EARTH MOVEMENTS ACCOMPANYING THE KATMAI ERUPTION

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INTRODUCTION

At the time of the eruption of Mount Katmai in June, 1912, earth movements occurred, some of which appear to have been of a character not often observed in connection with volcanic eruptions. Though all were probably related in some manner to the eruption, the manifestations were of several different forms.

The field studies of the Katmai region made by the present writer were conducted during the summers of 1919 and 1923. In 1919 the work was carried on in co-operation with an expedition of the National Geographic Society of Washington, to which three members of the staff of the Geophysical Laboratory were attached. In 1923 a continuation of the studies was rendered possible through the courtesy of the United States Geological Survey. Arrangements were made by which the writer was enabled to accompany one of the parties working in this part of the Alaska Peninsula, and by means of the assistance thus kindly provided, access to this difficult region was very greatly facilitated. In this second visit much additional information on various matters connected with the eruption was obtained. In certain minor matters previous views were modified by the later studies, but not in a manner to affect important conclusions; rather were these strengthened.

In considering the phenomena that form the subject of this paper the presentation and discussion naturally fall into two parts. In Part I we shall take up the earthquakes known from observation to have accompanied the eruption, and inquire into their general nature. In Part II we shall make a study of the localized fissuring found in the Valley of Ten Thousand Smokes and attempt to ascertain its cause. An inquiry will also be made as to whether the formation of these fissures was responsible for the earthquakes described in Part I.

PART I. REGIONAL EARTHQUAKES

CONTEMPORARY OBSERVATIONS IN ADJACENT REGIONS

It is desirable to give at the outset a brief record of observations made at the time of the eruption, in so far as they have a bearing upon the matters to be discussed. Most of the available information of this kind was collected by G. C. Martin[1] and R. F. Griggs,[2] but other sources of information, which will be mentioned, have been utilized.

Soon after reports of the eruption were received and its magnitude was recognized, Martin was sent to the region by the National Geographic Society. His facilities did not enable him to approach nearer to the volcano than the shores of Katmai Bay, but he was able to get in touch with people who had observed the eruption and its effects, and has recorded the events described by them. This information, collected at a time when events were still fresh in mind, is of great value. Griggs has supplemented this with other data which he was able to collect during later expeditions.

According to the information gathered by these writers, Mount Katmai and the neighboring volcanoes had been quiescent for a long period of years, though disturbances which may, perhaps, be interpreted as a hint of developing activities, are recorded in Spurr's

[1] G. C. Martin, "The Recent Eruption of Katmai Volcano in Alaska," *Nat. Geog. Mag.*, Vol. XXIV (1913), pp. 131–81.

[2] R. F. Griggs has published numerous papers relating to the Katmai region, in the *National Geographic Magazine* and the *Ohio Journal of Science.* These have been collected and published in amplified form in *The Valley of Ten Thousand Smokes.* Washington, D.C.: National Geographic Society, 1922.

account of his trip through the region in 1898.[1] Spurr's party traveled up the valley later known as the Valley of Ten Thousand Smokes, and crossed Katmai Pass. He says:

> Extensive hot springs emerge from the Katmai side of the mountains below the pass, and there are very frequent earthquakes and other evidences of volcanic activity. Our party itself experienced a slight earthquake just after crossing [the pass].

He has recorded also: "One of these volcanoes is said by the natives to smoke occasionally."[2]

Martin's account continues: "Earthquakes were felt at Katmai [village] for at least five days prior to the eruption, while more severe shocks were felt on June 4 and 5 at Kanatak, Uyak, and Nushagak." These places are distant 59, 56, and 131 miles from Mount Katmai to the southwest, southeast, and west-northwest, respectively.[3] Reports show clearly that shortly before and during the eruption earthquakes of considerable violence were felt at widely separated points. These have naturally been attributed to the activities of the volcano itself, but evidence to be presented indicates that not all were of this origin.

According to Martin, the volcano probably began to throw out large volumes of gas on the fifth of June, as observers at Cold Bay (about 40 miles to the west of south) noted that the northern sky looked black and stormy late that night,[4] though the weather on the coast was fair. From our later information it seems probable that this cloud was not from Katmai crater, but was due to the outburst of the great sand-flow in the Valley of Ten Thousand Smokes. We know now that the sand-flow, at least in great part, antedated the eruption of Katmai,[5] and the ash cloud that accompanied it should have been visible at a great distance.

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska in 1898," *U.S. Geol. Surv., 20th Ann. Rept.*, Part VII (1900), p. 92.

[2] J. E. Spurr, *op. cit.*, p. 232.

[3] Most of the distances given in this paper have been calculated by the appropriate formula from the latitude and longitude of the places. In a few cases, where the reference is to a somewhat indefinite point in an area, the distances have been scaled.

[4] At this time of the year there is almost no darkness throughout the twenty-four hours.

[5] R. F. Griggs, *op. cit.*, p. 255; C. N. Fenner, *The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes*, pp. 25–31. Washington, D.C.: National Geographic Society, 1923.

On the morning of June 6 there seem to have been frequent minor explosions and earthquakes, though it was only at Seldovia (144 miles to the northeast) and Nushagak (131 miles to the west-northwest) that these were noted. Early in the afternoon of June 6 the volcano passed into a state of violent eruption. The beginning of the violent phase was apparently at 1:00 P.M., June 6, at which time a terrific explosion and earthquake were noted at Cold Bay, and at the same time a heavy cloud rising over Mount Katmai was seen from the steamer "Dora," 55 miles to the east across Shelikof Strait. At 3:00 P.M. there was a second tremendous explosion,

> heard for hundreds of miles around, and the volcano passed into a state of continuous eruption, which lasted, except for possible short intervals, for several days. This explosion was noted at Uyak, at Iliamna Bay, at several places on Iliamna and Clark lakes, at Koggiung, and at a point 90 miles southwest of Eagle.

At about the same time (exact hour not noted) explosions were heard at Juneau, 745 miles to the east, and at Fairbanks, 513 miles to the north-northeast.

