A Summary of Volcanic and Seismic Activity in Katmai National Monument, Alaska *

P. L. WARD and T. MATUMOTO

Lamont Geological Observatory of Columbia University,
Palisades, New York

Abstract

A compilation of observations of volcanic eruptions since 1870 and ash stratigraphy shows that Katmai National Monument on the Alaska Peninsula has had a long history of volcanic activity. Six of the recently active vents lie in a gently curved arc, but two lie to the north of this arc and show no obvious structural relationship to it. Recent volcanic events have consisted of fumarolic activity, steaming from main vents, ash eruptions, extrusion of viscous lava flows, and pyroclastic eruptions. The observed activity shows no obvious correlation with a compilation of seismic events recorded teleseismically since 1912 and relocated by the authors using a digital computer. The eruption attributed to Mt. Katmai in 1912 has left many unanswered questions including the thickness of the ash flow tuff in the Valley of Ten Thousand Smokes. Seismic refraction results show that this tuff has a compressional velocity of about 0.6 km/sec and that considerable morainal debris may underlie it at the northern end of the Valley.

Introduction

Katmai National Monument, consisting of 10,918 km^2 of glaciated plains and mountains is situated approximately 400 km southwest of Anchorage on the Alaska Peninsula (Figure 1). It is about 300 km northwest of the Aleutian Trench in a region of transitional crustal structure from continental Alaska to the Aleutian Island Arc (BURK, 1965) and lies on the northwest edge of the area which was tectonically deformed during the 1964 Alaska Earthquake (PLAFKER, 1965). At

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least fifteen volcanoes which have presumably been active since the Eocene lie within its limits and along the edge of Shelikof Strait.

Over 70 observations since 1870 attest to a wide range of historic volcanic activity from seven peaks. The eruption in 1912, attributed to Mt. Katmai, was among the four largest in recent history and formed Katmai Crater, a lava dome in Novarupta, and the ash flow

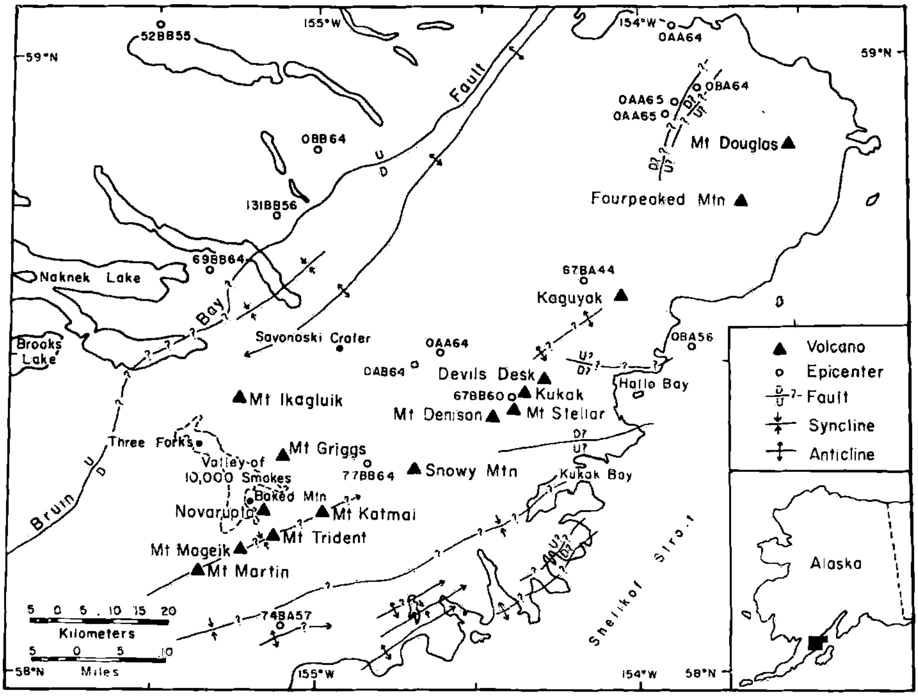

FIG. 1 - A structural map of Katmai National Monument (KELLER and REISER, 1959) showing the location of the volcanic vents and of the earthquake epicenters recorded teleseismically since 1912. Epicenters are given with depth, Q (see text), and year.

in the Valley of Ten Thousand Smokes. Since 1949, Mt. Trident has erupted explosively at least ten times and has extruded on the order of 0.4 km^3 of blocky lava flows.

This paper tabulates the volcanic and seismic observations in the Katmai Region. In addition, it summarizes the nature of the observed volcanic activity and many of the theories concerning it in an effort to bring together the scattered published and unpublished work.

