Microearthquake Study of Mount Katmai and Vicinity, Alaska[1]

TOSIMATU MATUMOTO AND PETER L. WARD

Lamont Geological Observatory of Columbia University
Palisades, New York 10964

A seismic investigation was made during the summer of 1965 in Katmai National Monument, Alaska. During 39 days of nearly continuous recording with a high-gain high-frequency tripartite array of seismometers, 1800 events were recorded. The majority of events were shallower than 10 km, although some occurred at depths up to 150 km. Most of the events were associated with the volcanic axis that trends northeast–southwest along the Alaska Peninsula. Although there are fifteen volcanic vents in the Katmai area, historic volcanic activity, ranging from minor steaming to major explosive eruptions has been limited to seven peaks. Seismic activity was generally greatest near the more recently active volcanos and was quite low near the volcanos with no record of historic eruptions. Two exceptions to this general tendency, however, were near Snowy and Fourpeaked Mountains. Most of the events in these two areas were attributed to short-term increases of seismicity in aftershock or swarm-type sequences. The b value in a log-log plot of frequency versus amplitude for all shocks was 1.4, which is intermediate between that of tectonic earthquakes ($b = 0.5$ to 1.0) and that of volcanic earthquakes ($b = 2$ to 3). This b value plus the nature of the earthquakes observed imply a mixture of tectonic and volcanic shocks in a highly heterogeneous structure with locally concentrated stresses. A comparison of seismograms recorded at Brooks, Overlook, and Katmai Canyon shows a disappearance of the S phase along a path crossing the volcanic range. A study of specific events suggests this is due to a shadowing effect by a magma chamber rather than to a source mechanism. A slight increase of seismicity was observed in early August near Mounts Trident and Martin, coinciding approximately with evidence for a minor eruption in that region. Detailed and confirming evidence of an eruption was limited because of remoteness and unfavorable weather conditions. A normalized count of seismic events in early August indicates that an increase of seismicity associated with a major eruption could be comparable to that observed at other volcanos of the explosive type and suggests that continuous seismic monitoring of the Katmai area would be of considerable value.

INTRODUCTION

Katmai National Monument is situated about 400 km southwest of Anchorage on the Alaska Peninsula (Figure 1). This area first attracted worldwide attention in 1912 when a violent eruption was attributed to Mount Katmai, one of the largest historic eruptions in the world. Since that time a wide range of volcanic activity from minor steaming and ash eruptions to extrusion of viscous lava flows and pyroclastic eruptions has been observed from Mounts Martin, Mageik, Trident, Katami, Novarupta, Griggs, and Kukak. Since 1953 Mount Trident has built a new summit cone nearly 260 meters high and has extruded nearly 0.4 km^3 of blocky lava flows up to 300 meters thick. The historic volcanic and seismic activity in Katmai is summarized in detail in a companion paper [*Ward and Matumoto*, 1967].

Because of the great variety of volcanic activity in the Katmai region, the authors initiated a field program during the summer of 1965 to determine the temporal and spatial distribution of earthquake hypocenters and their relationship to geologic structure and volcanic events. This paper describes the analyses in space and time of 1800 earthquakes recorded in 39 days by a high-frequency high-gain tripartite array of seismometers.

Very few seismic studies have been made in the remote Katmai region. The first seismic observation on the Alaska Peninsula was by the U. S. Geological Survey in 1927, using a Hawaiian type seismograph on Kodiak Island and later at Dutch Harbor on Unalaska Island [*Jones*, 1932]. In 1963, Decker and Ward set up the first seismograph in the Katmai area [*Decker*, 1963]. Their system consisted of a

[1] Lamont Geological Observatory Contribution 1038.

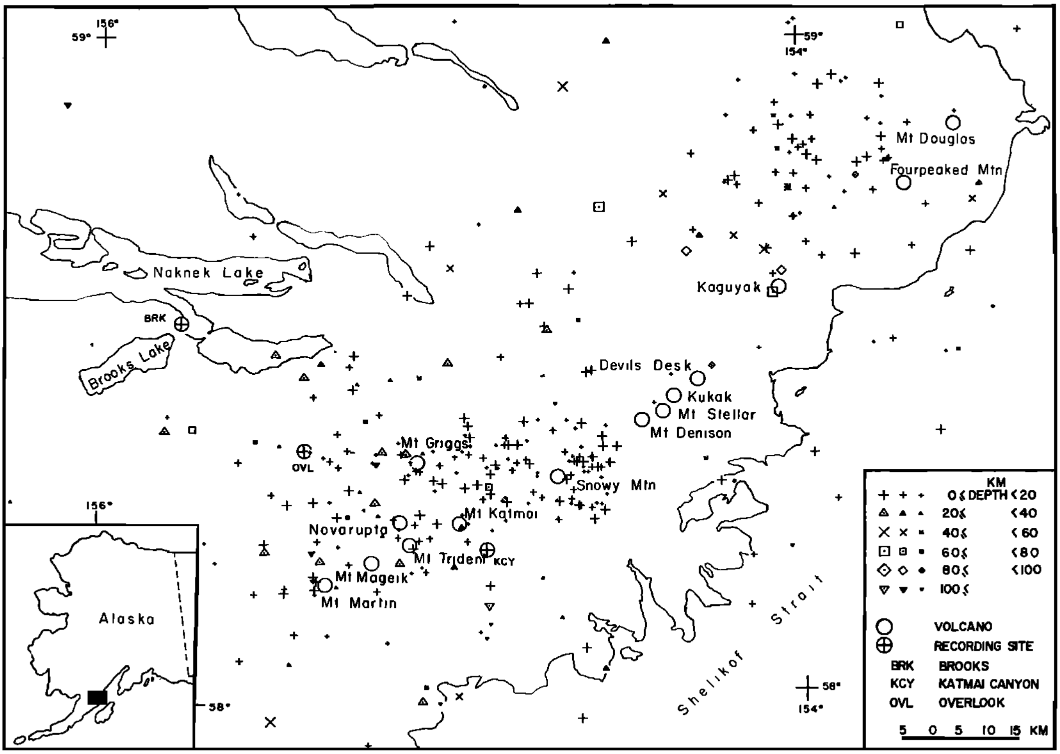

Fig. 1. Map of Katmai National Monument showing the location of the volcanos, instrument recording sites, and epicenters determined from the tripartite array at Overlook Hill. The different symbols represent the depth of the hypocenters. The three sizes of symbols indicate the precision of the hypocentral determination which is primarily governed by the time resolution of the first arrivals and the clarity of the *S* phase. A larger symbol indicates a more precise determination.

