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ABSTRACT

A continuously recording seismic network was constructed in 1962 by the U.S. Geological Survey to locate epicenters and record incidence of bumps (bounces, rock bursts) that occur in the bituminous coal mines of the Book Cliffs coal field near Sunnyside, Utah. The coal is mined because of its value as coking coal, although these bumps may be a hazard to life and property.

Daily records of tremors caused by bumps for 1-3/4 years indicate that a seasonal pattern, as well as a daily pattern, exists for the number of bumps that occur in a given period. Maxima occur in May and June and in November and December. Marked increases at 5- to 9-day intervals are superimposed on these seasonal maxima. The largest bumps commonly occur during seasonal maxima when the rate of occurrence suddenly decreases and the amplitude of the individual bumps increases. Knowledge of this pattern may lead to prediction of general locations and periods of increased hazard from bumps. Experience to date has shown that prediction of precise times and locations of hazardous bumps is not possible, and may never be, primarily because even a small bump can be a hazard to life and property. Some bumps or bump sequences are actually composites, consisting of two or more discrete bumps a few tenths of a second to a few seconds apart.

INTRODUCTION

Violent and spontaneous releases of coal and rock from faces, ribs, and roofs of mines (termed "bumps" or "bounces" by miners) are a common hazard to life and property in the coal mines located in the Book Cliffs near Sunnyside, Utah (Fig. 1). These bumps are generally the result of spontaneous releases of strain energy induced by local stress buildup. Most of the coking coal for the United States Steel Corp. mills at Provo, Utah, and for the Kaiser Steel Corp. mills at Fontana, Calif., is produced from these mines, which are worked though hazards to life and property may exist.

The U.S. Geological Survey began to investigate the mines in 1958 to determine whether or not many bumps were significantly influenced by geologic conditions. This work was originally undertaken at the request of, and in cooperation with, the U.S. Bureau of Mines. Since July 1961 the work has been carried on by the Geological Survey with continuing informal cooperation in the field. Detailed surface and subsurface mapping has revealed a close correlation between bumps and structural and lithologic conditions in the coal and associated rocks.[1]

1/ Publication authorized by the Director, U.S. Geological Survey.
2/ Geologists with the U.S. Geological Survey, Denver, Colo.

Bump activity was observed by the authors to vary with time during the subsurface and surface mapping. Activity in a bump-prone area apparently increased to a maximum and then decreased. Records of bumps were scarce, however, because miners were not present when many bumps occurred and did not report some that they did observe. Tremors from many such unreported bumps were felt during geologic fieldwork. The use of geophysical techniques was necessary to secure a record of bumps and to help study the complex interplay among bumps, geology, and existing engineering conditions--the use of the classic tools of geology was not enough.

Using a simple 3-component Sprengnether blast-and-vibration seismograph modified for 12-hour operation, Osterwald began to record tremors from bumps in the spring of 1960. Intermittent operation of this instrument for the following 1-3/4 years yielded these results: (1) many bumps were recorded that were not felt or observed in the mines, (2) frequencies of vibrations from many bumps were high, as much as 60 cycles per second or higher, and (3) at times bumps in the Sunnyside mines were frequent, at other times rare.

A continuously recording seismic network was considered necessary to determine epicenters of bumps. Many members of the Geological Survey assisted in the difficult and commonly unprecedented tasks of its planning and construction. Jerry P. Eaton assisted Osterwald in general planning. Construction of the recording station and the seismometer stations began in the summer of 1962. While the stations were being constructed, Osterwald helped John B. Bennetti, Jr., and D. R. Cunningham assemble amplifying and recording equipment. Jerry Hernandez assumed the responsibility of operating and maintaining the network during the winter months; first month of operation was January 1963.

The primary objectives of the network were: (1) to determine whether a pattern of bump incidence and location exists and, if so, whether hazardous bumps or bump-vulnerable areas can be predicted to save life and property; (2) to determine the origin of bumps by evaluating their recorded wave forms in terms of existing geologic and engineering conditions; and (3) to determine the cause or causes of time-dependent changes in bump activity.

INSTRUMENTS

The seismic network consists of three vertical Willmore seismometers arranged as a nearly equilateral triangle that is about 10 miles on a side (Fig. 1). Each seismometer is connected to a central recording station by 2-conductor military field telephone wire. Information supplemental to that of the basic network is obtained from two portable seismometer stations, one of which is located in the Sunnyside No. 1 mine, the other operated at various surface locations.

The seismometers of the basic network are housed within steel-reinforced concrete shelters anchored to bedrock. Ground motion induces voltage impulses from the seismometers. These impulses are amplified about 20,000 times by specially designed, battery-powered, transistorized preamplifiers and transmitted through as much as 20 miles of signal wire to the recording station.

