Jour. Research U.S. Geol. Survey
Vol. 3, No. 3, May–June 1975, p. 345–361

ROCKFALL SEISMICITY—CORRELATION WITH FIELD OBSERVATIONS, MAKAOPUHI CRATER, KILAUEA VOLCANO, HAWAII

By ROBERT I. TILLING, ROBERT Y. KOYANAGI, and ROBIN T. HOLCOMB,
Hawaiian Volcano Observatory, Hawaii

Abstract.—During August 7–13, 1972, intense and sustained rockfall activity occurred in Makaopuhi Crater on the east-rift zone of Kilauea Volcano. In a 4-day period (August 7–10), approximately 270,000 m^3 of rockfall debris accumulated in Makaopuhi's west pit, representing a total kinetic energy release of about 10^{19} ergs. Because the rockfalls happened within an area with an established seismic network, it was possible to correlate the seismic record of the rockfalls with onsite field observations. The seismic signatures of rockfalls are generally distinguishable from those of earthquakes and other recorded events. Approximate magnitudes determined for some of the largest rockfalls range from 0.8 to 1.2, corresponding to calculated seismic energy releases of 2×10^{11} to 10×10^{11} ergs, if the magnitude-energy relationship for earthquakes is applicable to rockfalls. The August 1972 swarms of rockfalls at Makaopuhi correlate in time not with moderate or large earthquakes but rather with local eruptive activity and are inferred to have been caused by eruption-induced modifications of stress patterns of the crater walls. However, the amount and nature of the stress change required to exceed the threshold stability of the crater wall and to trigger a rockfall flurry cannot be determined. The Makaopuhi activity is typical of most major rockfall episodes in other Kilauean pit craters in recent years, which also have been associated with volcanic activity, particularly during times of changes in eruptive behavior.

Landslide phenomena (avalanches, earthflows, rockfalls) have been studied intensively by civil engineers, engineering geologists, and geomorphologists but have received scant attention from seismologists. To our knowledge, very few publications contain mention of instrumentally recorded seismicity presumed to be generated by landslides. Richter (1958, p. 155, 156) describes ground motions thought to have been produced by slumps related to petroleum-drilling operations near Terminal Island, Calif. Rockfalls have long been observed at Kilauea (for example, Jaggar, 1930a, b), and even with the rather crude seismic instruments in operation shortly after the Hawaiian Volcano Observatory was established in 1912, attempts were made to distinguish between "seisms" and "tremors" of the "avalanche type" and those clearly of earthquake origin (see any volume of the Hawaiian Volcano Observatory Bulletin). Records from the modern dense seismic network on the island of Hawaii (fig. 1) indicate that rockfalls generate characteristic seismic signals that may be used to monitor such activity on remote areas of the volcano. The seismic network consists of 35 telemetered stations and two independent stations (one at Hilo and the other at Haleakala, Maui).

This report describes some especially vigorous rockfall activity at Makaopuhi pit crater (fig. 2) during August 1972, the most intense and sustained such activity recorded in recent years. Some of the largest rockfalls were observed, timed, and photographed, thus permitting correlation of the on-the-scene observations with the seismicity generated by the rockfalls. This provided an opportunity to calibrate the response of the seismic network to the rockfalls and thereby interpret the seismic records for rockfalls not directly observed. This report is intended to draw special attention to the potential of using seismic techniques in investigations of landslide processes.

Acknowledgments.—We gratefully acknowledge the help of our colleagues at the Hawaiian Volcano Observatory, who have participated in some of the field excursions to Makaopuhi Crater and provided stimulating discussion regarding the nature and causes of the rockfalls observed. We also thank G. F. Kaye, National Park Service, and G. A. Macdonald, University of Hawaii. for field observations and photographs of rockfall activity on August 9.

SETTING OF THE ROCKFALLS

Makaopuhi is the largest of several craters that indent Kilauea's east rift zone (fig. 1). Although it may have been much more complex, the formation of Makaopuhi appears to have resulted principally from two episodes of prehistoric collapse of the south flank of the lava shield Kane Nui o Hamo (fig. 2). The first collapse probably produced an elliptical pit about 1.3 km long, 1.0 km wide, and 200 m deep. This pit was partly filled by a lava lake and later flows totaling about 90 m thick. Subsequent collapse centered on the

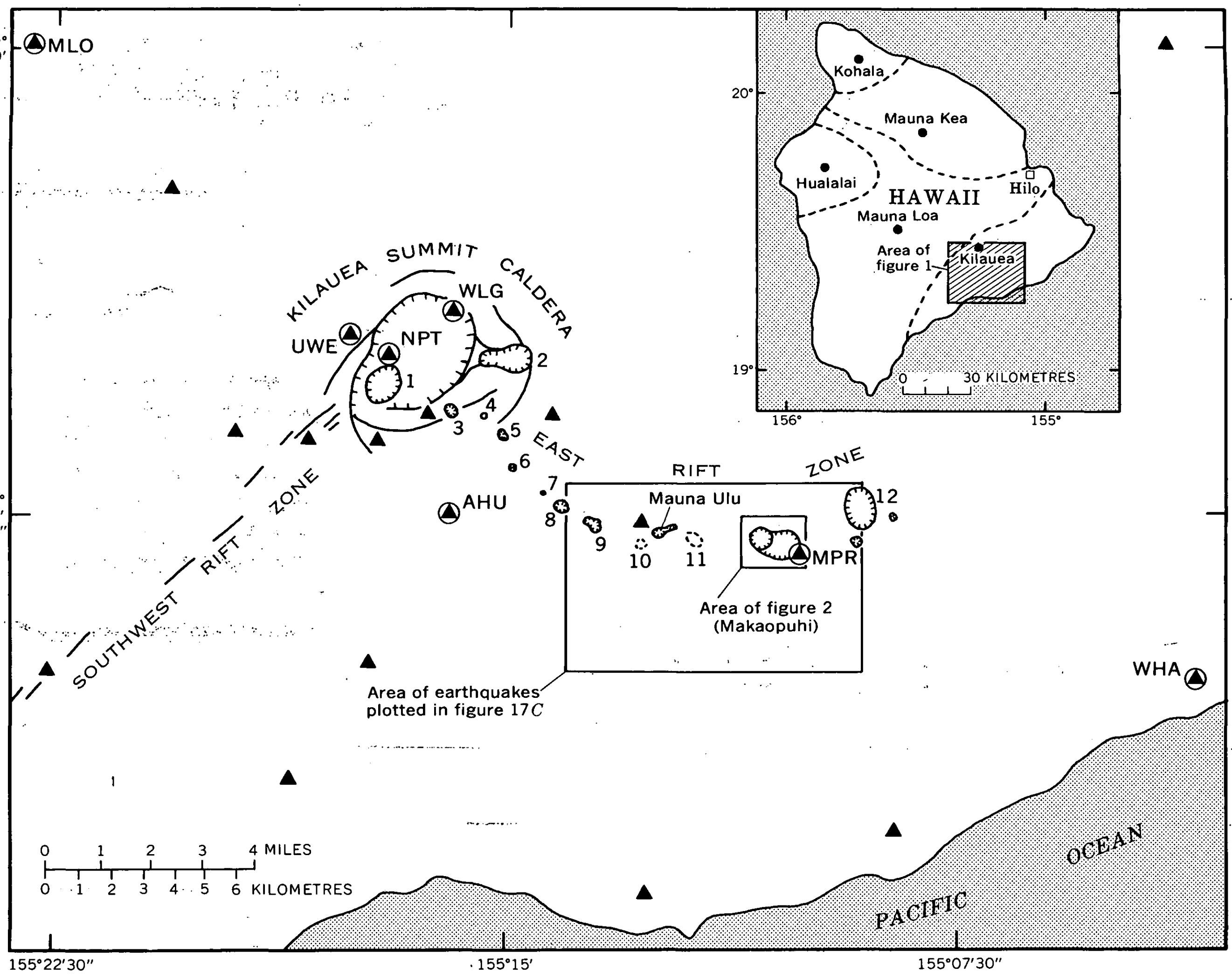

FIGURE 1.—Generalized map showing the location of Makaopuhi Crater relative to the summit caldera and rift zones of Kilauea Volcano. In addition to Makaopuhi, other Kilauean pit craters shown are 1, Halemaumau; 2, Kilauea Iki; 3, Keanakakoi; 4, Lua Manu; 5, Puhimau; 6, Kokoolau; 7, Devil's Throat; 8, Hiiaka; 9, Pauahi; 10, Aloi (buried); 11, Alae (buried); and 12, Napau. Twenty of the 35 telemetered seismic stations operated by the Hawaiian Volcano Observatory are shown by triangles; the stations (MLO, WLG, NPT, AHU, MPR, UWE, and WHA) mentioned specifically in the text are circled. Inset in upper right hand corner shows the five volcanoes that form the island of Hawaii; their summits are indicated by dots.

west rim elongated the crater to about 1.6 km and left the flat floor of the eastern compartment standing as a mezzanine about 200 m above the floor of the western pit.

In historic time Makaopuhi has been partly filled by lavas, and its steep-sided walls have been the site of many rockfalls. In 1922, lava that erupted from the northwest wall of the crater covered the floor of the western pit with a thin veneer (Stearns and Macdonald, 1946). In March 1965, lava that erupted from vents on the northwestern and northern walls produced a lava lake 83 m deep in the western pit and a small lava pad on the mezzanine (Wright and others, 1968). After the 1965 eruption, rockfalls began to litter the crust of the lava lake. Some rocks fell from the southern and eastern walls of the western pit, but most fell from the high north wall of the pit and accumulated as a talus cone adjacent to the main 1965 vent. In addition, a few larger rockfalls from the southeastern wall of the eastern pit littered the margin of the mezzanine. This activity peaked in late 1968 and early 1969 as eruptive activity and earthquakes in the east rift zone apparently triggered more rockfalls. Several rockfalls were recorded on the seismic network, and a few of the larger ones were observed and photographed by the Volcano Observatory staff (fig. 3). In February 1969, lava from fissures west of Makaopuhi cascaded over the western rim of the crater, and an aa