short-period vertical Benioff seismometer, phototube amplifier, and a Geotech Model C2 visible recorder. With 82 earthquakes recorded during 17 days, they showed the feasibility and promise of future seismic study. During part of the summer of 1965, a small conventional seismic network providing data on larger shocks was operated in the Katmai area by the University of Alaska.

Instrumentation

A high-gain high-frequency tripartite array of seismometers was used to provide ample data for a detailed study of the temporal and spatial distribution of regional earthquakes within a limited time. The array system was nearly identical to that used in aftershock measurements following the Alaskan earthquake of March 29, 1964 [*Matumoto and Page,* 1966].

The array system consisted of three matched, critically damped, HS-10 2 cps vertical geophones and modified Lamont short-period seismic amplifier [*Thanos,* 1964]. The geophones had a coil resistance of 1650 ohms and a voltage sensitivity of 2.2 volts/cm/sec. The amplifier had a gain of 100,000 in the frequency range from 0.2 to 80 cps and had an equivalent input noise voltage of 0.2 microvolt peak-to-peak. The seismic signals were recorded on a seven-channel Precision Instrument 5104 FM magnetic tape recorder with a tape speed of 3/8 inch/sec to provide a sufficient time resolution for the array recording. The frequency response of the tape recorder was flat from dc to 70 cps. The equivalent recording noise was less than 20 millivolts peak-to-peak, and the dynamic range was approximately 40 db/channel. The amplifiers were operated at 18 db below the maximum gain because of the background noise at the recording site. Nevertheless, with 18-db attenuation in the gain and the playback system described below, the visible records had a magnification of more than two million at 10 cps. Figure 2 shows the combined response and magnification of the tripartite system. The response curve for the short-period Benioff system of the World-Wide Standardized Seismograph Network operating at 100,000 gain is also shown for comparison. It may be seen that the array system has far better response from 5 to 20 cps, the frequency range containing much of the microearthquake energy.

The time signal was provided by a Bulova Accutron Chronometer and was recorded on the fourth channel of the magnetic tape recorder along with a low-gain seismic signal. With daily calibrations against WWVH or JJY time signals, the accuracy of the Bulova clock was sufficient for correlation with data from other stations. The low-gain signal was recorded for the purpose of obtaining a wide dynamic range.

Field Program

The tripartite array, with a spread of approximately 750 meters between geophones, was operated from July 11 to August 18, 1965

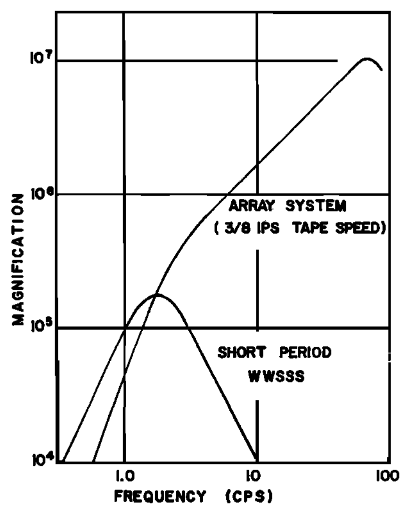

Fig. 2. The instrumental response of the tripartite array installed on Overlook Hill. The Benioff short-period seismograph of the World-Wide Standardized Seismograph Network operating at 100,000 gains is shown for comparison.

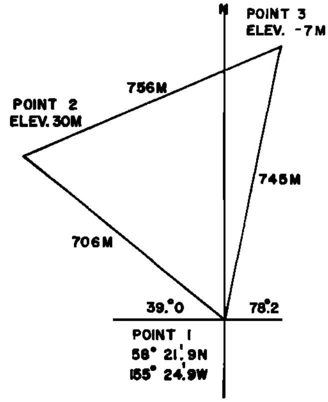

Fig. 3. The relative location of the seismometers of the tripartite array installed on Overlook Hill.

(GMT) on a nearly continuous basis on the west end of Overlook Hill, 27 km west-northwest of Mount Katmai (Figure 1). Figure 3 shows the relative location of the array seismometers installed on nearly horizontally layered Naknek sandstone.

The background noise in the area consisted of two sources, a ground noise with constant amplitude between 4 and 6 cps, due mainly to a stream, and occasional wind noise which varied in amplitude from time to time over the frequency range of 20 to 70 cps. During inclement weather, wind noise was high enough to obscure the smaller events.

In addition to the array station at Overlook Hill two stations with single vertical component seismometers were operated at Brooks Camp, 22 km northwest of Overlook, and at Katmai Canyon, 6 km southeast of Katmai Crater and 4 km west of Katmai Lakes (Figure 1). At Katmai Canyon, recording was continuous from July 21 to July 27, using a PI 5104 magnetic tape recorder with a tape speed of 15/160 inch/sec. At Brooks recordings were made intermittently on the southeast flank of Dumpling Mountain during the month of July. Over 50 hours of observation were accumulated, using either a Sanborn 299 stripchart recorder with a paper speed of 5 mm/sec or the tape recorder mentioned above.