At the recording station, the signals are amplified to a suitable level and recorded on 12-hour drum recorders. At present (1964), 660-mm amplitude on the chart represents approximately 1 mm of vertical ground motion. A synchronous time reference of 1-min interval is placed on the records of each seismometer station by a chronometer that induces a signal to each amplifier connected to a recorder. The time marks are referenced to National Bureau of Standards time by a radio receiver that traces a synchronous electrical impulse on each record at the beginning and end of each 12-hour recording period.

INTERPRETATION

Geologic and topographic setting: The Sunnyside seam, from which the coal is mined, occurs in a thick sequence of beds of sandstone, siltstone, and shale of Late Cretaceous age. These beds dip eastward 5^{o} to 15^{o}. The coal is underlain by a massive to thickly layered, fine to very fine grained sandstone, and is overlain by thin to thick layers of siltstone, sandy siltstone, limestone, and shale. Overburden thickness varies from a few hundred feet to 2500 ft. Erosion has sculptured bold cliffs as much as 2000 ft high from the dominantly resistant units associated with the coal (Fig. 1). Streams have dissected deep canyons 300 to 500 ft below the coal seam along the cliff front. The seismometer stations of the network are located on sedimentary rock layers of Late Cretaceous and Tertiary ages that are stratigraphically separated by as much as 3000 ft.

Interpretation of seismograms for location of bump epicenters: In general, seismograms of bumps occurring close to seismometer stations are characterized by wave groups of high frequency and large amplitude (Fig. 2). Frequencies for these close events may be as high as 60 cycles per second or even higher (bumps with frequencies well up in the audible spectrum were heard by the authors during underground mapping). The high-frequency wave groups are not clearly recorded or resolved by our present equipment at present recording speed, and the arrival time of the shear wave, which is necessary for determining an accurate epicentral location, may be obscured. Under these circumstances, interpretation of seismograms is a difficult and time-consuming task. During periods of maximum bump activity, much time is necessary to merely index them.

The correct origin time of a bump and the correct seismic velocity for the area through which the seismic waves travel are necessary to determine accurate epicentral locations. Determination of exact origin times of bumps has not yet been possible at Sunnyside. Such determination would probably require that a seismometer be recording at the site of the bump. This is, in most cases, impossible. Origin times of bumps are determined graphically (Fig. 3) by plotting the arrival time of the slower shear wave minus the compressional wave (t_s-t_p) versus the arrival time of the compressional wave (t_p) for each bump. The resulting curves are commonly linear functions for bumps monitored by the network. Since t_s and t_p must be coincident at the time of origin of the bump, the intersection of the curve with the abscissa is the origin time (t_o). A correct determination of origin time depends on the correct and consistent identification of the shear wave, which can be very difficult. Seismic velocities for the area are estimated from known locations of damage centers of bumps and graphically determined origin times. These damage centers may occur at ribs and faces that could be quite a distance from the bump foci, particularly if the bumps occur along faults or in mined-out areas; but the bumps may damage ribs and faces at a considerable distance away from the foci. This possibility could cause a large error in estimating seismic velocities, especially for those bumps that occur close to seismometer stations.

The epicenter of each bump is located graphically on a map of the network area by use of the arrival times of the compressional wave (t_p) at the several recording stations and by use of reconstructed origin times (t_o). A circle, whose radius is determined from the value of (t_p-t_o) times the estimated seismic velocity for the area, is drawn around each seismometer station recording the bump. Chords common to each pair of intersecting circles are then drawn. The point (or triangle) of intersection of these common chords is the epicenter of the bump.

Accurate location of epicenters depends on the identification and the arrival times of the compressional and shear waves, and, of course, on the accuracy of seismic velocities. The accuracy of location is in general probably within 500 to 1000 ft, but for some bumps may be less than 500 ft or more than 1000 ft. For example, the seismically determined epicenter for a violent bump that occurred in the Sunnyside No. 3 mine on Sept. 30, 1963, was 750 ft from the observed damage center.

RESULTS

A cyclic pattern in the number of recorded bumps per day occurs in all the coal mines within the seismic network, as well as within specific local areas. Daily records, from the No. 1 seismometer station, of the frequency of bumps since January 1963 (Figs. 4, 5) show that two seasonal and regional maxima occur, one in November and December and the other in May and June. Smaller, local increases also occur in January, February, March, April, and September. Superimposed on this seasonal variation are maxima at 5- to 9-day intervals. Records of bumps from a seismometer in the left side of the Sunnyside No. 1 mine reveal a generally similar pattern in this local area; variations in the pattern are caused by local geologic conditions and mining methods (Fig. 6). The 5- to 9-day cycle is similar to that observed by Blanchard[2] at Springhill, Nova Scotia, but is not directly related to coal production (Fig. 4) as was Blanchard's cycle.

Since recording began, most large bumps have occurred during periods of increased bump abundance. These large bumps commonly occur when the daily bump rate suddenly decreases from the 5- to 9-day peak levels and the amplitude of individual bumps commensurately increases. Many epicenters of large bumps in the Sunnyside district have been located near faults or fault intersections that are part of an extensive north-northwest fault system transecting much of the area. Some of these bumps (or bumplike phenomena) occur near faults in unmined areas and may actually represent spontaneous stress releases along faults. The stress may be caused by either tectonic or mining activity or by both.