After the outbreak at 3:00 P.M., according to Martin, the activity became somewhat less. The next violent explosion was probably about 11:00 P.M. At about that time a severe earthquake was noted at Cold Bay and a strong glare of light at Kanatak, a few miles farther to the southwest. At Kodiak (102 miles to the east-southeast) a number of severe earthquakes were reported during the night of the sixth. On June 7, Father Patellin at Kanatak (59 miles south of west from Katmai) noted earthquakes nearly all day, with short intervals between. Many of them were strong, and there was continuous rumbling. That evening after ten o'clock came the strongest earthquake, accompanied by heavy rumbling and rock-slides from all around. There seems to have been a strong glare of light from the volcano, for it was recorded that "the mountains were like sunshine." After midnight he heard "a big noise like thunder from the Katmai side," after which everything was quiet. At Iliamna Bay (104 miles to the north-northeast) earthquakes lasted throughout the night of the seventh, and it was said that the earth never ceased to move for nearly twelve hours. At 2:00 A.M. on the eighth, cannonading at irregular intervals was heard at Cordova, 362 miles east-northeast. This may have been due either to explosions or to earthquakes. Earthquakes were reported from 90 miles southwest of Eagle (probably 500 miles or more to the northeast of the volcano) at 11:00 P.M., June 6 or 7. During a period of several hours at about midnight of the seventh, both volcanic and seismic disturbances seem to have reached a climax of violence.

On June 8 there seems to have been an abatement, though considerable activity persisted. At Cold Bay (40 miles to the southwest) records of earthquakes and explosions were kept from June 6 to August 15. On fifty of the seventy days from June 8 to August 15 earthquakes were recorded. The most severe were on June 11 and 21 and on July 30. On August 17 an earthquake at Naknek (about 76 miles to the west-northwest) was said to have been so strong as to upset lamps on a table.

On June 8 the Parker-Browne mountaineering expedition, engaged in the ascent of Mount McKinley, 350 miles or more to the northeast, heard deep, booming noises, which lasted all day and which they attributed at the time to movements of the glacier on which they were camped. Later they believed them to have been reports from the Katmai explosions. Since, however, information from near Mount Katmai indicates that the greatest violence of the eruption had passed by that time, mild earthquakes may have been the source, though this is not certain. On July 6 the same party, then at the northern base of Mount McKinley, experienced an undoubted earthquake of great violence. The earth heaved and rolled, and the country far and near was scarred with landslides.[1]

A short report of observations made at Seldovia during the eruption of Mount Katmai was submitted to the Coast and Geodetic Survey by I. M. Dailey, assistant, and a copy of the manuscript has been kindly furnished me by Colonel E. Lester Jones, director of the Survey. The features of the account that are pertinent here are as follows:

During the morning of June 6 low, deep reports as of distant blasting were heard, and some people even then believed them to be volcanic. As the day passed the reports came oftener and louder, and continued all day. The next morning there was a light fall of

[1] Belmore Browne, *The Conquest of Mount McKinley*, pp. 323 and 356. New York, 1913. For an account of the effects visible at Mount McKinley a year later, see Hudson Stuck, *The Ascent of Denali*, pp. 40 and 41. New York, 1914.

volcanic ashes. No mention of explosions on June 7 or June 8 is made, but on June 9 the explosions are spoken of as continuing at irregular intervals. There were ashfalls also. Explosions at intervals all of June 10 are noted, but none were heard on June 11. There was no ordinary thunder and no lightning at Seldovia.

CHARACTERISTICS OF VOLCANIC AND TECTONIC EARTHQUAKES

The accounts that have been presented summarize the chief features of the eruption as noted at the time, in so far as they are concerned with earth shocks and related phenomena. It is evident that during the eruption and for some time afterward shocks of various degrees of intensity affected near and distant points. Some of the tremors and even stronger shocks felt at localities not far distant from the volcano might belong in the class of volcanic earthquakes. Others, however, were felt at such distances that something more seems to be demanded. Our first inquiry, therefore, will be directed toward determining whether at the time of the eruption true tectonic movements affected the region.

If such was the case the association is unusual. Milne[1] says that

> although in many countries there may be displays of volcanic and seismic activity taking place almost side by side, it is only rarely that there is direct relationship between the two. . . . . This is true even for the largest and most violent eruptions, when mountains have with practically a single effort blown off their heads and shoulders. Thus the earthquake which accompanied the eruption of Bandaisan, in central Japan, in 1888, was felt only over a radius of 25 miles.

Davison[2] divides earthquakes into two main classes: tectonic and volcanic; and the latter again into two kinds, (1) those which are purely volcanic in their origin, and (2) those which are of tectonic origin in so far as they are due to the growth of faults, but of volcanic origin in that the slips are precipitated by present or past volcanic operations. The latter are, as a rule, not coincident with volcanic eruptions, but precede or follow them and only rarely accompany them, but a remarkable exception is noted in the earthquakes accompanying the outbreaks of Sakura-jima, Kirishima-yama, and Iwo-jima in Japan in 1914.

[1] J. Milne, "Earthquakes," *Encyc. Brit.*, Vol. VIII (11th ed.), p. 821.

[2] Charles Davison, *A Manual of Seismology* (1921), pp. 215 ff.

When three volcanoes situated as these are and all of infrequent activity, burst into eruption so nearly together, and when two of the eruptions are accompanied by strong and deeply-seated earthquakes, it is difficult not to regard both phenomena as different manifestations of a common cause, namely, the gradually growing stresses along the whole volcanic chain. But there is no reason for supposing that the earthquakes result from the volcanic operations. They should therefore be considered as tectonic, and not as volcanic, earthquakes.[1]

Moreover, purely volcanic earthquakes possess characteristics which differentiate them sharply from tectonic earthquakes.

No feature of volcanic earthquakes is so marked and none so significant as the smallness of the disturbed area, considering the great intensity of the shock at the epicenter. We may have an earthquake, like that of Nicolosi in 1901, destroying houses within a minute meizoseismal area, and yet imperceptible at a distance of more than 4 miles, or one like that of Fondo Macchia in 1865, causing utter ruin over an area of 5 square miles and yet not felt outside an area of more than 113 square miles, or, again, one like that of Ischia in 1883, leveling every building within an area of 3 square miles, and only just perceptible at a distance of 20 miles from the epicenter.[2]

From these quotations two facts stand out clearly. The first is that only rarely do tectonic earthquakes accompany volcanic eruptions, though instances are known; and the second is that a volcanic earthquake diminishes very rapidly in violence from the epicenter outward. From this latter circumstance we are led to expect that if the very perceptible shocks felt at considerable distances during the Katmai eruption were of volcanic origin, the destructive effects in the immediate vicinity of the volcano should have been of great intensity. During my two visits to the Katmai region, in 1919 and 1923, the terrain was examined with this idea in mind.