Principal Previous Work

The first geologic work in the Katmai area was done by SPURR (1900) in 1898. After the 1912 eruption, Griggs led several expeditions between 1915 and 1919 exploring the whole volcanic region and particularly the Valley of Ten Thousand Smokes. This work has been described principally by GRIGGS (1920, 1922) and FENNER (1920, 1923, 1926, 1930, 1950). FENNER (1925) compiled all the seismologic records and observations for the 1912 eruption. Later SMITH (1925) and MATHER (1925) mapped areas contiguous to the Monument on the north and south, respectively. The next major work was done in the 1950's during the « Katmai Project » of the National Park Service (LUNTEY, 1954; KELLER and REISER, 1959; CURTIS, 1955). The only detailed observations of a volcanic eruption in this area were by SNYDER (1954). BURK (1965) has done detailed mapping to the southwest of the Katmai region and has summarized the structural and historical geology of the whole Alaska Peninsula. In 1963 the first seismograph was operated in the Monument (DECKER, 1963 and 1964). More detailed seismic investigations were carried out in 1965 by MATUMOTO and WARD (1966) and by E. BERG of the University of Alaska.

Structural and Geologic Relations

The structural features of the Katmai area trend generally northeast-southwest along the Aleutian range and lie on a slight homocline dipping to the southeast. In the northeast sector, Lower to Middle Jurassic intrusives and Tertiary extrusives are upthrown on the northwest side of the Bruin Bay Fault into surface contact with relatively flat-lying Upper Jurassic Naknek sandstone on the southeast side (KELLER and REISER, 1959). Farther to the southeast, the sandstone is overlain and to some extent surrounded (FENNER, 1930) by Tertiary to Quaternary volcanics.

In detail, however, the structure is far more complex. The volcanic peaks lie along a gently curved arc concave northwestward, extending from Mt. Douglas in the northeast to Mt. Martin in the southwest. Figure 1 shows the nearly linear trend of most of the active vents. Parallel with this arc are an en echelon series of gentle anticlines, synclines, and a few faults in the Late Tertiary to Quaternary volcanics (KELLER and REISER, 1959). Two faults, however, trend east-west into this arc near Hallo Bay.

In the Katmai Region the volcanic arc diverges slightly from the trend of the Bruin Bay Fault. This fault is a dominant structural feature in the northern half of the Alaska Peninsula and was principally active during the Middle to Late Jurassic and the Cretaceous (BURK, 1965). The extension of the arc to the northeast of the map area in Figure 1 and through Mts. St. Augustine, Iliamma, Redoubt, and Spurr crosses this fault and other pre-Quaternary geologic trends. The earthquakes deeper than 70 km tend to follow the volcanic arc and likewise cut across the regional surface geology (TOBIN and SYKES, 1966). It should be noted that the whole chain of volcanoes along the Alaska Peninsula might better be represented by a series of arcs rather than a single arc.

In the Katmai region, Mts. Ikagluik, Griggs (formerly Knife Peak), and Novarupta lie well to the northwest of the volcanic trend. Ikagluik does not appear to have been recently active and may simply be an eroded lacolith or sill (FENNER, 1930). Novarupta, however, played an important part in the eruption of 1912 (CURTIS, 1955) and in 1965 still displayed mild fumarolic activity on the northwest edge of the crater. A fumarole high on the west flank of Mt. Griggs was also steaming actively during 1965. These peaks show no obvious structural relationship to the other volcanos. Their interconnections may be related to an extensive system of conjugate (?) joints to their east (MULLER and WARD, 1966), to the probable collapse crater to the northeast near the confluence of the Rainbow and Savonoski Rivers (MULLER and WARD, 1966), and to the widespread Tertiary (?) intrusives which have been found throughout the area to the northwest of the volcanic range (SMITH, 1925; FENNER, 1930; KELLER and REISER, 1959; and MULLER and WARD, 1966). BURK (1965) has discussed similar lines of volcanoes and faults lying transversely or obliquely to the main structural trends elsewhere on the Alaska Peninsula and in the Aleutian Islands as well as on the Kamchatka Peninsula and Kurile Islands.

KELLER and REISER (1959) show the volcanic peaks situated on top of a gentle and questionable anticline. FENNER (1923) gives evidence against the existence of a large anticlinal structure and explains the presence of sedimentary beds over 1,800 m up on Mt. Katmai (FENNER, 1930, p. 15) as due to erosion of the adjacent terrain with the sediments in the peaks being effectively capped by the recent volcanics. He also explains the striking upturn of the bedding at the southern end of the Buttress Range as due to a local intrusion (p. 20).

Except for early thrust movement on the Bruin Bay Fault, the Alaska Peninsula was primarily a depositional feature until Pliocene time. Essentially all major tectonic features in the region were formed during the Pliocene, although regional uplift still persists (BURK, 1965). Several elevated marine terraces may be noted south of Dakovak Lake, 23 km southeast of Mt. Katmai.