Case histories: One of the most violent bumps in the history of the Sunnyside district occurred at 7:50 a.m. on Dec. 24, 1963, in the faulted area of the right side of the Sunnyside No. 2 mine (Fig. 7). The bump climaxed a period of increased bump activity that began during the last week of October 1963 (Fig. 4). Small to moderately large bumps occurred in this part of the mine on Nov. 29, and on Dec. 1, 3, 4, 6, 11, 12, 15, 19, 21, and 23. Many of these bumps occurred within 500 ft of faults, a distance which roughly corresponds with the limit of accuracy of location obtained by the intersecting-circles method. The number of bumps recorded each day increased progressively for about 6 weeks, then decreased markedly for about 2 weeks. The magnitude of individual bumps increased during the time of the numerical decrease. Several bumps were located in the right side of the No. 2 mine. The location of the large bump on Dec. 24 was determined seismically to be near two faults that intersect at nearly right angles, although violent and extensive damage was reported by miners at a large pillar about 1000 ft northwest of this location. The large-amplitude wave recorded at the seismic stations may have been caused by stress release in coal or rock near the fault intersection which triggered a smaller release of stress (bump) in the large pillar, or the violent bump in the pillar may have been merely the visible damage area caused by a violent release of energy at the fault intersection.

A moderate bump, which caused the deaths of two miners, was recorded by two seismometers at 3:45 p.m. on June 3, 1964, in an active mining area of Sunnyside No. 1 mine. The bump was actually a composite, consisting of four bumps that were 3 to 5 sec apart; the first of these was of largest amplitude (Fig. 2A). A miner who escaped reported that the men started to leave at the sound of the first bump. Two men and a continuous miner (mining machine) were covered by rock and coal from the roof when the second bump occurred. This sequence of bumps, which was only one in a series of damaging bumps throughout the Sunnyside district during early June 1964, was preceded by a buildup of seismic activity similar to that preceding the bump of Dec. 24, 1963. About April 5, 1964, the number of bumps per day began to increase progressively. About May 28, the number of bumps per day dropped markedly, but the magnitude of bumps increased. A seismometer located underground in the Sunnyside No. 1 mine, 800 ft from the site of the fatal bump of June 3, began to record a marked increase in the number of bumps on June 1, and on June 3, recorded a maximum number of 1167 (Fig. 6). Most of this local activity consisted of very small bumps that were detected by the other stations of the network. After June 3, the number of bumps per day recorded by this instrument decreased.

In the area of the Geneva mine the number of bumps per day began to increase about May 18, 1964. Instrument failures prevented accurate determination of locations, but most bumps were thought to occur in the southern part of the mine. On June 5 at 11:44 p.m. a bump of large magnitude occurred in the southern part of the mine (Fig. 2B). At approximately the same time, fan-gauge records at the mine showed a sudden drop in air pressure equivalent to pressure exerted by 0.7 inch of water, probably as a result of an air blast produced by the bump. Concrete block stoppings were blown out by concussion, pillars were crushed, the roof was sheared and caved, and raise workings and crosscuts were almost completely filled with coal in a 300- by 500-ft area. The epicenter of this bump, as determined from seismic records, was located 2.5 miles north of the damage area near a fault in an unmined area. Two small bumps that were also thought to be in the south part of the Geneva mine occurred at 11:48 and 11:52 p.m. The large-magnitude bump probably originated at the site of the extensive damage in the mine, but it may have resulted from stress release along the fault.

These case histories indicate that precise times and places of hazardous bumps are very difficult to predict. Periods of increased activity, hence of potential hazard, in generalized locations can be predicted by careful interpretation of seismograms. The reliability of such predictions depends upon the location of seismometers with respect to a seismically active area, the precision of the instruments used, and the time and methods available for analysis of the seismograms.

CONCLUSIONS

Bumps in the Sunnyside area are cyclic on both seasonal and weekly scales. On the basis of records obtained over the 1-3/4-year period from Jan. 14, 1963, to Sept. 25, 1964, it is determined that seasonal maxima occur in November and December and in May and June, and that weekly maxima occur every 5 to 9 days. Some recorded seismic events are composites consisting of two or more separate bumps that occur a few tenths of a second to a few seconds apart.

Seismic methods are a useful supplemental tool to the study of the geologic and engineering causes of coal mine bumps in the Sunnyside district. Case studies of the large and damaging bumps of Dec. 24, 1963, June 5, 1964, and of others reveal a general pattern of preceding incidence and amplitude that may permit future prediction of general areas of perhaps a square mile or less in which large, damaging bumps could occur within a time span of a few days. Most large bumps occur during periods of increased district-wide activity. They commonly happen when the daily bump rate sharply decreases from a very high level and when almost simultaneous commensurate increase in amplitudes of the individual events occurs. We cannot predict now, and may never be able to predict, a definite time and place in which a specific bump will occur. However, further extensive research on the specific nature of generation and transmission of seismic waves through the entire Sunnyside mining area may permit a closer approach to such a goal. Unfortunately, for purposes of prediction, a small or even seismically undetectable bump can be a serious, but local, hazard to life and property, whereas a large bump in an abandoned area of a mine may not be hazardous.