Data Analysis

After returning from the field, the magnetic tapes were first played back with paper speeds of 3.8 and 15 mm/min of recorded time. During 39 days of nearly continuous operation at Overlook Hill, more than 1800 shocks were recorded. An occasional increase in noise level due to wind was observed. During these periods the noise would sometimes rise to 10 times that of the calm periods, obscuring events of small amplitude. For the purpose of comparing the seismicity with other areas 10 calm days were chosen, and the daily number of earthquakes with a trace amplitude of 2 mm or larger was counted. The count ranged from 40 to 85 shocks/day with an exception of 190 shocks/day on July 21. Excluding the unusual count on July 21, there was an average of 65 shocks/day.

Among the 1800 microearthquakes recorded, nearly 560 events with a significant signal-to-noise ratio were chosen for the analysis by means of the array method. The *P*-wave portion of these events was played back at a speed of either 25 or 50 mm/per sec of recorded time to provide a time resolution of 5 msec for measuring the difference of *P*-wave arrivals across the array. A tracing of a sample microaftershock from a playback record is shown in Figure 4. Although the *P* wave has an impulsive character, generally the first several cycles were used in determining the arrival time differences between traces.

From the difference in *P*-wave arrival times across the array, the azimuth, angle of propagation path, and apparent velocity were calculated.[2] Earthquake hypocenters were then calculated using the azimuth, apparent velocity, and *S-P* interval together with a crustal model.[2] When the *S* phase could not be identified, only azimuth and apparent velocity were determined. Because no information on crustal structure was available for the Katmai area, a crustal model for the Kenai Peninsula was used. This crustal model was obtained from the study

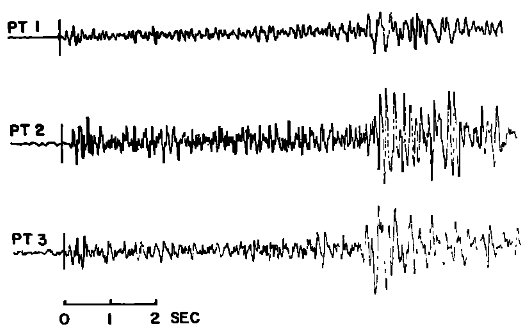

Fig. 4. A sample seismogram of microearthquakes recorded by the tripartite array at Overlook Hill on July 25, 1965, 1519 GMT. A good similarity of the first several peaks and troughs can be seen.

of aftershocks following the Alaska earthquake of March 29, 1964 [*Matumoto and Page,* 1966] (Table 1).

The accuracy in the calculated azimuth and apparent velocity depends on the spacing between geophones, the uniformity of local structure under the station, and the relative time resolution between elements of the array. The resultant uncertainties in the computed azimuth and apparent velocity were estimated to be 15 degrees and 5 per cent, respectively [*Matumoto and Page,* 1966]. During the period of recording, 11 earthquakes were recorded both

TABLE 1. Velocity-Depth Distribution

Depth, km	*P*-Wave Velocity, km/sec
0	5.20
5	5.46
10	5.86
15	6.59
20	7.19
25	7.58
30	7.73
35	7.84
40	7.92
45	7.95
50	7.99
55	8.11
60	8.16
65	8.21
70	8.29
75	8.27
80	8.20
85	8.15
90	8.20

[2] A table giving epicenters and depths of the microearthquakes from the array measurement at Overlook has been deposited as Document 9336 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington, D. C. A copy may be obtained by citing the document number and remitting $2.50 for photoprint or $1.75 for 35mm microfilm. Advance payment is required. Make checks or money orders payable to: Chief, Photoduplication Service, Library of Congress.

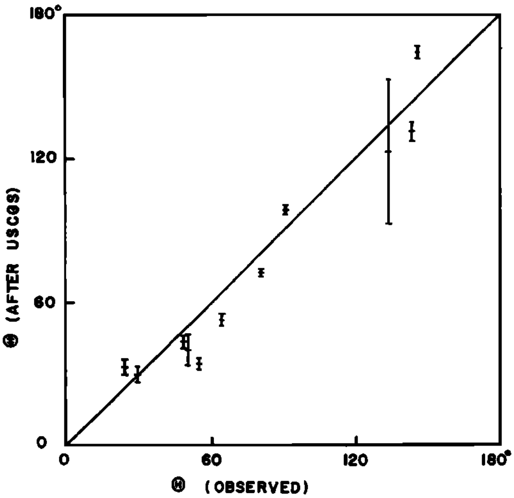

Fig. 5. A comparison of azimuthal angles determined from the tripartite array and the U. S. Coast and Geodetic Survey preliminary epicenters. The vertical lines passing through the data points indicate the precision of the determination of the U. S. Coast and Geodetic Survey.

by the tripartite array and by the U. S. Coast and Geodetic Survey World-Wide Network. These events were distributed along the Alaska Peninsula and in or near the gulf of Alaska with the distances ranging from 64 to 460 km at Overlook. Figure 5 shows a comparison of azimuthal angles determined from the array data and the determination of the U. S. Coast and Geodetic Survey. All data points lie within the expected range of uncertainty, and there is no systematic deviation between the two azimuths.

Data

Using recordings from 9 calm days, the frequency versus amplitude relation was studied. A log-log plot of frequency versus amplitude (Figure 6) approaches a straight line with a b value of 1.4 in the relation

$$\log N = a - b \log A$$

where N is the number of earthquakes with trace amplitude larger than A and a is a constant that depends on the magnification of the instrument and general seismicity of the area. When A denotes the number of earthquakes with trace amplitude between A and A plus ΔA, m is used in place of b where

$$m = b + 1$$

Miyamura [1962], among others, has shown that b is normally between 0.7 and 1.2 for tectonic earthquakes, whereas *Minakami* [1960] has found that b is between 2.1 and 3.0 for what he calls B-type volcanic earthquakes. Minakami pointed out that B-type earthquakes take place directly under some active vents, that the focal depth is generally shallower than 1 km, and that the amplitude builds up and dies out gradually with no distinct seismic phases. Another type of volcanic earthquake of deeper origin also takes place in volcanic regions, and such shocks are called A-type volcanic earthquakes by Minakami. Their seismograms resemble those of ordinary tectonic earthquakes.