No detailed geologic or structural mapping has been done on the volcanic range. Some petrographic work, however, has been carried out by FENNER (1926), CURTIS (unpublished), KELLER and REISER (1959), BORDET *et al.* (1963), and, during 1965, by R. FORBES of the University of Alaska. The recent volcanic rocks of this area are generally rhyolites to andesites. Samples from the dome in Novarupta and the ash flow have been noted for their high silica content (up to 77 %) (BORDET, *et al.*, 1963).

Recent Volcanic History

Due to the remoteness of this area, observations of volcanic activity are at best fragmentary (Table 1). It must be remembered that these observations are limited to particular times when people were in the area or, as following the 1912 eruption, were attracted to it. In addition, the observer was often at some distance and may have attributed the activity to the wrong vent. In cases of doubt, no peak has been listed or question marks have been given in Table 1.

Even when several people are in the area, observations may be poor. During August 3-5, 1965, pulverized ash filled the air in the region from the Valley of Ten Thousand Smokes to Brooks Lake. Although several people were within ten miles of Mts. Trident and Martin, the suspected sources, no aerial or ground reconnaissance could establish whether this ash was of volcanic origin or simply windblown (WARD and WARD, 1966). This event emphasized the need for closer observation to understand the nature of the eruptions and to correlate their volcanic and seismic activity. The prevailing atmospheric conditions should also be studied, since fumaroles appear more active during days of low temperature and pressure and the nature of the ashfalls observed depends heavily on the wind direction (WILCOX, 1959).

This fragmentary record of observations shows the continuing activity of the Katmai volcanoes. The trend, since 1912, seems to have been a slow cooling of Novarupta, the Valley of Ten Thousand Smokes, and Mt. Katmai, with more or less constant fuming of Mts.

TABLE 1 • Observed volcanic activity.

Date	Volcano	Activity	Reference
1870	Kukak	Solfataric activity, eruption questioned.	COATS (1950) p. 41
1898, Oct.	Trident	« Extensive hot springs » on southwest flank. « One of them occasionally smokes ». « Very frequent earthquakes ».	SPURR (1900) p. 89
1912, June 6-9	Katmai?	Largest known eruption in Alaska.	GRIGGS (1922)
1912, Oct.	Novarupta	Minor explosive eruption.	COATS (1950)
1912	Katmai	Ash eruption.	POWERS (1958) p. 64
1912	Mageik	Steaming.	POWERS (1958) p. 63
1913, Sept.	Trident	Minor eruption.	EICHER (1951) p. 71
1913-1919	Martin	Steaming, most active volcano in the area.	GRIGGS (1922) pp. 85, 180.
1914	Katmai	Activity not specified.	COATS (1950)
1915	Mageik	Thin column of steam.	GRIGGS (1922) p. 78
1916	Trident	Large fumarole on the southwest flank.	GRIGGS (1922) p. 98
1919	Trident	Less active than in 1916.	GRIGGS (1922) p. 219
	Martin		
	Mageik		
1920-1921	Trident	More active than in 1919.	GRIGGS (1922) p. 220
	Martin		
	Mageik		

1920, Mar. 9	Katmai ?	Minor eruptions.	Coats (1950)
1921, Nov. 27	Katmai ?	Minor eruptions.	Coats (1950)
1923	Katmai	Mud geyser in caldera, no lake.	Fenner (1950) p. 8
1923	Griggs	Slightly active.	Smith (1925) p. 186
		« Several of the volcanoes constantly send columns of white fumes many hundred feet in the air ».	Smith (1925) p. 186
1923	Kudak	Slender plume of steam.	Mather (1925) p. 172
1923	Mageik	Constant heavy roar and steam. « Rocks and ash on rim of crater suggest recent eruption ».	Fenner (1930) p. 14
1927		Ash eruption reported in the area.	Jaggar (1927)
1927, May	Martin	Steaming.	Jaggar (1945) p. 89
	Mageik		
1927, Aug.	Mageik	Five day explosive eruption.	Powers (1958) p. 71
1929	Martin	Steaming.	Jaggar (1929) p. 246
	Mageik		
1929, Aug. 19	Mageik	Smoking, volcanic ash fell.	Heck (1958) p. 76
1931, May 8	Katmai Group	Steaming.	Coats (1950)
1931, July	Katmai Group	Steaming.	Coats (1950)
1936, July 4-5	Mageik	Major explosive eruption, ash.	Coats (1950)
1946	Mageik	Eruption questioned.	Coats (1950)

TABLE 1 - (*continued*).