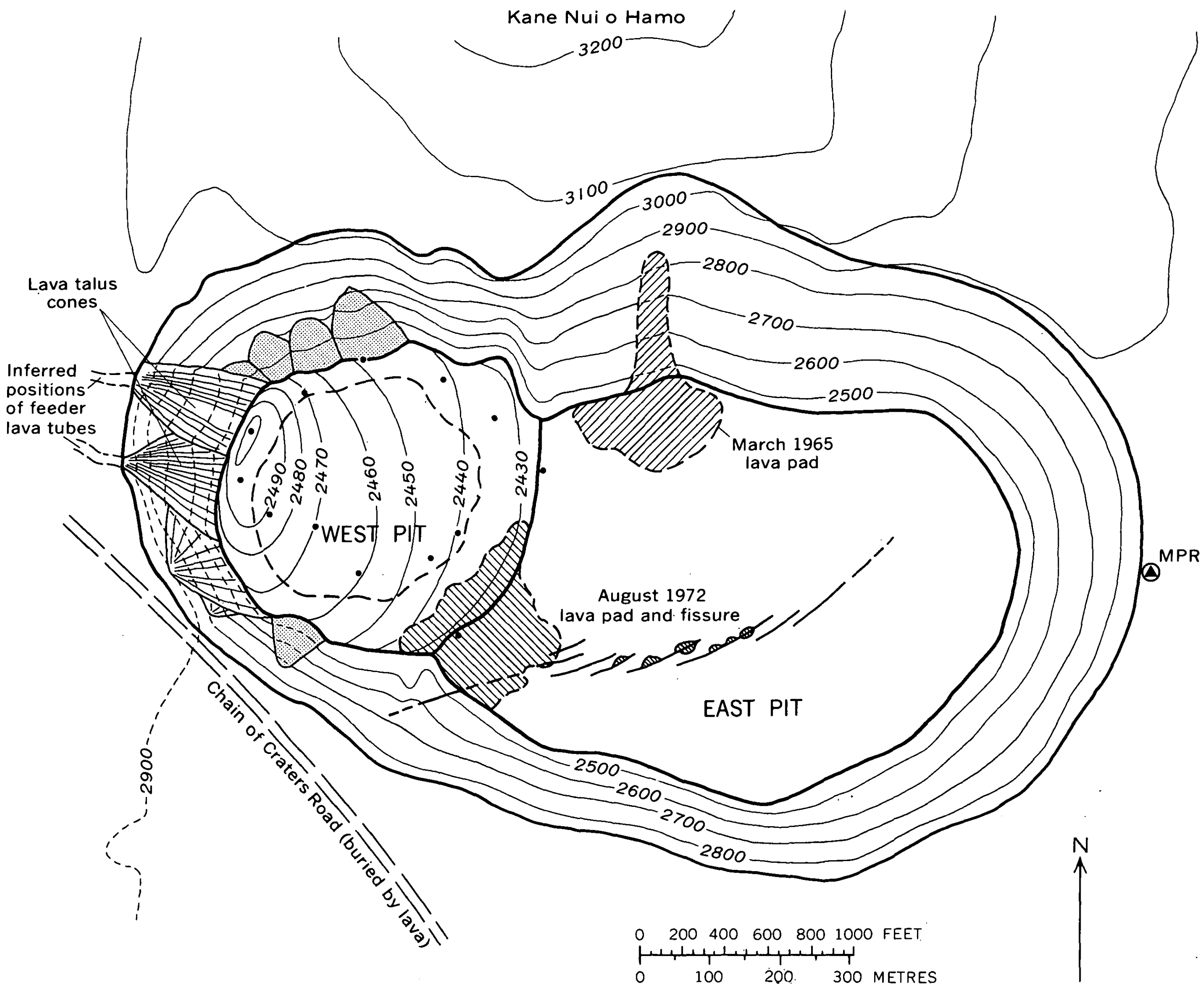

FIGURE 2.—Sketch map, refined by transit measurements and aerial photographs, showing the configuration of Makaopuhi Crater on August 10, 1972, and the distribution of rockfalls (shaded) in its west pit. The seismic station (MPR) closest to the site of rockfall activity is located on the eastern rim. The topographic base is from the Makaopuhi Crater 7½-min quadrangle (1:24,000) of the U.S. Geological Survey (1963) modified by elevation data obtained by transit measurements. The inferred buried perimeter of the west pit (dashed line) after the March 1965 eruption is estimated from the data of Wright, Kinoshita, and Peck (1968). Stations in the west pit used for repeated transit measurements are indicated by dots.

flow about 3 m thick covered much of the 1965 lake surface (Swanson and others, 1975). In 1969 eruptive activity was localized at Mauna Ulu (Swanson and others, 1971) about 3 km west of Makaopuhi, and rockfalls in Makaopuhi temporarily ceased.

From March 1972 to March 1973, the west pit of Makaopuhi intermittently received tube-fed lavas from the Mauna Ulu–Alae region (Tilling and others, 1973). Inflow continued, with variations in rate but no interruptions, from mid-June through late August of 1972 and almost filled the west pit to the level of the mezzanine (fig. 4). All the lava filling the west pit originated from the Alae vent, except possibly for lava fed by a brief, small-volume fissure eruption on the mezzanine observed on August 9 and 10 (fig. 4). (The precise beginning of the mezzanine eruption is not known but can be bracketed between late afternoon of August 7 and early morning of August 9.) Peak rockfall activity coincided with the eruptive outbreak on the mezzanine, suggesting a genetic association between them. Inflow from Alae vent apparently stopped in late August but then resumed sporadically and less copiously in succeeding months. At the end of the final inflow in March 1973, the west pit was completely filled by a

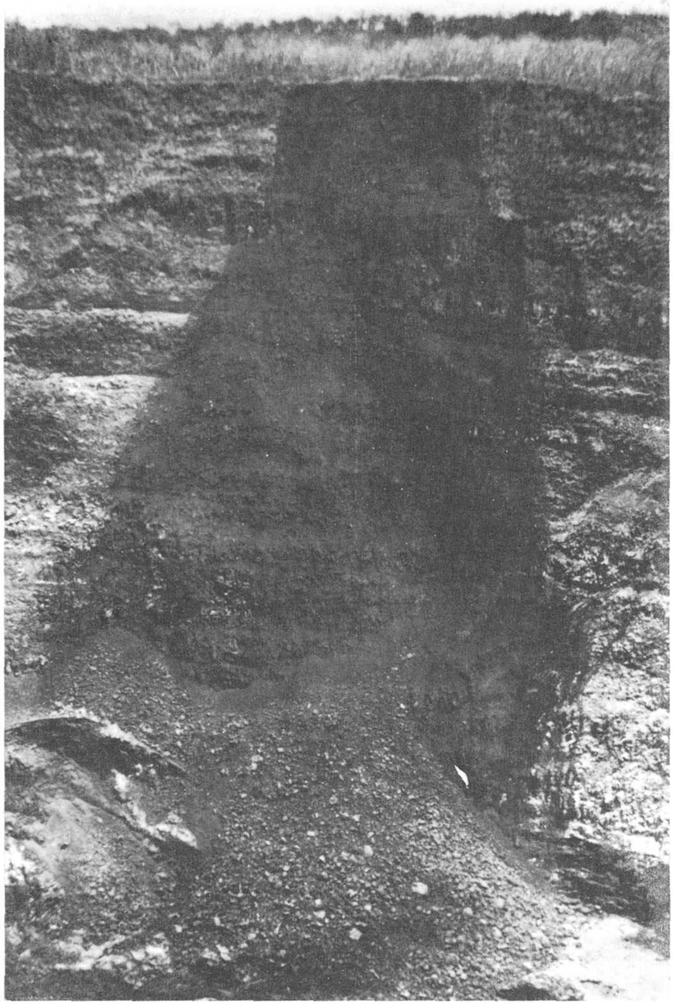

FIGURE 3.—View of the north wall of Makaopuhi's west pit immediately after a rockfall in March 1969, showing the dark fresh scar and rockfall talus. The vertical distance from the rim to the crater floor is approximately 220 m. Part of the March 1965 spatter cone can be seen in the lower left corner. (Photograph courtesy of J. C. Forbes.)

lava pile which spread over nearly two-thirds of the east-pit floor. This partial filling of Makaopuhi Crater, like the earlier complete filling of Alae Crater (Swanson and others, 1972), was complex.

FIELD OBSERVATIONS OF THE ROCKFALLS

During June–August 1972, periodic observations were made to measure the rate of filling of the west pit of Makaopuhi and to document the accumulation of lava-talus cones by the infalling of lava against the west wall of the crater. A few rockfalls occurred during June and July, but not until early August did we begin to take special notice of the rockfall activity. Table 1 summarizes all observed and inferred rockfall activity in Makaopuhi during August. Observations were made from vantage points along the rim of Makaopuhi, from the mezzanine, and from the floor of the west pit itself during a leveling survey on August 10 (during which wary glances were cast at the crater walls).

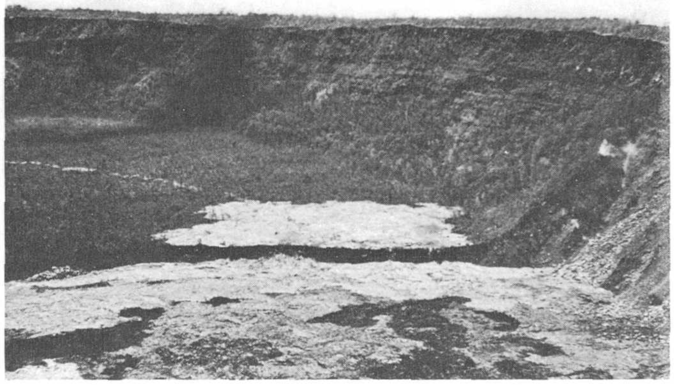

FIGURE 4.—View of Makaopuhi on the morning of August 10, 1972, from its west rim showing the fissure and lava pad related to the eruptive outbreak in its east pit (mezzanine). Two active lava cascades over the mezzanine brink into the west pit may be seen in the southern (right hand) part of the August 1972 lava pad. The surface of the lava in the west pit (foreground) was approximately 9 m below the mezzanine at this time.

Rockfall activity on August 10, 1972

The most complete observations of rockfalls were made on August 10. We consider the activity on that day to be representative of the more vigorous activity during the August 7–13 period. On the morning of August 10, Makaopuhi had the general configuration shown in figures 2 and 4. Three coalescing rockfall-talus cones against the north wall had accumulated since late afternoon of August 7 (fig. 5); another large cone lay against the south wall. Numerous small rockfalls trickled down the north wall nearly continuously. Lava from the mezzanine fissure vent, first observed on August 9, continued to spill into the southeastern part of the west pit, while lava entered the west part of this pit via the tube system leading from Alae (figs. 2 and 4). The floor of the west pit was a broadly domical surface gently sloping toward the mezzanine; much of the floor periphery consisted of a low moatlike area several meters wide into which lava tended to flow.

Observed rockfalls on August 10 typically began as a cohesive mass that slowly but perceptibly peeled away from the wall. Within seconds after the onset of downslope movement, however, the mass fragmented as it fell (fig. 6), forming a shower of debris ranging from blocks measuring several meters in diameter (fig. 7) to

TABLE 1.—*Summary of rockfall activity in the west pit of Makaopuhi Crater during August 1972*

[N.o., no observations]

August	Onsite observations			Large rockfalls recorded seismically			
	Rockfall time [1]	Rockfall location	Remarks	Time [2]	Approximate duration (s)	Magnitude [3] (M_b)	Seismic energy [4] release (ergs)
1	------	N.o	N.o	-------	------	------	--------
2	------	Scattered	Very infrequent and small	-------	------	------	--------
3	------	N.o	N.o	-------	------	------	--------
4	------	Mainly west wall	Few and small	-------	------	------	--------
5–6	------	N.o	N.o	-------	------	------	--------
7	≈1130	Mainly north wall, but widespread.	During observation period (morning and afternoon) rockfalls generally small but nearly continuous.	1938 S	54	1.1	7×10^{11}
	≈1200			2022 S	45	1.1	7×10^{11}
	≈1600						
8	------	N.o	N.o	-------	------	------	--------
9	------	All around pit, but mainly north wall.	Many rockfalls some very large; photographed but not timed by observers.	1120 M	62	0.8?	2×10^{11}
				1244 M?	64	0.8?	2×10^{11}
				1501 M	72	0.8?	2×10^{11}
				1837 S	49	0.8?	2×20^{11}
				1844 M	76	0.8?	2×10^{11}
10	1055	North wall	Nearly continuous rockfalls in various parts of the pit, but mainly off north wall.	0021 M?	94	0.8?	2×10^{11}
	1107			0640 M?	50	0.8	2×10^{11}
				0704 M	57	0.8	2×10^{11}
	1155*			1156 M	113	1.2	1×10^{12}
	1205*			1206 M	242	1.1	7×10^{11}
	1213	South wall	------------------------	-------	------	------	--------
	≈1230	Nose of northern lava tube, west wall.	Large rockslide. As impressive visually as many of the rockfalls, but little seismicity recorded.	-------	------	------	--------
	1625	South wall, near west edge of mezzanine.	------------------------	1340 M	151	1.1	7×10^{11}
11	≈0900	North wall	Many small falls closely spaced in time.	0528 M?	65	0.8?	2×10^{11}
	1053	Northern lava tube, west wall.	Scattered smaller falls elsewhere, but mainly the north and south walls.	-------	------	------	--------
	1058						
12	0900	Uncertain	Evidenced by large dust cloud observed upon approach to pit.	-------	------	------	--------
13	------	N.o	N.o	0655 S?	56	1.0	7×10^{11}
14–15	------	N.o	N.o	-------	------	------	--------
16	------	N.o	None seen during period of observation.	-------	------	------	--------
17–22	------	N.o	N.o	-------	------	------	--------
23	------	N.o	No obvious activity	-------	------	------	--------
24–31	------	N.o	N.o	-------	------	------	--------