ACKNOWLEDGMENTS

The study was greatly facilitated by the cooperation of Kaiser Steel Corp. and United States Steel Corp. John Peperakis, of Kaiser Steel Corp., had the site for the recording station leveled and an access road built and maintained; without his help we could not have operated nor could we have continued to operate the system. R. M. von Storch and Ray Bowen, of United States Steel Corp., had an access road rebuilt and provided many other facilities without which the work would have been much more difficult.

REFERENCES

[1]F. W. Osterwald, and C. R. Dunrud: Geology applied to the study of coal mine bumps at Sunnyside, Utah, SME-AIME paper, 1965.

[2]J. E. Blanchard: Memorandum submitted to the Royal Commission appointed to enquire into the upheaval or falls or other disturbances commonly called bumps at No. 2 mine, Springhill, Nova Scotia, on the 23d day of October 1958, in McInnes, Donald, Wilton-Clark, Harry, and McLachlan, Thomas, Report of the Royal Commission appointed to enquire into the upheaval or fall or other disturbance sometimes referred to as a bump in No. 2 mine at Springhill, in the County of Cumberland, Province of Nova Scotia, operated by the Cumberland Railway and Coal Company, on the 23d day of October, A. D. 1958, 9 p., Appendix C.

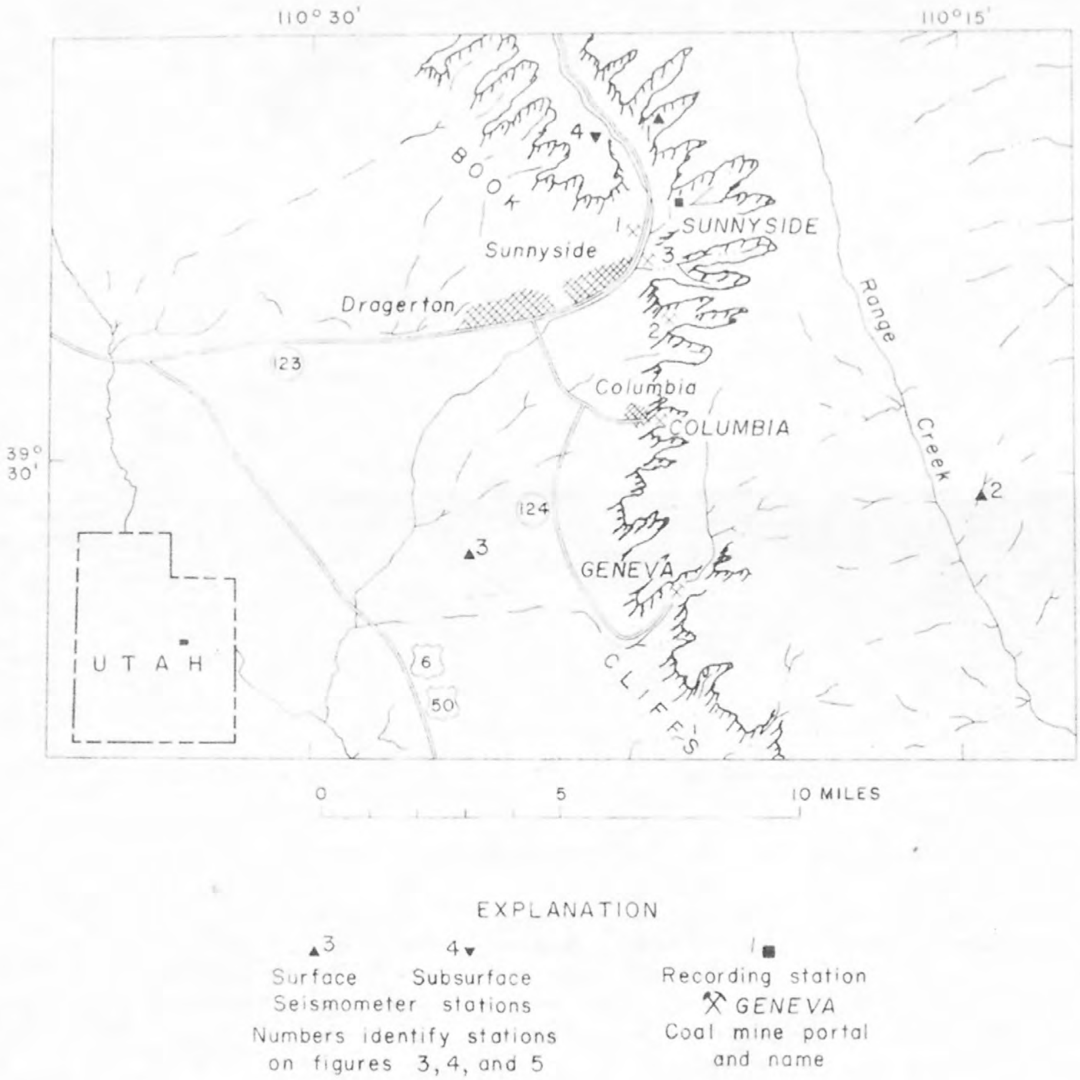
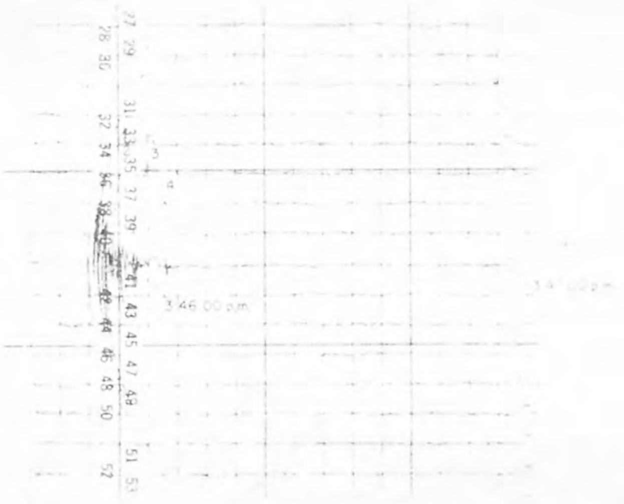
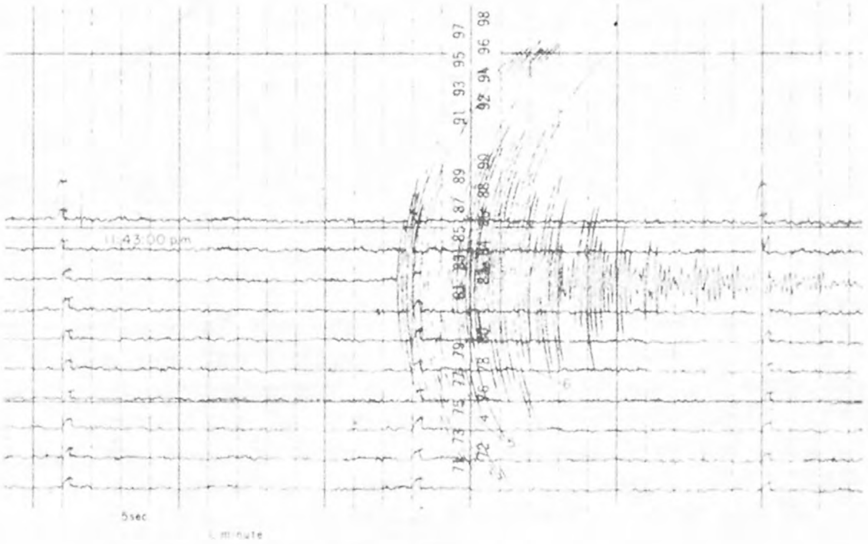