FIELD OBSERVATIONS NEAR MOUNT KATMAI INDICATE LACK OF VIOLENT EARTHQUAKES

At our first landing place on the beach in 1919, just south of Katmai Bay and about 17 miles south of Mount Katmai, cliffs of sedimentary strata, perhaps 100 feet in height, showed many blocks of rock hanging loosely and evidently undisturbed for years. Later, while we were encamped on the shore of Naknek Lake, a mountain

[1] See also an article on "Volcanic Earthquakes," by the same writer, in *Jour. Geol.*, Vol. XXIX (1921), p. 97.

[2] Charles Davison, *op. cit.*, p. 225.

just to the south was ascended (height a little over 4,800 feet above the sea and practically the same above the lake). At the top the western and northwestern faces were found to present an extremely precipitous scarp for several hundred feet, evidently the upper portion of an old glacial cirque. The summit rock consisted of dense hornblende andesite-porphyry, and was in a greatly shattered condition as a result of the opening up of intersecting joints through frost action. There were quantities of rock in precarious positions, both in place and on the steep talus slopes of the cirque cliffs, which would seemingly be dislodged by even gentle earthquake shocks. This mountain is about 21 miles northwest of Mount Katmai.

About 13 miles northwest of the volcano a mass of columnar basalt (probably an ancient volcanic neck) showed among its cliffs many loose columns apparently just ready to give way and fall. These last two occurrences are even nearer to the Valley of Ten Thousand Smokes than they are to Mount Katmai, and indicate even more strongly that the outbursts in the valley, later to be discussed, did not give rise to violent earthquakes a few miles away.

In 1923 similar occurrences of masses of rock hanging loosely on cliffs were noted on the southern flanks of Mount Katmai itself. They are so near the focus of eruption as to appear of special significance. Such occurrences were seen in the deep, narrow canyon from which issued the flow of pumice and ash that Griggs has called the Katmai mud-flow. This locality is about 2½ miles from the edge of the crater.[1] In places the walls of the canyon are nearly vertical, and probably 500 feet high. The general rock is a dense andesite, often of very platy structure. The precipitous walls of this narrow gorge appear loose in many places, and in a condition such that large masses of rock should be easily dislodged (Fig. 2).

A little to the east and east-northeast of here the canyon of Katmai River is bounded by high cliffs. On the southeast side are the sediments of the Barrier Range, and on the northwest are the dark crimson and gray lava flows of Mount Katmai. At the place shown in Figure 3, the tops of cliffs in the foreground on the left, at the brink of the chasm, are composed of quantities of shattered, platy andesite, large amounts of which look ready to fall. That there has been no

[1] For position consult the accompanying map (Fig. 1).

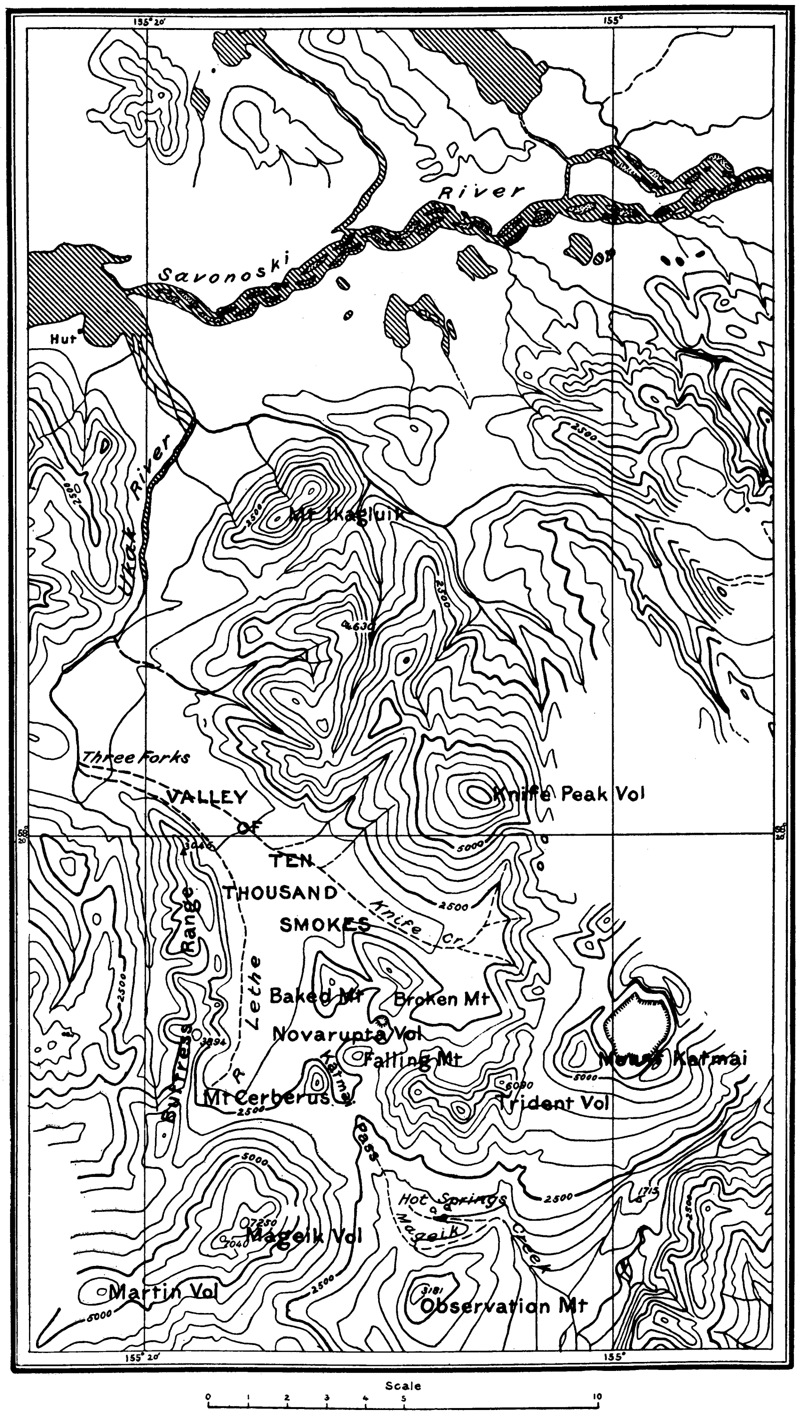

FIG. 1.—Map of the Valley of Ten Thousand Smokes and vicinity, from drawings of the Kachemak-Katmai map of the U.S. Geological Survey, based on surveys of the U.S. Geological Survey and the National Geographic Society. Contour interval 500 feet.