[1] Beginning times (Hawaiian standard time) of moderate or large rockfalls (relative to others observed for a given day). Rockfalls denoted by * were recorded seismically as large falls; time shown may not agree exactly with the more precise timing from the seismic record.
[2] Beginning times of large rockfalls recorded at seismic station MLO, 26 km distant (see text); S, single event; M, multiple event.
[3] Determined from seismic amplitudes measured on Uwekahuna (UWE) Sprengnether short-period records.
[4] Calculated from magnitudes of events after Richter's (1958) equation: $\log E = 9.9 + 1.9\,M_b - 0.024\,M_b^2$, where E is energy in ergs and M_b is magnitude of the local earthquake.

dust-size particles. As they fell onto the talus cone, these fragments were sorted crudely by size so that the coarser debris was concentrated near the base of the cone. During the observed rockfalls, most of the descending debris remained near the crater wall, sliding or bouncing down it. However, many blocks, especially those produced by shattering of originally larger blocks upon secondary impact (against the wall or other blocks) during descent, fell freely for several to many meters before striking the wall again or the floor of the pit. Some blocks traveled considerably farther than other debris and came to rest as much as 10 m beyond the toe of the talus, appearing as isolated blocks on the lava surface. As debris continued to fall from the crater walls, sluggish lava flows slowly engulfed the toes of the cones. Rockfall and eruptive activity overlapped complexly; field relations show that some blocks fell into or were partly buried by molten lava (fig. 8), whereas others came to rest on solidified lava crust.

The rockfalls were accompanied by tremendous crashing sounds and copious clouds of dust, some of which rose 100 m or more into the air. We were too close to the source to photograph the large dust plumes originating at Makaopuhi, but figure 9 shows a similar rockfall-generated dust cloud at Mauna Ulu in May 1973. The large rockfalls generally were preceded and followed by flurries of smaller rockfalls. On one occasion a rockfall from the north wall was followed within seconds by a flurry of smaller rockfalls, not only in the vicinity of the original fall but also elsewhere along

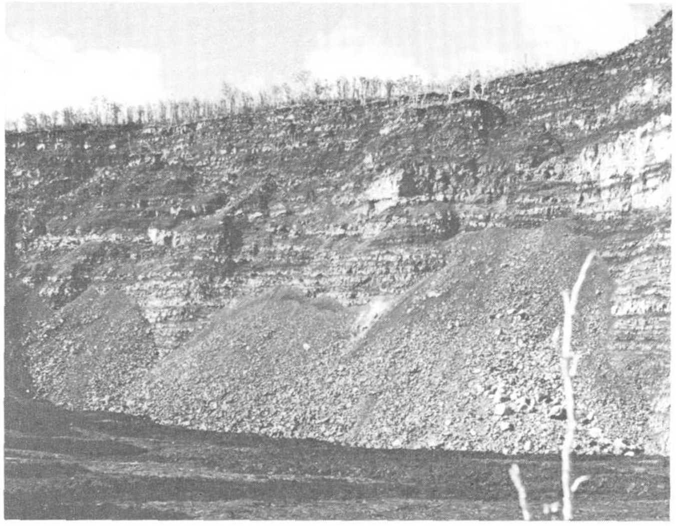

FIGURE 5.—View of the north wall of Makaopuhi's west pit on August 12, 1972, showing the three rockfall-talus cones, which were well developed by August 10 as a result of vigorous rockfall activity that began on August 7 (see fig. 2). Note the small rockfall in progress between the two cones near center of photograph. The vertical distance from the rim to the crater floor is approximately 150 m.

the north wall and, to a lesser extent, the south wall. These observations suggest that large rockfalls may trigger smaller rockfalls. Because of the overlapping nature of the rockfalls, it was not possible in the field to determine precisely the duration of any given rockfall; hence, we recorded only the beginning times of rockfalls visually larger than background activity (table 1). However, in general the larger rockfall episodes lasted about 1 to several minutes.

Estimate of mass of rockfall debris

Because rockfalls were virtually continuous and overlapping during periods of peak activity at Makaopuhi, it was impossible to obtain the repeated field measurements necessary to determine the mass of any given rockfall or series of rockfalls. However, field observations and photographic evidence prove that the major rockfalls shown in figure 2 took place during August 7–10; a much smaller but unknown amount of material was added to these rockfall-talus cones between August 11 and 13. Measurements from a topographic map of the talus cones along the north wall yield a calculated aggregate volume of about 2.7×10^5 m^3 of debris (adjusted for 20 percent open spaces)[1] accumulated during August 7–10. This estimate is crude but probably accurate to within a factor of two or less. Assuming the average bulk density of the rock to be about 2.6 g/cm^3, the total mass of rocks that fell during the 4-d period would be approximately 7.0×10^8 kg, or 7.0×10^5 metric tons.

Assuming complete transformation of gravitational potential energy to kinetic energy, the rockfall debris would represent a total maximum energy release of about 10^{19} ergs. Some of the large individual blocks (for example, those shown in fig. 7) have volumes on the order of 10 m^3 and could generate about 4×10^{14} ergs. Similarly, using the same assumptions, the estimated volume of the debris produced in the large rockfall (8,000 m^3) shown in figure 6 would represent an energy release of about 3×10^{17} ergs. A rockfall episode at Mauna Ulu crater on August 31, 1971, that involved about 5,000 m^3 of debris falling approximately 70 m could generate about 9×10^{16} ergs (Hawaiian Volcano Observatory, unpub. data, 1974).

ROCKFALL SEISMICITY

Seismic network

Details concerning the seismic network and instrumentation of the Hawaiian Volcano Observatory have been published elsewhere (Endo and others, 1972; Koyanagi and others, 1972; Koyanagi, 1969); hence only a brief description is given here. Most seismometers in the network are battery-operated, short-period vertical instruments, whose signals are transmitted to the observatory via radio or cable; a few stations are not linked to the observatory. Signals received at the observatory are recorded on 16-mm film by two Develocorders and on smoked paper as well for a few selected stations. The seismic records are read daily, and foci of earthquakes, depending on magnitude or urgency of need for information, are located either manually at the observatory or by computer in Menlo Park or both.

Standard Hawaiian Volcano Observatory telemetered seismic recording systems on the Develocorder film viewer have a peak magnification of 2×10^5 at a period of 0.1 s. For periods between 0.1 and about 1.0 s, the response falls off 6 dB per octave (Endo and others, 1972). With the instrumental response and preset recording speed, our reading capability to differentiate seismic wave frequencies is limited to periods of about 0.1 to 1.0 s (or about 10 to 1 c/s).

Seismic signature of rockfalls

Natural seismic events recorded and analyzed at the Hawaiian Volcano Observatory include local earthquakes, teleseisms, harmonic tremor, and, if pronounced and prolonged, rockfall activity. Other disturbances recorded but not routinely analyzed include

[1] The unadjusted figure (that is, for no open spaces) would be $3.4\times10^5 m^3$; regardless of the amount of open spaces assumed, the calculated kinetic energy rounds out to 10^{19} ergs.

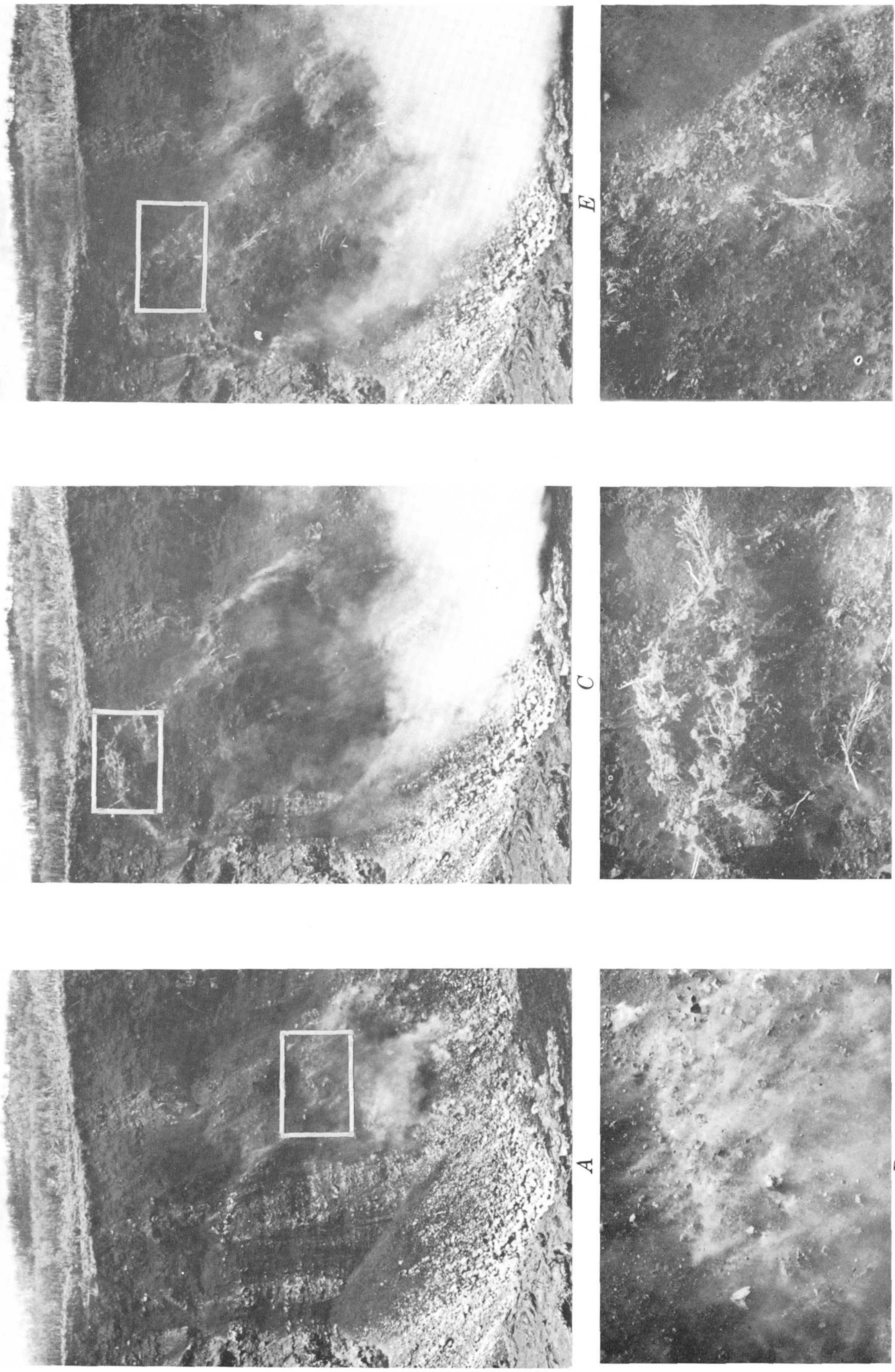

FIGURE 6.—Sequential views of the large rockfall flurry at 1205, August 10, 1972. (See figs. 13, 15, 16, and table 2 for the seismic data recorded for this event.) Trees at the rim are between 6 and 10 m tall. *A*, Photograph taken at 1204 showing a rockfall in progress prior to the collapse of the western half of the block which was already detached from the wall (top center); inset gives the approximate area shown in *B*, a telephoto view taken at about the same time. *C*, Photograph taken at 1205 showing the downward movement and disintegration of detached crater-wall block; inset gives the area shown in *D*, a telephoto view taken a few seconds later. *E*, A view of the rockfall a few seconds later showing complete disintegration of block; inset gives the approximate area shown in *F*, a telephoto view taken at about the same time.