Date	Volcano	Activity	Reference
1949, May 19		Violent eruption attributed from a distance to Novarupta.	EICHER (1957) p. 71
1949, June	Trident	Eruption.	EICHER (1957) p. 71
1950, July 2	Trident ?	Explosive eruption.	DECKER (1963) p. 37
1950, Aug. 1	Trident ?	Explosive eruption.	DECKER (1963) p. 38
1950, Aug. 16-18	Trident ?	Explosive ash eruption.	DECKER (1963) p. 38
1951, July	Trident	Steaming « from a vent » at an approximate altitude of 3600 feet, southwest of the middle peak.	MULLER (1954) p. 319
1951, July 22	Martin ?	Ash eruption.	MULLER (1954) p. 320
	Mageik		
1953, Feb. 15	Trident	Major explosive eruption from a new vent on west flank just SE of Katmai Pass. Extrusion of blocky, viscous lava lasting several days with possible simultaneous activity from Martin or Mageik, as well as a fumarole on SE flank of Trident.	SNYDER (1954) p. 1
1953, July	Martin	Steaming.	MULLER (1954) p. 320
1953	Douglas	Quiet steaming from several small vents near the crater lake.	MULLER (1954) p. 320
1953	Mageik	Steaming.	SNYDER (1954) p. 4
1953, July	Griggs	Mild fumarolic activity.	MULLER (1954) p. 320
1953	Katmai	Latent heat in caldera still prevents freezing.	MULLER (1954) p. 320
1953	Kukak	Steamed steadily.	KELLER (1959) p. 268

1953, July 22	Kukak	Large puff of smoke escaped from a large cavern on the flank of Hook Glacier.	MULLER (1954) p. 320
1953, July	Mageik	Quiet steaming, ash eruption.	MULLER (1954) p. 320
1953-1954	Novarupta	Continuing to steam mildly.	MULLER (1954) p. 320
1954	Kukak	Steamed steadily.	KELLER (1959) p. 268
1954	Douglas	Quiet steaming from several small vents near the crater lake.	MULLER (1954) p. 320
1954	Mageik	Steaming.	KELLER (1959) p. 268
1954	Griggs	Steaming.	KELLER (1959) p. 268
1954	Martin	Steaming.	KELLER (1959) p. 268
1954	Trident	Lava flows increased in size.	DECKER (1963) p. 33
1954, Oct. 5	Trident ?	Smoke cloud to 40,000 ft.	*Anchorage Daily Times*, MULLER, personal communication
1956, Sept. 8-9	Trident ?	Ash eruption.	DECKER (1963) p. 38
1957	Trident	Lava flow.	DECKER (1963) p. 44
1958	Trident	Active all year, lava flow.	DECKER (1963) p. 38
1959-1960	Trident	Lava flow.	DECKER (1963) p. 38
1960, Aug. 10	Trident	Violent explosive eruption in the morning and steam cloud in the evening.	DECKER (1963) p. 39
1961, June 30	Trident ?	Ash in the air.	DECKER (1963) p. 40
1961	Trident	Plume all summer.	DECKER (1963) p. 40
1962, June	Katmai	A « milky spot » in the caldera lake suggested sub-surface fumarolic activity.	BORDET (1963) p. 29

TABLE 1 - (*continued*).

Date	Volcano	Activity	Reference
1962, June 10	Trident	Explosive eruption.	DECKER (1963) p. 40
1962, June 17	Katmai	The « milky spot » in the caldera disappeared.	BORDET (1963) p. 30
1962, June	Mageik	Steaming.	BORDET (1963) PL 13
1962, June	Martin	Steaming.	BORDET (1963) PL 13
1963, Apr. [illegible]	Trident	Explosive eruption.	DECKER (1963) p. 40
1963	Trident	Smoke plume all summer.	DECKER (1963) p. 40
1963, Nov. 17	Trident	Explosive eruption.	DECKER (1963) p. 42
1964, June 20	Trident ?	Thick ash cloud at Brooks Lake.	DEWEY (personal communication, 1966)
1965	Martin	Fumed steadily.	WARD (observation)
1965	Griggs	Very active fumarole high on west flank.	WARD (observation)
1965, Aug. 3-5	Trident or Martin?	Ash eruption?	WARD (1966)
1965	Snowy Mtn	Rumblings heard at Kukak bay from near Hook Glacier.	DUMOND (personal communication, 1966)

Martin and Mageik and a remarkable increase in activity of Mt. Trident. In addition, there seems to have been sporadic but continuing activity of Mts. Griggs, Kukak, and Douglas, although the latter two are far from the more travelled region of the Monument and therefore have not been observed regularly.

While the authors were unable to find any historic reports of observations prior to 1870, D. DUMOND of the University of Oregon (personal communication, 1965) has dated several ash layers at Brooks River by radiocarbon methods and has established an archeologically

TABLE 2. - Ash layers at Brooks River (after DUMOND)

Date	Thickness (cm)	Comments
1912 A. D.	20	Katmai
1778 ? A. D.	1	Eruption of Mt. Iliamna?
1450-1500 A. D.	10	Well dated
1100-1280 A. D.	.5	
900-1100 A. D.	1	
1100 B. C. - 900 A. D.	6-8	At least 3 ash deposits which are difficult to differentiate
1900 B. C.	2.5	Well dated
1900-2300 B. C.	.5	Similar to 1900 B. C. deposit except in glass shard index of refraction
2300-5400 B. C.	5	Three deposits. Bottom one is heavily weathered

significant tephrochronology for this region. The ashes in Table 2 from Brooks River between Brooks and Naknek Lakes, show evidence of at least twelve events prior to 1912. In addition, 2 to possibly 6 ash deposits have been found in Kukak Bay dating between 5400 and 7100 B.C. One may be related to the formation of the Kaguyak Crater, 64 km northeast of Katmai. Petrographic work is in progress at the University of Oregon, but unfortunately, little can be said about the origin of the ashes, since no adequate study has been made of their areal variation in thickness.