recent rock-fall of importance here is shown by the fact that just below these cliffs more gradual slopes carry dead bushes (killed by the eruption) and fresh grass. In general, the material in the cliffs at

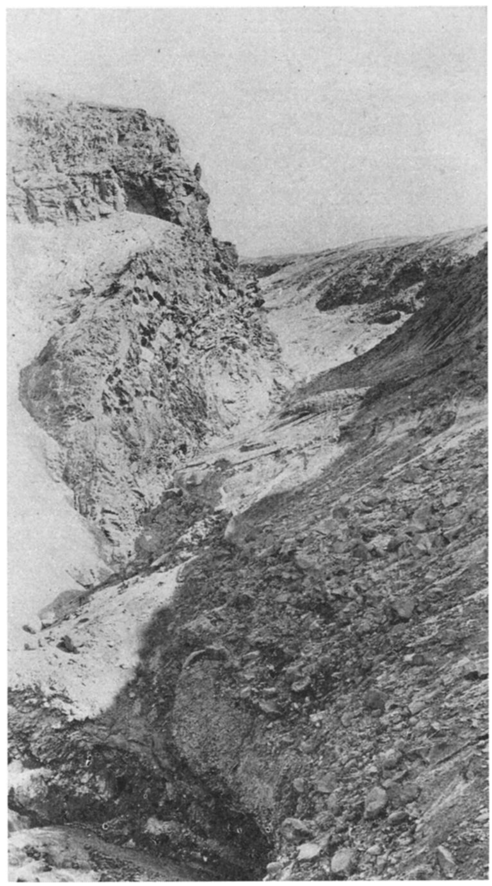

FIG. 2.—Steep-walled gorge on southern flank of Mount Katmai. Abundance of loose rock in walls and on slopes indicates lack of recent severe earthquakes. (Photo by C. N. F., 1923.)

the brink of the narrow gorge is shattered rock in precarious position.

Numerous other occurrences were noted and might be cited. There may be a query whether the relations might not be explained by supposing that severe earthquakes had shaken down the outer faces of cliffs, leaving the inner portions in the shattered condition in which we see them. The evidence is opposed to this. In the last case cited, for instance, the evidence is very positive that no important rock-fall has occurred, and in other cases it is almost equally strong. In general, the appearance of the loosely hanging cliff faces is that normally produced by the slow operation of atmospheric agencies in opening up joint cracks. The presence of perched blocks and loosely supported columns gives further confirmation. The general conclusion drawn was that no shocks of major violence disturbed the region during the eruption. In many places the relations are of such a character that it is difficult to understand how they could have survived even moderate shocks, but that such occurred is shown by other phenomena.

At a number of places in the region recent bowlder flows or landslides, of considerable magnitude, have been discovered. The exact date of occurrence of these cannot be definitely fixed, but it is fairly certain that most of them, if not all, were closely associated with the eruption.

These landslides, when set in motion, seem to have acted in a similar manner to others which have been described in the literature, such as that of Bandai-san,[1] in Japan; that of Frank,[2] in Alberta; and that of Elm,[3] in Switzerland. The essential conditions leading to movement seem to be the presence of a mass of fragmental material, resting in such a position that it may easily be set in motion. When such a mass is dislodged from a height and precipitates itself down a steep gradient, it behaves astonishingly like a liquid, even when it flows out on a gentle slope, though it may be made up largely of bowlders. Its consistency appears to resemble that of a concrete batter.

One of these Katmai landslides, called by Griggs the "Mageik landslide," has been described in detail by him.[4] His investigations

[1] S. Sekiya and Y. Kikuchi, "The Eruption of Bandai-san," *Jour. Col. Sci., Imp. Univ. Japan*, Vol. III, Part II (1889), pp. 91–172.

[2] R. G. McConnell and R. W. Brock, *Report on the Great Landslide at Frank, Alberta, 1903; Ann. Rept. Dept. Int., Can.* (1903), p. 10.

[3] E. Buss and A. Heim, "Der Bergsturz von Elm," *Zs. Deutsch. Geol. Gesell.* (1882), pp. 74 and 435.

[4] R. F. Griggs, *op. cit.*, pp. 135–45. In 1919 I was able to visit the lower part of this slide, and to observe some of the remarkable features that Griggs describes, but I did not see the place where it originated.

showed that at the time he studied it parts of the slide were covered with Katmai ash, and other parts were free of it—a rather puzzling circumstance in attempting to fix its date; but his view

FIG. 3.—Cliffs on brink of canyon of Katmai River. In the foreground, quantities of loose rock in place and on slopes show lack of severe shocks during the eruption, while just beyond is shown the place from which a great landslide started. (Photo by C. N. F., 1923.)

is that the movement probably took place about the time of the eruption.

The material started at a cliff of disrupted lava and sandstone at the head of a valley, but the evidence regarding the nature of the forces that set the mass in motion is not easy to interpret. Griggs says:

> Closely adjacent to the part of the cliff that fell away, colossal columns several hundred feet high are still hanging, apparently so ready to topple over that one wonders how they survived the shock that set off their neighbors.

This landslide occurred about 12 miles southwest of Katmai crater.