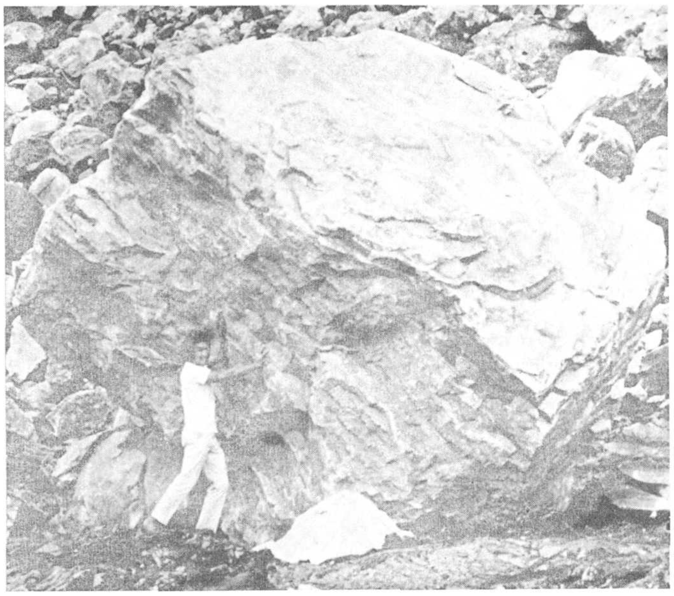

FIGURE 7.—One of the large blocks that fell during the rockfall episode shown in figure 6.

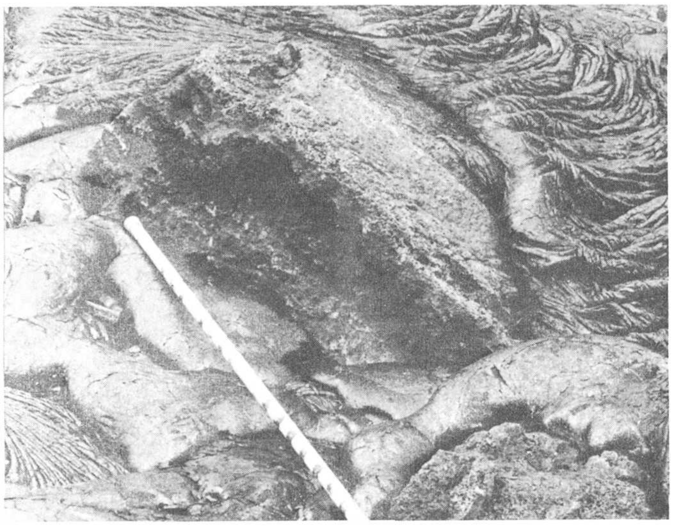

FIGURE 8.—Closeup view showing lava oozing around a block that probably fell into molten, or at least still plastic, lava; markings on range pole are about 3 cm.

seismic noise related to extreme weather conditions (wind, rain, high surf, lightning, thunder), occasional large quarry blasts, vehicular and pedestrian traffic, and sonic disturbances caused by military firing exercises.

Seismic events are commonly recorded at frequencies varying from about 1 to 10 c/s with diverse amplitude characteristics. Local short-period (S–P) earthquakes occurring near a station yield patterns characterized by very high frequency, large amplitude, relatively short duration, and sharp onset, giving a single-cone appearance to the seismic trace (fig. 10*A*, *a*). More distant

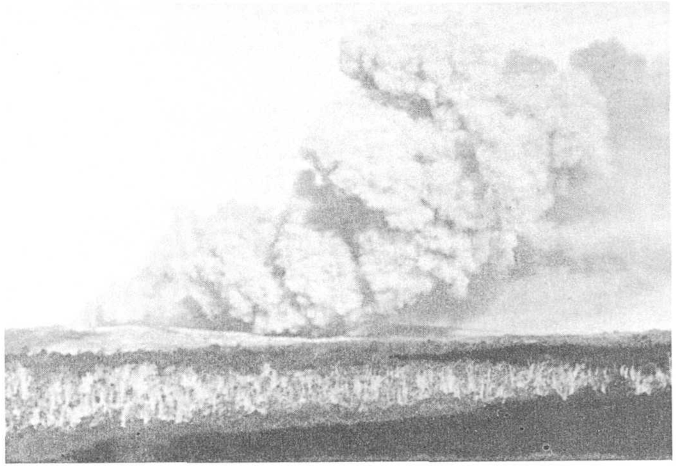

FIGURE 9.—A dust cloud generated by a large rockfall that occurred at Mauna Ulu during May 1973, (photograph taken by J. C. Forbes from the Hawaiian Volcano Observatory approximately 11 km away). The top of the cloud is about 540 m above the ground; this dust cloud was larger than similar clouds generated during the August 1972 rockfall activity in Makaopuhi.

but still local earthquakes produce a double-cone pattern characterized by high frequency and distinction between primary (P) and secondary (S) waves (fig. 10*A*, *a*). For local long-period (L–P) quakes, the onset of the seismic phase is emergent (that is, gradual), commonly with some high-frequency waves preceding or superimposed on the predominant low-frequency waves (fig. 10*A*, *b*). The trace for a teleseism shows long-period, nearly sinusoidal P-waves recorded at about 1 c/s; deep events generally have sharper onset (fig. 10*B*, *a*). The waterborne teleseismic phase (T-phase) gives a cigar-shaped pattern with nearly sinusoidal waves recorded at a frequency of about 2 c/s that is generally recorded widely across the seismic network (fig. 10*B*, *b*).

Harmonic (volcanic) tremor (see Finch, 1949; Omer, 1950; Shimozuru and others, 1966), typically recorded before and during eruptive activity, is believed to be caused by movement of lava (surface) or magma (subsurface). This type of continuous microseismic disturbance (fig. 10*C*) may last from several minutes to many days or even many months; recorded frequencies commonly range from about 2 to 5 c/s. Disturbances due to extreme weather conditions, blasting, gunfire, or traffic are not discussed here, but their seismic traces (fig. 10*F–J*), in general, can be readily distinguished from earthquakes, harmonic tremor, and rockfalls (see also Krivoy and others, 1967; Krivoy and Eppley, 1964).

The seismic signature of a rockfall (fig. 10*D*) is characterized by relatively emergent (that is, gradual)

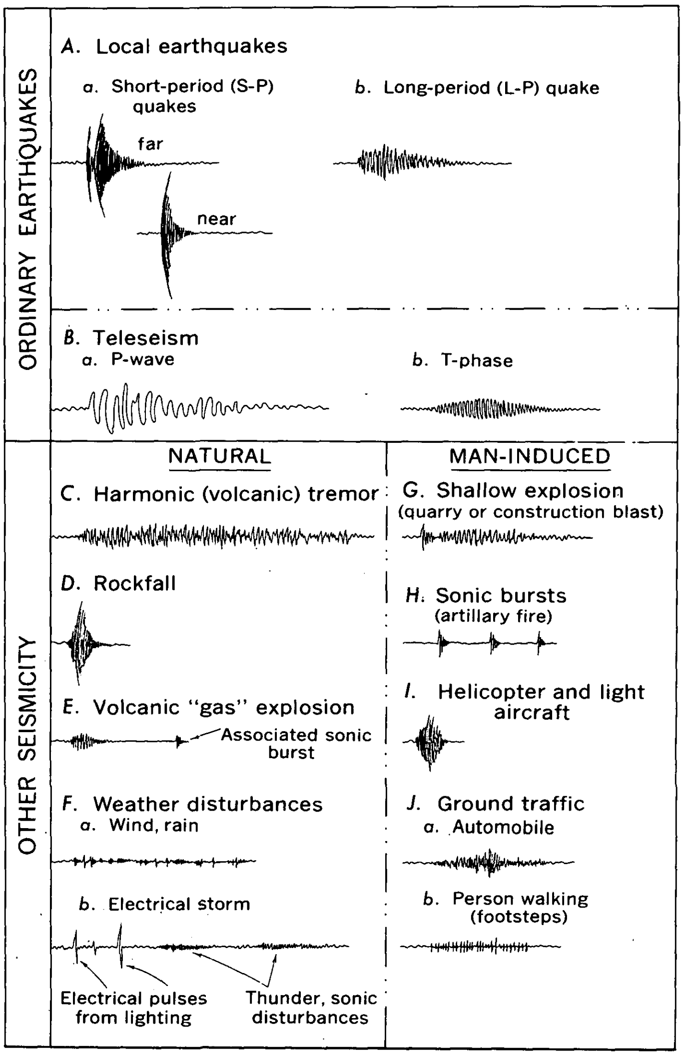

FIGURE 10.—A schematic comparison of various seismic traces of natural and man-induced events. These sketches portray seismic disturbances often observed on 60 mm/min smoke-drum recordings from the stations located around the summit of Kilauea.

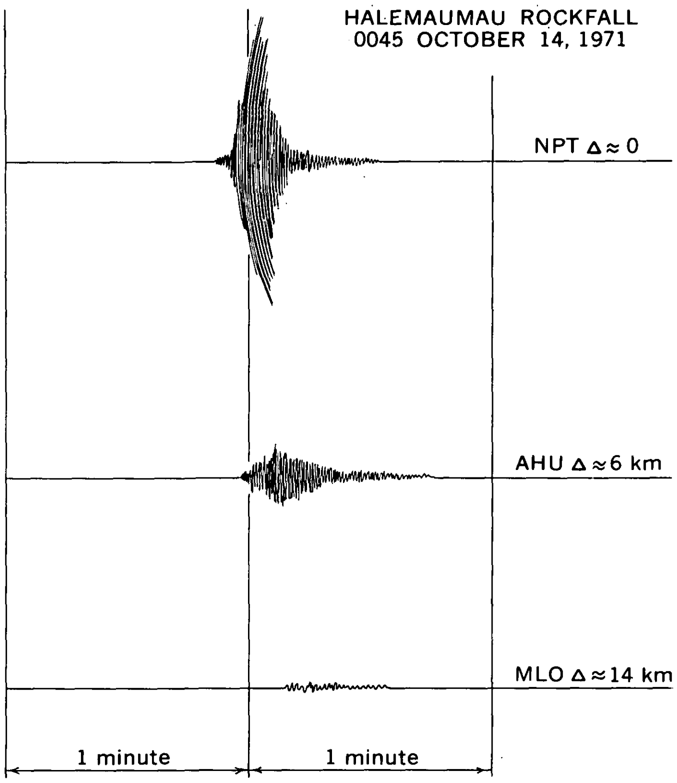

FIGURE 11.—Smoke-drum traces of a rockfall in Halemaumau pit crater, October 1971, showing the differences in seismic signature as recorded by three instruments located at increasing distances from the rockfall site (fig. 1): NPT (≈0 km); AHU (≈6 km); and MLO (≈14 km).

onset, frequencies ranging from 1 to 5 c/s, and high attenuation of signal with increasing distances, especially for the higher frequencies. Figures 11–13 show the actual traces or quantitative depiction of seismic signals as recorded for some rockfalls and earthquakes. The relatively low propagation velocities of rockfalls, as implied by the lag time of the first arrival across the seismic net, reflect the predominance of surface waves. At some stations, the signature of a rockfall may superficially resemble that of an L–P quake. However, on a network-wide basis, the decrease of trace amplitude with distance is noticeably more pronounced for rockfalls than for L–P quakes.