NAYUDU (1964) has discussed three distinct ash layers found in studying 37 cores from the Gulf of Alaska. The uppermost ash had a silica content of 74 % and is considered to be from the 1912 Katmai eruption. The middle basaltic ash is inferred to be 12,000 to 15,000 years old by radiocarbon dating of the contiguous sediments. Its source probably lay on the Alaska Peninsula. The lowest andesitic ash was found only in two cores in the central part of the Gulf. It is inferred to be between 25,000 to 30,000 years old but its source is unknown.

The Eruption of 1912

The eruption in June 1912, attributed to Mt. Katmai, is still one of the largest and perhaps least understood historic volcanic events. Numerous hypotheses were proposed (GRIGGS, 1922 and FENNER, 1922, 1923, 1926) to explain the origin of the ashflow in the Valley of Ten Thousand Smokes, Katmai Crater, and particularly the light and dark banded pumice. The most recent interpretation, based on the compilation of isopachous maps of the ash layers (CURTIS, 1955), is that the majority of the activity came from Novarupta, a crater 10 km west of Mt. Katmai. The first explosive phase was of white pyroxene-free rhyolitic pumice and ash. This was apparently followed by the emplacement of the main ash flow (BORDET *et al.*, 1963) in the Valley of Ten Thousand Smokes from Novarupta or from fissures near the head of the Valley and then by several minor ash eruptions of grayer pyroxene-bearing pumice. It is thought that after this material had been drained out through or near Novarupta, but from under Mt. Katmai, Katmai's summit collapsed (WILLIAMS *et al.*, 1956). The only reported evidences of volcanic activity in the caldera itself are a small cone or « Crescentic island », a mud geyser (FENNER, 1930, p. 8), a small deposit of tuff (CURTIS, 1955), some recent fumarolic activity (CURTIS, 1962, table 1), and the fact that it still remains unfrozen in winter. The dark uppermost ash may have originated from Katmai during the caldera subsidence (CURTIS, 1955). Finally, a white rhyolite dome was emplaced in the vent on Novarupta (BORDET *et al.*, 1963).

One of the most debated questions of the 1912 eruption is when and how was the banded pumice formed? This pumice has a marble cake type structure with light, rhyolitic and dark, andesitic streaks. In recent years, it primarily occurs as wind and water-borne deposits lying on top of the Valley fill and is most abundant near Three Forks. The total volume of this banded pumice is very small in comparison with the volume of the main ash flow and ash. Massive pyroxene rich pumice is quite rare, except in the deposits along the stream from the west side of Mt. Griggs. This distribution and the apparent increase in the pyroxene content of the extrusives during the eruption (CURTIS, 1955 and BORDET *et al.*, 1963) seem to indicate that the banded pumice was formed only during the later stages of the activity.

Another puzzling question about the 1912 eruption is the origin and nature of the tuff in the Valley of Ten Thousand Smokes. GRIGGS (1922) proposed that it was underlain by a granite batholith. FENNER (1923) later suggested a sill. A new interpretation by WILLIAMS *et al.*, (1956) and later BORDET *et al.* (1963) suggests that the fill is a surficial deposit coming from fissures near Novarupta and that it is an ignimbrite, the products of the settling of frothy magma. The fumaroles would then be due to the gas sweated out during cooling and settling. This seems to explain best the short life and chemical composition of the fumaroles.

Certain details in the Valley, however, remain unexplained. Along the west central edge of the valley and on the west side of Baked Mountain are prominent benches which have been variously interpreted as due to flow crests, differential compaction, or settling over pre-existing benches. These benches have two of the more prominent lines of fumaroles. The vents on the west bench of Baked Mountain are the only ones still active within the Valley today. It is difficult to explain the prominence and persistence of these fumaroles as stemming only from the surficial deposits in an area along the edge of the Valley where the covering must be relatively thin.

In addition, many observers have noticed a prominent stratigraphy in the tuff, particularly in the canyons near Three Forks. Here there are at least two tuffs, the lower one a darker brown, as well as a whole sequence of ash layers including recent wind and water deposits. JUHLE and MULLER (personal communication, 1964) noted three tuff units exposed in a gorge near the base of Mt. Griggs. These observations strongly indicate that the sequence of events in 1912 was more complicated than previously described.