Less than 7% of the earthquakes observed at Overlook were of the B-type. This does not imply, however, that B-type earthquakes are not common in the area, but that a higher rate of attenuation at the shallow structure along the volcanic range and a greater distance for the recording of such events may be responsible. For a more detailed study it will be necessary to install a seismograph in the immediate vicinity of the active vents.

A first interpretation of the intermediate b value for the Katmai area is that a mixture of tectonic or A-type earthquakes including swarm

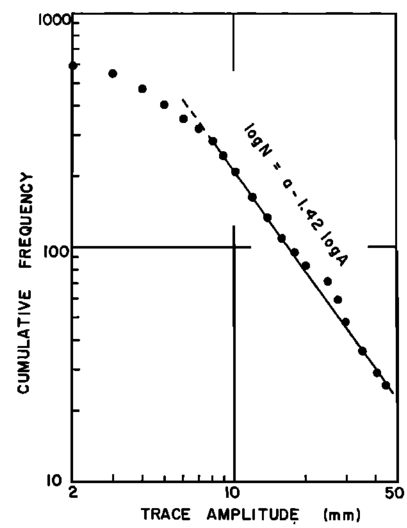

Fig. 6. A log-log plot of cumulative frequency (N) versus maximum trace amplitude (A) for records with low background noise.

and aftershock sequences and B-type volcanic earthquakes has been recorded. Further consideration suggests the existence of a locally concentrated stress distribution that may be caused both by the heterogeneity of the materials near the volcanic range and by a stress concentration as a result of movement of magma. *Mogi* [1962; 1963*a*, *b*] indicated in his model experiments that the *b* value of the elastic shocks generated in very porous and extremely heterogeneous pumice is clearly larger (1.2 to 1.7) than the *b* value for shocks in granite and andesite specimens (0.6 to 1.0).

Figure 7 shows the frequency distribution of earthquakes as a function of 1-sec *S-P* intervals. For the purpose of comparing the distribution during different periods, the data were divided into 5-day samples, and the *S-P* interval versus frequency relations for eight different periods are illustrated. Only the events with trace amplitudes of 5 mm or larger were selected and counted in order to eliminate the influence of the fluctuation in noise level. Graph b shows a

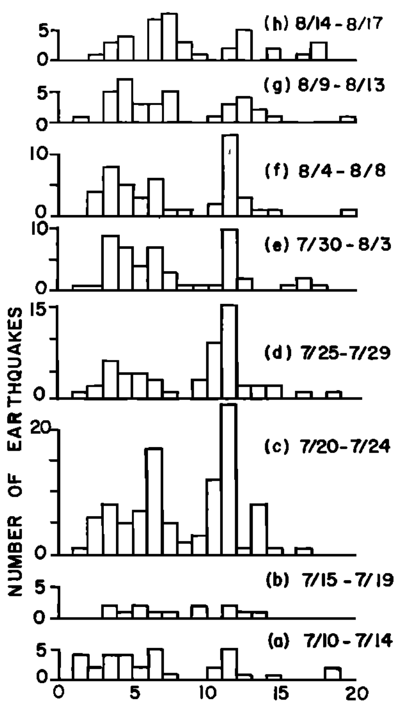

Fig. 7. The frequency distribution of earthquakes at 1-sec *S-P* intervals. The data are divided into 5-day intervals from *a* through *h*.

regional calm during July 15 to 19. Maximums in frequency occur at *S-P* intervals of 3 to 4 sec, 6 to 7 sec, and 10 to 12 sec. There are particularly strong peaks at 6 sec on graph c, and at 11 sec on graphs c through f. These peaks indicate short-term increases in seismicity in limited areas.

Such sudden increases of seismicity are more readily observed in Figure 8, in which the daily frequency of events is shown for each 40° interval of azimuth. The saw-tooth form of the curves is influenced slightly by noise level and by 30 hours, out of 900, lost when the magnetic tape was changed every 2¾ days and when animals had broken the cables. No normalization has been attempted. Nevertheless, several peaks in activity are clear and are limited to certain small areas. Most of the events in the prominent peak on July 23 were located near Snowy Mountain between an azimuth of 82° and 105° and at a distance of 40 to 50 km from Overlook. This was a swarm-type sequence where the activity gradually increased and faded away within 30 hours and where no principal earthquakes were observed. These swarm-type sequences are rather common in volcanic areas and suggest possible subterranean magma activity [*Nasu et al.*, 1931; *Nakamura and Kato*, 1937; *Minakami*, 1960; *Hagiwara et al.*, 1966].

Most of the events in the sharp peaks on July 21 and 28 were located west of Fourpeaked Mountain in an area between an azimuth of 55° and 65° and at a distance of 90 to 110 km from Overlook. These events were primarily aftershocks of two magnitude 4.5 earthquakes shown in Figure 9, as reported by the U. S. Coast and Geodetic Survey and relocated by the authors [*Ward and Matumoto*, 1967] using a program developed by Sykes [*Sykes and Landisman*, 1964]. An exponentially decaying aftershock sequence was clearly recorded following the main shock on July 21. The hourly count of the aftershocks with trace amplitudes of 1 mm or larger and with an *S-P* interval of near 11 sec is given in Table 2. The seismic activity west of Fourpeaked Mountain was more prolonged than that near Snowy Mountain. These earthquakes seem to be of tectonic origin and are apparently related to the two faults mapped by *Keller and Reiser* [1959] and shown in Figure 9.