We chiefly analyzed the seismic records of five stations at increasing distances from the west pit of Makaopuhi Crater: (1) MPR, 1 km, (2) AHU, 9 km, (3) WLG, 11 km, (4) WHA, 17 km, and (5) MLO, 26 km (fig. 1). Events recorded only at MPR are defined as small, those recorded at stations from MPR to WLG moderate, and those recorded from MPR to MLO large. However, even large rockfalls were not recorded at stations more distant than MLO.

Velocity, frequency, and duration of rockfall-induced seismic waves

The recorded rockfall-generated seismic waves generally showed emergent arrival times, so that determination of velocity was difficult. Nonetheless, by measuring onset times as well as maximum-amplitude times recorded on various stations we were able to obtain rough apparent velocities. The apparent velocity at distances of several kilometers to about 26 km from Makaopuhi ranges from less than 1 km/s to nearly 2 km/s. This is appreciably lower than body-wave velocities determined from the region beneath the island of Hawaii (Eaton, 1962; Hill, 1969). Surface waves are probably dominant in the wave group observed on the seismograms.

For rockfalls, the seismic waves attenuate rapidly with distance traveled, as expected for shallow seismic

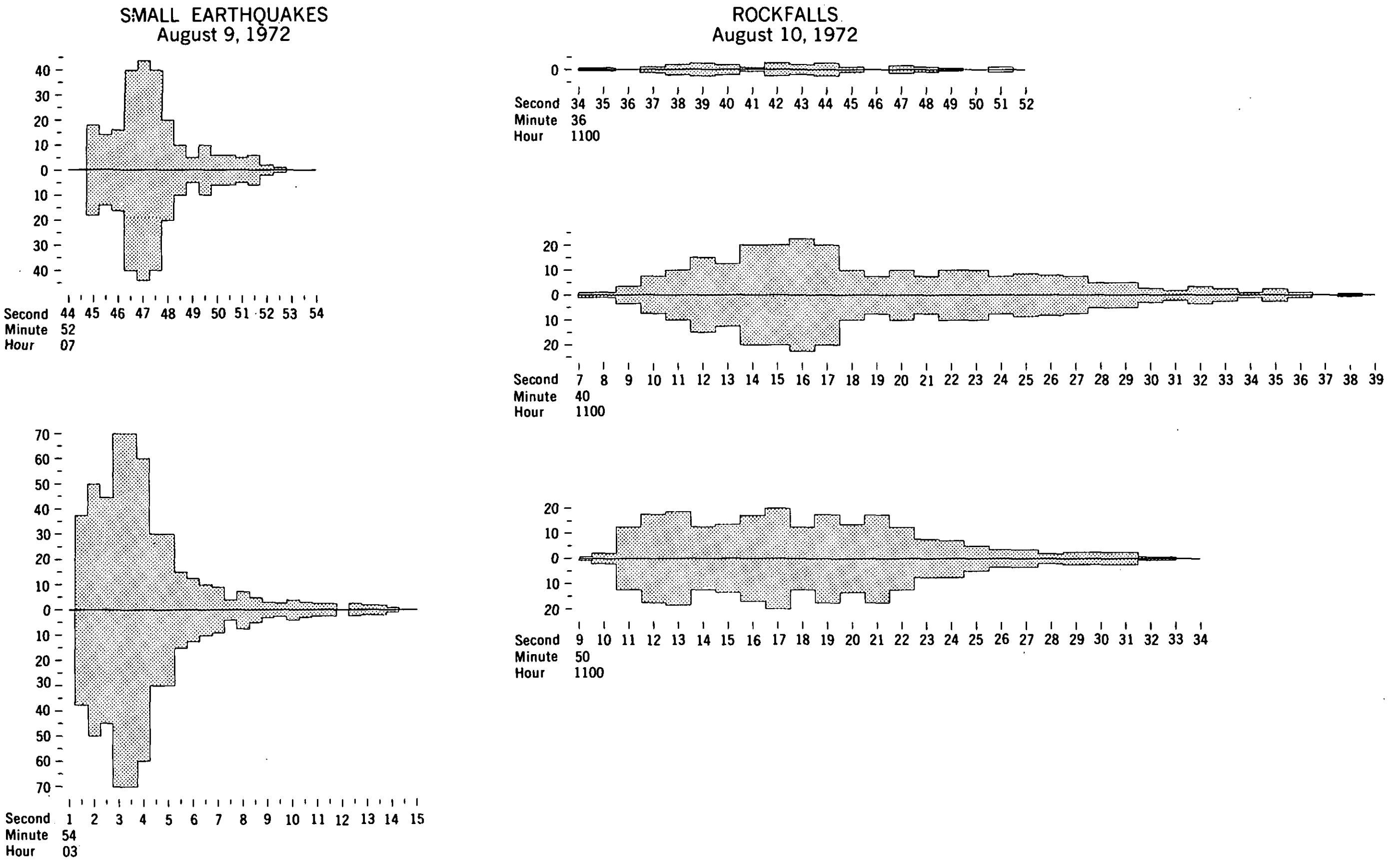

FIGURE 12.—Comparison of the amplitude-duration patterns of small earthquakes of August 9 and rockfalls of August 10, 1972, recorded on the seismograph (MPR) located on the east rim of Makaopuhi Crater (fig. 2). Amplitude readings were made from 16-mm strip-film (Develocorder) recordings magnified to 60 cm/min. The amplitudes were averaged at ½- or 1-s intervals plotted consecutively above and below a zero-amplitude reference line to quantitatively depict the amplitude-duration pattern of the seismic signal.

events (figs. 11, 13). The higher frequency component of the seismic waves attenuates much more rapidly than the lower frequency component. For example, at MPR station the predominant recorded frequency appears to be about 10 c/s, or about our reading threshold for high frequencies, but at AHU station about 9 km away the predominant recorded frequency is about 4 c/s. At MLO station, approximately 26 km from the site of rockfalls, the predominant recorded frequency is still lower, about 1.5 c/s. In general, the recorded predominant frequencies appear to decrease exponentially with distance of the recording stations from Makaopuhi (fig. 14).

Seismic waves generated by small, single rockfalls at Makaopuhi are generally less than a minute in duration, but larger events may last more than 1 min, in general accord with field observations. However, many of the events, especially the large ones, are complicated by the related occurrences of smaller events that tend to prolong the seismic disturbance at nearby stations. In addition, we speculate that the recorded duration also may depend on the nature of the rockfall. For example, a limited number of large, free-falling blocks impacting against a solid surface could result in a seismic trace of relatively large amplitude but short duration. In contrast, an event primarily involving the sliding and breaking up of material might produce a seismic signal of relatively small amplitude but long duration. Although the field and seismic data are inadequate to test these speculations, the lack of obvious correlation between duration and magnitude of large rockfalls (table 1) suggests that the recorded duration does not simply reflect rockfall size.

Seismic energy release of rockfalls

Approximate magnitudes for the large rockfalls were calculated from seismic amplitudes read on Uwekahuna (UWE) Sprengnether short-period records (fig. 1 and table 1). During the interval August 7–13, the fifteen largest rockfalls were 0.8 to 1.2 in magnitude. Using the magnitude-energy relation of Richter

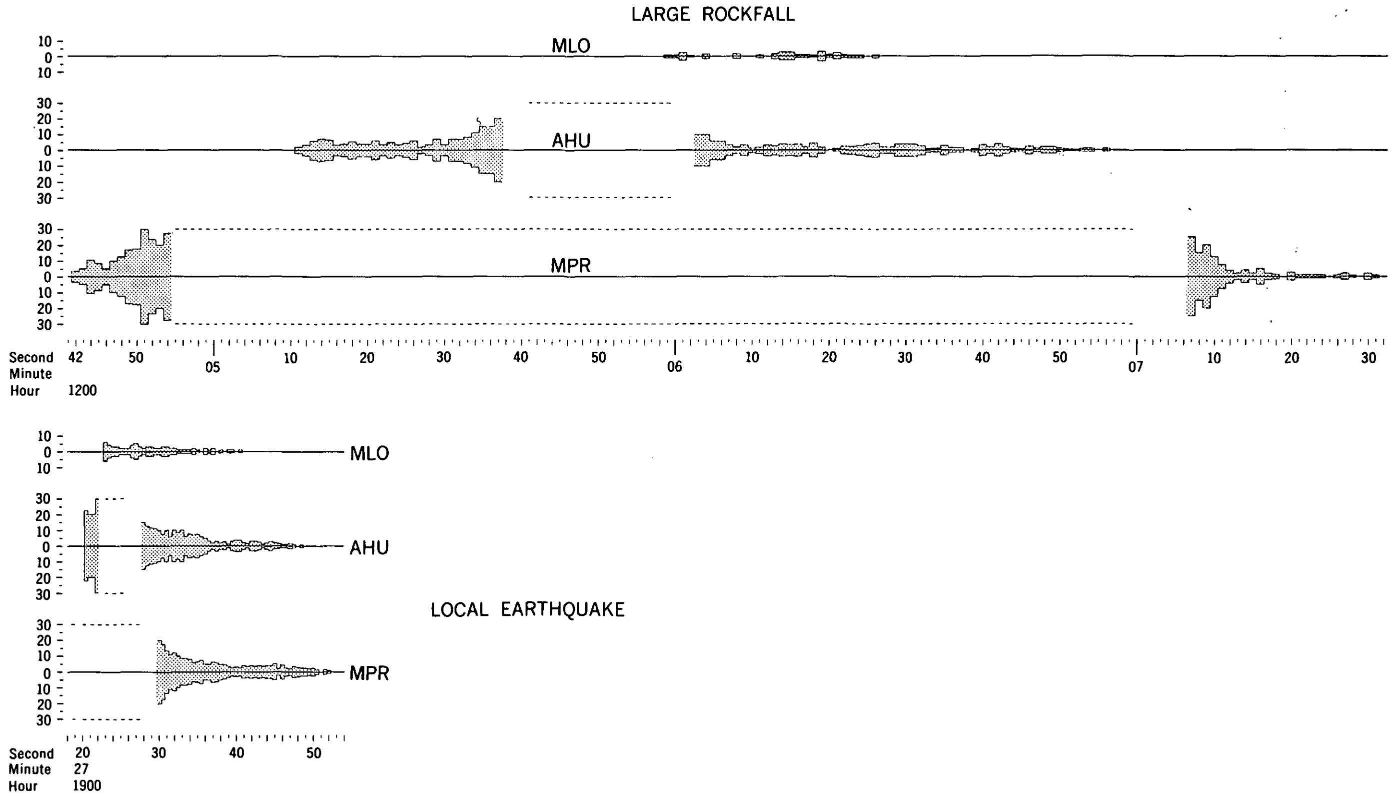

FIGURE 13.—Comparison of the amplitude-duration patterns of the large rockfall at 1206, August 10, 1972 with those of a local earthquake in the Makaopuhi area as recorded by three seismic stations at different distances from the site of the events (fig. 1): MLO, 26 km; AHU, 9 km; and MPR, 1 km. Amplitudes were determined from Develocorder 16-mm film traces and were averaged at 1-s intervals. The dashed portions of the AHU and MPR records indicate clipping of the seismic trace because of high amplitude.

