheaval of the roof, but with its progress checked when the areas underlying heavily loaded mountain blocks were encountered. With the escape of a portion of the magma through the fissures a partial subsidence followed. The deposit of extruded tuff itself conceals part of the evidence regarding the nature of the movements, but as much of the record as is visible is in accordance with expectation. The high sand-mark forms an especially important clue. This feature shows that at the time of extrusion the level of the tuff surface in the valley area was about 200 feet higher than at present. After the extrusion the floor collapsed, with an opening up of fissures following the margin of the high sand-mark, and with a down-tilting of blocks between the marginal fissures and the flat portion of the floor.

A very perceptible diminution in the temperature and volume of fumarolic vapors has taken place between the two visits of 1919 and 1923, and this adds further confirmation to the idea that the source of the emanations is a comparatively small body of igneous rock, rather than one of batholithic magnitude.

The possibility that the fracturing in the Valley of Ten Thousand Smokes might have been the cause of the tectonic earthquakes has been investigated. This supposition is shown to be untenable because the period at which the fractures must have been formed was not the period during which earthquakes were recorded at distant stations.[1]

WASHINGTON, D. C.
May, 1924

[1] Attention should be called to an article by E. Tams (Erdbeben und Ausbruch des Katmai im Jahre 1912; *Zeitschr. für Vulkanologie*, Bd. VII, Heft 3,, pp. 137–49, October, 1924) which has appeared since the present paper was written and in the hands of the editor. The main subject of Mr. Tams's article is the coincidence of tectonic earthquakes with the Katmai eruption, and on this his conclusions are altogether in accord with mine. He, however, correlates these tectonic earthquakes, in part at least, with the fracturing in the Valley of Ten Thousand Smokes. This is hardly surprising, as he, of course, had not visited the region and appears not to have seen articles relating to it which have been published within the last few years. The reasons for favoring another interpretation are set forth in the present paper.