Seismic Refraction Profile

To date no one has adequately studied the thickness of the pyroclastic deposits in the Valley, partly because explosives are prohibited in the National Park. During July 1965, however, a small refraction experiment was carried out one mile east-southeast of Three Forks. The instruments consisted of a Lamont short-period seismic amplifier (THANOS, 1964), a Sanborn 299 stripchart recorder with 5 mm/sec paper speed, a Hall Sears 4.5 cps HS-1 geophone, and an energy source consisting of a five gallon can of water with an inertial timing switch dropped from a ten foot tripod. Good first arrivals with a predominant frequency of about 80 cps were observed up to 180 m. Figure 2 shows the travel time graph and the calculated depths and the calculated depths and velocities assuming horizontal layering. The error in reading the travel times may be as large as 5 milliseconds, so that the precision of the highest velocity, which is the most sensitive to a timing error, could be as much as ± 0.3 km/sec. The 2.4 m thickness and 0.3 km/sec velocity of the first layer have been calcu-

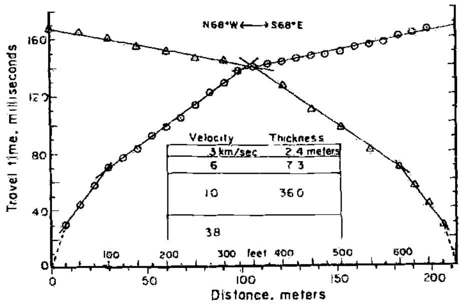

FIG. 2 - The travel-time graph and calculated layer velocities and thicknesses for a seismic refraction profile about 1.6 km east-southeast of Three Forks in the Valley of Ten Thousand Smokes.

lated by joining the first receiving point at 8 m with the origin. In reality this layer is probably less than a meter thick and has a lower velocity corresponding to the uncompacted wind and water deposits observed. The second layer with a velocity of 0.6 km/sec and a thickness of 7.3 m is the tuff. The third layer with a velocity of 1.0 km/sec and a thickness of 36 m is glacial gravel, while the final layer with a velocity of 3.8 km/sec is the underlying Naknek sandstone. This traverse was 200 m east of a canyon where 1 m of loose sediments and 29 m of tuff overlie glacial gravel, and it was about 1 km north of several moraines transecting the Valley. Therefore, these data would imply that there are more moraines buried by the tuff. Some of these may be seen in the canyon walls along Knife Creek south of Three Forks.

GRIGGS (1922, p. 253) suggested that farther up the Valley the fill is at least 152 m thick. CURTIS (1956, p. 70) by comparing stream profiles throughout the Monument (CURTIS, personal communication, 1966) showed that the tuff could be 210 m thick in the upper parts of the Valley. MULLER (personal communication, 1966) pointed out that the moat at the terminus of the Third Knife Creek Glacier (MULLER and COULTER, 1957), possibly due to a phreatic explosion after the emplacement of the tuff, indicates 30 m as a minimum thickness of the tuff at this point. However, no accurate determination of the largest thickness of the fill has been made. If it is over 50 m deep, an energy source which is larger than that used for our experiment would be needed for refraction studies.

Nature of Recent Volcanic Activity

Since 1912, the observed volcanic activity has consisted primarily of fumarolic activity, active steaming from main vents, ash eruptions, extrusion of viscous lava flows, and pyroclastic explosions.

Although most of the thousands of fumaroles studied by ALLEN and ZIES (1923), ZIES (1921, 1924, 1929), and SHIPLEY (1920), became extinct within fifteen years, several have persisted. In 1965, three in a north-south line on the west bench of Baked Mountain were still active. These had temperatures barely over 100°C and had opened up into pits as much as 6 m square and 20 m deep. Warmer fumaroles with opening of a few centimeters had also remained active on the north-west rim of Novarupta. SNYDER (1954, p. 7) reported an active fumarole near the north end of the Buttress Range (LOVERING, 1957) and one on the southeast flank of Trident (GRIGGS, 1922, p. 98). Both of these were inactive in 1965. Varied fumarolic activity has been reported on Mt. Griggs with one vent just below the summit to the west being very active in 1965. The new cone on Mt. Trident is covered with active solfataras encrusted with molten and crystalline sulphur. These had temperatures greater than 200°C in 1963, but appeared cooler in 1965.

Seven of the main vents have at one time or another been reported with plumes of steam (Table 1) consisting of water vapor and several toxic gases, notably compounds of sulphur. Mt. Trident had an extremely heavy plume during the summer of 1963.

Numerous ash eruptions have been observed either alone or in combination with more violent activity. The pulverized ash normally fills the air like a heavy haze often cutting the visibility to a few hundred yards. The magnitude and effects of the observed ash fall depend heavily on the prevailing atmospheric conditions (WILCOX, 1959), so that many such eruptions may go unnoticed or may be misinterpreted from nearby points (WARD and WARD, 1966).