Figure 1.--Relief map of the Sunnyside area showing location of seismic stations and of coal mines under investigation.



a



b

Figure 2.--Seismograms of two bumps--time marks are at 1-minute intervals. a. A bump consisting of 4 separate impulses which occurred in the 11th left entry at the Sunnyside No. 1 mine at 3:45:49.8 p.m., June 3, 1964, and that caused the deaths of two miners. b. A bump which occurred in the 7th west raise of the south part of the Geneva mine at 11:43:57.1 p.m., June 5, 1964, and which caused extensive damage to workings and machinery.

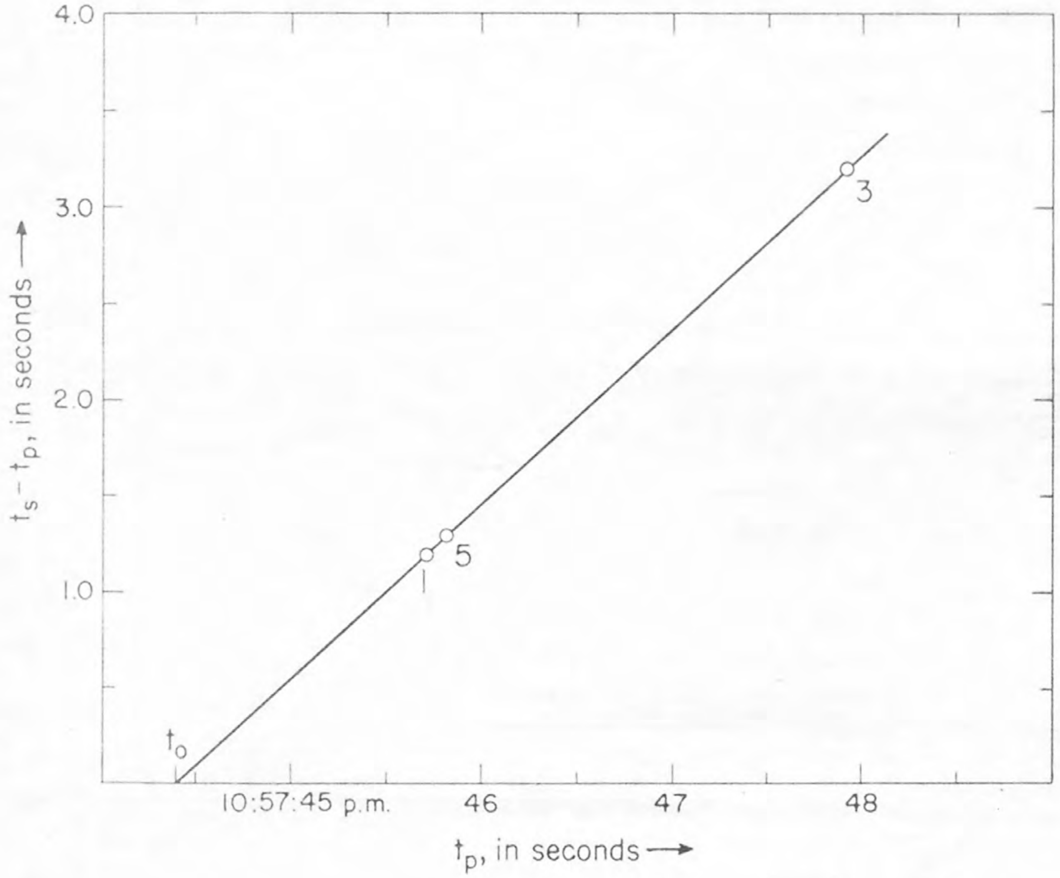


Figure 3.--Graph of the arrival time of the shear wave (t_s) minus the arrival time of the compressional wave ($t_s - t_p$) versus the arrival time of the compressional wave (t_p) for a moderately large bump which occurred at 10:57:44.4 p.m., June 8, 1964, in the long wall section of the Sunnyside No. 3 mine. The origin time (t_o) is determined from the intersection of the curve and the abscissa.