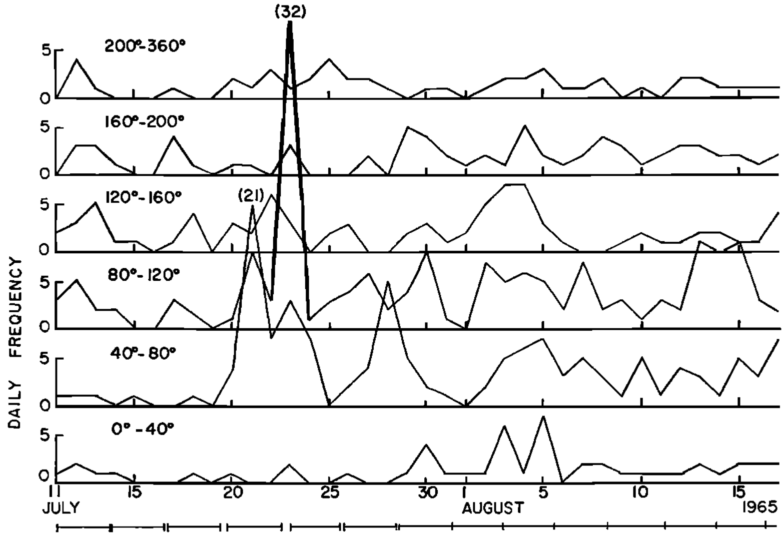

Fig. 8. The daily frequency of events for each 40° interval of azimuth. Periods where recording was interrupted are indicated on the lowest horizontal axis by through-ruled marks and gaps extending over the length of the interruption. The sharp increase of events on July 23 at the azimuthal range 80° to 120° is a swarm-type sequence near Snowy Mountain. Peaks on July 21 and July 28 are aftershock sequences following magnitude 4.5 earthquakes west of Fourpeaked Mountain. A slight increase of activity in early August can be seen particularly in the azimuthal range of 120° to 180°.

Figure 1 shows the distribution of the epicenters determined by the array data listed in Table 3. The different symbols represent the depth of hypocenters classified in 20-km intervals. The three sizes of the symbols indicate the precision of the epicentral determination, governed mainly by the time resolution of the first arrivals and the clarity of the *S* phase. The larger symbols indicate the more precise determinations.

The two prominent features seen on the map are the asymmetrical distribution of the hypocenters around the Overlook Station and their dense distribution along the northeast- to southwest-trending volcanic range. In fact 411 of the 490 epicenters are southeast of a NE-SW line passing through the array. The most active seismic area lies from due east to due south of Overlook Station and includes most of the active volcanos. As has been described above, the high density of epicenters near Snowy Mountain is attributed to a swarm-type sequence. These events should be separated from a consideration of regional seismicity since swarm-type sequences usually continue only for a short period of time, several hours to several months.

To study the distribution of hypocenters in depth, the most accurately determined hypocenters were projected on a northwest-southeast vertical plane that is approximately perpendicular to the axis of the Alaska Range (Figure 10). About 60% of the events are shallower than 10 km and are distributed tightly around the volcanic axis. This phenomenon implies that the major part of the seismic activity at the Katmai area is associated with dynamic processes near the volcanos. Another 25% are less than 50 km deep and are distributed together with the deeper events in a root-like structure. The events with deeper origins may outline a boundary to the seismic domain dipping northwestward under the continent [*Benioff*, 1954]. The limited accuracy of the single tripartite technique and the limited number of data do not permit a much more detailed analysis of the distribution at this point.

Figure 11 shows a comparison of seismograms recorded at Brooks, Overlook, and Katmai Canyon. An earthquake from the Fourpeaked

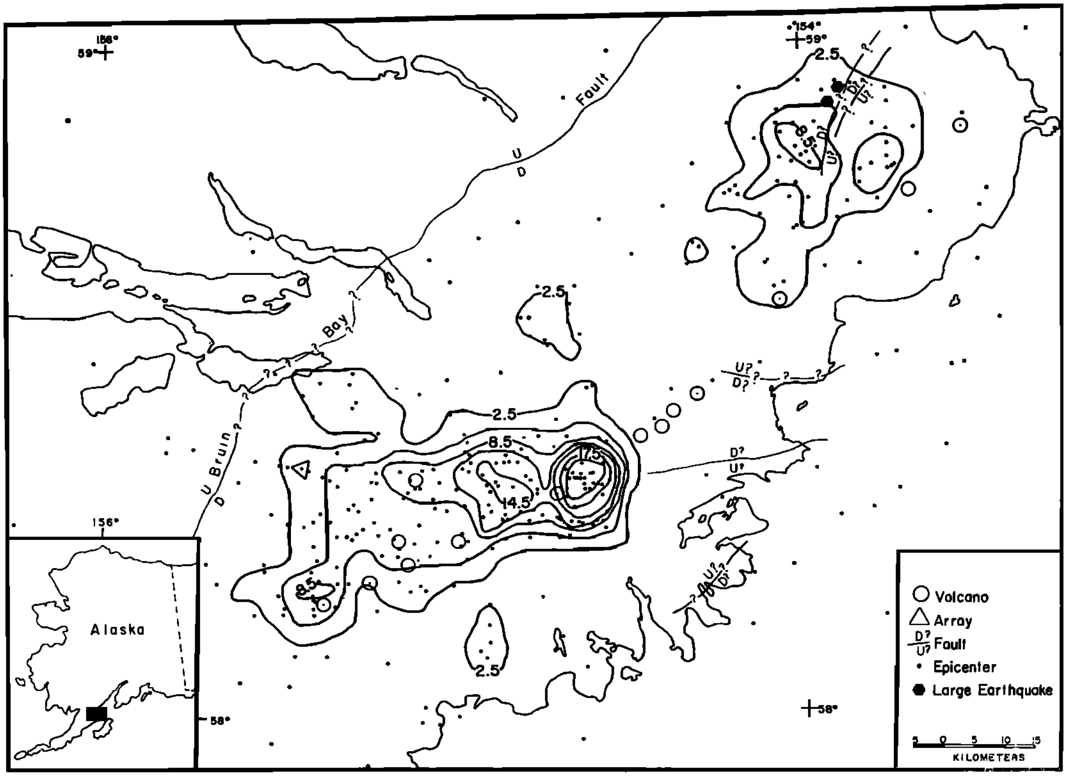

Fig. 9. Seismicity map of the Katmai region. The contour lines were based on the number of events included in a circle of 5-km radius counted on an arbitrary 5-km grid. The effect of distance on the number of events recorded and the accuracy of the epicentral locations has not been corrected for. Faults located by *Keller and Reiser* [1959] are shown for comparison. The cluster of epicenters in the northeast quadrant are primarily aftershocks of two magnitude 4.5 earthquakes whose epicenters are shown as relocated by *Ward and Matumoto* [1967] from teleseismic data.