A similar flow, but of smaller mass, is to be seen at the place where the canyon of Mageik Creek discharges into the valley of Katmai River, 5 or 6 miles south of Katmai crater. Here great bowlders,

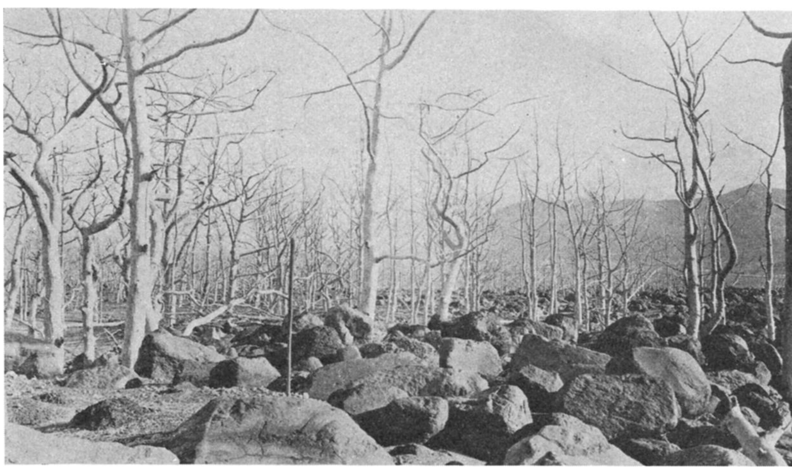

FIG. 4.—Bowlder flow from the canyon of Mageik Creek, spreading out over the floor of Katmai Valley. The mass was presumably set in motion by earth movements during the eruption. (Photo by C. N. F., 1923.)

many of them 6 feet in diameter, mixed with gravel and sand, were spread along the lower part of the canyon, and were carried out into the open valley beyond, covering a wide area of very gentle slope (Fig. 4). The source of the material has not been searched for. As most of the bowlders and gravel are well rounded, and as they consist of a variety of rocks, they had probably formed a secondary deposit before the flow occurred. The time of movement was after the pumice ejections from Katmai.

Other flows or slides described by Griggs are the Katmai slide, which dammed Katmai Canyon, and caused, when it broke, the flood that occurred just before Griggs's first visit to the region in 1916; and the Noisy Mountain slide, which issued from a side valley, farther up Katmai River. These last two apparently antedated the eruption. The Katmai slide is of interest in that it originated from the breaking away of a large section of cliff close to the shattered face shown in Figure 3. Evidently the shocks that caused these large masses of rock to let go were not sufficient to shake down the all-but-detached portions of the neighboring cliffs.

These phenomena appear somewhat contradictory in their implications, and it is not easy to form an estimate as to the severity of the shocks denoted by them. In the commonly used Rossi-Forel scale of earthquake intensity, as revised and simplified by the Investigation Commission of the California earthquake,[1] the more severe effects are graded as follows, in increasing intensity:

VII. Violent shock, overturning of loose objects; falling of plaster; striking of church bells; some chimneys fall
VIII. Fall of chimneys; cracks in the walls of buildings
IX. Partial or total destruction of some buildings
X. Great disasters; overturning of rocks; fissures in surface of earth; mountain slides

These effects relate chiefly to edifices of human construction, and the criteria are therefore lacking in the region under consideration. As near as comparison may be made, it seems that a shock severe enough to overthrow chimneys or even to cause the fall of plaster would have been sufficient to dislodge many of the loosely hanging rocks seen near Mount Katmai. On the other hand, the formation of fissures and the occurrence of mountain slides are associated in the scale with maximum shocks; but on this point the Commission makes some very pertinent comments. Their *Report* says:

> Finally in grade X of the scale, fissures in the ground are taken as a criterion of the highest grade of intensity, when in reality such fissures have under different conditions very different values from this point of view. The fissures which extend down into the earth's crust, and are due to its actual rupture on a fault-plane, are of course significant of the highest degree of disturbance usually experienced in earthquakes; but those cracks and fissures which occur in valley bottoms, due to the slumping of soft material toward the stream trench, or those

[1] "The California Earthquake of April 18, 1906," *Report of the State Earthquake Investigation Commission*, Vol. I, p. 161. Washington: Carnegie Institution of Washington, Pub. No. 87, 1908.

cracks which are associated with landslides, in those cases where the landslide was imminent and was merely precipitated by the earth jar, are superficial phenomena and do not necessarily indicate so high a degree of intensity as that marked X on the scale.[1]

This is evidently sound reasoning, and indicates the necessity of caution in drawing inferences on severity from landslides. If, however, we eliminate the consideration of landslides, we have no other visible indication of shocks; but this elimination would be obviously unfair. The number of landslides indicates disturbances of some severity at least, but they were not so strong but that many loose rocks were left hanging, and were not at all of the magnitude that would be expected if the shocks felt at distant points were solely of volcanic origin with the crater as the center of disturbance. As we have already seen, a characteristic of volcanic earthquakes is very rapid decrease of intensity from the center outward. Davison says: "In volcanic earthquakes, strong enough to ruin the epicentral villages, the area [of sensible disturbance] ranges from 50 to about 1,000 square miles,"[2] corresponding to radii of 4 and 18 miles, respectively. This is doubtless related to the fact that "the more rapid the decline outwards in the intensity of the shock, the less is the depth of the focus."[3]

From the phenomena described we may draw the tentative inference that the earthquakes felt at distant points were not the direct result of volcanic disturbances emanating from Mount Katmai or from its immediate neighborhood. We are then led to inquire whether there is evidence that tectonic movements affected the region. The data that will be presented indicate that such was the case, and that these movements probably originated at a number of somewhat widely separated points.

EVIDENCE OF TECTONIC EARTHQUAKES

The chief source of information used is the compilation for 1912 of the well-known seismological tables which the late Dr. Otto Klotz issued for several years.[4] These are based upon the records of

[1] *Op. cit.*, p. 162.

[2] Charles Davison, *op. cit.*, p. 50. [3] *Ibid.*, p. 133.

[4] Otto Klotz, "Location of Epicentres for 1912," *Jour. Roy. Astronom. Soc. of Can.*, Vol. VII (1913), p. 229.

most of the first-class observatories of the world (though not all of this class are included), and probably represent the best available information on the matter in question for one who is not a specialist in seismology. They show the epicenters of those earthquakes of the year whose positions can be calculated, together with others whose data do not yield satisfactory determinations of epicenters.