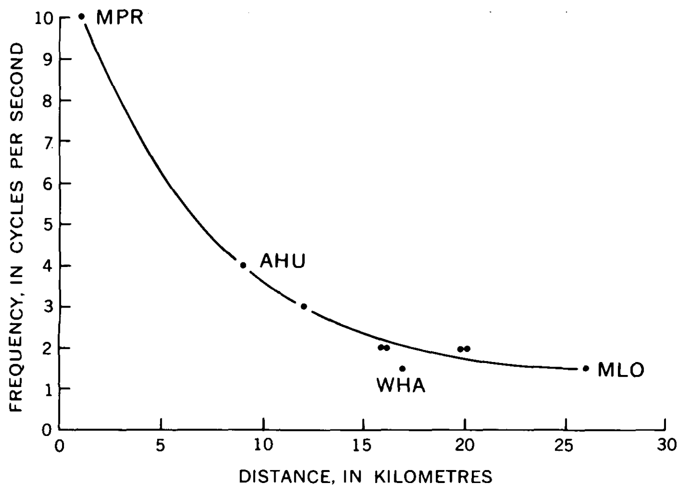

FIGURE 14.—Plot of predominant frequency (cycles per second) against distance of recording seismic station for a rockfall at Makaopuhi Crater, August 1972. See figure 1 for locations of stations denoted by MPR, AHU, WHA, and MLO.

(1958, p. 366) we estimated that the energy release of these events ranges from 2×10^{11} to 1×10^{12} ergs (table 1). If only these large events are considered, a minimum value of total seismic energy generated by the August 1972 rockfalls at Makaopuhi would be about 6×10^{12} ergs. A comparison of the seismic energy release and the kinetic energy release of some observed rockfalls shows no systematic relation between rockfall mass, kinetic energy, and seismic energy (table 2). Although the data given in table 2 are imprecise, they suggest a rather low efficiency of conversion of kinetic energy into seismic energy during rockfalls. The differences between the estimates of kinetic and seismic energies by several orders of magnitude stem partly from the assumptions used in their estimation. The values for kinetic energy are maxima because they assume complete transformation of gravitational potential energy to kinetic energy in frictionless freefall. On the other hand, the seemingly low estimates of seismic energies suggest that rockfall-generated seismicity for any given part largely reflects the impact of a relatively small number of large blocks against solid ground, rather than the total mass involved in downslope movement. Also, because of inherent differences in efficiency of energy transmission between earthquakes (deep) and rockfalls (surficial), Richter's (1958) magnitude-energy relation for earthquakes simply may be inapplicable for estimating the seismic energy of rockfalls.

TABLE 2.—*Comparison of seismic energy release and kinetic energy release of some rockfall events Kilauea Volcano, Hawaii*

Time and place of event(s)	Estimated volume (m^3)	Estimated mass [1] (kg)	Kinetic energy [2] (ergs)	Seismic energy [3] (ergs)
Aug. 31, 1971, at Mauna Ulu summit crater	5,000	1.3×10^{7}	9×10^{16}	4×10^{12}
1206 on Aug. 10, 1972, at Makaopuhi (see fig. 6)	8,000	2.1×10^{7}	3×10^{17}	7×10^{11}
Aug. 7–13, 1972, at Makaopuhi (all rockfalls)	[4] 270,000	7.0×10^{8}	1×10^{19}	[5] 6×10^{12}

[1] Calculated from volume assuming bulk density of rock to be 2.6 g/cm³.
[2] Assumes complete transformation of gravitational potential energy to kinetic energy in frictionless freefall; height of freefall for the Mauna Ulu event is 70 m and for the Makaopuhi events, 150 m.
[3] Calculated from energy-magnitude relation of Richter (1958); see table 1.
[4] Adjusted for assumed 20 percent open spaces in rockfall-talus cones.
[5] Sum of seismic energy for the large rockfalls given in table 1: because the seismic energies of the small and moderate rockfalls cannot be calculated, the value given is a minimum figure.

Seismic record of rockfalls

The proximity of rockfalls to station MPR made continuous monitoring possible, and this seismic record (fig. 15) indicates that rockfall activity, relatively minor between August 4 and 6, increased dramatically on August 7, both in number and in size of falls. The activity, except for a lull on August 11, remained at a high level through the afternoon of August 13 but waned noticeably that evening. Rockfall activity ceased by noon of August 14, but, after a 5-d respite, resumed weakly and intermittently during August 19–22 (fig. 15).

Figure 15 does not distinguish between small and moderate rockfalls but does indicate the times of large events. (See text, last paragraph under "Seismic signature of rockfalls," for size designations.) However, data shown in figure 16 illustrate that relative sizes of rockfalls can be readily determined by detailed study of records from more than one station. Larger rockfalls tend to be more common when the frequency of falls is high (figs. 15 and 16); this is compatible with some field observations that large rockfalls generally are associated with flurries of smaller rockfalls, some of which themselves are possibly induced by the large falls.

The large rockfalls at 1156 and 1206, August 10, that were well recorded seismically were also sufficiently impressive visually to cause onsite observers to take special notice. The seismic record, however, indicates another large rockfall at 1340 that escaped the attention of the observers and was not timed in the field as a large event (table 1). Conversely, the visually and audibly conspicuous rockslide on the west wall observed, photographed, and timed at ≈1230 apparently produced little seismicity; examination of the record for the interval 1215–1245 revealed no significant event, only the background seismicity generated by lava movement and the many small rockfalls from the north and south walls. The 1230 event well illustrates the fact that field and seismic evaluations of comparative rockfall intensity do not always agree.

The feeble seismicity of the 1230 event is puzzling but perhaps reflects one or both of the following factors: (1) The material moved down the gentler lava-talus slope of the west wall primarily by sliding and tumbling instead of free falling, and (2) various parts of the crater floor receiving rockfalls may have differed in gross elasticity related to varying proportions of solidified lava, molten lava, and unconsolidated lava-talus or rockfall-talus debris. If so, these observations imply that the rockfall seismicity is generated mainly by the impact energy of falling rocks striking the wall, crater floor, or previously fallen blocks, rather than by the energy released by fracturing, sliding, and jostling preceding and during the fall. A rockfall into mushy sluggish lava flows would have caused a weaker seismic response than a rockfall of comparable size onto solidified lava crust or unconsolidated but solid debris. Our observations also demonstrate that it might be difficult to attempt to correlate rockfall volume with seismic trace without supporting field observations. The fact that high-energy events can occur unnoticed by onsite

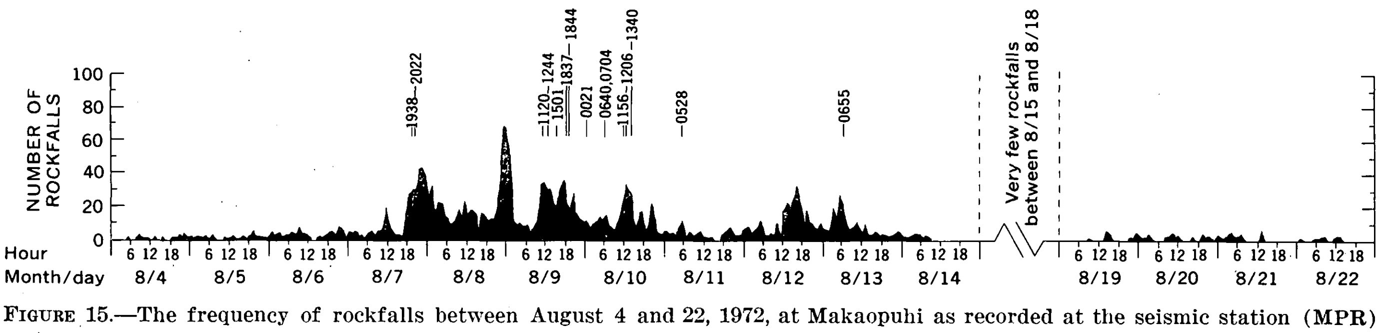

FIGURE 15.—The frequency of rockfalls between August 4 and 22, 1972, at Makaopuhi as recorded at the seismic station (MPR) on the east rim of the crater. The number of rockfalls, plotted on an hourly basis, includes all events regardless of size. However, the times of the large rockfalls (table 2) are indicated above the frequency curve. No rockfalls sufficiently large to be recorded even at MPR, only about 1 km from site, occurred between August 15 and 18.

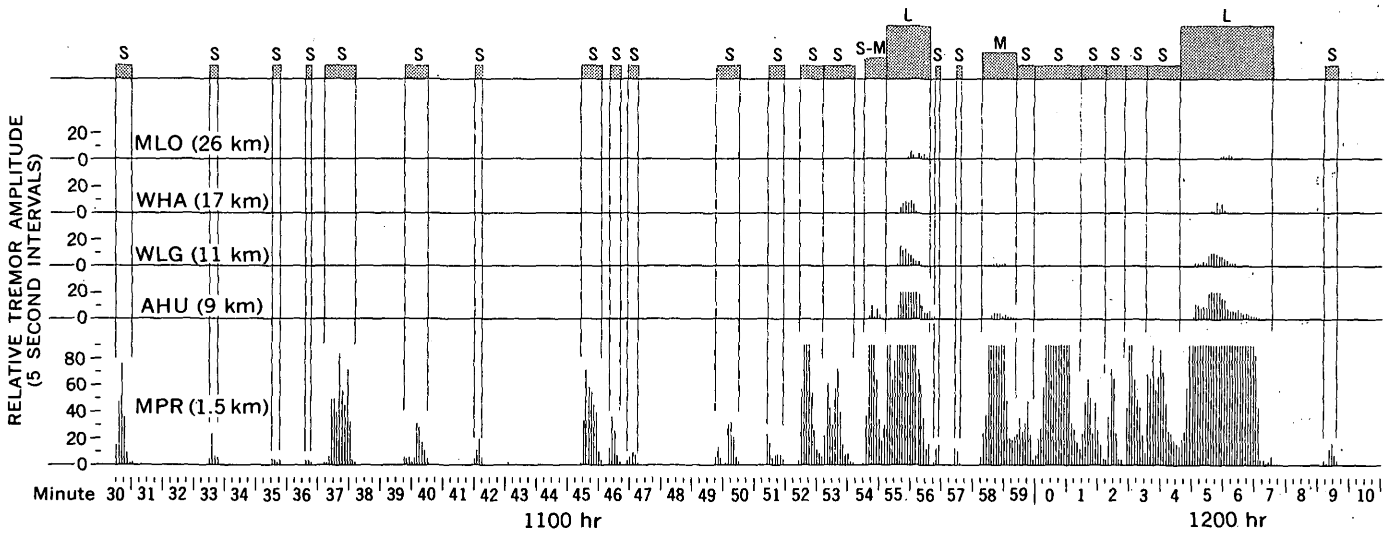

FIGURE 16.—Detailed seismic record of the rockfall activity at Makaopuhi between 1130 and 1210, August 10, 1972, as registered on five selected seismic stations at different distances from Makaopuhi's west pit (see fig. 1 for locations of stations). The letters S, M, and L refer to the arbitrary size classification (small, moderate, and large) based on the seismic trace amplitude. (See text.) In general, the size classifications based on seismicity were confirmed by field observations. Part of the large event at ≈1206 was documented photographically (fig. 6).