TABLE 2. Number of Events with *S-P* Interval between 10 and 13 sec Following the Earthquake of July 21, 1966

Time (GMT) July 21, 1966	Number	Remarks
09h 00m 15s		Foreshock
09h 08m 17.6s		Main shock $m = 4.5$
09h 08m to 09h 38m	39	
09h 38m to 10h 08m	22	
10h 08m to 10h 38m	13	
10h 38m to 11h 08m	11	
11h 08m to 11h 38m	10	
11h 38m to 12h 08m	5	
12h 08m to 12h 38m	1	
12h 38m to 13h 08m	3	

Mountain area on July 21 (no. 422) had clear *P* and *S* phases at Overlook and Brooks but had no clear *S* as recorded at Katmai Canyon. Inversely, an earthquake on July 23 (no. 566) approaching Overlook across the volcanic axis from the southeast had a clear *S* phase at Katmai Canyon only. It should be noted first that the angles between Overlook and Katmai Canyon measured from the epicenter are 18° for no. 422 and 14° for no. 566. Since the *S* phases recorded at Katmai Canyon and Overlook came from a small area of the focal sphere, their differences cannot simply be explained by the focal mechanism. Second, the paths of the waves with no observed *S* phase cross the volcanic axis. Third, the seismograms that consist of a *P* phase alone show a lower predominant frequency than the seismograms that consist of both P and S phases. These phenomena imply a shadowing effect of magma chambers on the S phase and possibly the higher-frequency components of P rather than an effect of the source mechanism. The same phenomenon has been reported by *Gorshkov* [1954]. Such an effect would be of great value in the determination of volcanic structure and deserves further study.

Seismicity near Mount Trident in Early August 1965

From August 4 to August 6, 1965 (GMT), a heavy concentration of dust and some sulphurous fumes were noted in the Valley of Ten Thousand Smokes and the Brooks River area. Despite a careful compilation of all observations, it was impossible to establish clearly whether the dust was of aeolean or volcanic origin. During this period, however, Mount Martin was steaming vigorously and clouds of possible volcanic origin were observed to rise over Mount Trident. All visual observations have been compiled and discussed in detail by *Ward and Ward* [1966].

There was a slight increase in seismicity during early August. Figure 12 shows the epicenters in the Mount Trident and Mount Martin area. The solid circles are events between August 1 and 5. The records have been reread for these events in order to provide the most accurate epicenters possible. Figure 8 shows the increase not only in locatable earthquakes but also in B-type volcanic earthquakes, which are often associated with magmatic activity. The most pronounced increase over the average number of events was between the azimuths of 120° and 160°, the region near Mount Trident. Seven events occurred on both August 3 and 4, more than three times the average daily number. There was a general increase in seismicity throughout the Katmai region during this period. If there was a minor eruption at this time, this regional increase may be a reflection of the interconnections between the Katmai volcanos suggested by several earlier observations [*Ward and Matumoto*, 1967].

Prior to a major eruption, an increase of seismicity has been reported by *Minakami* [1960] at Mount Asama, Japan, and by *MacDonald* [1959] for the Hawaiian volcanos. This is not surprising since magma rising to the surface would provide new stresses in the crust. According to *Minakami* [1960], the number of earthquakes recorded during a calm period by seismographs with a peak magnification of 4000 near 4 cps and at distances from the crater of

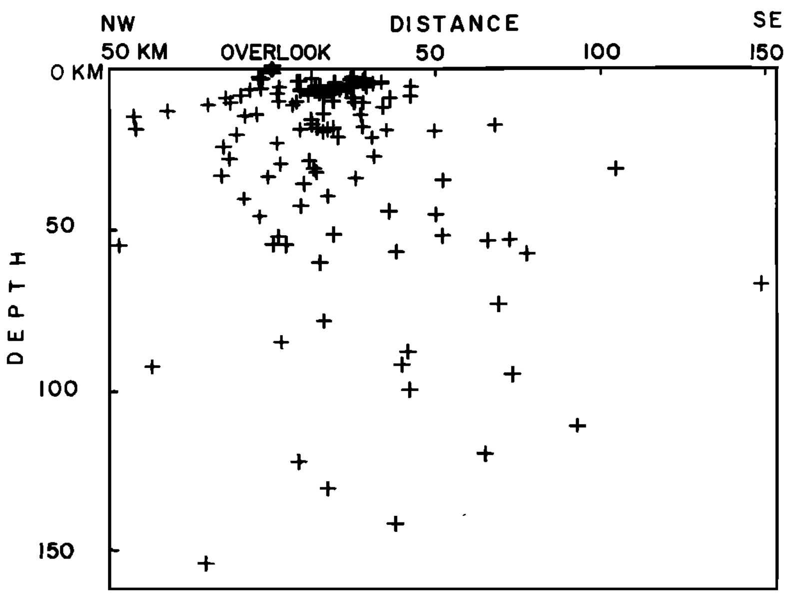

Fig. 10. The projection of the most accurately determined hypocenters on a northwest-southeast vertical plane that is nearly perpendicular to the axis of the volcanic range.