Klotz's compilations have been supplemented to some extent by other data. Professor J. B. Woodworth, in charge of the Seismographic Station at Harvard, has, at my request for information, very kindly supplied me with a copy of their monthly *Bulletin* for June and for those parts of July and November, 1912, in which Alaskan earthquakes are recorded. Professor Bailey Willis, of Leland Stanford University, has kindly obtained from Father Jerome S. Ricard, S.J., a report showing that seismic disturbances were recorded at Santa Clara, California, on May 6, June 7, and June 9, 1912, which were believed to be of Alaskan origin. Father Francis Tondorf, S.J., Georgetown University, Washington, was so good as to look up his records, and report that in the case of all the quakes recorded at about the date of the eruption the amplitudes were very large. The calculated distances had been found to fit, approximately at least, the distance to Alaska, and there seemed to be no doubt of a connection between the eruption and the tectonic quakes recorded.

In Table I the principal data are assembled in parallel columns, showing in one case the disturbances noted by direct observation at the time of the eruption, and in the other case the effects produced at distant seismographic stations. For convenience of comparison, the Greenwich mean time in which stations record their observations has been changed to standard time of the one hundred and fiftieth meridian, west, by subtracting ten hours. The symbols ϕ and λ have their usual significance of latitude and longitude. For Katmai $\phi = 58^\circ 15'$ N., $\lambda = 155^\circ$ W.

Klotz's determination of epicenters, included in the second column of Table I, is made by the usual method of triangulation. The intersection of three or more arcs at or near a common point gives an epicenter. In some cases a point thus determined from one set of stations may differ considerably, even several degrees, from another point similarly determined from other stations. As Klotz points out,

TABLE I

COMPARISON OF LOCAL OBSERVATIONS WITH RECORDS OF DISTANT SEISMOGRAPHIC STATIONS

(Time given is that of the 150th Meridian, West)

Local Observations	Records of Distant Stations
1912	
	Jan. 4. Seismic records of Aachen, Hamburg, Manila, Ottawa, and Pulkowa give $\phi = 50°40'$; $\lambda = 179°54'$ E. Galitzin's calculations give $\phi = 49\frac{1}{2}°$; $\lambda = 175°$ E. Zeissig's calculations give $\phi = 50\frac{1}{2}°$; $\lambda = 176°$ W. The epicenter falls in or near the western Aleutian Islands
Jan. 31. Heavy earthquake shocks felt throughout southwestern Alaska (according to Klotz)	Jan. 31. Cartuja, Göttingen, Hamburg, Ottawa, Pulkowa, St. Louis, Strassburg, Zi-ka-wei, give $\phi = 60°00'$; $\lambda = 146°36'$ W.
	May 6. At Santa Clara, California, a tremor recorded, thought to be of Alaskan origin
June 1–6. Earthquakes at Katmai village (14 miles south of volcano)	
June 4–5. Severe shocks at Kanatak (59 miles SW.), Uyak (56 miles SE.), and Nushagak (131 miles WNW.)	
June 6, morning. Frequent minor explosions and earthquakes noted at Seldovia (144 miles NE.) and Nushagak (131 miles WNW.). Probably about this time the fissures in the Valley of Ten Thousand Smokes opened and the incandescent sand flow was poured out	
June 6, 13 hr. Terrific explosion and earthquake noted at Cold Bay (40 miles SW.); smoke cloud seen from steamer "Dora" (55 miles E.), rising over Mount Katmai. Probable beginning of violent phase of eruption, continuing until June 8	June 6, 12 hr. 41 min. Seismic shock recorded at Seattle Observatory, according to press report
June 6, 15 hr. Second tremendous explosion heard for hundreds of miles around	June 6, from 18 hr. 5 min. to 23 hr. 45 min. Seismic shocks at Harvard, of unknown origin

TABLE I—*Continued*

Local Observations	Records of Distant Stations
1912	
June 6, 23 hr. Severe earthquake at Cold Bay (40 miles SW.), and a strong glare of light seen from Kanatak (59 miles SW.)	June 6, 24 hr. (1) Seismic records ar Harvard, Irkutsk, Ottawa, and Pulkowa give $\phi=58°24'$; $\lambda=152°45'$ W.
June 6. During the night, a number of severe earthquakes at Kodiak (102 miles ESE.)	(2) Records of Cartuja, Pulkowa, and Zi-ka-wei give $\phi=58°10'$; $\lambda=161°15'$ W.
June 7. Earthquakes noted all day at Kanatak (59 miles SW.)	June 7, from 1 hr. 02 min. to 9 hr. 12 min. A series of merging seismic shocks at Harvard, known to be of Alaskan origin
	June 7, 2 hr. Ottawa, Pulkowa, and Zi-ka-wei give $\phi=57°40'$; $\lambda=157°40'$ W.
	June 7, 8 hr. (1) Strassburg, Tiflis, Vienna, and Zi-ka-wei give $\phi=58°42'$; $\lambda=142°40'$ W.
	(2) Cartuja, Irkutsk, and Tiflis give $\phi=56°56'$; $\lambda=159°00'$ W.
	June 7, 12 hr. Seismic shock at Georgetown Observatory (Washington, D.C.)
	June 7, 21 hr. Cartuja, Harvard, Ottawa, and Pulkowa give $\phi=57°56'$; $\lambda=154°00'$ W.
June 7, 23 hr. Strong earthquake, with heavy rumbling, rockslides, and glare of light, at Kanatak (59 miles SW.). After midnight a noise like heavy thunder from the direction of Katmai	June 7, 23 hr. 13 min. Seismic shock at Harvard
June 7, evening, to June 8, morning. Severe earthquakes at Iliamna Bay (104 miles NNE.)	
June 6 or 7, 23 hr. Earthquakes reported 500 miles to northeast of Katmai	
	June 8, 0 hr. 26 min. Seismic shock at Harvard
	June 8, 0 hr. 54 min. Seismic shock at Harvard
June 8, 2 hr. Cannonading heard at Cordova (362 miles ENE.)	
June 8. Eruption of volcano continuing, but with lessened violence	June 8, 3 hr. Irkutsk, Pulkowa, and Strassburg give $\phi=57°58'$; $\lambda=152°03'$ W.