Amplitudes were read at 1-s intervals on the 16-mm Develocorder film recordings. To compensate for varying levels of background introduced on the seismic recordings from harmonic (volcanic) tremor in the Mauna Ulu-Alae area and from various microseismic noises, amplitude readings were reduced to an appropriate threshold for each station. The 1-s readings were compiled and averaged for consecutive 5-s intervals; the 5-s averages were then plotted chronologically.

The conspicuous pickup of amplitude for signals from the Makaopuhi station (MPR) is due to the impact of rockfall at Makaopuhi Crater. In general, larger events were recorded at more distant stations, with attenuation, and amplitude peaks delayed according to distance from Makaopuhi. Seismic traces that approached high amplitude and that were inappropriately placed on the film made some measurements difficult. As a partial compensation for this problem, an upper limit of measurement was placed for the purpose of plotting, depending on the readability of each station read.

observers primed to watch for them indicates that seismic instruments may be superior to human observations in identifying such events during periods of intense and overlapping rockfall activity.

CAUSE OF THE ROCKFALLS

The rockfall activity at Makaopuhi Crater during August 7–13, 1972, relative to other recent Kilauean rockfall episodes, was particularly vigorous and sustained. Why did the rash of rockfalls occur there at that time, with only minor activity before and since? Can seismic and other evidence provide clues to possible causes of the abnormally intense rockfall activity?

We recognize that many processes may have acted to weaken or "work" the walls of Makaopuhi prior to the rockfall activity in 1972. One important process probably was the collapse that formed the west pit of the crater itself, resulting in steep-sided, probably oversteepened, walls. In addition, a few relatively incompetent strata (clinkery parts of aa flows, cinder deposits, and other rubbly zones) interlayered with the more massive, ledge-forming lavas have been weathered to form notched, locally undercut areas on the crater walls. Since the initial collapse, doubtless the combined processes of mechanical weathering, mass wasting, deformation associated with pre-1972 eruptions in and near Makaopuhi, and previous minor rockfalls further contributed to slope instability. On the supposition that the walls of Makaopuhi's west pit had been significantly weakened prior to 1972, we have considered the following hypotheses regarding factors that might have triggered the intense rockfall activity: (1) Chain reaction, (2) heavy rainfall, (3) strong earthquakes, and (4) magma movement.

Chain reaction

According to this model, a few small rockfalls of unknown origin undermined and shook the crater wall, triggering larger rockfalls that in turn triggered still larger ones until the peak activity on August 9 and 10. We disfavor this hypothesis because seismic data indicated an abrupt rather than gradual increase of rockfall activity the evening of August 7 (fig. 15). Moreover, field observations showed that the occasional small rockfalls prior to August 7 were distributed widely on both the north and the south walls and not localized in any one area, as might be expected from chain-reaction processes. It is unlikely that small rockfalls from one wall could initiate rockfalls on the opposing wall 500 m away, although some field evidence suggests that large rockfalls can trigger minor activity on the opposite wall. (See "Rockfall activity on August 10, 1972.")

Heavy rainfall

This process requires vigorous percolation of rainwater into fractured ground to lubricate the contact points between individual blocks until the frictional threshold is exceeded to allow slip and, eventually, fall of the blocks. Minor rockfalls have occurred in Halemaumau and other Kilauean pit craters during and immediately after abnormally heavy rainfalls. However, precipitation records for the observatory area, which generally receives precipitation similar to that received by the Makaopuhi area (Taliaferro, 1959), indicate no precipitation in excess of normal; in fact, records for May–August 1972 show the rainfall to be slightly below average. Also, our field observations at Makaopuhi in August generally were made under sunny conditions or sometimes under intermittent light showers.

Strong earthquakes

The hypothesis that the Makaopuhi rockfalls were caused by an unusually high incidence of moderate to large earthquakes preceding or during the intense rockfall activity is not tenable because seismic data clearly show that the months of July and August were not anomalous in earthquake activity. Only two earthquakes of magnitude 2 to 2.5 (both located within 5 km of Makaopuhi) were recorded in August, which also was low in the total number of quakes (all magnitudes), especially during the interval of intense rockfall activity. (Compare figs. 15 and 17.)

Magma movement

The prime agent in causing the rockfalls may be the deformation associated with surface or subsurface

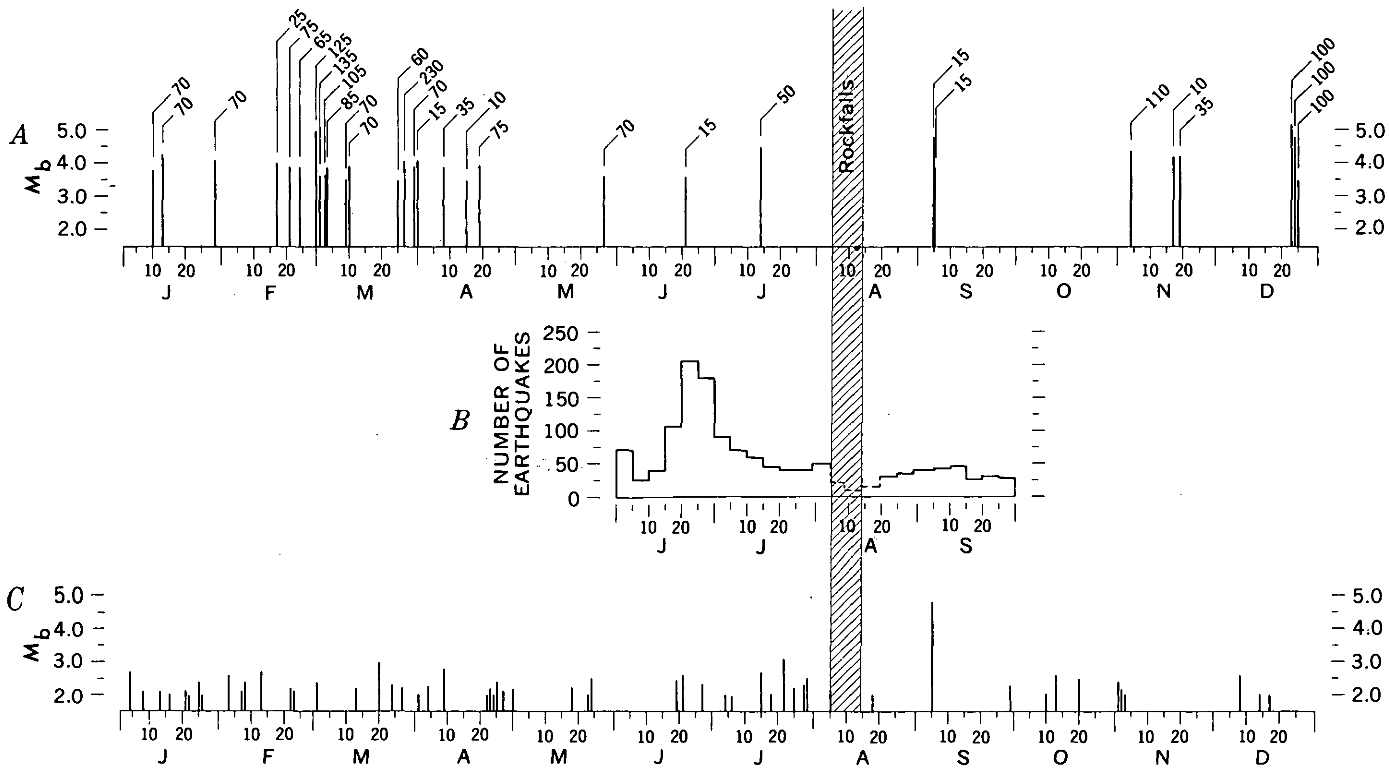

FIGURE 17.—Plot of island-wide earthquakes of magnitude (M_b) ≧3.5 for the calendar year 1972; approximate focal distances in kilometres relative to Makaopuhi's west pit are given by the numbers above each event. *B*, Plot of total number of earthquakes (5-d averages) on Kilauea's upper east rift and adjacent south flank regardless of magnitude. Precise counts of the earthquakes during August 6–14 were not possible because intense rockfall activity and high winds obscured the record. Thus, only large earthquakes that could readily be identified in the seismic records were counted for the August 6–14 interval. The actual total count probably would not exceed the minimum count (shown by dashed line) by more than a factor of two. *C*, Plot of earthquakes of magnitude ≧2 and depths ≦15 km located near the rockfall area within the coordinates lat 19° 20′–23′ N. and long 155° 09′–14′ W. for 1972. (See fig. 1 for location of area relative to Makaopuhi Crater.)

magma movement. Because most major rockfall episodes in Kilauea's caldera and pit craters in the past have been associated with volcanic activity (table 3),

TABLE 3.—*Some notable episodes of rockfall activity at Kilauea Volcano in recent years in pit craters other than Makaopuhi Crater*

[See fig. 1 for locations of sites]

Date	Site	Remarks
December 1962	Aloi Crater (later buried by 1969–70 lavas).	One large rockfall immediately after the short eruption (Dec. 7–9, 1962) and many smaller ones on the next day.
July 1963	Devil's Throat	Numerous small rockfalls during earthquake swarm and ground cracking associated with inferred intrusive event (no lava erupted in the Koae-upper east rift area).
December 1967–July 1968	Halemaumau pit (summit).	Several rockfalls, observed as well as recorded seismically, during the 1967–68 summit eruption (Nov. 5, 1967–July 13, 1968). Also a few rockfalls at Makaopuhi.
February 1969	Alae Crater	Moderate rockfall activity during the February 1969 east-rift eruption. Also some rockfalls at Makaopuhi.
May 1969–summer 1971	Mauna Ulu Crater (and the numerous smaller pits which preceded it).	Rockfalls, commonly observed either directly or indicated by dust cloud (see fig. 9), throughout the eruption, particularly after abrupt lowering of lava-lake levels.
October–November 1971	Halemaumau pit (summit).	Apparently no significant rockfall activity during the September 24–29 eruption; however, the number of rockfalls recorded increased significantly in early October. Moderate activity continued sporadically through November.
February 1972–June 1973	Mauna Ulu Crater and fissure trough; Alae shield (site of former Alae Crater).	With resumption of eruptive activity at Mauna Ulu-Alae, (Feb. 4, 1972), rockfall activity has also resumed.

we favor this hypothesis. Commonly, rockfall activity begins or increases during times of significant changes in eruptive behavior, such as the opening of new vents, changes in old vents, fluctuations in lava-lake levels, and increase in harmonic tremor (Tilling, 1974). Deformation produced by intrusive activity could probably trigger rockfalls. Subsurface magma movement is known to measurably deform the volcanic edifice (for example, Fiske and Kinoshita, 1969; Swanson and others, 1971a, b; Koyanagi and others, 1972), and the persistent jostling of rocks accompanying such deformation should not only prepare the ground for rockfalls but could also trigger them.

Assuming that the Makaopuhi rockfalls, like most Kilauean rockfalls, were produced by volcanic processes, we have speculated on several mechanisms that could have altered the stress patterns in the crater walls to cause them. These mechanisms all assume a genetic link between the rockfalls and the mezzanine eruption but differ according to the following volcanic-structural settings: (1) A local surface lava reservoir, (2) a local subsurface magma reservoir, and (3) a general east-rift dilation.