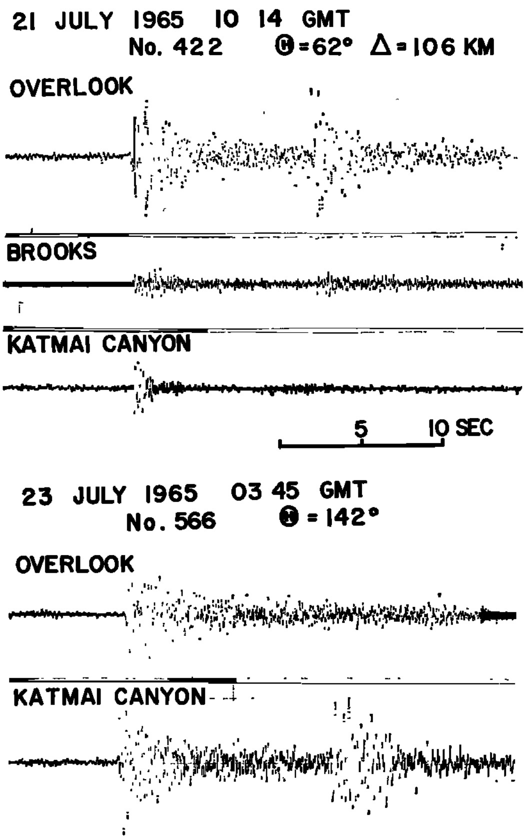

Fig. 11. A comparison of seismograms recorded at Brooks, Overlook, and Katmai Canyon. Disappearance of the *S* phase implies a possible shadow effect of a magma chamber.

Asama of 0.9, 2.5, and 4.0 km, were 20, 16, and 6 per day, respectively. There was an increase of several fold about two months before the commencement of eruptive activity and as much as twentyfold several days before an eruption. About 400 B-type volcanic earthquakes per day were associated with eruptions from October to December 1958, beginning 1 week before the first eruption.

It is of interest to compare the increase of seismicity observed in the Katmai region during early August to that preceding major eruptions of volcanos elsewhere. Mount Asama, in Japan, is in approximately the same tectonic environment and has a viscous magma with a silica content slightly lower than that in Katmai. To relate the 7 earthquakes, including both A- and B-types, recorded per day from the Mount Trident area on August 3 and 4 to Minakami's data, the number of events recorded is assumed to be proportional to the magnification of the instrument and to the inverse square of the distance from the volcano. With a value of 1×10^6 for the magnification at 5 cps and 25 km distance, an equivalent daily count recorded 0.9 km from Mount Trident would be $7 \times 4 \times 10^3/(1 \times 10^6) \times (25/0.9)^2 \approx 22$.

According to *Minakami* [1959, 1960], a measure of the kinetic energy (E) of an eruption can be estimated from the maximum amplitude (A) of the horizontal ground movement at a distance of 4 km during the largest eruption earthquake. For the energy range from 5×10^{17} to 5×10^{19} ergs, Minakami gives the formula

$$E = (0.03 + 4.5A + 0.75A^2 \pm 0.08) \times 10^{19} \text{ ergs}$$

He calculates an energy of 4×10^{19} ergs for the 1958 eruption of Mount Asama.

Using the same formula for the activity in the Katmai area in early August and substituting 2.0×10^{-3} mm for A, as recorded on a vertical seismometer and corrected to a distance of 4 km, the kinetic energy would be of the order of 4×10^{17} ergs. If we assume that the daily number of earthquakes associated with an eruption is proportional to the square root of the kinetic energy released, an eruption in the Katmai region of the order of that at

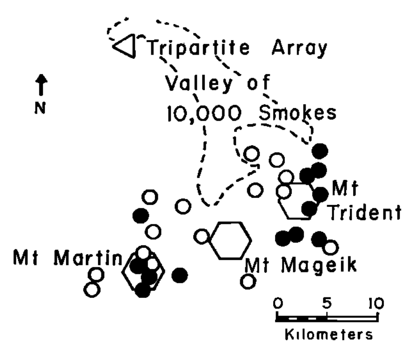

Fig. 12. The location of epicenters of earthquakes recorded during July and August from the Mount Trident-Mount Martin area. The closed circles indicate the earthquakes during the period from August 1 to 5, and the open circles are for the rest of the recorded period.

Mount Asama would have approximately 220 earthquakes per day during the active phase.

Conclusions

A high-gain high-frequency tripartite array has provided sufficient microearthquake data in 39 days to sketch the seismicity of Mount Katmai and vicinity. Figure 9 shows contour lines of seismicity based on the number of events within a circle of 5-km radius counted on an arbitrary 5-km grid. If the effect of distance on the number of events recorded and the accuracy of the epicentral locations were corrected for, there would probably be lower seismicity near the array and a closer clustering of events in the northeast quadrant of the map.

The most striking feature of this map is that regions of high seismicity fall predominantly along the volcanic range. A closer examination shows a fair correlation between regions of high seismicity and recent volcanic activity. Mounts Martin and Trident, both recently active [*Ward and Matumoto*, 1967], have moderate seismicity. Mounts Mageik, Novarupta, and Katmai, which have had little activity recently, show moderate to low seismicity. Mounts Kukak, Dennison, Stellar, Devils Deck, and Kaguyak have had nearly no reported activity and have very low seismicity. The most notable exception is Snowy Mountain, which has had no observed eruptions and which has the highest seismicity by a factor of two. Most of these events were in a swarm-type sequence. Their relation to possible future volcanic activity is not clear. Another exception is Mount Griggs, which has moderate seismicity but has had little recent volcanic activity; nevertheless, there was a very active fumarole near its summit during 1965.

With the epicentral uncertainty, the events in the northeast quadrant of Figure 9 could be associated with Mount Douglas and Fourpeaked Mountain, which have had little recent volcanic activity. Nonetheless these events appear to be associated with tectonic faulting, since they were primarily aftershocks of the two magnitude 4.5 earthquakes shown. This is more evidence of high microearthquake activity observed during limited periods in regions of recent faulting [*Oliver et al.*, 1966, and *Brune et al.*, 1967].