Viscous lava flows seem to make up the bulk of all of these composite cone volcanoes. The only recent flows have been on Mt.

FIG. 3 - Mt. Trident looking north. The new summit cone is in the center, surrounded by the lava flows which have been extruded since 1953. This photograph was taken on August 10, 1960 by a Park Service Ranger.

Trident in 1953, 1957, 1958, and 1959-60 (SNYDER, 1954 and DECKER, 1963). Since aerial photographs were taken in 1951, a small vent on the southwest flank of Mt. Trident has had frequent eruptions building its cone up to nearly 260 m and extruding a sequence of flows up to 300 m thick and covering 5 km^2 (SNYDER, 1954 and DECKER, 1963), a volume on the order of .4 km^3 of lava (Figure 3) ([1]).

([1]) Park Service Ranger, D. BOGART, has carefully compiled a set of photographs which show the sequence of the flows since 1953 (available for study at Brooks Lake Ranger Station).

The latest activity has been pyroclastic explosive eruptions. There have been at least ten such eruptions of Trident since 1949. Clouds of smoke and steam have been observed up to 12 km high by radar from King Salmon, 150 km to the northwest (DECKER, 1963).

Recent eruptions of Mt. Trident have been heard and well observed from Brooks Lake, 50 km to the northwest. These have cleared the throat of the volcano of a central spine or small lava dome. Blocks nearly 1 m in diameter have been found over 3 km from the vent with the largest breadcrust bombs approaching 2.5 m in diameter.

One of the most striking characteristics of the Katmai volcanos is their apparent interconnection (GRIGGS, 1922; SNYDER, 1964, and BORDET *et al.*, 1963). Table 1 shows several instances in which major activity at one peak has been accompanied by continuing and changing activity at another (notably February 15, 1953 and June, 1962). One of the still mystifying aspects of the 1912 eruption is the interrelation of Mts. Katmai, Novarupta, and the hypothesized fissures under the Valley.

Seismic Activity

GRIGGS (1922) and TAMS (1924) report that numerous earthquakes were felt throughout the Alaska Peninsula during the 1912 eruption. FENNER (1925) has summarized the sequence and nature of these events and concluded, somewhat questionably, an apparent coincidence of tectonic shocks with major outbursts during the eruption (p. 138). Many earthquakes were recorded from this region during 1912 but with the low precision of epicentral determinations possible at that time, it is impossible to make any conclusions about the distribution or the relation of these shocks to the eruption. Since the data were so poor, no relocation of these events was attempted.

Table 3 lists all the earthquakes from the Katmai region that have been recorded teleseismically since 1912 and through 1965. These hypocenters have been relocated by a program developed by Sykes (SYKES and LANDISMAN, 1964) using the Jeffreys-Bullen travel time tables and data from the *International Seismological Summary,* used exclusively for events prior to 1950, the *Seismological Bulletin,* and the *Bulletin Mensuel* of the Bureau Central International de Séismologie. Several events, when relocated, moved outside of the Katmai area and therefore have not been included. Column Q in Table 3

TABLE 3 - Hypocenters in the Katmai Region recorded teleseismically since 1912. Column SE is the standard error. No. is the number of stations used for the redetermination, Mag. is the magnitude given by the U.S. Coast and Geodetic Survey, and Q is the uncertainty of the hypocenter (see text).