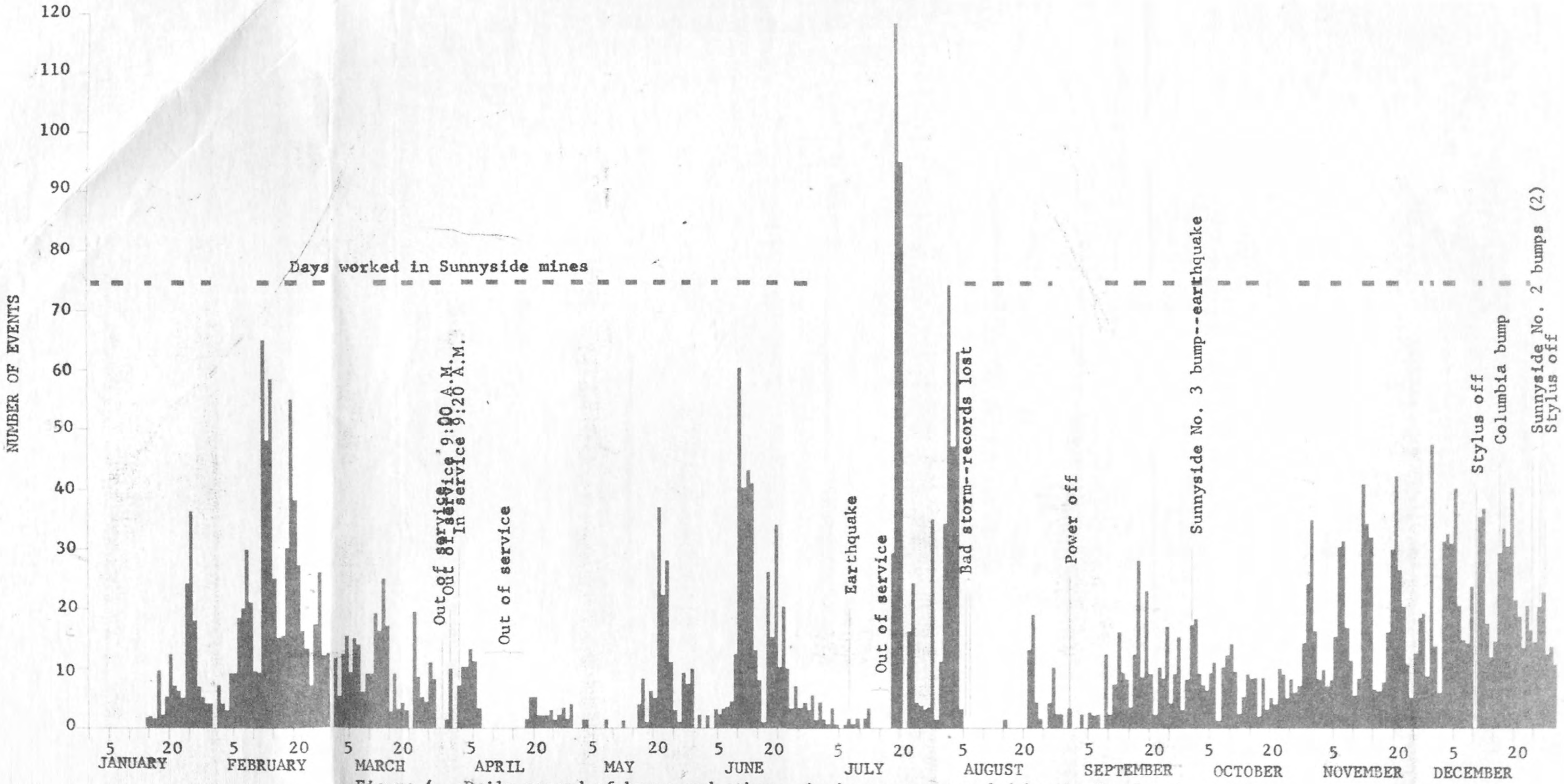


Figure 4.--Daily record of bumps and other seismic events recorded by the No. 1 seismometer station, located in Bear Canyon, for the period Jan. 14 to Dec. 31, 1963.