It should be noted that a comparison of large earthquakes from the Katmai region that have been recorded teleseismically since 1912 and observed volcanic data shows no distinct correlation between them [*Ward and Matumoto*, 1967]. This is particularly true in the better recorded period since 1950, even though the recent eruptions of Mount Trident have been heard and felt at Brooks Lake 50 km to the northwest.

The high acquisition rate of microearthquakes has allowed a detailed initial study of the seismic and volcanic activity in the Katmai region during a short field season. With the knowledge to be gained from a more detailed seismic study, already in progress, microearthquakes should prove to be a valuable tool in comparing the seismicity of many volcanic regions.

Acknowledgments. The authors wish to thank Mr. D. Coe and the National Park Service and Mr. R. Dewey and the U. S. Fish and Wildlife Service for their invaluable assistance with the field work. We also thank the University of Alaska for the use of the facilities in the Katmai area. Mr. W. Best, Geophysics Division, AFOSR, and Maj. Gen. Jensen, Alaskan Air Command, who kindly arranged and furnished precious air transport to reach the remote site. Finally, we are grateful for the perceptive guidance of Professor J. Oliver and the advice and comments of Professor R. Decker, Dr. E. Berg, Dr. J. Dorman, and Dr. P. Pomeroy.

This work was supported by the National Science Foundation under grant GP-4441.

References

Benioff, H., Orogenesis and deep crustal structure—additional evidence from seismology, *Bull. Geol. Soc. Am.*, *65*, 385–400, 1954.

Brune, J. N., C. R. Allen, F. Press, Microearthquake survey of the southern San Andreas Fault, *Bull. Seism. Soc. Am.*, in press, 1967.

Decker, R. W., Proposed volcano observatory at Katmai National Monument: a preliminary study, Dartmouth College, unpublished report, 54 pp., Nov. 1963.

Gorshkov, G. S., Volcanic tremor related to the eruption of Bylinkina volcano, *Akad. Nauk. SSSR Lab. Vulkanol., Byull. Vulkanol, Stantii*, no. 23, 33–37, 1954.

Hagiwara, T., et al., Research on the Matsushiro earthquakes (1), *Bull. Earthq. Res. Inst.*, *44*, 307–445, 1966.

Jones, A. E., Earthquakes recorded at the Kodiak and Dutch Harbor stations, *Volcano Letter*, *377*, 1932.

Keller and Reiser, Geology of Katmai, *U. S. Geol. Surv. Bull.*, *1058G*, 1959.

Matumoto, T., and R. Page, Microaftershocks following the Alaska earthquakes of March 28, 1964: Determination of hypocenters and crustal velocities in the Kenai Peninsula-Prince William Sound area, in *The Prince William Sound, Alaska Earthquake of 1964 and Aftershocks*, U. S. Coast and Geodetic Survey, Washington, D. C., 1966.

MacDonald, G. A., The activity of Hawaiian volcanos during the years 1951-1956, *Bull. Volcanol.* [2]*22*, 2-70, 1959.

Minakami, T., Fundamental research for predicting volcanic eruptions, 1, *Bull. Earthquake Res. Inst. Tokyo Univ.*, *38*, 480-496, 1960.

Minakami, T., et al., The study of eruptions and earthquakes originating from volcanos, parts 1-3, *Volcanol. Soc. Japan, Bull.*, [2] *4*(2), 104-114 1959; *4*(2), 115-130 1959; *5*(3), 133-151, 1960.

Miyamura, S., Seismicity and geotectonics, *Zisin*, *15*, 23-52, 1962 (in Japanese).

Mogi, K., Study of elastic shocks caused by the fracture of heterogeneous materials and its relation to earthquake phenomena, *Bull. Earthquake Res. Inst. Tokyo Univ.*, *40*, 125-173, 1962.

Mogi, K., The fracture of a semi-infinite body caused by an inner stress origin and its relation to earthquake phenomena (second paper), *Bull. Earthquake Res. Inst. Tokyo Univ.*, *41*, 595-614, 1963*a*.

Mogi, K., Some discussion on aftershocks, foreshocks and earthquake swarms—the fracture of a semi-infinite body caused by an inner stress origin and its relation to earthquake phenomena (third paper), *Bull. Earthquake Res. Inst. Tokyo Univ.*, *41*, 615-658, 1963*b*.

Nakamura, S. T., and Y. Kato, Earthquake swarm in the neighbourhood of towns Osarusawa and Hanawa in November 1936, *Zisin*, *9*, 159-164, 1937 (in Japanese).

Nasu, N., F. Kishinouye, and T. Kodiara, Recent seismic activities in the Izu Peninsula, *Bull. Earthquake Res. Inst. Tokyo Univ.*, *9*, 22-35, 1931.

Oliver, J., Alan Ryall, J. N. Brune, and D. B. Slemmons, Microearthquake activity recorded by portable seismographs of high sensitivity, *Bull. Seismol. Soc. Am.*, *56*, 899-924, 1966.

Sykes, L. R., and M. Landisman, The seismicity of East Africa, the Gulf of Aden, and the Arabian and Red Seas, *Bull. Seismol. Soc. Am.*, *54*, 1927-1940, 1964.

Thanos, S. N., A low-noise transistorized seismic amplifier, *Bull. Seismol. Soc. Am.*, *54*, 347-368, 1964.

Ward, P., and T. Matumoto, A summary of volcanic and seismic activity in Katmai National Monument, Alaska, *Bull. Volcanol.*, in press, 1967.

Ward, P., and S. Ward, Volcanic activity in Katmai National Monument, Alaska, in early August 1965, *Earthquake Note*, *37*, 19-34, 1966.

(Received August 5, 1966.)