Date	Time h	Time m	Time s	Lat. North	Long. West	Depth	SE	No.	Q	Mag.
Aug. 14, 1944	11	07	22.6	58.63	154.16	67	0.92	55	BA	
Nov. 25, 1955	14	24	33.8	59.05	155.50	52	0.99	10	BB	*
Nov. 27, 1955	13	06	59.5	57.91	155.86	76	0.76	10	BB	*
Jan. 23, 1956	00	46	39.4	57.95	154.05	34	1.68	25	AA	*
Feb. 19, 1956	04	13	14.5	58.52	153.74	0	1.59	75	BA	*
Nov. 10, 1956	11	53	33.0	58.72	155.12	131	0.76	11	BB	*
Apr. 04, 1957	00	13	02.2	58.06	155.18	74	1.41	100	BA	*
Apr. 14, 1959	07	20	27.3	57.95	155.01	67	1.43	103	AA	*
Dec. 28, 1960	19	45	27.3	58.43	154.40	67	0.81	14	BB	*
Aug. 10, 1961	00	58	37.4	58.60	153.57	0	0.40	6	BC	
Feb. 20, 1964	02	30	21.1	58.34	154.85	77	0.85	12	BB	4.5 *
Mar. 29, 1964	00	43	14.5	58.7	153.3	25	0.3	6	CS	3.9
Mar. 29, 1964	10	38	29.4	59.2	155.1	10	0.1	8	CS	4.1
Mar. 29, 1964	12	33	10.7	59.17	153.79	24	0.81	19	AA	4.8
Mar. 29, 1964	20	59	22.4	59.22	153.14	0	1.00	18	CB	4.6
Apr. 06, 1964	15	01	32.0	58.1	154.4	33	0.4	6	CS	3.8
Apr. 07, 1964	01	43	24.1	58.52	154.59	0	1.21	47	AA	5.1
Apr. 12, 1964	21	02	09.4	58.50	154.68	0	1.06	7	AB	4.0
May. 21, 1964	15	35	58.3	58.94	153.81	0	1.52	79	BA	5.3
Jun. 10, 1964	23	25	04.1	59.05	153.92	0	1.56	38	AA	5.1
Aug. 31, 1964	23	55	22.6	58.5	154.8	33	0.9	7	CS	
Sep. 09, 1964	02	41	39.8	58.84	155.00	0	0.72	7	BB	
Sep. 13, 1964	19	40	40.9	58.65	155.30	69	0.74	9	BB	4.7
Oct. 03, 1964	15	05	19.5	59.1	153.2	60	0.1	5	CS	4.1
Apr. 24, 1965	10	20	51.7	58.62	153.04	68	0.80	24	AB	4.7
Jul. 21, 1965	09	08	06.0	58.90	153.93	0	1.16	11	AA	4.5
Jul. 28, 1965	14	26	14.8	58.91	153.88	0	1.14	16	AA	4.5

* Calculated by TOBIN and SYKES, 1966.

is the uncertainty of the hypocenter. The first letter of this column refers to the depth. An « A » signifies that one station was within 5° of the Katmai area or that pP arrivals were used for calculating depth. These depths may be in error as much as 25 km. « B » signifies that at least one station was in Alaska (usually College at a distance of about 6°) and that depths may be in error up to 50 km. The second letter refers to the azimuth control in locating the epicenter. « A » signifies a station distribution of more than 180°, while « B » is more than 90°. The precision of the epicenters of « A » events probably does not exceed 10-20 km. « CS » in this column means that not enough data were available for an accurate relocation so that the preliminary determination of the U.S. Coast and Geodetic Survey or other value is used. These hypocenters are quite unreliable and are included only for completeness of the time sequence for comparison with Table 1. Zero depths were first calculated as negative and therefore were held to zero for the epicentral determination.

There may be a systematic error in these hypocenters. The two events in July, 1965 were located about 20 km north of a cluster of their aftershocks located (assuming a crustal structure) by a tripartite array near Three Forks during July and August (MATUMOTO and WARD, 1966). When the tripartite first arrivals were added to the teleseismic data, the epicenters (values given in Table 3, formerly Q = BA) were moved 10 km south and their depths changed from about 45 km to zero. Furthermore, a location of LONGSHOT (October, 1965) on Amchitka Island in the Aleutians using the same program and travel time tables was 25 km too far to the north (TOBIN and SYKES, 1966). However, these differences are within the precision of the available data.

The apparent increase in seismic activity since February, 1964 is primarily due to the increase in sensitivity and data handling efficiency of the World-Wide Standardized Seismograph Network. The magnitude of most events prior to 1964 may well be greater than 5. This would imply that at the same sensitivity only three events, at most, would have been reported during 1964 and 1965. Prior to 1955 events reported were probably larger than magnitude 6. At this same sensitivity no events would have been recorded in 1964 and 1965.

A comparison of Tables 3 and 1 shows that with the scanty data available since 1912, there has been no distinct correlation between large earthquakes and observed volcanic activity. This is particularly true in the better recorded period since 1955, even though the recent eruptions of Mt. Trident have been heard and felt at Brooks Lake, 50 km to the northwest (Dewey, personal communication, 1965).

The epicenters with Q of BB or better are plotted in Figure 1 with their depth, Q, and year. It is seen that three lie close to the Bruin Bay Fault, four lie in a cluster near two faults west of Mt. Douglas, and four earthquakes lie close to Snowy Mountain, a region found to have high seismicity in 1965 (Matumoto and Ward, 1966).

Conclusion

This brief review shows that the Katmai region in Alaska has been and continues to be volcanically and seismically active. Eight vents have shown varied amounts of activity from single fumaroles to major explosive eruptions and extrusion of a very viscous blocky lava similar in form to the flows which have apparently built up the volcanoes in this region since the Tertiary.

The 1912 eruption, attributed to Mt. Katmai, was one of the largest but least understood in recent history. The Valley of Ten Thousand Smokes is one of the few historic pyroclastic flows and yet much of its nature still remains a mystery.

Twenty-seven earthquakes since 1912 with magnitudes probably greater than 4.5 have been recorded and located in this region, but none show any direct correlation with observed volcanic activity even during the vociferous eruptions of Mt. Trident over the past 15 years.

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