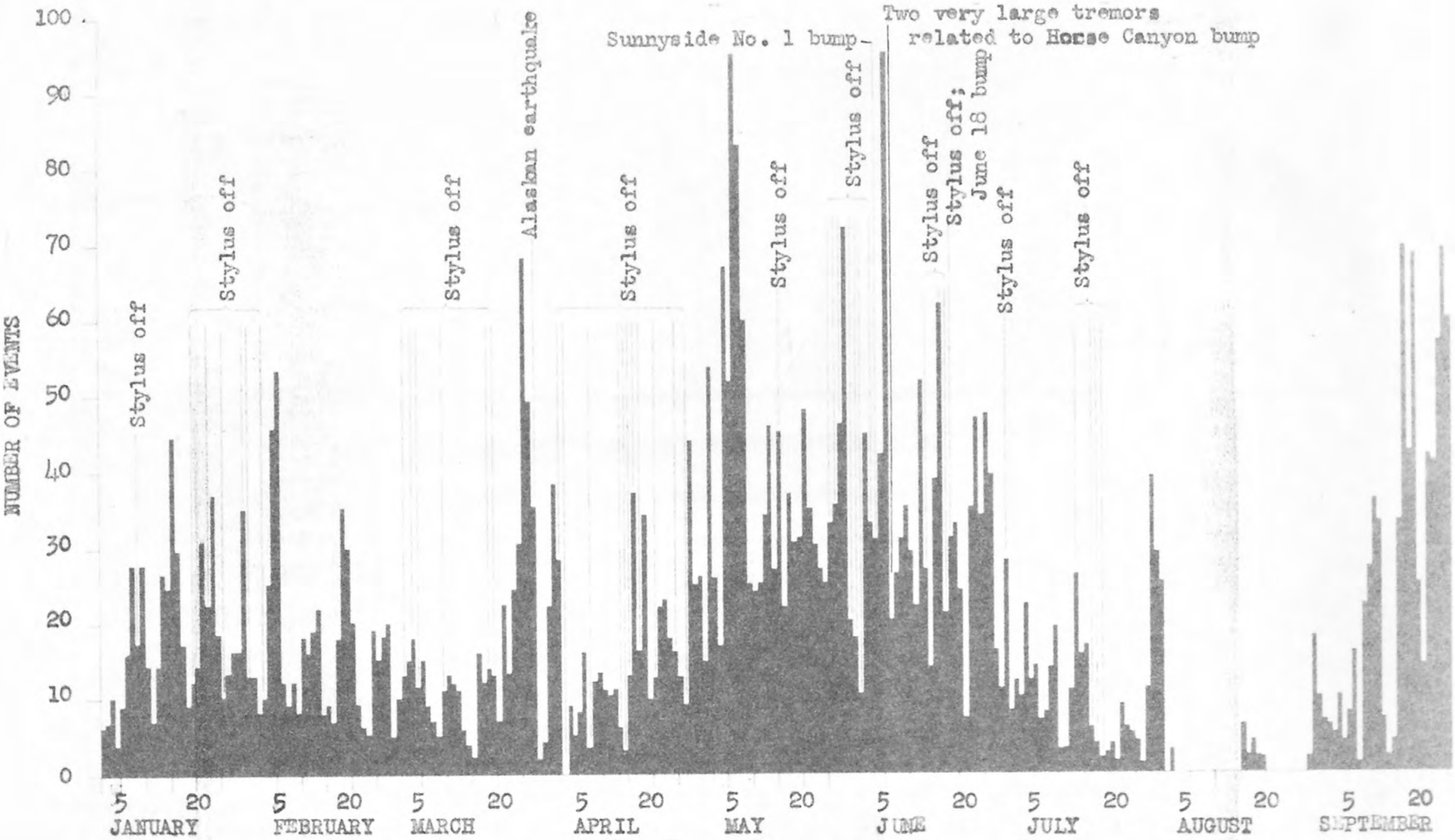


Figure 5.--Daily record of bumps and other seismic events recorded by the No. 1 seismometer station, located in Bear Canyon, from Jan. 1 to Sept. 25, 1964.