TABLE I—*Continued*

Local Observations	Records of Distant Stations
1912	
June 8. Rumblings (possible quake) heard at Mount McKinley (350 miles NE.)	
June 8–Aug. 15. Shakings at Cold Bay nearly every day	
June 9. Reports from Kaflia Bay (26 miles E.) indicate continuance of eruption. Explosions heard throughout the day at Seldovia (144 miles NE.)	June 9, 7 hr. 42 min., 12 hr. 05 min., 12 hr. 37 min. Seismic shocks at Harvard
	June 9. Irkutsk, Ottawa, and Pulkowa give $\phi=56°48'$; $\lambda=156°33'$ W.
	June 10, 6 hr. 15 min. to 7 hr. 57 min. Seismic shocks at Harvard, known to be of Alaskan origin.
	June 10. Aachen, Harvard, Irkutsk, Ottawa, and Pulkowa give $\phi=57°02'$; $\lambda=154°30'$ W.
June 11. Earthquake at Cold Bay	June 11, 21 hr. Data indicate an epicenter at approximately $\phi=57.7°$; $\lambda=149.3°$ W.
	June 17. Galitzin's calculations give $\phi=57°$; $\lambda=149.7°$ W.; confirmed approximately by data from Pulkowa and Vienna
June 21. Earthquake at Cold Bay	
July 6. Very severe earthquake at Mount McKinley (350 miles NE.)	July 6, 22 hr. to July 8 (no time given). Many stations record severe shocks, calculation of whose epicenters gives origins near Mount McKinley
July 30. Earthquake at Cold Bay	
Aug. 17. Earthquake at Naknek (76 miles WNW.)	
	Oct. 12. Irkutsk, Pulkowa, Tiflis, and Vienna give $\phi=50°24'$; $\lambda=178°45'$ E. (Just south of western Aleutian Islands)
Nov. 6 or 7. Quake reported at Seward (234 miles NE.).	Nov. 6, 22 hr. Reports from thirteen stations give intersections of 1. $\phi=56°42'$; $\lambda=156°20'$ W. 2. $\phi=58°12'$; $\lambda=153°33'$ W. 3. $\phi=56°18'$; $\lambda=150°33'$ W.
	Dec. 5. Reports of shocks from eight stations give $\phi=57°08'$; $\lambda=154°15'$ W.

this is necessarily the case from the nature of the data; and he indicates several sources of error, such as uncertainties in the reading of the grams, false interpretation of the grams, and imperfections of velocity tables. Another important factor is that an earthquake itself does not emanate from a point, but from a surface or volume. As a result of these uncertainties, it is often not possible to feel confidence that the location of an epicenter has been determined closer than within 100 miles. Nevertheless, the computed epicenters for the quakes of the period June 6–10 fall so near the Katmai region as to make it appear certain that during the eruption a number of tectonic quakes emanated from one or more foci not far distant from the volcano, and produced world-wide tremors. It does not appear possible to decide satisfactorily how close to the mountain the foci were. The epicentral determinations from distant stations are not sufficiently exact for the purpose, and the evidence on the ground is inconclusive. As already noted, several rock avalanches are known to have occurred immediately adjacent to the mountain itself, and one about 12 miles to the southwest. Even at Kanatak, 59 miles to the southwest, rock slides were reported, and severe shocks at a number of distant points. There are vast stretches of territory where avalanches might have occurred, but which are unexplored. During the journey to the valley from Cold Bay in 1923, a number of places along the route were seen where minor landslips had taken place within a few years, but their relation to the events of 1912 is problematical. The most that can be said safely on the general problem is that quakes of tectonic character were associated closely in point of time with the eruption, and rather closely in point of space. The relation that the fissuring in the Valley of Ten Thousand Smokes bears to the question is important, but its discussion is best deferred to later pages.

The movements during the eruption had been preceded in January by a quake in or near the western Aleutian Islands and one in the Prince William Sound region. After the intensity of the eruption subsided, recorded quakes continued to emanate from the Katmai region for several days. On July 6 there was a severe earthquake near Mount McKinley, far to the northeast. On November 6 and December 5 there were movements whose computed epicenters were near Kodiak Island. During 1913 and 1914 there are records of further movements in the middle and western Aleutian Islands.

THE ERUPTION AND QUAKES OCCURRED IN A ZONE OF STRUCTURAL INSTABILITY

It cannot be said with certainty that all these movements were causally related, but the points of origin lie within a comparatively narrow zone of distinct characteristics, which would, with little hesitation, be considered of close structural relationship. During the year no important quakes outside of this zone for great distances are noted by Klotz.

Moreover, the features of the zone are those held to be characteristic of earthquake belts. Davison expresses the principle as follows:

> The most important law of seismic distribution is that earthquakes are as a rule strongest and most frequent in those portions of the earth in which the average slope of the ground is greatest;[1]

also:

> In . . . . groups of islands arranged in the festoon form, such as Sumatra and Java and the Aleutian Islands, or in mountain chains like the Himalayas and those of Alaska, ... the steep convex side is visited by more frequent and more violent earthquakes than the gently sloping concave side.[2]

In a minor point Davison, in the foregoing quotation, is in error. The slope on the concave side of the Aleutian festoon, as well as on the convex side, is very steep. There seems to be a common impression that the whole of Bering Sea is shallow; on the contrary, a great area lying to the north of the Aleutians, from Unalaska Island westward, is very deep.[3]

The Aleutian Islands, throughout most of their length, form the summits of a remarkably narrow and steep ridge, which drops to abyssal depths on each side. Its northeastward continuation forms the Alaska Peninsula, which is bounded by a shallow sea on the northwest, but on the southeast side the shelf drops abruptly to depths of 1,000–2,000 fathoms at a distance of 50–125 miles from the coast. The edge of the shelf is most distant from the peninsula in the vicinity of Kodiak Island. This is a mountainous mass com-

[1] Charles Davison, *op. cit.*, p. 168.

[2] *Ibid.*, p. 172.

[3] See Charts 8802 and 9102 of the Coast and Geodetic Survey. Suess has recognized this fact. See *The Face of the Earth* (Eng. transl.), Vol. IV, p. 349.

posed chiefly of contorted sediments, diorite, and granite,[1] which rises abruptly from the submerged shelf, and suggests a horst.[2]

The island is separated from the peninsula by the shallow waters of Shelikof Strait, whose northwestern shore is formed by moderately high but precipitous mountains, among which the volcanic peaks of Katmai and its neighbors are situated. Beyond the Katmai region the ranges of the Alaska Peninsula continue to the northward. Their termination is conventionally placed in the region lying between Cook Inlet and Lake Clark, which has been little explored but is known to be of high relief.[3] There is, however, no obvious break in continuity at this point, but under the name of the Alaska Range, high and rugged mountains continue several hundred miles in a broad arc, trending first northeastward, then eastward, and finally southeastward, and including the culminating peaks of Mount McKinley and its neighbors. In this region a parallel inner arc is formed by the mountains of Kenai Peninsula and the Chugach Mountains. To this the mountains of Kodiak Island may belong.