Local surface lava reservoir.—The rockfalls were triggered by stress changes related to the accumulation of lava in Makaopuhi's west pit. By August 7 lava filling the pit began to exert sufficient hydrostatic pressure to affect the crater walls, exceeding their threhold stability and initiating rockfalls. The increased hydrostatic pressure also caused breakout on the mezzanine of lava injected laterally from the west pit. This mechanism is appealing because it invokes only the observed filling of the west pit; no other structural complexities or volcanic processes are required.

Local subsurface magma reservoir.—Both the rockfalls and mezzanine eruption were caused by local stress-pattern shifts associated with the inflation or deflation of a subsurface magma reservoir near Makaopuhi. (Evidence presented by Jaggar (1930b) and by Richter, Moore, and Haugen (1962) indicates that the widening of cracks around craters, eventually leading to rockfalls, can be caused by either inflation or deflation.) The mezzanine lava was derived from the same reservoir. This mechanism is considered plausible because several lines of evidence suggest that such a subsurface reservoir may have existed and was operative as late as 1969 (Jackson and others, 1975; Swanson and others, 1975; Hawaiian Volcano Observatory, unpub. data, 1975).

General east-rift dilation.—Changes in stress patterns to induce rockfalls and to cause the mezzanine eruption were local responses to a more general dilation of the east-rift zone in the vicinity of Makaopuhi. The fundamental cause of the gross dilation was the movement of magma from Kilauea's summit reservoir into the east-rift zone. This mechanism is attractive because repeated dilations of Kilauea's east rift zone and related mobility of its south flank have been well documented (for example, Fiske and Kinoshita, 1969; Swanson and others, 1971a, b; and Koyanagi and others, 1972).

Several approaches can be used in evaluating the three mechanisms outlined above: (1) Comparison of ground-deformation effects in the vicinity of Makaopuhi before and after the rockfall swarms in August 1972, (2) comparison of mineralogy and chemistry of the lava erupted on the mezzanine with the mineralogy and chemistry of the 1965 Makaopuhi lavas and 1972 Mauna Ulu–Alae lavas, and (3) analysis of seismicity (earthquake and rockfall) before, during, and after the August activity. Unfortunately, because the previously monitored deformation network in the Makaopuhi area has been destroyed and not reestablished owing to eruptive activity during and since 1969, critical evidence regarding ground deformation is lacking. Although chemical analyses of the mezzanine and other 1972 lavas are not yet available, we anticipate that they could be used to determine whether or not the mezzanine lava is petrologically relatable to lava in Makaopuhi's west pit, thereby providing a test of the local surface reservoir mechanism. At present, however, in lieu of other data, only the approach involving seismic evidence can be considered.

For many weeks prior to the rockfall swarms in August, seismic data for the upper east rift showed an increase in harmonic tremor and, possibly, small earthquakes. Then tremor level decreased beginning about midmorning of August 6 and remained comparatively low throughout the week of intense rockfall activity (August 7–13). We interpret these observations to suggest a period of heightened local dilation and ground vibration caused by near-surface magma movement and injection before vigorous rockfall activity. The overall decrease in tremor after the onset of rockfall flurries may indicate that the stressed areas were relaxing as pressure was relieved when lava eventually broke through to the surface on the mezzanine. However, this interpretation is compatible with any of the three hypothesized mechanisms involving magma movement.

Therefore, presently available data suggest that the Makaopuhi rockfalls in 1972 were caused by ground deformation related to magma movement but are insufficient to pinpoint the exact nature of such deformation and the actual mechanisms that trigger and sustain the intense rockfall activity. Ground-deformation data and more detailed seismic information before, during, and after the activity are essential to identify unambiguously the causes of the rockfalls. In this respect, the deployment of a dense seismic net around Makaopuhi would have been most useful to better determine the locations of small earthquakes and to analyze harmonic tremor more accurately.

A denser seismic network around Makaopuhi would have enabled us to locate more precisely the small earthquakes detected on the MPR station before the major rockfalls. If magma had forced itself along a confined shallow zone from near Alae to the Makaopuhi mezzanine, the hypocentral distribution of the small quakes may provide evidence for such magma movement. A more quantitative analysis of harmonic tremor would probably involve more sensitive and sophisticated instrumentation because of the need to distinguish between the nearly continuous but fluctuating tremor related to activity at the Mauna Ulu–Alae vents approximately 3 km to the west and the tremor reflecting magma movement local to Makaopuhi.

SUMMARY

In about a week's time during August 1972, rockfall activity at Makaopuhi Crater deposited about 2.7×10^5 m^3 of debris in its west pit, representing a maximum total kinetic energy release of about 10^{19} ergs. The calculated combined seismic energy release for the 15 largest events during this interval is about 6×10^{12} ergs, which is a minimum estimate because the seismic energies for many hundreds of small to moderate rockfalls cannot be considered.

Seismic signatures of rockfalls are distinct from those of other seismic events, natural or man-induced, and large falls are recorded at seismic stations as much as 26 km distant. Rockfall seismicity apparently registers mainly the impact energy of blocks falling against solid material (crater wall, floor, or previously fallen blocks) and only subordinately the energy released by fracturing, jostling, and sliding immediately preceding and during downslope movement.

The immediate cause of the rockfalls at Makaopuhi pit crater was sustained local deformation related to volcanism. The rockfall activity in the west pit of Makaopuhi and the eruptive outbreak on the floor of its east pit (mezzanine) were genetically related and were caused by the same dynamic forces. Changes in stress configurations of the crater walls to induce rockfalls are not known but are believed to be related to local deformation caused by magma movement on or beneath the surface in the Makaopuhi area.

Seismic data provide an accurate chronology of rockfalls, estimates of their relative impact energies, and other key information about landslide mechanisms. The seismic network employed in this study was established primarily to record earthquakes and harmonic tremor related to volcanism, but nonetheless we believe our results show the potential of studying rockfall seismicity in certain geomorphology, engineering geology, or geologic hazards investigations. Seismic studies with use of a specially designed network could constitute an important adjunct in systematic research on rockfalls and other landslide phenomena, particularly in areas not amenable to repeated direct field observations because of remoteness or logistic difficulties.

REFERENCES CITED

Eaton, J. P., 1962, Crustal structure and volcanism in Hawaii: Am. Geophys. Union Geophys. Mon. 6, p. 13–29.

Endo, E. T., Koyanagi, R. Y., Okamura, A. T., 1972, Hawaiian Volcano Observatory summary 57, January, February, March 1970: U.S. Geol. Survey, 54 p.

Finch, R. F., 1949, Volcanic tremor, part I: Seismol. Soc. America Bull., v. 39, p. 73–78.

Fiske, R. S., and Kinoshita, W. T., 1969, Rift dilation and seaward displacement of the south flank of Kilauea Volcano, Hawaii, *in* Volume of abstracts *of* Symposium on volcanoes and their roots: Internat. Assoc. Volcanology Chemistry Earth's Interior, Oxford, England, 1969, p. 53–54.

Hill, D. P., 1969, Crustal structure of the island of Hawaii from seismic-refraction measurements: Seismol. Soc. America Bull., v. 59, p. 101–130.

Jackson, D. B., Swanson, D. A., Koyanagi, R. Y., and Wright, T. L., 1975, The August and October 1968 flank eruption of Kilauea Volcano, Hawaii: U.S. Geol. Survey Prof. Paper 890. (In press.)

Jaggar, T. A., 1930a, Meaning of crater avalanches: The Volcano Letter, no. 269, p. 1–3.

——— 1930b, Rim cracks and crater slides: The Volcano Letter, no. 283, p. 1–3.

Koyanagi, R. Y., 1969, Hawaiian seismic events during 1968, *in* Geological Survey research 1969: U.S. Geol. Survey Prof. Paper 650–D, p. D168–D171.

Koyanagi, R. Y., Swanson, D. A., and Endo, E. T., 1972, Distribution of earthquakes related to mobility of the south flank of Kilauea Volcano, Hawaii, *in* Geological Survey research 1972. U.S. Geol. Survey Prof. Paper 800–D, p. D89–D97.

Krivoy, H. L., and Eppley, R. A., 1964, T-phase of May 11, 1962, recorded in Hawaii. *in* Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501–B, p. B105–B107.

Krivoy, H. L., Johnson, C. G., and Koyanagi, R. Y., 1967, An usual example of pseudo-seisms resulting from military exercises: Pacific Sci., v. 21, p. 119–128.

Omer, Guy C., Jr., 1950, Volcanic tremor, Part 2, The Theory of volcanic tremor: Seismol. Soc. America Bull., v. 40, p. 175–194.

Richter, C. F., 1958, Elementary seismology: San Francisco, W. H. Freeman, 768 p.

Richter, D. H., Moore, J. G., and Haugen, R. T., 1962, Recent growth of Halemaumau, Kilauea Volcano, Hawaii, *in* Short papers in geology, hydrology, and topography: U.S. Geol. Survey Prof. Paper 450–B, p. B53–B56.

Shimozuru, Daisuke, Kamo, Kosuke, and Kinoshita, W. T., 1966, Volcanic tremor of Kilauea Volcano, Hawaii, during July–December 1963: Earthquake Research Inst. Bull., v. 44, p. 1093–1133.

Stearns, H. T., and Macdonald, G. A., 1946, Geology and groundwater resources of the island of Hawaii: Hawaii Div. Hydrography Bull. 9, 363 p.

Swanson, D. A., Duffield, W. A., Jackson, D. B., and Peterson, D. W., 1972, The complex filling of Alae Crater, Kilauea Volcano, Hawaii: Bull. Volcanol., v. 36, p. 105–126.

Swanson, D. A., Duffield, W. A., and Okamura, R. T., 1971a, Seaward displacement of the south flank of Kilauea Volcano [abs.]: Am. Geophys. Union Trans., v. 52, no. 4, p. 372.

——— 1971b, Mobility of Kilauea's south flank related to rift intrusion [abs.], *in* Symposium on volcanism and upper mantle earthquakes: Internat. Union Geodesy and Geophys., 15th Gen. Assembly, Moscow, U.S.S.R., Program, p. 29.

Swanson, D. A., Jackson, D. B., Duffield W. A., and Peterson, D. W., 1971, Mauna Ulu eruption, Kilauea Volcano: Geotimes, v. 16, no. 5, p. 12–16.

Swanson, D. A., Jackson, D. B., Koyanagi, R. Y., and Wright, T. L., 1975, The February 1969 east-rift eruption of Kilauea Volcano, Hawaii: U.S. Geol. Survey Prof. Paper 891. (In press.)

Taliaferro, W. J., 1959, Rainfall of the Hawaiian Islands: Hawaii Water Authority, 394 p.

Tilling, R. I., 1974, Rockfall activity in pit craters, Kilauea Volcano, Hawaii, *in* Volume of abstracts *of* International Symposium on Volcanology: Internat. Assoc. Volcanology Chemistry Earth's Interior, Santiago, Chile, 1974, p. 71–72.

Tilling, R. I., Peterson, D. W., Christiansen, R. L., and Holcomb, R. T., 1973, Development of new volcanic shields at Kilauea Volcano, Hawaii [abs.]: Internat. Union Quarternary Research, 9th Cong., Christchurch, New Zealand, Dec. 2–10, 1973, Program, p. 366–367.

Wright, T. L., Kinoshita, W. T., and Peck, D. L., 1968, March 1965 eruption of Kilauea Volcano and the formation of Makaopuhi lava lake: Jour. Geophys. Research, v. 73, p. 3181–3205.

JOURNAL OF RESEARCH

OF THE U.S. GEOLOGICAL SURVEY

MAY-JUNE 1975
VOLUME 3, NUMBER 3

Scientific notes and summaries of investigations in geology, hydrology, and related fields

U.S. DEPARTMENT OF THE INTERIOR