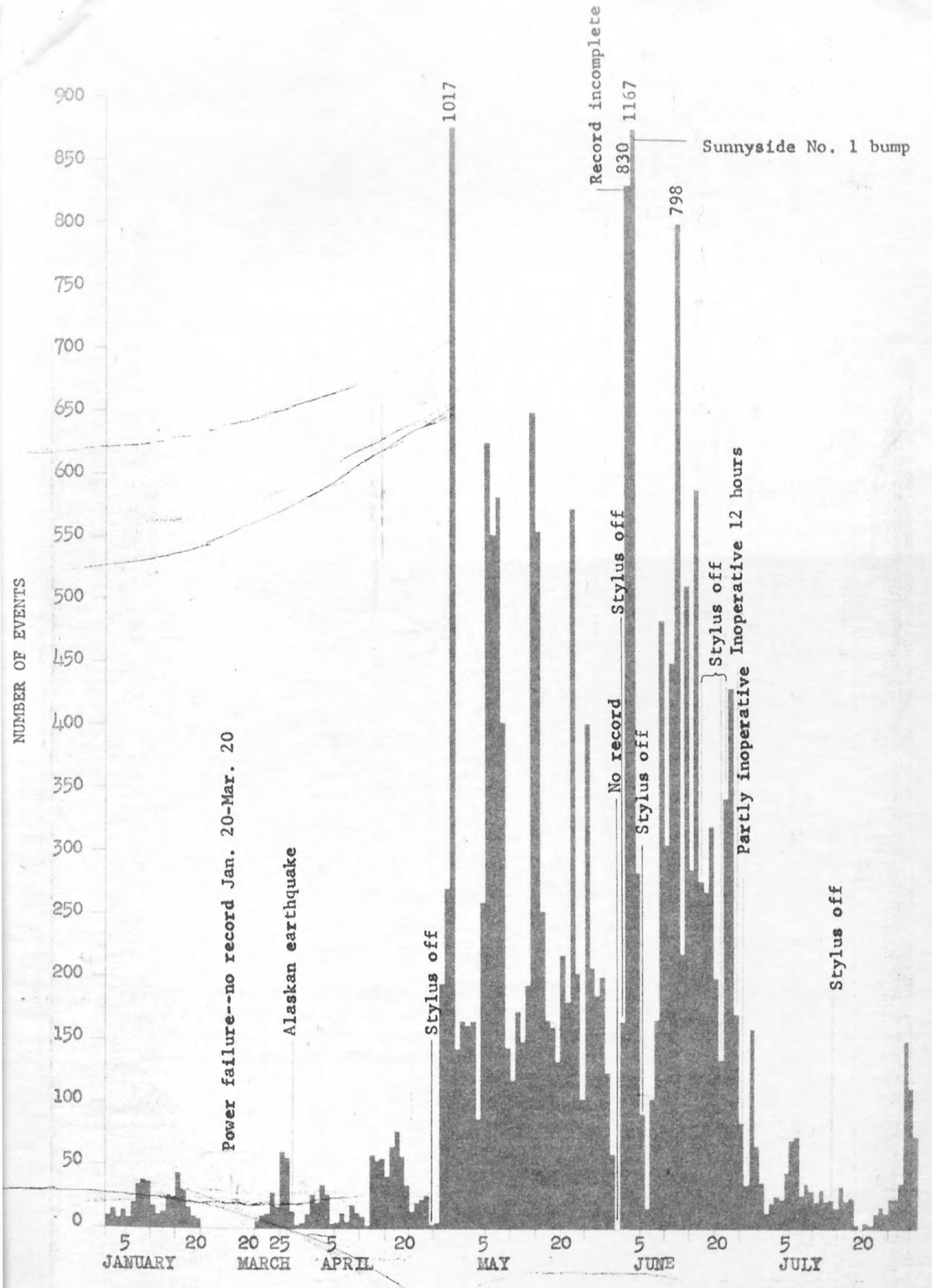


Figure 6.--Daily record of bumps and other seismic events recorded by the No. 5 seismometer station, located in the left bleeder of the Sunnyside No. 1 mine, for the period Jan. 1 to July 30, 1964.

Figure 7.--Map of a part of the right side of the Sunnyside No. 2 mine showing the extensive damage center (+) and the seismic location (x) of a very large bump which occurred at 7:50 a.m., Dec. 24, 1963. Pillars that have been extracted are indicated by crosshatching.