Throughout this province the trend lines of major tectonic structure are continuous, or where a second line of mountain axes appears, this is parallel to the first. Brooks applies the term "Pacific Mountain system" to the main mountainous area, and describes this system as

made up of a number of parallel ranges forming a rugged highland of crescentic outline sweeping around the Gulf of Alaska. Its central part is upwards of two hundred miles in width, but the system narrows to the southeast and to the

[1] Closely folded slates and graywackes make up most of the explored portion of the island. Martin describes old metamorphic schists near Uyak, on the northwestern side (*U.S. Geol. Surv. Bull. 542*, p. 128). Diorite was found by Becker at Karluk, on the northwestern side (*U.S. Geol. Surv., 18th Ann. Rept.*, Part III, p. 41), and granite was reported by him to form "the southern end of the ridge running along the westerly coast" (*op. cit.*, p. 36). Granite or diorite occurs east of Kizhuyak Bay and at the south end of Uganik Island (Martin). In 1923, during a stop by our steamer at the cannery at Alitak Bay, at the southern end of the island, the rocks of the vicinity were found to be coarse quartz-mica diorite. On another occasion the cliffs for several miles near Cape Kuliuk, as seen from the deck of a steamer not far from shore, had the appearance of granite or similar rock. Their light-gray color and massive appearance had a very different look from the dark fissile slates. In lithology and structure Kodiak Island is entirely dissimilar from the Jurassic areas of the adjacent shores of the peninsula. Its relationship seems to be rather with the mountains of Kenai Peninsula.

[2] Suess regards Shelikof Strait and Cook Inlet as having the characters of a fault trough. See *op. cit.*, p. 378.

[3] A. H. Brooks, "The Mount McKinley Region, Alaska," *U.S. Geol. Surv., Prof. Paper 70* (1911), p. 45.

southwest. It is continued to the southeast by the Coast Range of British Columbia, and to the southwest by the rugged Aleutian Islands.[1]

Throughout the zone, from the western Aleutian Islands around into British Columbia, there are abrupt descents from mountains to lowlands, or from the summits of ocean ridges to abyssal depths—conditions favorable for earthquake movements. A rather remarkable feature of the zone is the reversal in direction of curvature of the trend lines in proceeding from the Aleutian Islands to the Alaska Range. The interpretation of this in terms of theories of mountain-building is not evident.

APPARENT COINCIDENCE OF TECTONIC SHOCKS WITH MAJOR OUTBURSTS OF MOUNT KATMAI

A comparison of the data given in the two columns of Table I serves to bring out indications that tectonic earthquakes were almost coincident with some of the greatest outbursts of the volcano, though an element of uncertainty arises because of the difficulty of deciding in all cases just what phenomena observed from afar were indicative of major phases of the eruption. A minor uncertainty is due to the fact that in these out-of-the-way places the accuracy of clocks and watches is not ordinarily of great importance, and the reported time of events may be somewhat in error. The salient features of apparent correlation are as follows:

The first violent explosion on June 6, at thirteen hours, coincided closely with a shock recorded at Seattle, according to the daily press, but not given in Klotz's compilation nor in the Harvard record. The second great explosion on June 6, at fifteen hours, preceded by a few hours shocks received at Harvard, of unknown origin, from eighteen hours, five minutes, to twenty-three hours, forty-five minutes. At twenty-three hours a strong glare of light was noted at Kanatak, and a hard earthquake at Cold Bay. These almost coincided with the first world-wide tremors received at seismographic stations. On June 7, at twenty-three hours, an earthquake, rock slides, and glare of light were noted at Kanatak, followed some time after midnight by heavy noises from the direction of Katmai. These probably denoted another major outburst, and may be correlated with the

[1] A. H. Brooks, "The Physiographic Provinces of Alaska," *Jour. Wash. Acad. Sci.*, Vol. VI (1916), p. 252.

shocks reported by numerous observatories from June 7, twenty-two hours, to June 8, three hours.

This apparent synchronism between great outbursts and tectonic earthquakes is remarkable, but a similar coincidence apparently occurred during the eruption of Sakurajima, in 1914. It will be remembered that this great eruption also was accompanied by tectonic earthquakes, and at least one of these seems to have been nearly simultaneous with an increase of the volcanic activity. According to an account given by T. A. Jaggar,[1] the main volcanic outbreak began on January 12, at 10:05 A.M., after several days in which volcanic earthquakes occurred in swarms. The intensity of the eruption increased during the afternoon. At 6:29 P.M., there was a terrific earthquake, recorded on seismographs in Europe, and simultaneously a sudden lava glow was observed on the smoke from the volcano, continuing for some time. The detonations reached a maximum of intensity at midnight. Jaggar's conclusions are stated as follows:

> It seems probable that the big earthquake of Monday evening was the climax of strain in the crust of the earth's surface, and that the midnight detonations were the climax of the explosions in the lava column that had been released. The glow which occurred at the time of the quake was probably due to the spouting lava.

A connection between volcanism in general and earthquakes is brought out in an investigation made by H. H. Turner for the Seismological Committee of the British Association.[2] Records of volcanic eruptions and of earthquakes for the one hundred and ten years, 1790–1900, were studied with reference to periods of increasing and decreasing activity of the two manifestations, and a factor of correlation of 0.39 ± 0.05 was derived. He says: "The conclusion seems justifiable that earthquakes and eruptions are affected by the same cause." It appears that in a broad way the phenomena are fundamentally related, and it is perhaps not surprising that occasionally the manifestations should be simultaneous.

[1] "Sakurajima, Japan's Greatest Volcanic Eruption," *Nat. Geog. Mag.*, Vol. XLV (1924), p. 441.

[2] *Report of the British Association for the Advancement of Science* (1913), p. 65.

[*To be continued*]